Ensuring a Sustainable Supply of Raw Materials for Electric Vehicles

A Synthesis Paper on Raw Material Needs for Batteries and Fuel Cells

Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

About

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PRODUCED ON BEHALF OF

Agora Verkehrswende
Anna-Louisa-Karsch-Str. 2
10178 Berlin, Germany
T +49 (0)30 700 14 35-000
F +49 (0)30 700 14 35-129
www.agora-verkehrswende.de
info@agora-verkehrswende.de

PROJECT LEADER

Kerstin Meyer
kerstin.meyer@agora-verkehrswende.de

PRODUCED BY

Öko-Institut e. V.

Darmstadt Office
Rheinstraße 95
64295 Darmstadt
T +49 (0)30 61 51 81 91-0

Dr Matthias Buchert, Stefanie Degreif, Peter Dolega

Typesetting: Juliane Franz, Agora Verkehrswende
Cover image: fotolia.com/Galyna Andrushko
Translation: WordSolid

Published March 2018
08-2018-EN

ACKNOWLEDGEMENTS

As part of this study, we held a workshop in May 2017 that brought together representatives from the worlds of business, academia, civil society and government. The workshop facilitated an exhange of views on the future demand for raw materials for electric vehicles and the challenges this rising consumption will pose. The results of the workshop have been incorporated into our findings. We would like to thank the workshop participants for sharing their expertise and for the many fruitful discussions to which they contributed. This study's conclusions and recommendations for action nevertheless do not necessarily reflect the opinions of the individual workshop participants. Agora Verkehrswende and the Öko-Institut assume sole responsibility for content.

Please cite as:
Öko-Institut (2018): Ensuring a Sustainable Supply of Raw Materials for Electric Vehicles: A Synthesis Paper on Raw Material Needs for Batteries and Fuel Cells.

Foreword

Dear readers,

At Agora Verkehrswende, we believe there are two main pilars to the impending transformation of transport systems worldwide – namely, a change in how transport is used (i.e. the *Mobilitätswende*, or "mobility transition") and a change in the way vehicles are powered (i.e. the *Energiewende im Verkehr*, or "energy transition in transport").

The mobility transition is urgently needed to slash energy consumption in the transport sector without restricting mobility as a whole. To make the transport sector largely climate neutral by the middle of the century, it is imperative to not only shift to renewables, but also to halve the energy required by the transport sector as a whole.

Regarding the energy transition in transport, electric vehicles will play a crucial role. Electric vehicles are extremely energy efficient, and with greater reliance on solar and wind energy, they may become virtually climate neutral in future. By promoting the expansion of the electric vehicle sector, we can significantly reduce our overall fossil fuel consumption. This will not only help us to meet carbon reduction targets for the transport sector, but will also serve to reduce our dependency on oil imports.

It would nevertheless be a mistake to believe that adopting electric vehicles will automatically rid us of our dependency on raw material imports. Electric vehicle production requires a range of finite and non-renewable metallic raw materials and rare earth elements, which are sometimes only found in a small number of countries.

Twenty-five years ago, China's then president, Deng Xiaoping, summed up the political challenges posed by the raw material needs of new technologies when he remarked that "The Middle East has oil, but we have rare earths." It would seem he was presciently aware of the strategic significance of rare earths for the transport systems of tomorrow.

The significance of specific raw materials is now abundantly clear, for these commodities are essential for the manufacture of electric vehicles, and, by extension, they are crucial to the decarbonisation of the transport sector as a whole. Yet are these raw materials available in sufficient quantities to enable the rapid development of the electric vehicle market, or might their potential scarcity bring widespread adoption to a premature halt? This is one of the key questions addressed by the authors of this study.

Clearly, sustainability means much more than just "long-term availability". It also means ensuring environmental standards and viable conditions for workers across the entire supply chain. Accordingly, the study takes the environmental impacts and working conditions associated with each raw material into account.

Based on our analysis, we have developed strategic recommendations for action to help ensure a sustainable supply of raw materials for electric vehicles. Our paper is intended to stimulate discussion, and we look forward to hearing your comments, critiques and suggestions.

Let's work together to ensure a propitious future for electric vehicles and the climate neutral transport systems of tomorrow.

Christian Hochfeld
On behalf of the Agora Verkehrswende team
Berlin, 5 October 2017

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Executive Summary

Electric vehicles are the key to decarbonising the transport sector. Indeed, research shows that the rapid, robust and widespread adoption of vehicles powered with electricity from batteries or fuel cells is essential for the global transport sector to become climate-neutral by 2050. However, a range of non-renewable materials that are only mined in a limited range of countries are required to manufacture batteries and fuel cells. This study examines whether these commodities (i.e. lithium, cobalt, nickel and graphite for batteries, and platinum for fuel cells) are available in sufficient quantities for the large-scale production of electric vehicles. In this connection, it explores how market prices for key commodities could potentially develop in coming decades. It also considers measures for ensuring raw-materials mining is socially and environmentally sustainable.

The study's estimates are based on the climate protection scenarios developed by the International Energy Agency (IEA). Specifically, we estimate the commodity needs in 2030 and 2050 that would be associated with the IEA's forecasts for growth in electric-powered trucks, cars, buses, motorcycles and pedelecs. Our study assumes continued use of lithium-ion batteries up to 2050.[1]

1 We assume that lithium-ion batteries are the dominant battery type up to 2050. Our conclusions with regard to the future availability of raw materials would need to be re-assessed if new battery technologies that are not used commercially today were to achieve widespread adoption.

Key Findings

1. Lithium, cobalt, nickel, graphite and platinum are available in sufficient quantities to enable the rapid, worldwide adoption of electric vehicles. Proven global reserves in each case greatly exceed forecasted demand, even when factoring in rising demand for these raw materials for other technological applications.

2. Temporary supply bottlenecks and price increases are possible, particularly for cobalt and lithium. This is predominantly attributable to two factors: First, some new mining sites may not be operational in due time. Second, source countries may not be able to export raw materials in sufficient quantities at all times.

3. The extraction of raw materials is inherently associated with environmental and social problems, and the commodities needed for battery technology are no exception in this regard. The problems in this area are multifarious and include the high energy consumption of mining operations, acid mine drainage, water conflicts between mining companies and indigenous peoples, and poor working conditions in mines. The artisanal mining in the Democratic Republic of Congo, where most known cobalt reserves are located, is a particularly egregious example of such problems.

Recommendations for Action

In light of our findings we have developed seven recommendations for action to safeguard the supply of raw materials needed to manufacture electric vehicle batteries and fuel cells. On the one hand, these recommendations seek to reduce the demand for primary raw materials in order to minimise the possibility of temporary bottlenecks or price increases. On the other hand, our recommendations are designed to improve environmental and social conditions across the entire commodities supply chain, particularly in source countries. This, in turn, should improve the integrity and reliability of supply networks.

Reducing demand for primary raw materials

Systematic recycling of the raw materials used to produce batteries and fuel cells would reduce demand for primary raw materials. As a result, recycling would help to ward off temporary production bottlenecks and associated price increases that could impair the adoption of electric vehicles. In order to improve the legal basis for an efficient recycling system, we recommend **reforming the EU Battery Directive.** A revised directive could establish quotas for the recycling of lithium, cobalt, nickel, and graphite. We also recommend the development of a **global recycling system for lithium-ion batteries.** Moreover, we advocate a **research offensive in the area of battery technology** in order to promote material efficiency, the use of substitute materials and the improvement of recycling techniques.

Beyond reducing demand for raw materials, a comprehensive recycling system could alleviate environmental and social problems across the entire supply chain for lithium-ion batteries.

Improving Environmental and Working Conditions in Raw Materials Extraction

In order to improve the environmental and working conditions associated with the mining of raw materials necessary for manufacturing electric vehicles, we recommend the establishment of a **global industrial alliance for sustainable lithium.** The goal of this initiative would be to develop and implement standards to ensure raw materials extraction is socially and environmentally sustainable. Against the backdrop of the problematic mining of cobalt in the Democratic Republic of Congo, we recommend that companies adopt a **Due Diligence Codex for Cobalt.** Such due diligence practices have previously proven beneficial for minimising the risks posed by conflict materials for workers, human health and the environment. One route for supporting the adoption of such practices is by promoting **international cooperation in sustainable mining.** Cooperative activities in this area should aim to facilitate the sharing of technology and knowledge that enables sustainable industrial and artisanal mining practices. Such activities would have the added benefit of enhancing security of supply for important raw materials.

As one cannot forecast the precise developments that will be witnessed in the coming years and decades in the dynamic market for the commodities needed to fuel the rise of electric vehicles, we advocate the adoption of an **Electric Vehicle Commodities Radar** to monitor the availability of raw materials on an ongoing basis. The goal of such a monitoring system would be to anticipate supply bottlenecks and price increases as well as to enable the implementation of targeted countermeasures.

01 | Key Questions

Both the Paris Agreement and the German Climate Action Plan 2050 set significant CO_2 reductions targets for the transport sector. These targets can only be reached by greatly increasing the number of electric vehicles on the road. Electric vehicles contain a range of special components, including electric motors, powerful batteries, fuel cells and power electronics. The manufacture of these components requires various commodities, including rare earths, lithium, platinum, cobalt and natural and synthetic graphite.

In 2011 export restrictions were imposed on a number of source countries for technology metals. Rare earth prices subsequently exploded, resulting in temporary supply bottlenecks. As a consequence, experts began to ask whether similar supply shortages might be encountered with other strategic raw materials in future.

In this vein, this study examines the supply situation for raw materials required to make electric vehicle batteries and fuel cells. The study incorporates the latest findings and data in this area, which have been used to calculate future raw material demand in two different scenarios. It focusses on lithium, cobalt, nickel, graphite and platinum.

The paper aims to address the following key questions: How will the growth of the electric vehicle sector affect demand for strategic raw materials? What potential challenges might result from this growth and where might supply bottlenecks arise? How are we to address these challenges and what are the most appropriate recommendations for action? A number of sub-chapters then consider various aspects of these topics, in order to do justice to their complexity.

02 | Global Scenarios for the Development of the Electric Vehicle Sector

Introduction

In 2015, lithium usage in the battery sector exceeded usage in the ceramic and glass sector for the first time. This was largely the result of rising demand for electric vehicles. In future, demand for a number of strategic raw materials will continue to be determined by the growth of the electric vehicle sector. The key aim of this study is thus to calculate the future rise in demand for these raw materials and to address the challenges this will pose. To this end, we consider two potential scenarios with differing levels of vehicle sales.

Scenario Selection

Various organisations, institutions and corporations have published their predictions for the future growth of the electric vehicle sector. In both their initial assumptions and their resulting projections, these studies have often varied considerably. Most independent institutions have nonetheless tended to take a maximum global temperature rise of 2°C by 2100 as a positive future scenario. The models based on such a scenario include the *Global Change Assessment Model* (GCAM), elaborated by the *Pacific Northwest National Laboratory* (PNNL); the *MESSAGE transport* model, by the International Institute for Applied Systems Analysis (IIASA); the *Roadmap Model* by the *International Council on Clean Transportation* (ICCT); and the *Mobility Model* (MoMo) by the *International Energy Agency* (IEA) (Yeh et al. 2016). Since the latter model is in part publicly accessible and contains a wealth of detailed and up-to-date data, we chose to base our projections on it. We consider both a positive scenario in which the global average temperature does not rise by more than 2°C by 2100 (two-degrees scenario, or 2DS) and a reference scenario (four-degrees scenario, or 4DS), which provides for a temperature rise of up to 4°C (IEA 2016 a).

Methodology in Brief

On the basis of the IEA data, we elaborated two scenarios for sales of cars, HGVs, buses, motorcycles[2] and pedelecs up to 2050. We distinguished both between different vehicle types and between different powertrain types (see Table 2.1). The IEA figures were used to derive annual sales figures for the different vehicle types on each scenario, on the basis of a Gaussian distribution incorporating specific vehicle end-of-life cycles. Wherever possible, we drew on official sales statistics for the 2015 base year. On this basis, we were able to calculate the annual demand for raw materials for 2015, 2030 and 2050.

2 Which include motorbikes, mopeds, and scooters.

Vehicle types referred to in the present study — Table 2.1

Internal combustion engine (ICE)	Diesel or petrol-driven vehicle with a conventional engine.
Hybrid electric vehicle (HEV)	Vehicle containing an internal combustion engine and an electric motor with a small battery that cannot be externally charged
Plug-in hybrid electric vehicle (PHEV)	Vehicle with an internal combustion engine and an electric motor with a large battery that can be externally charged
Battery electric vehicle (BEV)	Battery-powered electric vehicle with a large battery
Fuel cell electric vehicle (FCEV)	Vehicle powered by a fuel cell

Compilation: Öko-Institut e.V.

The Scenarios

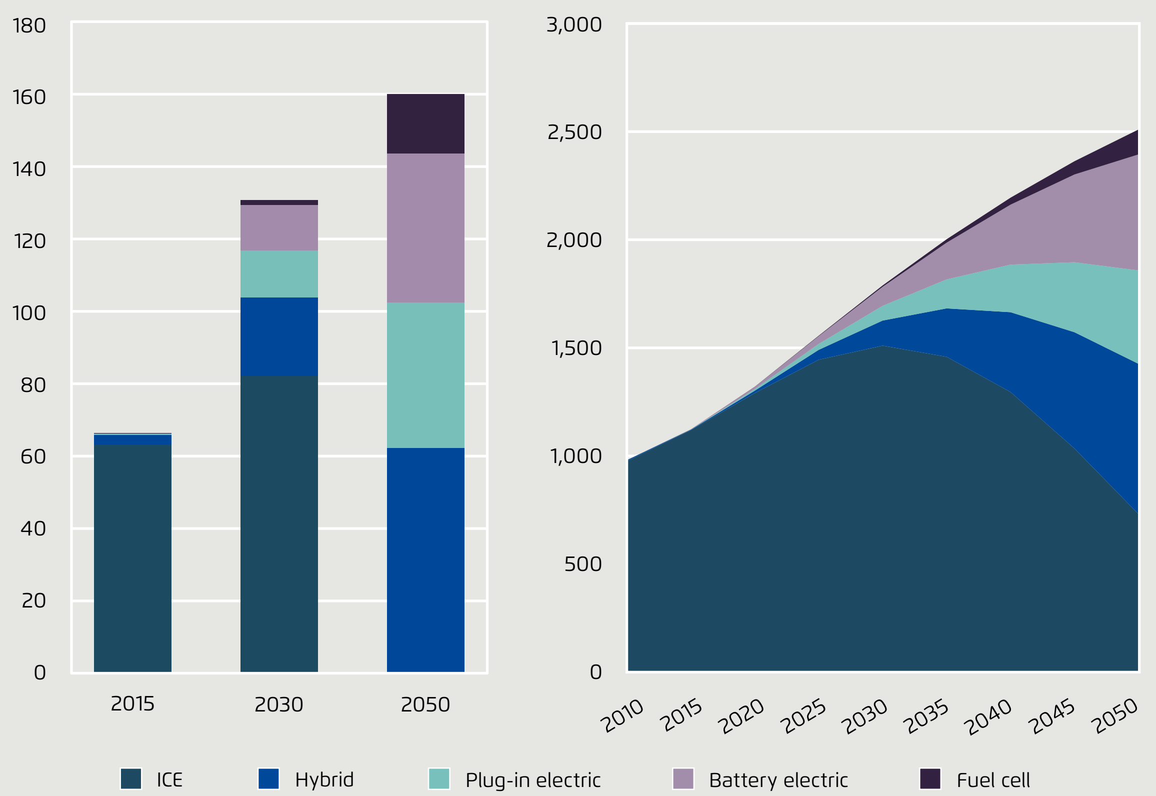
The four-degrees scenario, or 4DS, provides for a global average temperature rise of up to 4°C by the year 2100. The scenario assumes that global warming will be maintained within these limits through moderate progress in terms of political intervention and technological advancement. The former will primarily consist of measures that have already been introduced or at least announced. The 4DS is nonetheless a very conservative scenario and is undesirable with a view to climate protection, since it falls short of key international climate goals.

Our study therefore focusses on the two-degrees scenario, or 2DS, which provides for an average global temperature rise of up to 2°C by 2100. The 2DS presupposes that ambituous political intervention, behavioral changes and technological developments will prevent global warming from exceeding this limit. According to the IEA, one way to meet this target is to make internal combustion engines more expensive, potentially by raising fuel taxes and eliminating subsidies for conventional powertrain systems. The IEA recommends that vehicle tax rates be pegged to emissions levels, and that the additional tax revenue generated should be used for infrastructure projects and research and development (IEA 2016 a).

Cars

The 2015 base year saw sales of around 66 million cars globally. The total number of cars on the road was just short of 1.1 billion. In the same year, around 330,000

Annual sales (left) and total number of cars on the road (right) in the 2DS (in millions) Figure 2.1



Total number of cars on the road: IEA 2016a; annual sales: authors' own calculations and visualisation.

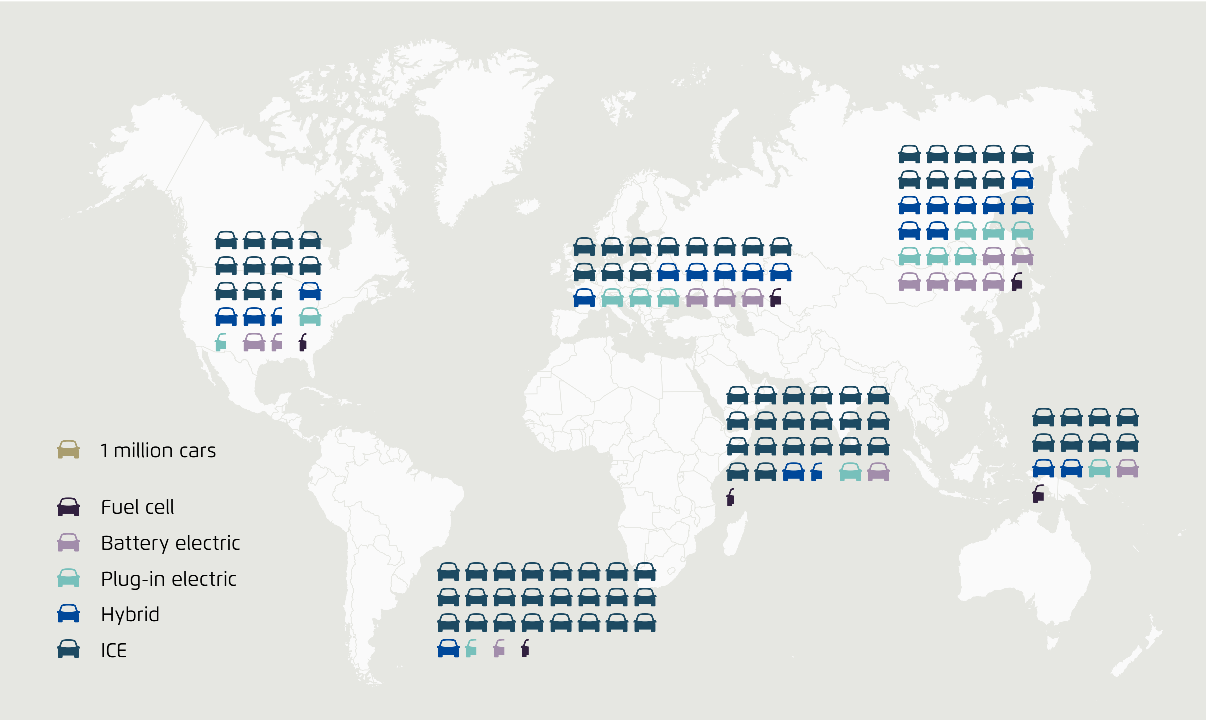
battery-driven cars were sold worldwide, along with 220,000 plug-in hybrids. Hybrids performed significantly better, with around 2.62 million units sold. Cars with alternative powertrain systems therefore accounted for around 0.01 per cent (or 5 per cent including hybrids) of all car sales in the base year.

In the 2DS, total sales are set to double by 2030, with the share of conventional petrol- and diesel-driven cars only increasing slightly over this period. Overall growth will primarily be driven by additional sales of battery electric vehicles (BEVs), plug-ins, and hybrids, and there will also be limited sales of fuel cell vehicles (see Figure 2.2). The total number of cars on the road will rise to 1.8 billion units, when the number of internal combustion engine (ICE) vehicles will reach its peak. In the 2DS, electric vehicles (including hybrids) will account for around 16 per cent of all cars on the road and around 37 per cent of all sales in 2030. BEVs and plug-ins will enjoy sales of around 13 million units apiece, and hybrids of almost 22 million units (see Figure 2.1 and Table 2.2).

In the 2DS, ICE vehicles will no longer be sold in 2050, and will only account for around a quarter of all vehicles on the road. Global car sales will rise to around 160 million units. Hybrids will account for over a third of these, plug-ins and BEVs for a quarter each, and fuel cell cars for around a tenth. In the same year, there will be around 2.5 million cars on the road (see Figure 2.1, Figure 2.3, and Table 2.2).

On the whole then, the 2DS predicts significant growth in alternative powertrain vehicles. Indeed, in comparison to the 4DS, we can observe a significantly higher level of electrification even by 2030. In 2050, moreover, alternative powertrains (including hybrids) will only account for 28 per cent of all car sales in the 4DS – well below the 37 per cent market share enjoyed by such vehicles in 2030 in the 2DS. In comparing sales figures and total car numbers on the two scenarios, it becomes clear that private transport plays a more significant role in the 4DS. In this scenario, there will be almost 3 billion cars on the road in 2050, compared with 2.5 billion in the 2DS. Per unit sales

Global distribution of car sales in 2030 (2DS scenario) — Figure 2.2



Authors' own calculations and visualisation on the basis of IEA 2016a

will also be higher in the 4DS, with 210 million cars due to be sold – 50 million more than in the 2DS (see Table 2.2).

HGVs

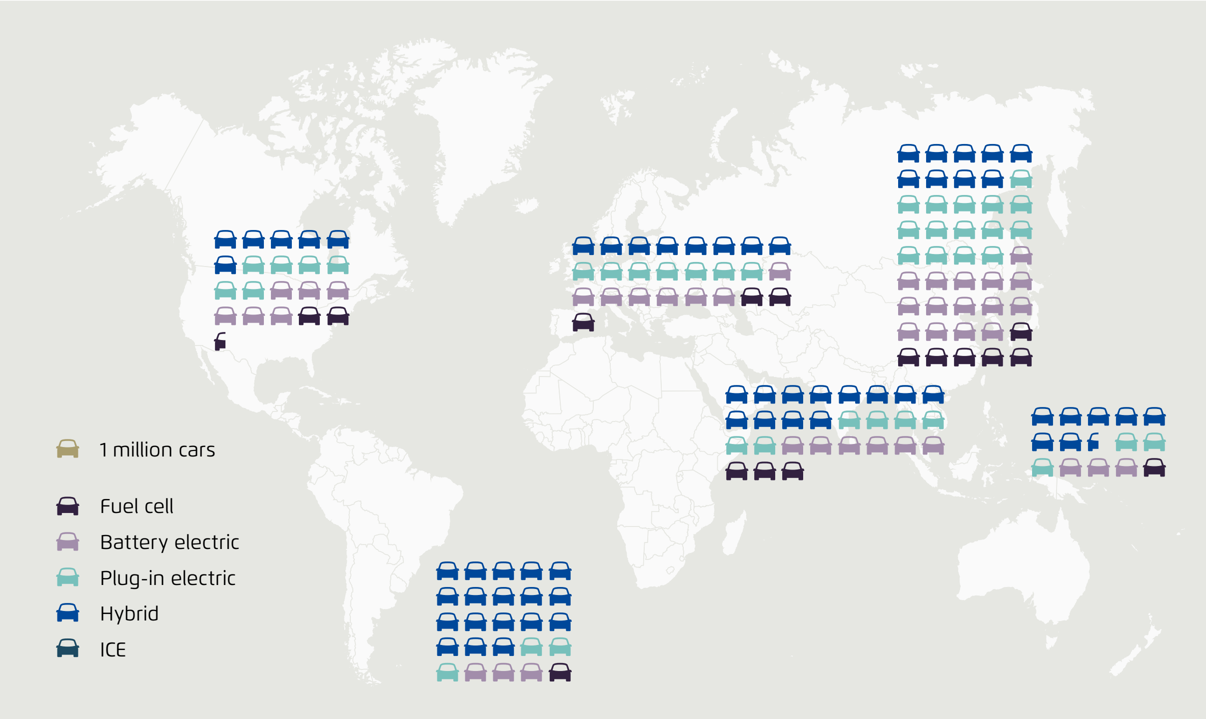
In the 2DS, HGV sales will rise less sharply than car sales. From 2015 to 2050, sales are set to grow by around 70 per cent overall. In the same period, car sales are expected to surge by almost 250 per cent. This is largely because the 2DS assumes that freight transport will increasingly shift from the road to rail and ships.

As with cars, the market for electric HGVs will develop more rapidly from 2030 on. Alternative powertrains will then account for nearly 30 per cent of all sales (see Figure 2.4). Nevertheless, since battery powered vehicles have a limited range, HGV users will show a clear preference for hybrids and plug-in vehicles. Peak numbers of internal combustion engine HGVs will be seen between 2025 and 2030. This will also be reflected in the falling sales figures for such HGVs from 2030 on. In 2050, traditional powertrains will make up less than a third of all sales, hybrids 40 per cent, and plug-ins around 20 per cent. Battery driven and fuel-cell HGVs will account for only 6 per cent and 3 per cent of sales, respectively. The number of HGVs on the road will continue to rise, reaching nearly 90 million in 2050. In the 2DS, the number of HGVs on the road will then equal the number of electric cars sold in 2050 (BEVs, plug-ins, FCEVs).

In the 4DS, a large share of freight will continue to be transported by road, which is reflected both in the HGV sales figures and the overall number of HGVs on the road. On this scenario, seven million HGVs will be sold in 2050 (72 per cent with ICEs) – 50 per cent more than in the 2DS. The total number of HGVs on the road, meanwhile, will be 20 per cent higher, at 100 million vehicles.

Global distribution of car sales in 2050 in the 2DS

Figure 2.3



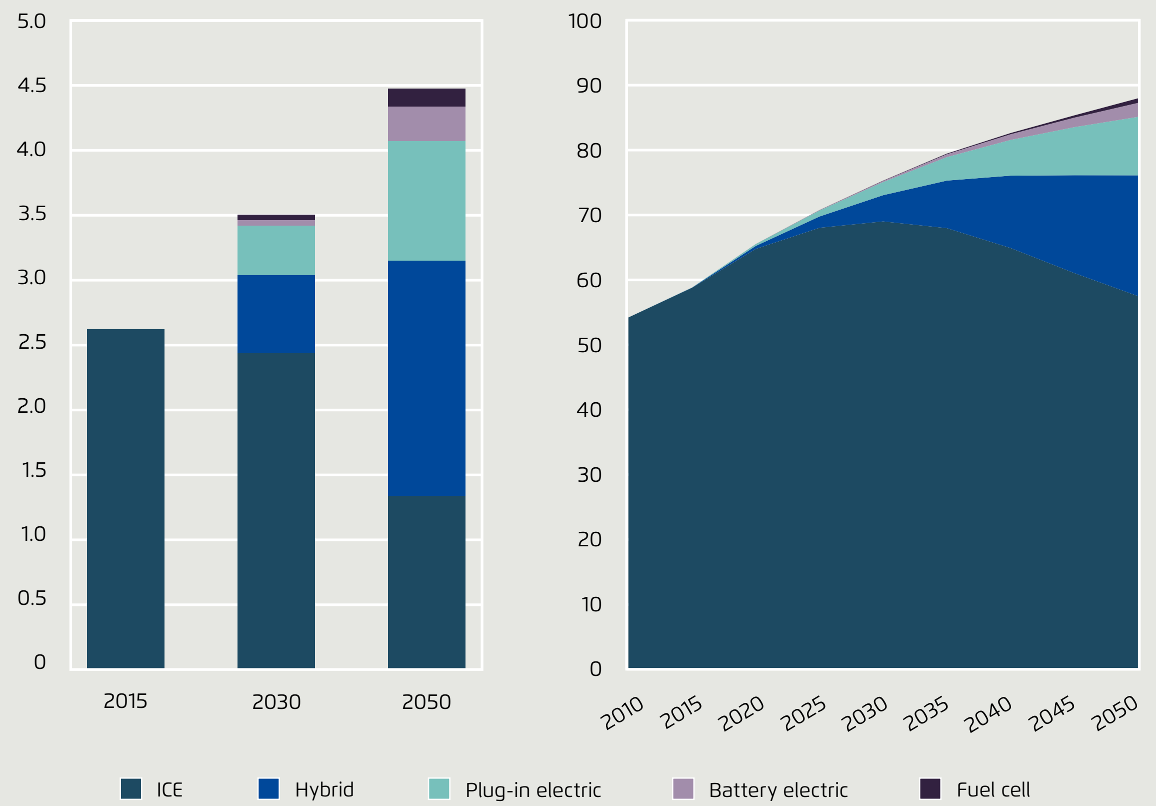
Authors' own calculations and visualisation on the basis of IEA 2016a

Annual car sales by powertrain type and scenario (in millions) — Table 2.2

	2015	2030		2050	
	Year 1	2DS	4DS	2DS	4DS
ICE	63.14	82.20	133.33	0.00	151.93
Hybrid	2.62	21.65	5.57	62.27	44.96
Plug-in electric	0.22	12.90	1.72	40.22	6.85
Battery electric	0.33	12.71	2.02	41.04	7.29
Fuel cell	0.00	1.27	0.37	16.40	1.52
Total	**66.31**	**130.72**	**143.01**	**159.92**	**212.55**

Authors' own calculations on the basis of IEA 2016a

Annual sales (left) and total number of HGVs on the road (right) on the 2DS (in millions) — Figure 2.4



Total number of cars on the road: IEA 2016a; annual sales: authors' own calculations and visualisation.

Buses

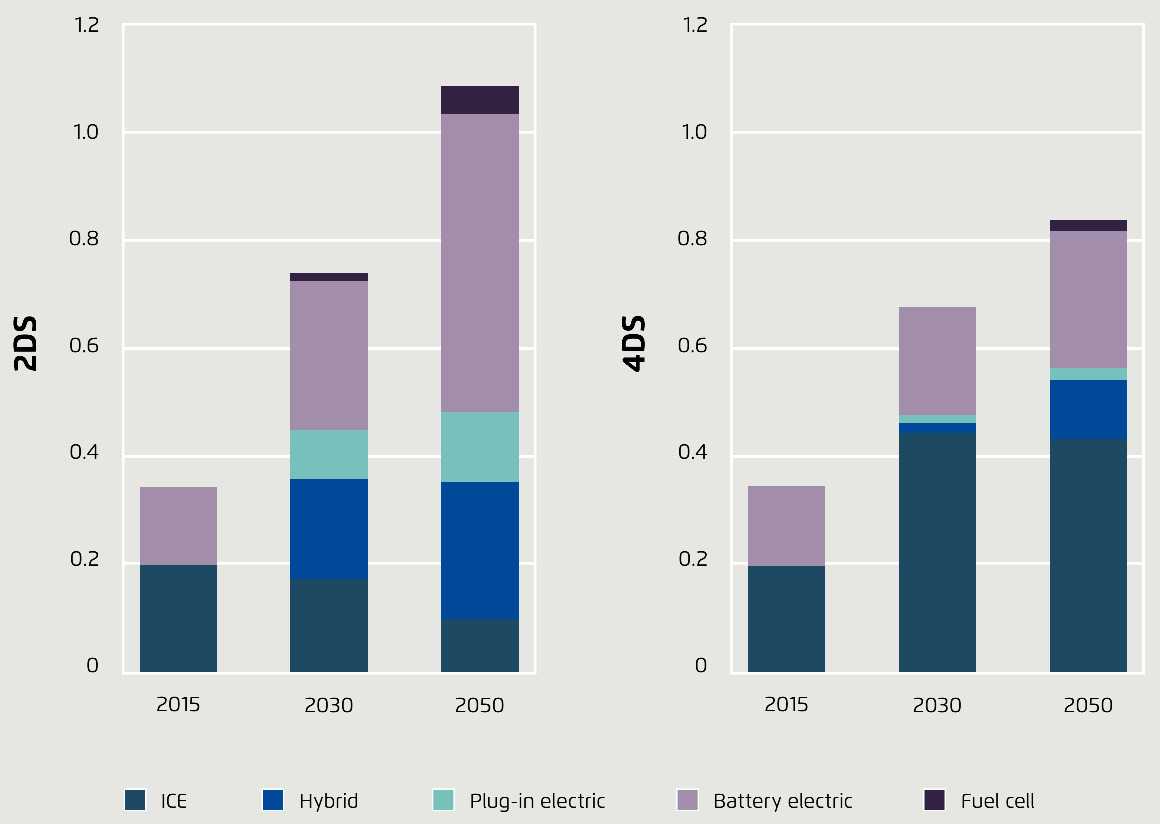
Sales figures for buses were determined differently from the other vehicle types,[3] since the IEA study contains no data for buses (IEA 2016a). The figures for the base year were derived from current bus production figures published by the OICA[4] and from data on electric bus sales in China. In 2015, 140,000 electric buses were sold in China. Sales in other countries were negligible, with India possessing 100 electric buses in total, the Netherlands 94, Sweden 30, and Japan 21 (IEA 2016 b).

3 Authors' own estimates.

4 Organisation Internationale des Constructeurs d'Automobiles

The 2DS assumes a significant shift from private to public transport, which goes hand in hand with a more rapid rise in bus sales in this scenario. The comparative growth in bus sales in the 2DS is thus related to the rise in car sales in the 4DS. Likewise, the comparative growth in car sales in the 4DS is correlated with the growth in bus sales in the 2DS. Our classification of bus powertrain types follows that used for HGVs. Despite the physical similarities between buses and HGVs, buses are expected to use a greater proportion of battery electric powertrains. This is because buses are mainly used in urban environments and therefore more easily able to access charging infrastructure, and because bus timetables can be scheduled to allow for charging periods.

Annual bus sales in the 2DS (left) and the 4DS (right) (in millions) Figure 2.5



Authors' own calculations and visualisation.

In the 2DS, bus sales are set to increase threefold between 2015 and 2030, despite a drastic fall in sales of traditional powertrain vehicles. Battery electric buses will enjoy a particular boom, with half a million units set to be sold in 2050 in the 2DS. These will account for more than 50 per cent of all sales (see Figure 2.5).

In 2DS, bus sales will nonetheless be outnumbered four to one by HGV sales in 2050.

Motorcycles

Since the definition of a motorcycle may vary, it is not always easy to compare statistics and projections for such vehicles. The IEA study, for example, refers to the number of "2 and 3-wheeled" vehicles on the road. Depending on one's definition, this category might also include pedelecs. We have nonetheless chosen to exclude pedelecs from the following calculations and will treat them independently in the next section. In light of the definitional difficulties here, our projections nonetheless have to be considered more tentative than for the other vehicle types. Where motorcycles are concerned, we distinguish between ICE and battery electric powertrains.

In many Chinese cities with serious air pollution problems, sales of conventional motorcycles have been outlawed. China and South-East Asia are therefore already seeing significant sales of electric scooters, and we can observe a relatively high proportion of electric motorcycles in the region in the 2015 base year (IEA 2016 b). At present, however, these motorcycles often rely on lead-acid batteries rather than lithium-ion batteries. Our study projects that the proportion of motorcycles equipped with lithium-ion batteries in China will increase from 4 per cent in 2015 to 50 per cent in 2030, before reaching 100 per cent by 2050. In the rest of world, lithium-ion batteries are also expected to dominate the market by the end of the forecast period.

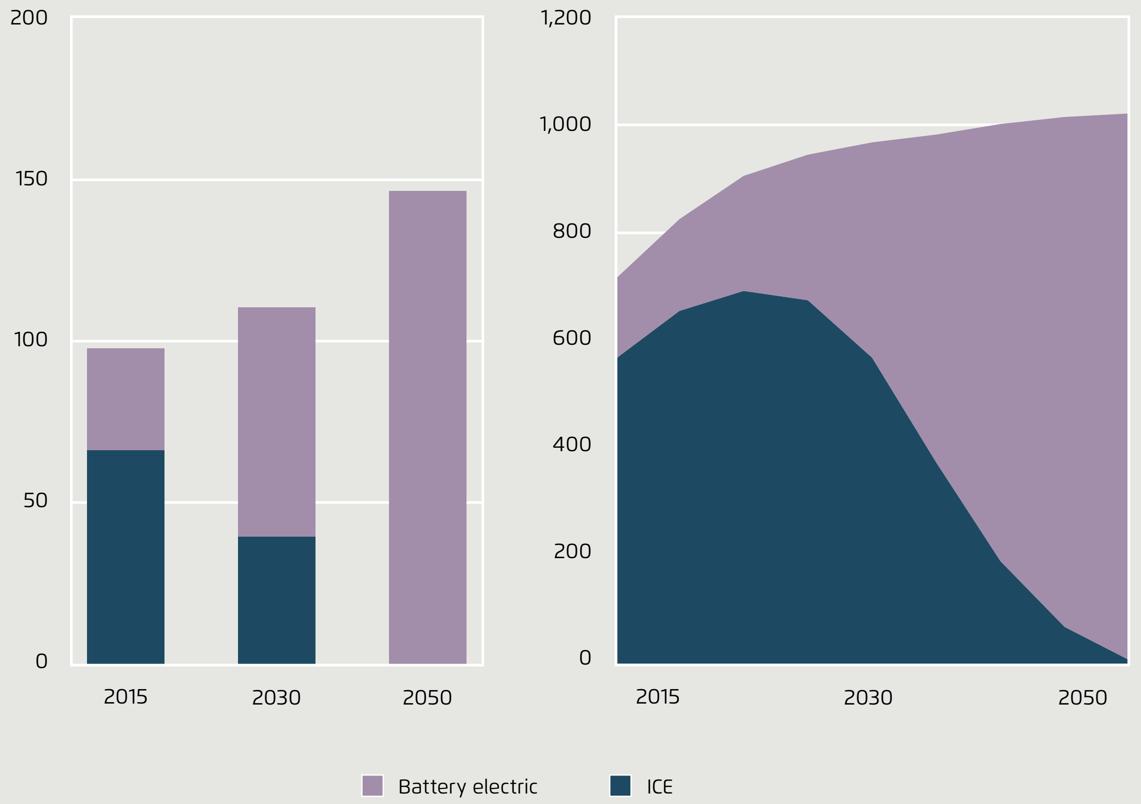
In 2015, around 30 per cent of the almost 100 million motorcycles sold were electric. In the 2DS, total sales are expected to climb by 14 per cent to just short of 115 million units in 2030. At this point, petrol-driven motorcycles will only account for around a third of all sales. By 2050, the motorcycle sector is expected to be completely electrified. This is also reflected in the projected 1 billion motorcycles on the road at this point. In the 2DS, motorcycle sales will rise to just under 150 million units in 2050. (see Figure 2.6)

The overall number of motorcycles on the road will be slightly higher in the 2DS than in the 4DS, since many urban road users are expected to trade in their cars for two-wheeled modes of transport. In the 4DS, by contrast, the majority of road users will continue to favour conventional motorcycles up to 2050, with over half the 105 million units sold having an internal combustion engine.

In the 2DS, the motorcycle category is the only one in which there will be no new sales of conventional powertrain vehicles after 2050 and no longer any such vehicles on the road. This sector is poised to develop with particular speed, since the average life-cycle of a motorcycle is around seven years – five years less than a car. The lower price of motorcycles will also play an important role in driving this sector's growth.

Annual sales (left) and total number of motorcycles on the road (right) in the 2DS (in millions)

Figure 2.6



Total number of cars on the road: IEA 2016a; annual sales: authors' own calculations and visualisation.

Pedelecs

As we indicated in the previous section, statistics on two-wheeled vehicles tend to vary depending on the definitions employed. Since the IEA study does not contain any data on pedelecs, we again based our projections on alternative sources here. Furthermore, since pedelecs do not contain any counterpart to an internal combustion engine or alternative powertrain, only battery-driven vehicles will be considered in the following (see Figure 2.7).

In the 2DS, projected sales figures up to 2035 are drawn from the Electric Bikes *Worldwide Report*[5] and carried forward up to 2050 (Jamerson, Benjamin 2015). Nearly three million pedelecs were sold in 2015, predominantly in Europe, Japan, and North America. By 2030, sales are set to rise by 750 per cent. They will then double between 2030 and 2050, reaching almost 40 million units. In the 4DS, there will also be a significant spike in sales, though these will remain around 30 per cent below the 2DS levels.

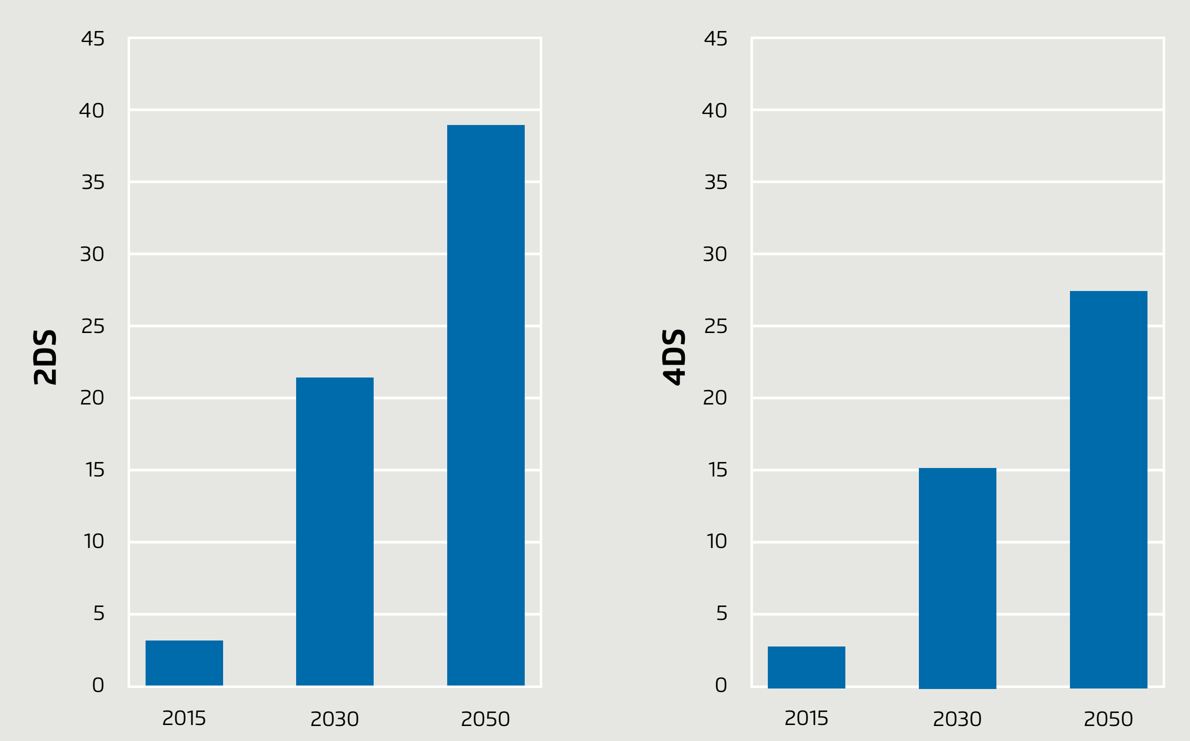
5 This study includes scooter-style electric bikes (SSEBs) in its statistics on pedelecs. In the present paper, such vehicles have been excluded from the pedelec category, since they are already covered under "motorcycles."

Summary

In the 2DS, we can observe significant differences between the proportion of electric vehicles in each vehicle category. In the base year, for example, a third of all buses sold were electric, whereas all HGVs were driven by ICEs. In considering the progress of electrification as a whole, therefore, what matters most is the overall sales figures for electric vehicles, rather than the percentage of electric vehicles in each category. Though a significant percentage of all buses are electric, for example, they only account for a small proportion of electric vehicle sales as a whole. In terms of units sold, motorcycles will dominate electric vehicle sales across the forecast period in the 2DS. Nevertheless, cars are set to account for an increasing proportion of all electric vehicle sales, and for more than a third by 2050 (see Figure 2.8). Pedelecs are expected to make up over ten per cent of all electric vehicle sales in 2050. Despite their significant market share, however, it is important to bear in mind that their batteries are far smaller than those used in electric cars. Conversely, though comparatively large quantities of raw materials are needed for electric buses and HGVs, sales of these vehicles are expected to be low, and will have little effect on overall raw material demand. The majority of electric vehicle sales will come from cars and motorcycles; accordingly, these vehicle types will determine demand for strategic raw materials. On account of their size and perfomance characteristics, cars can be assumed to require significantly higher quantities of raw materials than motorcycles (see Chapter 3).

In the following chapter, we calculate demand for selected raw materials in 2015, 2030, and 2050 in each of our two scenarios.

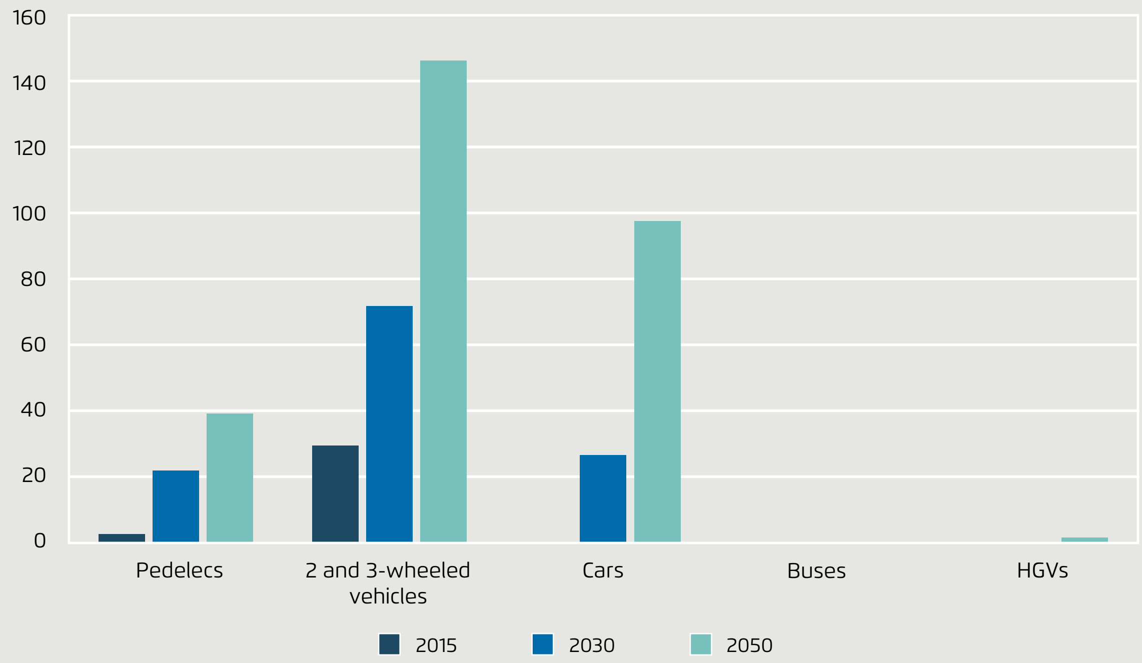
Annual pedelec sales in the 2DS (left) and the 4DS (right) (in millions) Figure 2.7

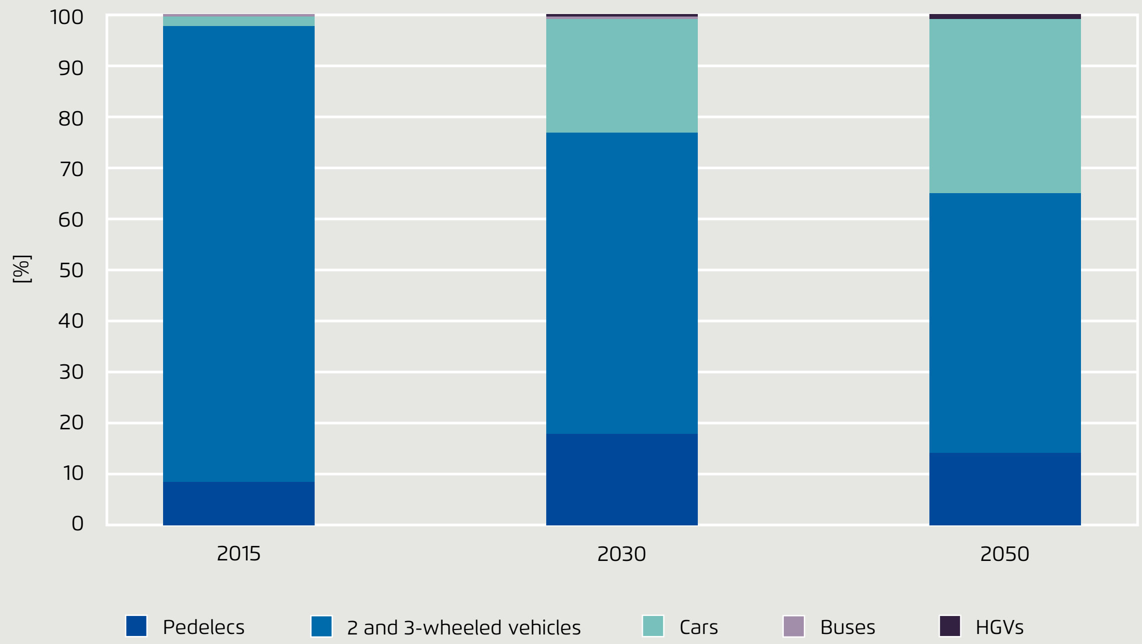


Authors' own calculations and visualisation on the basis of Jamerson, Benjamin 2015

Annual sales of all electric vehicle types (PHEV, BEV, FCEV) in absolute terms (above) and by percentage (below) in the 2DS

Figure 2.8





Authors' own calculations and visualisation on the basis of IEA 2016a

03 | Growth in Global Demand for Raw Materials Required to Manufacture Electric Vehicles

In this chapter, we consider future growth in demand for five raw materials required to manufacture electric vehicle batteries and fuel cells – namely, platinum (which is used in fuel cell components and ICE catalytic converters) and lithium, cobalt, graphite and nickel (which are used to produce lithium-ion batteries).

In predicting global demand for these raw materials, we based our calculations on the electric vehicle sales outlined in Chapter 2. Our projections therefore incorporate future demand for cars, electric buses, HGVs, 2 and 3-wheeled vehicles, and pedelecs. The quantity of each raw material required for the various components (fuel cells, LFP, NMC, and NCA batteries) was determined based on specialist sources and face-to-face interviews with experts.[6]

3.1 Lithium

Lithium is the central element in lithium-ion batteries. It is contained in all types of lithium-ion electric vehicle batteries.[7] In the future, optimisations in the design of battery cells are expected to extend their range.

In Figure 3.1, we can observe a sharp rise in demand for lithium for electric vehicle components across the forecast period. In the 2DS (represented by the turquoise columns), demand is set to rise to almost 160,000 tonnes p.a. in 2030 and to nearly 500,000 tonnes in 2050. In the 4DS (the dark grey columns), by contrast, much slower growth in demand is anticipated. For the purposes of comparison, the yellow column indicates global primary lithium extraction levels in 2015. In Chapter 4, we shall discuss lithium reserves and resources in more detail.

Demand for raw materials from primary sources can be reduced by utilising secondary materials. While in Europe there is currently no real provision for lithium recycling, initial steps have been taken toward such programmes in countries such as South Korea (Posco 2017). Recycling experts suggest that we might optimistically expect the recycling industry to develop quickly on both scenarios, so that in 2030 around 10 per cent of lithium demand can be satisfied by secondary material from electric vehicles (i.e. recycled lithium-ion batteries). This figure is expected to rise to around 40 per cent by 2050. In Figure 3.1, secondary material is represented by hatched lines. In order to reach these ambitious recycling targets, it will be essential to ensure that batteries are collected and recycled as efficiently as possible. In this regard, we can take a cue from existing recycling systems for lead-acid batteries. Lead from these batteries has one of the highest recovery rates worldwide. The use of secondary material will serve to reduce demand for primary lithium by 148,000 tonnes in the 2DS and 36,000 tonnes in the 4DS. In 2050, demand for primary lithium will reach 307,000 tonnes in the 2DS and 70,000 tonnes in the 4DS.

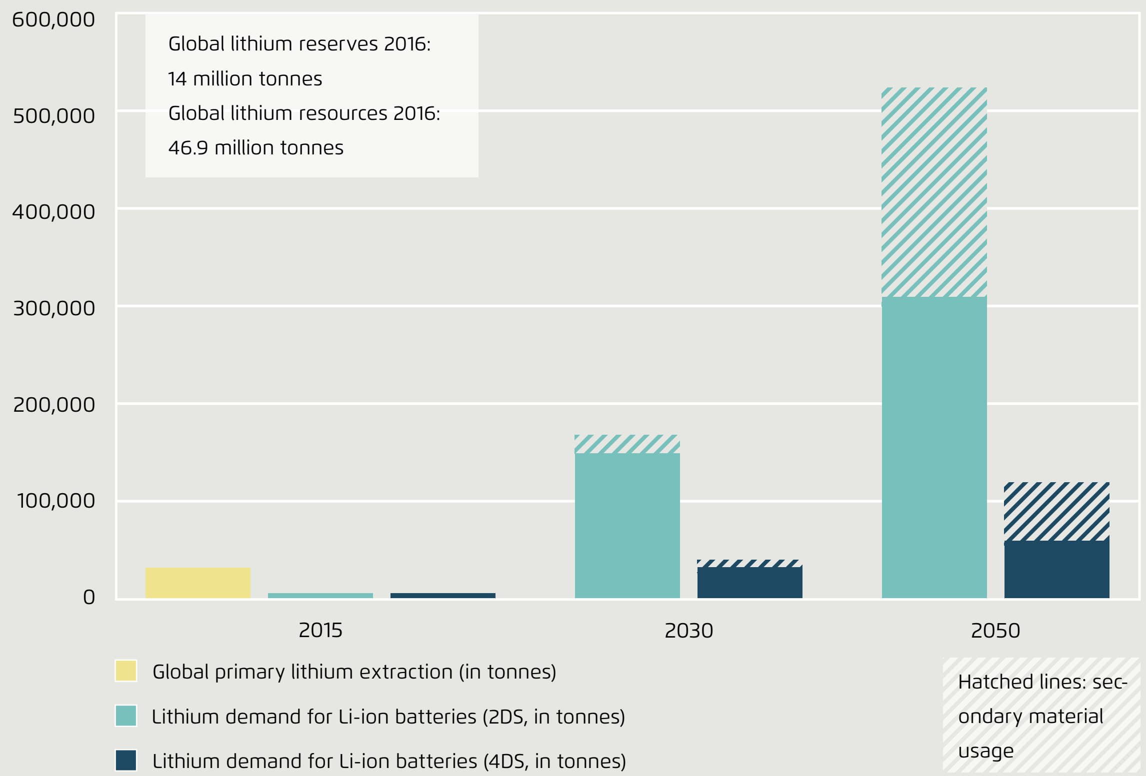
The electric car sector will be the main driver of this rapid rise. In 2015, this sector accounted for almost 40 per cent of worldwide lithium demand for electric vehicles. Around the same amount of lithium was required for electric bus components, as a result of China's bus electrification programmes. Electric car sales are set to rise significantly in 2030 and 2050 and will account for the lion's share of lithium demand in the electric vehicle sector. In the 2DS, electric cars will account for 82 per cent of lithium demand in 2030 and 83 per cent in 2050 (see Figure 3.2). In the 4DS, the corresponding figures will be slightly lower, at 63 per cent in 2030 and 73 per cent in 2050.

In the Appendix, we detail various other uses of lithium, such as in ceramics and glass-making, along with other uses of lithium-ion batteries (e.g. in energy storage facilities). It is nonetheless important to note that electric vehicles will account for the majority of the rise in lithium demand over the medium to long term (2030–2050). In Figure 7.1 of Appendix 7.1, we also provide projections for lithium demand across all areas (including electric vehicles). In the 2DS, expected growth in demand in other areas is nonetheless far lower than in the electric vehicle

6 UBA 2016, Umicore 2017

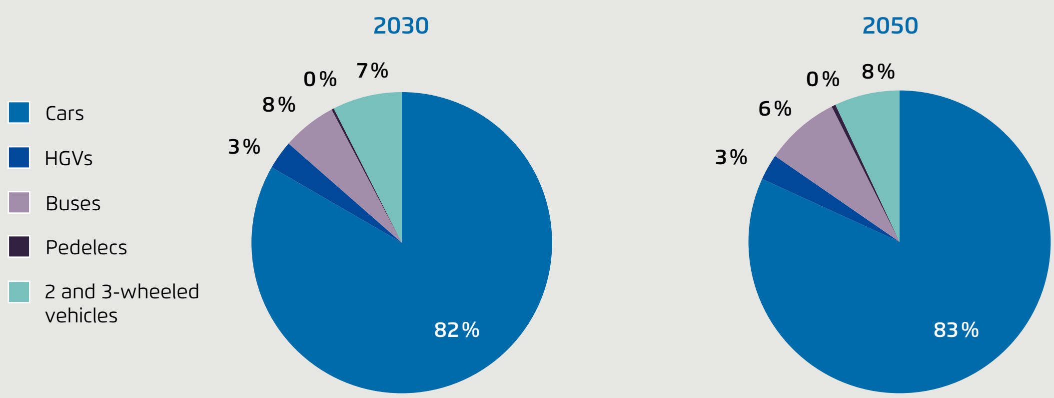
7 NMC (nickel manganese cobalt), NCA (nickel cobalt aluminium), LFP (lithium iron phosphate). See also Appendix 7.2.

Global lithium demand for lithium-ion electric vehicle batteries in 2015, 2030, and 2050 in the 2DS and 4DS, including secondary material usage (in tonnes) Figure 3.1



USGS 2017 for primary extraction levels and reserves and resources; authors' own calculations and visualisation

Lithium demand by vehicle type on the 2DS in 2030 and 2050 Figure 3.2



Authors' own calculations and visualisation

sector. In Chapter 4, our projections for future lithium demand are compared with the known global lithium reserves and resources, in order to assess the risk of supply shortages.

3.2 Cobalt

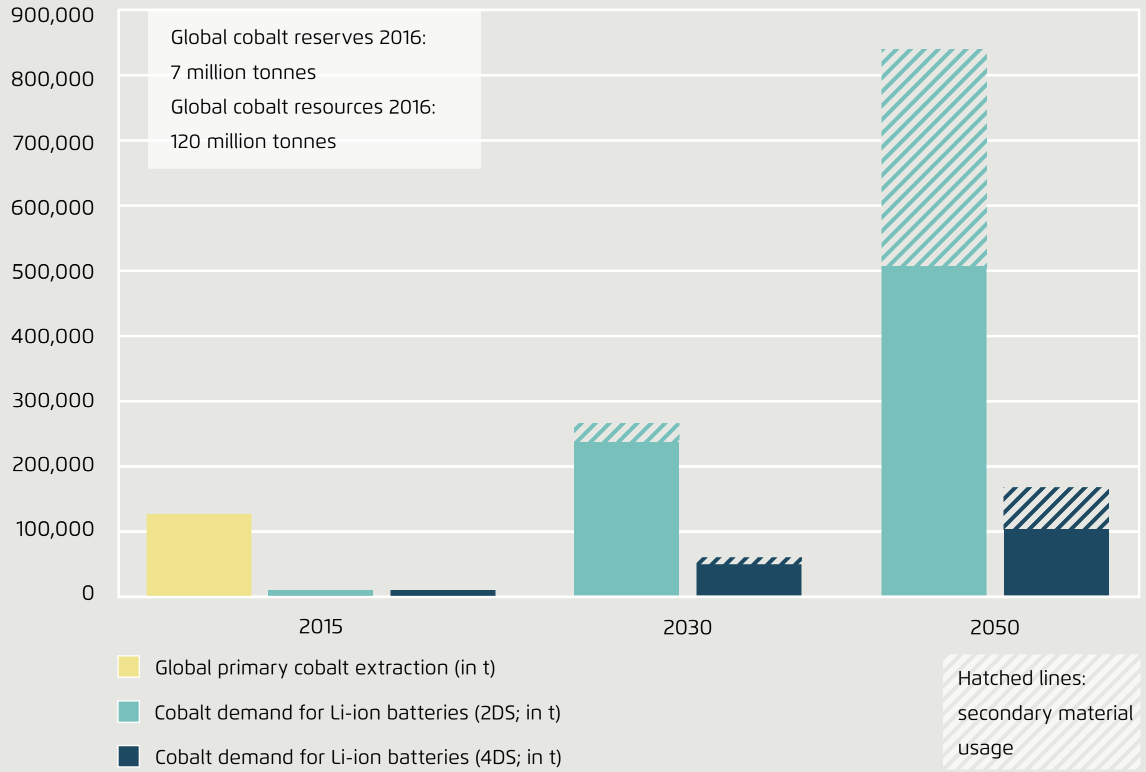
In the electric vehicle sector, cobalt is used in both nickel manganese cobalt (NMC) and nickel cobalt aluminium (NCA) batteries. Both battery types are already in use, alongside cobalt-free lithium iron phosphate (LFP) batteries (see Appendix 7.2 for battery capacities). NMC and NCA batteries have a very high energy density, and manufacturers are expected to increasingly favour NMC batteries over LFP units (which have a lower energy density) for electric buses, HGVs, and even cars. This is why demand for cobalt is currently rocketing. Demand will continue remain high even though technological optimisations are expected to reduce the cobalt content of NMC batteries by 2030 at the latest (Umicore 2017).

Figure 3.3 shows cobalt demand on both of our scenarios. In 2030, demand is expected to reach around 260,000 tonnes in the 2DS (the turquoise columns), compared to almost 60,000 tonnes in the 4DS (dark green columns). Demand in the electric vehicle sector will continue to rise up to 2050, to just over 800,000 tonnes in the 2DS and 165,000 tonnes in the 4DS. In Chapter 4, we discuss cobalt reserves and resources in further detail. Demand for cobalt can be reduced by using secondary material. Today, there are already systems in place to recycle cobalt (from catalytic converters, superalloys, and even batteries), and in 2015 secondary material accounted for around 35 per cent of all cobalt usage. Both the 2DS and the 4DS assume that secondary material from lithium-ion vehicle batteries will account for 10 per cent of usage in 2030 and 40 per cent in 2050. Both scenarios therefore presuppose a global lithium-ion battery recycling industry. In the figure, recycled material is represented by hatched lines.

In 2015, electric car production accounted for 97 per cent of all cobalt demand for electric vehicles. In the future, the shift from LFP to NMC and NCA batteries is expected to gradually increase the share of cobalt required for buses and HGVs. Car production will nonetheless continue to dominate demand, accounting for 80 per cent of vehicle-related consumption in the 2DS in 2030 and 2050, and for 58 and 68 per cent of consumption in the 4DS in 2030 and 2050, respectively. Demand by vehicle type is illustrated in Figure 3.4.

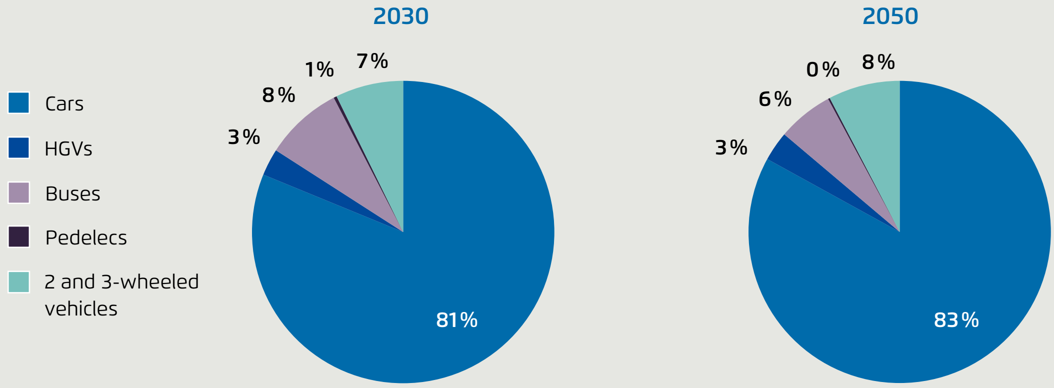
Figure 7.3 in Appendix 7.1 further shows cobalt demand across all areas in 2014, while Figure 7.4 gives a rough projection of future demand. Here we can nonetheless note that electric vehicles will account for much of the rise in cobalt demand over the medium to long term (2030-2050). In Chapter 4, we compare our projections for future cobalt demand with the known global cobalt reserves and resources.

Global cobalt demand for lithium-ion electric vehicle batteries in 2015, 2030, and 2050 in the 2DS and 4DS, including secondary material usage (in tonnes) Figure 3.3



USGS 2017 for primary extraction levels and reserves and resources; authors' own calculations and visualisation

Cobalt demand by vehicle type in the 2DS in 2030 and 2050 Figure 3.4



Authors' own calculations and visualisation

3.3 Nickel

Though the future optimisation of nickel manganese cobalt (NMC) battery cells is expected to reduce the quantity of cobalt required per battery, it will also increase the quantity of nickel needed. Like cobalt, nickel is not used in lithium iron phosphate batteries, but is used in NMC and nickel cobalt aluminium (NCA) batteries. In future, we can expect to see a trend toward NMC batteries with a 6:2:2 stoichiometric ratio (6 parts nickel, 2 parts manganese, 2 parts cobalt). In both scenarios, the shift toward high energy density NMC and NCA batteries will further add to demand.

Figure 3.5 depicts global demand for nickel in the electric vehicle sector in both the 2DS (turquoise columns) and the 4DS (dark green columns). In 2030, total demand is set to rise to around 830,000 tonnes in the 2DS and to almost 180,000 tonnes in the 4DS. By 2050, demand in the 2DS will have risen to 2.6 million tonnes. At this point it will exceed 2015 primary production levels (the yellow column). In the 4DS, by contrast, nickel demand will only reach around 570,000 tonnes by 2050. In Chapter 4, we shall discuss the known global nickel reserves and resources in further detail.

Today, nickel recycling systems are already in place (including small-scale programmes to recover the metal from lithium-ion batteries). In steel production, secondary nickel accounts for 25 to 50 per cent of all usage (UNEP 2011). On both of our scenarios, secondary material is projected to account for 7 per cent of all nickel usage in the battery sector in 2030, and for 40 per cent in 2050. This secondary material will be exclusively derived from electric vehicle batteries. In the figure, recycled nickel is represented by hatched lines.

Electric car production will account for the great majority of demand in the electric vehicle sector. Cars accounted for over 90 per cent of consumption in 2015. In the 2DS, this figure will remain above 80 per cent in 2030 and 2050. In the 4DS it will fall to 60 per cent in 2030, before climbing to 72 per cent in 2050. Demand by vehicle type in the 2DS is illustrated in Figure 3.6 for 2030 and 2050.

Figure 7.5 in the Appendix shows nickel usage in electric vehicle production and all other areas, including steel production. Figure 7.6, meanwhile, offers a rough projection of future demand across all areas (including the electric vehicle sector). Chapter 4 compares our projections for future nickel demand across all areas with the known global nickel reserves and resources.

3.4 Graphite

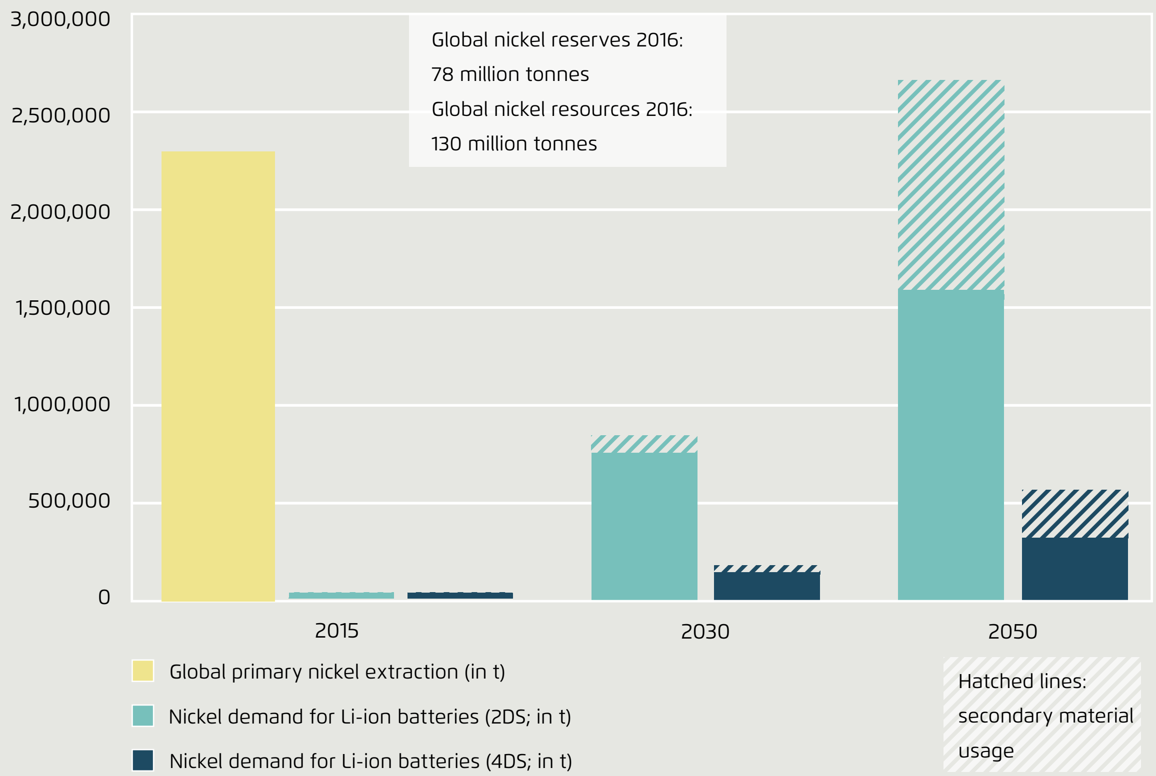
Like lithium, graphite is used in all lithium-ion batteries in the electric vehicle sector. Around the same quantity of graphite (in grams per kilowatt hour) is required in all battery types (LFP, NMC, NCA). Figure 3.7 shows graphite demand for electric vehicles for 2015, 2030 and 2050. In the 2DS, demand is set to rise to 1.6 million tonnes in 2030 and to just under five million tonnes in 2050. In the 4DS, meanwhile, demand will only reach 400,000 tonnes in 2030 and 1.2 million tonnes in 2050.

The yellow column represents primary natural graphite extraction in 2015. Graphite is unusual insofar as it can also be synthetically produced. Synthetic graphite is already used in some areas today, since it affords certain advantages over natural graphite. Since future demand for graphite will not need to be (exclusively) satisfied via primary raw materials, it is depicted in the figure by dotted columns. Some studies (including Pillot 2017) even assume that synthetic graphite production will eventually exceed primary extraction of natural graphite.

At present, there are no systems in place to recycle graphite, and we therefore have not included any recycled material in our calculations. In the 2DS, car production will account for 80 per cent of demand in the electric vehicle sector in 2030 and 2050, while in the 4DS, it will account for 64 per cent in 2030 and 73 per cent in 2050. Demand by vehicle type is illustrated in Figure 3.8.

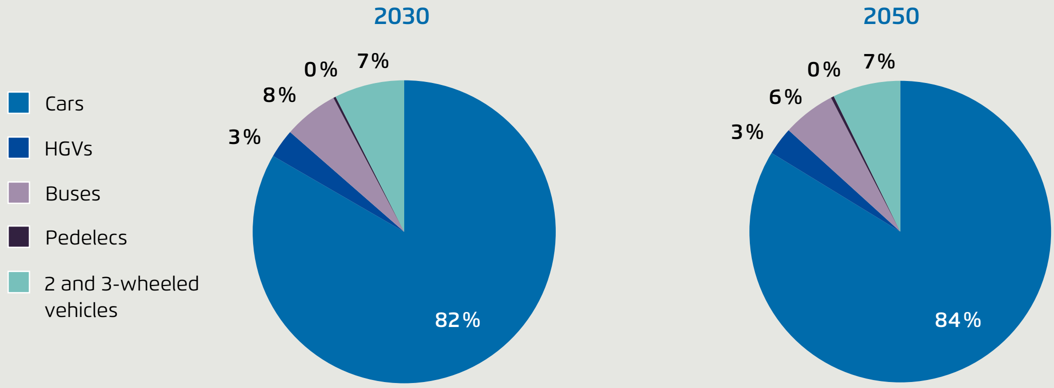
The various uses of natural graphite, including in steel production, are detailed in the Appendix, which also provides a rough projection for future demand across all areas (including the electric vehicle sector). In addition, Chapter 4 compares our projections for future graphite demand with the known global reserves and resources, in order to assess the risk of graphite shortages.

Global nickel demand for lithium-ion electric vehicle batteries in 2015, 2030, and 2050 in the 2DS and 4DS, including secondary material usage (in tonnes) Figure 3.5



USGS 2017 for primary extraction levels and reserves and resources; authors' own calculations and visualisation

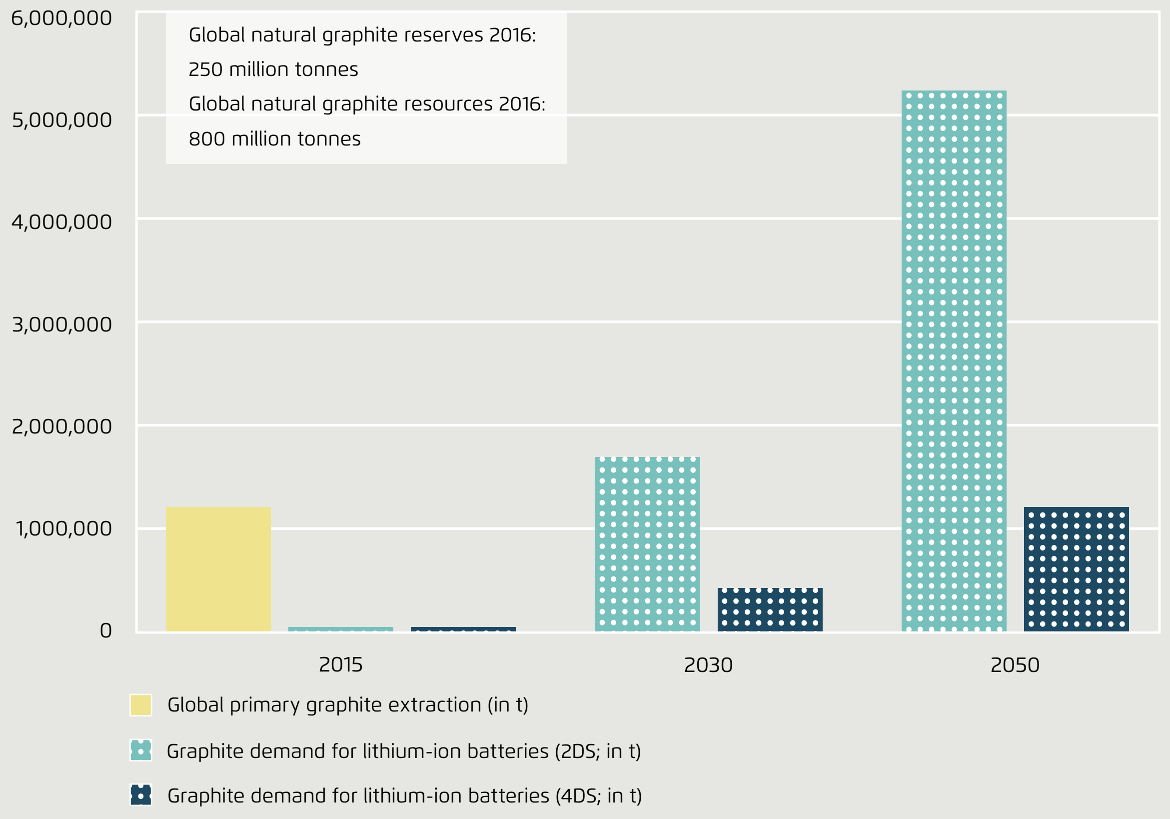
Nickel demand by vehicle type in the 2DS in 2030 and 2050 Figure 3.6



Authors' own calculations and visualisation

Global graphite demand for lithium-ion electric vehicle batteries in 2015, 2030, and 2050 in the 2DS and 4DS (in tonnes)

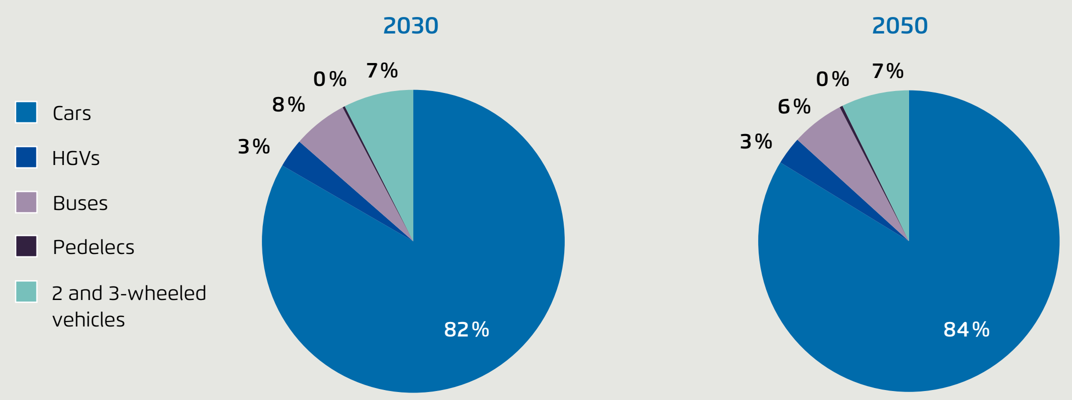
Figure 3.7



USGS 2017 for primary extraction levels and reserves and resources; authors' own calculations and visualisation

Graphite demand by vehicle type in the 2DS in 2030 and 2050

Figure 3.8



Authors' own calculations and visualisation

3.5 Platinum (Including in Catalytic Converters)

Platinum is used in electric vehicle fuel cells. In our two scenarios, we also consider platinum demand for catalytic converters in vehicles with internal combustion engines.[8] Each car catalytic converter contains on average 1.1 grams of platinum.[9] Figure 3.9 shows platinum demand in the 2DS (green columns) and the 4DS (blue columns). Each column is also divided within itself. The lower, darker section of each column represents demand for electric vehicle fuel cells. The upper, lighter section represents demand for catalytic converters in ICE vehicles. In 2015, we can already observe significant demand for platinum for catalytic converters (almost 70 tonnes).

In the 2DS, platinum demand for vehicle fuel cells and catalytic converters combined is set to reach around 110 tonnes by 2030. 80 per cent of this material will be used in ICE catalytic converters. In the 4DS, platinum demand will rise to 150 tonnes, 95 per cent of which will be used in ICE catalytic converters. By 2050, demand will have risen again on both scenarios. In the 2DS, fuel cell production will now account for 100 per cent of demand.

In the 4DS, by contrast, ICE catalytic converters will account for almost 90 per cent of demand.

Figure 3.10 shows platinum demand by vehicle type (including ICE vehicles) in the 2DS for 2030 and 2050.

Platinum is already widely recycled. According to Germany's Federal Institute for Geosciences and Natural Resources (BGR 2016), 23 per cent of global platinum demand is currently satisfied by secondary material. Furthermore, the end-of-life recycling rate for platinum in electric vehicles is now over 50 per cent (UNEP 2011). Demand for primary material can be significantly reduced through the use of such recycled platinum. In both of our scenarios, secondary material is set to account for 50 per cent of usage in 2030 and for 60 per cent in 2050. Figure 3.11 shows how this recycled material will offset demand for primary platinum. Secondary material is represented here by hatched lines.

In the present study, we shall only consider demand for platinum and will disregard other platinum group metals (such as palladium).

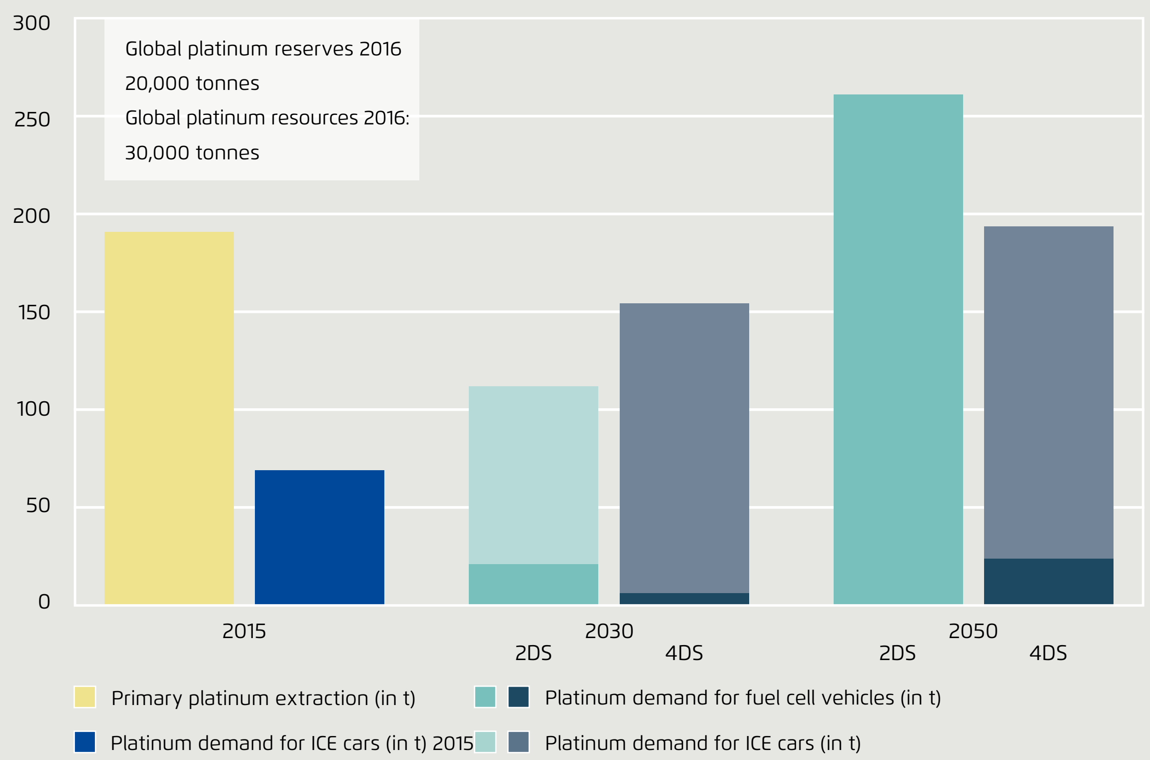
The various uses of platinum (including in the jewellery industry) are shown in the Appendix, which also provides a rough projection of demand across all areas (including the electric vehicle sector).

In order to assess the risk of shortages, Chapter 4 also compares our projections for future global platinum demand in all areas with the known global platinum reserves and resources.

8 Catalytic converters in HEVs and PHEVs also contain other platinum group metals (such as palladium).

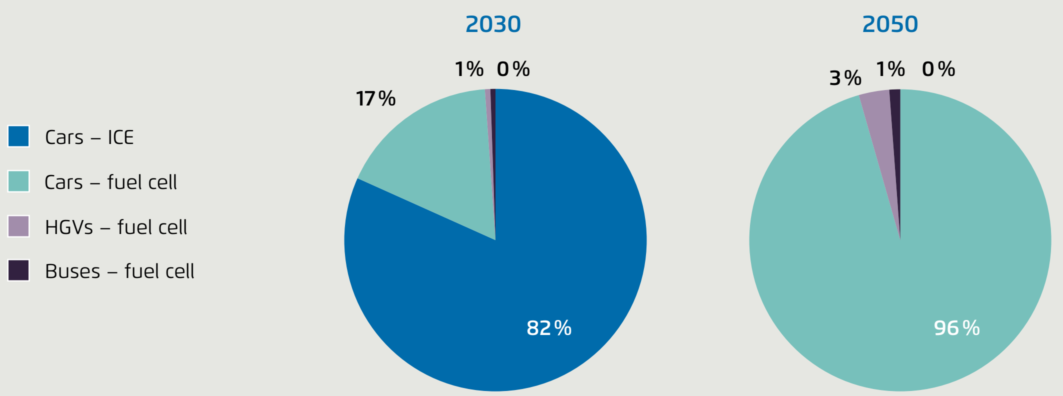
9 In addition, around 2.9 grams of palladium/rhodium are used in such catalytic converters (SubSKrit 2018).

Global platinum demand for fuel cells and catalytic converters in 2015, 2030, and 2050 on the 2DS and 4DS (in tonnes; not including secondary material) Figure 3.9



Authors' own calculations; USGS 2017 for primary extraction levels andreserves and resources; authors' estimates on the basis of USGS 2017 (on the assumption that platinum accounts for 30 % of all global reserves and resources of the platinum group metals)

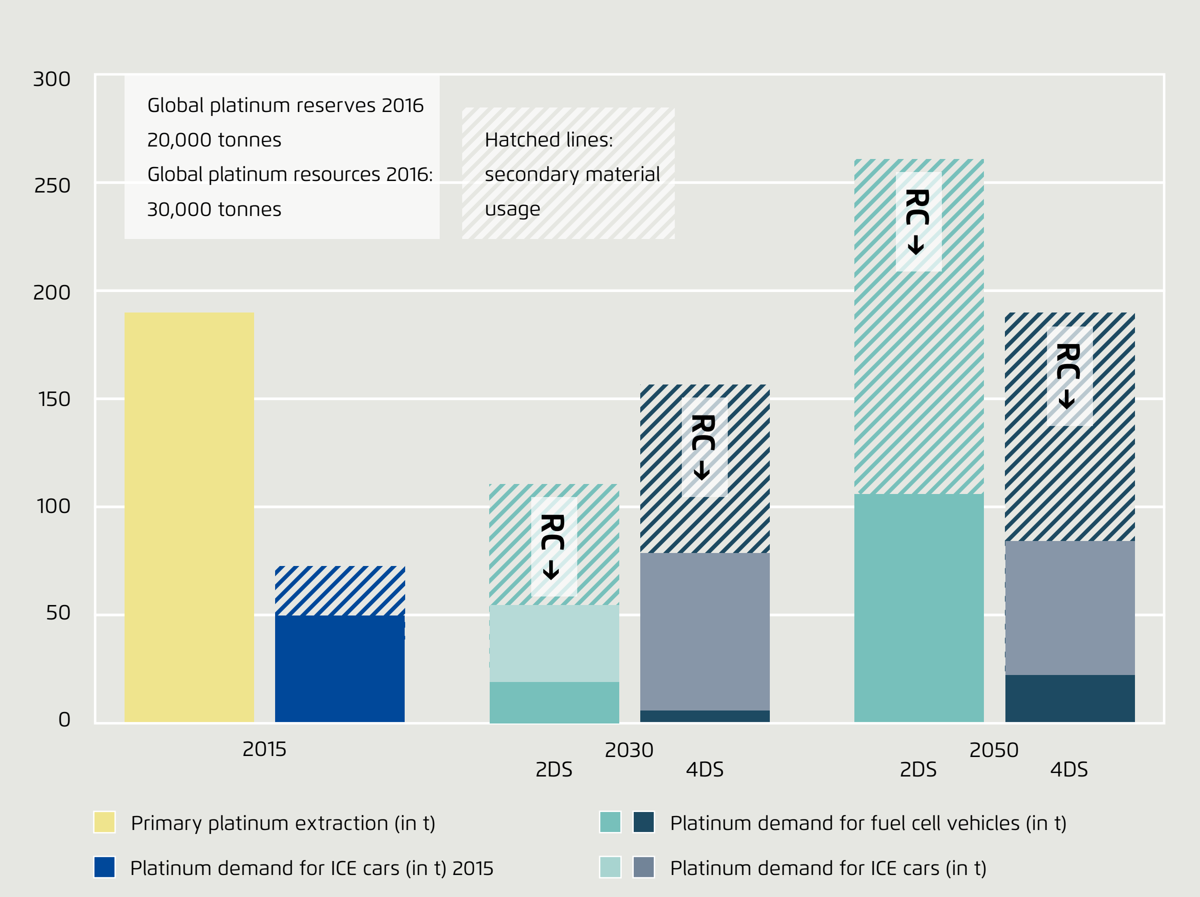
Platinum demand by vehicle type on the 2DS in 2030 and 2050 Figure 3.10



Authors' own calculations and visualisation

Global platinum demand for fuel cells and catalytic converters in 2015, 2030, and 2050 in the 2DS and 4DS (tonnes; including secondary material usage)

Figure 3.11



Authors' own calculations and visualisation; USGS 2017 for primary extraction levels and platinum reserves and resources; authors' estimates on the basis of USGS 2017 (on the assumption that platinum accounts for 30 % of all global reserves and resources of the platinum group metals)

As we have seen, global demand for the above raw materials is set to rise sharply. Weighed against global primary extraction levels in 2015, this is particularly true of lithium and cobalt. We can also assume that demand for these raw materials will increase in other areas, albeit at a lower rate. Projections for these are also provided in the Appendix. It should nonetheless be emphasised that the electric vehicle industry will drive demand for lithium and cobalt over the medium to long term (2030/2050).

3.6 Rare Earths: A Primer

The majority of electric motors in hybrids (HEVs), plug-in hybrids (PHEV), battery electric vehicles (BEVs), and fuel cell vehicles (FCEV) are permanent magnet synchronous motors (PMSMs) containing neodymium iron boron magnets (Buchert et al. 2011, Schüler, Schleicher, et al. 2016). These motors are chosen for their light weight, compactness, and energy efficiency. Neodymium iron boron magnets contain rare earth elements including neodymium, praseodymium, dysprosium, and terbium (which together account for around 30 per cent of the weight of each magnet). A few years ago, prices for rare earth metals and their compounds rocketed between ten and fifteen-fold in the space of a few months, not least as a result of China's almost exclusive dominance of global rare earth mining and processing.

Against this backdrop, magnet producers, electric motor manufacturers, and automobile companies invested heavily in new technologies that would be more resistant or even immune to supply chain failures resulting from rare earth shortages (Schüler, Schleicher, et al. 2016; Degreif et al. 2017). As a result, there are now a number of different motor designs for battery electric cars that do not require any rare earth elements. These include asynchronous motors (ASMs) and electrically/externally excited synchronous motors (EESMs), both of which have already been used in some BEV production models. The extent to which we will see a shift toward such alternatives in the hybrid sector is especially difficult to estimate, since the lightness and compactness of neodymium iron boron PMSMs makes them particularly well suited to such vehicles. A number of partial solutions have nonetheless recently been developed, including electric motors with neodymium iron boron magnets that do not require any dysprosium and terbium. The latter elements are only found in significant quantities in a limited number of rare earth deposits and are therefore particularly susceptible to price and supply volatility (Green Car Congress 2016).

PMSMs with neodymium iron boron magnets nevertheless remain the first choice among electric vehicle manufacturers in light of their numerous technological advantages and the significant drop in rare earth prices since the all-time high of 2010–2011. Should supply chain difficulties emerge due to rare earth shortages, however, a range of credible and in some cases fully developed and market-tested alternatives would relatively quickly be able to take their place.

04 | Potential Challenges: Real or Illusory Bottlenecks?

In the following sections we shall address the key questions formulated at the outset of the paper. These not only concern the potential challenges presented by raw materials shortages and the effects of raw materials price rises, but also the social and ecological risks of the relevant extraction processes.

4.1 How Likely Are Physical Raw Materials Shortages?

In light of the rapid expansion of the electric vehicle sector, this is a question on many stakeholders' lips. A physical shortage means that there are geologically insufficient quantities of a given raw material and that primary extraction will therefore be unable to satisfy global demand. The question of temporary shortages will be addressed in Section 4.2.

In the foregoing chapters, we showed how the rapid global development of the electric vehicle industry in the 2DS will lead to a surge in demand for strategic raw materials. Primary extraction will have to keep pace with this demand, since it will be impossible to satisfy it through recycled material alone. In the following sections, however, we consider the possibility of supply shortages of lithium, cobalt, nickel, graphite and platinum. At the end of the chapter we offer a comparative assessment of these risks.

Lithium

In the 2DS, demand for primary lithium for the electric vehicle sector is set to reach 148,000 tonnes in 2030 and 307,000 tonnes in 2050.[10]. In 2016, lithium production was dominated by Australia, Argentina, and Chile. Total production amounted to 35,000 tonnes (USGS 2017).[11] These figures nonetheless do not include US production.[12]

In estimating the potential for future shortages, it is crucial to consider the level of global lithium reserves.[13] In 2016, these totalled 14 million tonnes, 7.5 million of which were located in Chile alone (USGS 2017). Figure 4.2 shows the distribution of these reserves by country.

It is interesting here to compare these figures with the USGS data for 2006. Just ten years earlier, there were only 4.1 million tonnes of proven lithium reserves. The comparison therefore indicates just how much demand has risen over this period and the associated increase in exploratory research.

Nevertheless, the amount of lithium contained in the earth's crust greatly exceeds the 14 million tonnes of reserves identified to date. The USGS estimates the current known global lithium resources[14] at 46.9 million tonnes. Argentina and Bolivia each account for 9 million tonnes of these, Chile for 7.5 million tonnes, China 7 million tonnes, and the USA 6.9 million tonnes.

The data therefore indicate that despite the remarkable growth in demand, there is no risk of physical lithium shortages (i.e. the exhaustion of natural reserves), even in the long term. This remains true even when we take into account the various other uses of lithium (see Figure 7.1 in Appendix 7.1).

10 Total demand will be met through primary and secondary (recycled) material.

11 These and all subsequent figures refer to pure lithium content in tonnes, despite the fact that lithium is generally found and traded in the form of lithium compounds.

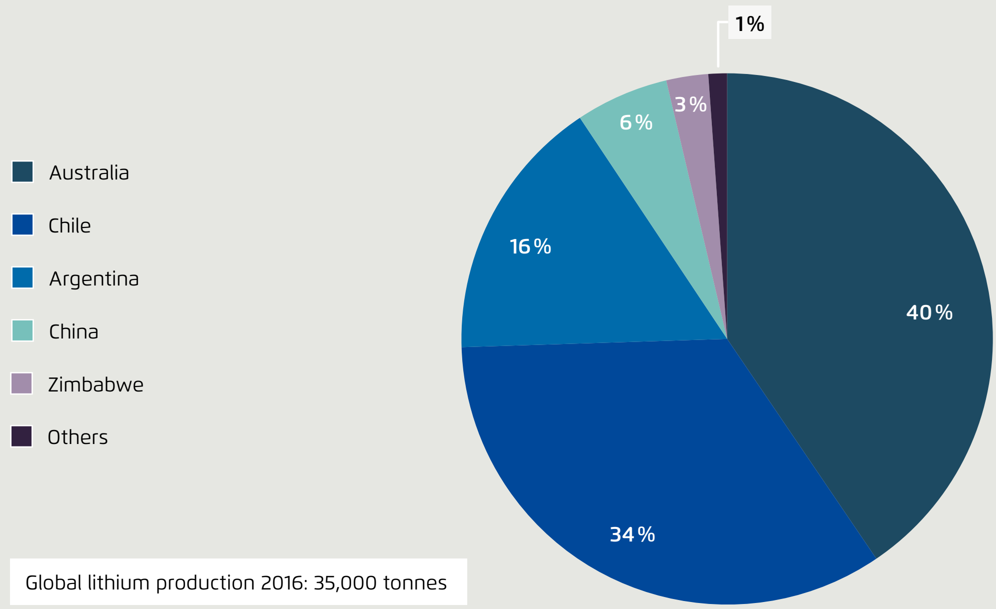
12 On our estimates, this was in the low four figures in 2016.

13 The term 'reserves' refers to those resources that are economically recoverable at the time of the data collection. The available reserves can vary from year to year. This may occur, for instance, when an increase in raw materials prices makes the recovery of additional resources economically viable.

14 The term 'resources' refers to the quantity of a given (solid, liquid, or gas) raw material naturally existing in the earth's crust that may be exploited either now or in the future (USGS).

Global lithium production by country in 2016

Figure 4.1

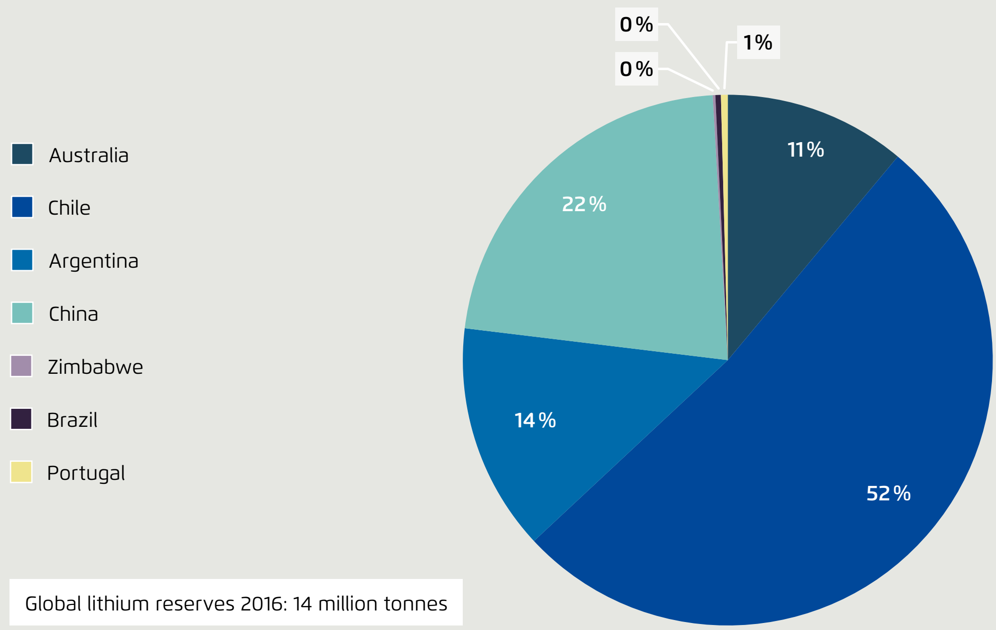


Global lithium production 2016: 35,000 tonnes

USGS 2017, excluding US production

Global lithium reserves by country in 2016

Figure 4.2



Global lithium reserves 2016: 14 million tonnes

USGS 2017, excluding US reserves

Cobalt

In the 2DS, demand for primary cobalt for the electric vehicle sector is set to reach 238,000 tonnes in 2030 and 501,000 tonnes in 2050.[15] In 2016, global cobalt production totalled 123,000 tonnes, 66,000 of which came from the Democratic Republic of Congo (DRC – see Figure 4.3). As the figure shows, the remaining output is divided among a relatively large number of other countries.

Figure 4.4 shows the distribution of global cobalt reserves (totalling seven million tonnes) in 2016 (USGS 2017). The DRC is also in first place here, with 49 per cent of all currently known reserves. Australia comes in a comfortable second, with 14 per cent of global reserves. The USGS (2017) estimates that worldwide land-based cobalt resources currently total around 25 million tonnes, most of are found in copper and nickel-bearing ores. Natural deposits in which cobalt is the main metal are rare, and currently only account for two per cent of global cobalt production (Al Barazi et al. 2017). It is estimated that there are also over 120 million tonnes of cobalt resources contained in manganese nodules on the ocean floor. Though the expansion of the electric vehicle sector in particular will lead to significant growth in demand between now and 2050, no physical cobalt shortages are expected.

Nickel

In the 2DS, demand for primary nickel for the electric vehicle sector is expected to reach 773,000 tonnes in 2030 and 1,576,000 tonnes in 2050.[16] In 2016, nickel production totalled around 2.25 million tonnes (USGS 2017 – see Figure 4.5).

The USGS (2017) estimates global nickel reserves at 78 million tonnes. Around 24 per cent of these are located in Australia, 13 per cent in Brazil, and roughly 10 per cent in Russia. As Figure 4.6 shows, the remaining nickel reserves are divided among a number of countries.

Global nickel resources, meanwhile, are estimated by the USGS (2017) at at least 130 million tonnes. Even taking into account other uses of nickel beyond the electric vehicle sector, physical shortages are therefore not expected.

Graphite

In the 2DS, demand for graphite for the electric vehicle sector will reach 1,657,000 tonnes in 2030 and 5,105,000 tonnes in 2050.[17] In 2016, natural graphite production totalled 1.2 million tonnes, 66 per cent of which came from China (USGS 2017). Only a small percentage of this overall output was used for lithium-ion electric vehicle batteries. According to the USGS (2017), worldwide natural graphite reserves currently stand at 250 million tonnes (36 per cent of these are in Turkey, 29 per cent in Brazil, and 22 per cent in China), while global resources total 800 million tonnes. Since synthetic graphite can be used to meet the growing demand for graphite for the electric vehicle industry, shortages can be ruled out even in the long term.

Platinum

In the 2DS, demand for primary platinum for fuel cell vehicles is expected to reach 10 tonnes in 2030 (45 tonnes for catalytic converters in ICE cars) and 103 tonnes in 2050 (0 tonnes for catalytic converters in ICE cars).[18] Global platinum output was 172 tonnes in 2016, 70 per cent of which derived from South Africa, 13 per cent from Russia, and 8 per cent from Zimbabwe (USGS 2017). Global reserves of the platinum group metals (platinum, palladium, rhodium, osmium, ruthenium, and iridium), meanwhile, totalled around 67,000 tonnes, 94 per cent of which were located in South Africa. Global resources are estimated to be over 100,000 tonnes (USGS 2017).[19] Furthermore, recycled material is an important source of platinum. According to Germany's Federal

15 Total demand will be met through primary and secondary (recycled) material.

16 Total demand will be met through primary and secondary (recycled) material.

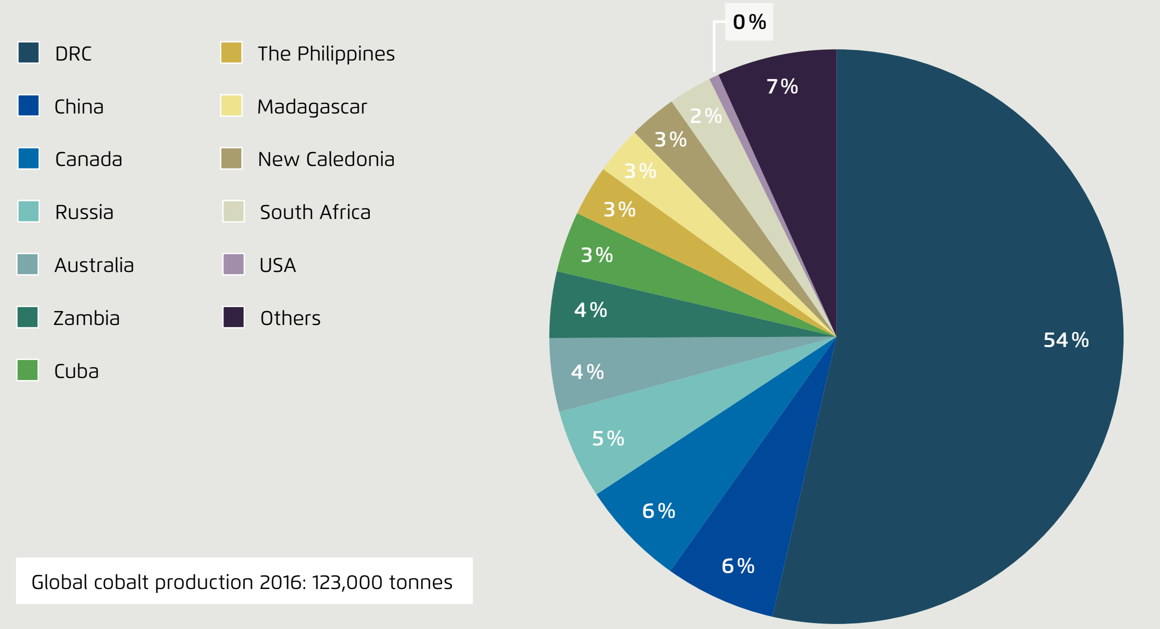
17 Graphite demand here refers to total demand. No graphite recycling has been assumed on our scenarios.

18 Total demand will be met through primary and secondary (recycled) material.

19 According to our own estimates, platinum accounts for at least 30 per cent of the total global resources and reserves

Global cobalt production by country in 2016

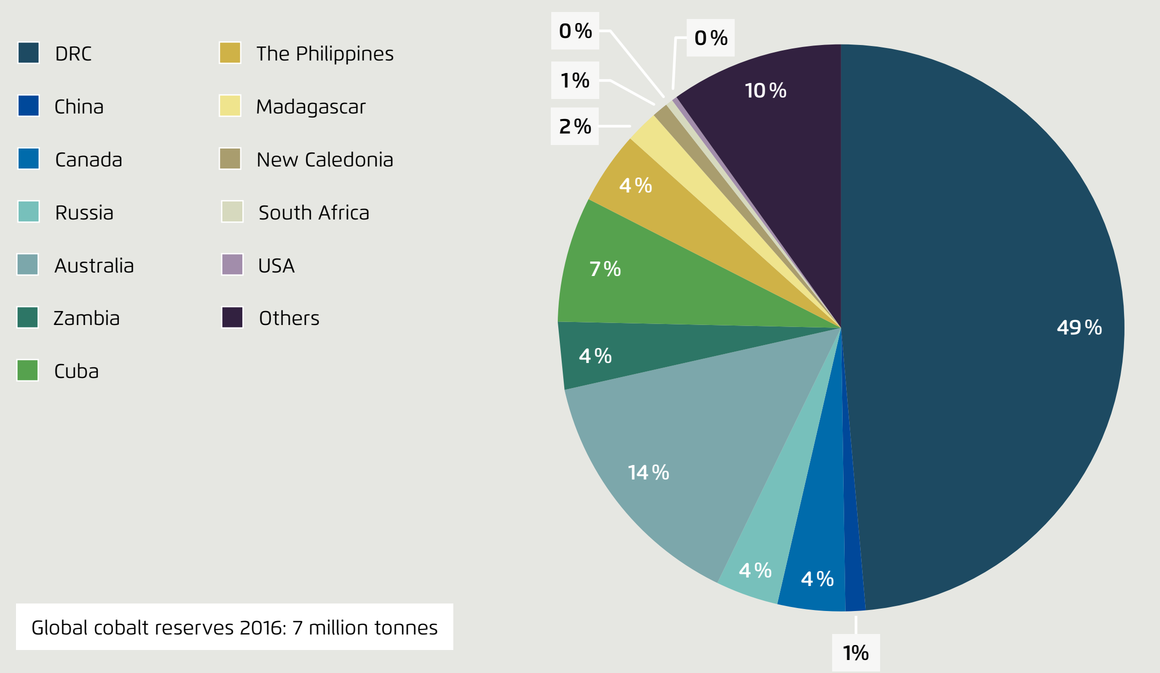
Figure 4.3



USGS 2017

Global cobalt reserves by country in 2016

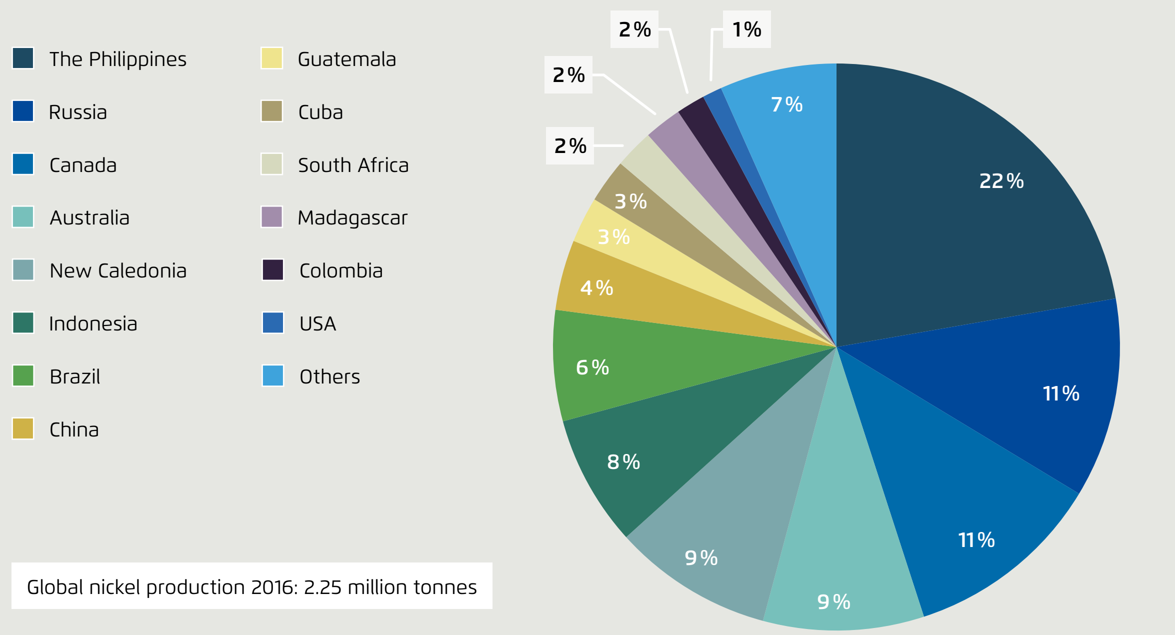
Figure 4.4



USGS 2017

Global nickel production by country in 2016

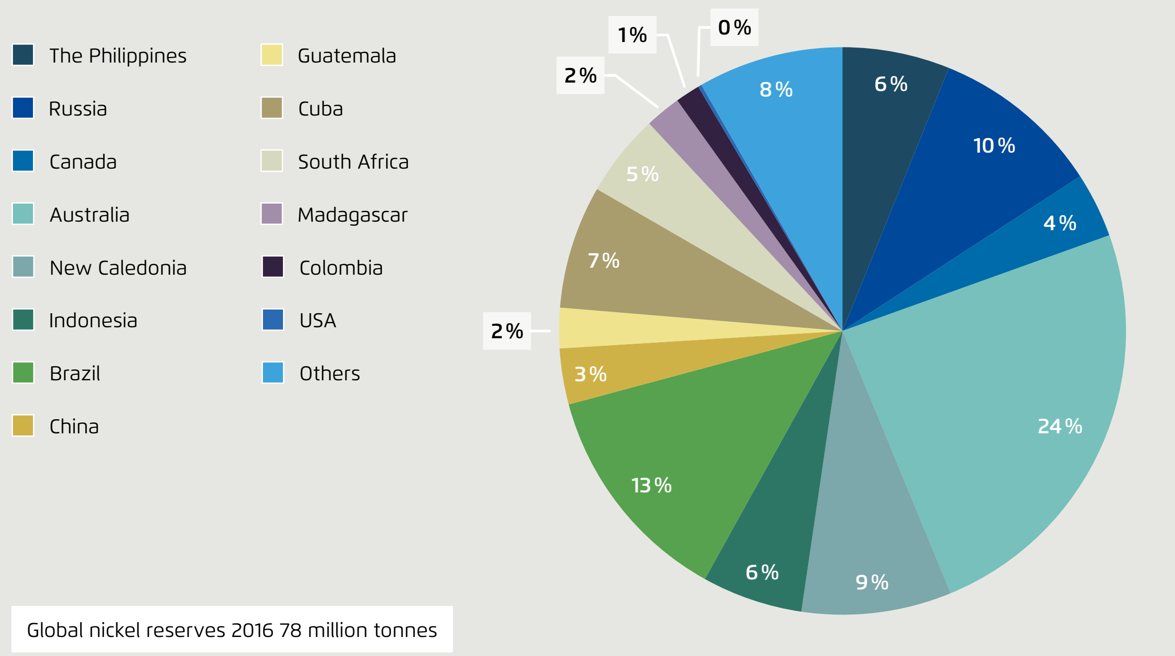
Figure 4.5



USGS 2017

Global nickel reserves by country in 2016

Figure 4.6



USGS 2017

Institute for Geosciences and Natural Resources (BGR 2016), refined platinum from recycling programmes accounted for around 25 per cent of global supply in 2013. In 2018, meanwhile, two different projections (Schmidt 2015) suggest that secondary material may account for between 28 and 29 per cent of supply. The global end-of-life recycling rate for platinum is between 60 and 80 per cent (UNEP 2011). In light of the extensive worldwide platinum resources and reserves and the ready supply of recycled material, no physical shortages are expected for the foreseeable future.

Summary

Growth in demand will vary for each of the raw materials in question, as will the ratio between demand and reserves/resources. Even if we include other uses of these materials in our projections, however, they will still be available in sufficient quantities to rule out the possibility of physical shortages over the course of the observation period.

- Lithium and cobalt will see the greatest increase in demand relative to primary extraction levels.
- Global nickel reserves and resources are spread across a number of countries and will comfortably exceed growth in demand.
- Growing demand for graphite, meanwhile, can be met by increasing the production of synthetic graphite. Where platinum is concerned, a fall in demand for conventional catalytic converters is expected be offset by an increase in demand for fuel cells. In addition, recycling programmes will further reduce pressure on primary production.

of the six platinum group materials.

4.2 How Likely Are Temporary Shortages?

A further question addressed by our study is whether any of our five raw materials may be subject to temporary shortages. A temporary shortage occurs when a given raw material is unavailable in sufficient quantities to satisfy demand for a number of weeks, months or, in the worst case, years. While we saw above that our five key raw materials are not at risk of physical shortages, they may still be subject to temporary shortages, with a range of causes and consequences. Such causes include:

- Political crises in key mining countries, ranging all the way from disputes to armed conflicts.
- Supply chain monopolies (on the part of producing countries or companies) that can be used as political levers.
- Interruptions to mining activity as a result of natural disasters (e.g. earthquakes and floods) or serious accidents (such as breaches in dam basins holding mining waste).
- Delays in gaining approval for new mining projects or the expansion of existing facilities.
- Mismatches between growth in demand and real growth in supply (exploration and development work for new mines takes at least five years to complete, and often longer).
- Interruptions to mining activity resulting from energy or water shortages.
- Changes in the supply of/demand for a major metal on which the supply of a minor metal (such as cobalt) depends.[20]

In the following, we assess the likelihood of temporary shortages for our key raw materials.

20 A minor metal is a metal derived as a by-product of the extraction of another, 'major' metal.

Where **lithium** is concerned, the challenge in the coming decades will be to ensure that global mining of natural deposits keeps pace with the considerable growth in demand from the electric vehicle sector. The risk of temporary shortages can be limited by introducing and continually expanding industrial recycling programmes for lithium from batteries and other sources (on the scale already attained for platinum, for example). This challenge will be addressed in the recommendations offered in Chapter 6. Depending on the pace at which the electric vehicle sector expands, temporary lithium shortages cannot be entirely ruled out. Their likelihood can nonetheless be reduced by expanding recycling programmes to provide a new source of lithium. Furthermore, since lithium exploration and development is booming in many countries, long-term shortages are unlikely.

The likelihood of future **cobalt** shortages depends largely on developments within the Democratic Republic of Congo. Where cobalt is concerned, however, no problems have been encountered here in recent years (we shall later discuss the DRC and cobalt in greater detail). Cobalt is already recycled from a range of sources (including superalloys, catalytic converters and batteries). Going forward, it will be crucial to ensure there are efficient systems in place to collect and sort these materials, before transporting them to recycling facilities that can guarantee high recovery rates at minimal environmental cost. As a minor metal, cobalt is almost always derived as a by-product of copper and nickel mining. Since demand is set to rise for these two major metals, however, cobalt production is also expected to increase.

Of the five metals under consideration here, **nickel** mining activities and existing nickel reserves are the most geographically widespread. Temporary shortages resulting from political crises or monopolistic interventions are therefore unlikely. Furthermore, nickel is already recycled on an industrial scale from stainless steel, catalytic converters, and nickel-metal hydride and lithium-ion batteries. The future expansion of nickel recycling capacities will serve to further reduce the likelihood of nickel shortages. Stainless steel recycling is nonetheless a closed-loop cycle, and the nickel recovered through it cannot be used to form the high purity nickel salts required for electric vehicle batteries.

Where **graphite** is concerned, synthetic graphite will assume an ever more important role in meeting demand for the electric vehicle industry. Rapidly expanding synthetic graphite production will help to offset any temporary natural graphite shortages. In this connection, it will be essential to ensure that such production keeps pace with the expected growth in demand from the electric vehicle sector. Since graphite can be synthetically produced in this way, temporary shortages are not expected.

With respect to **platinum**, temporary shortages cannot be entirely ruled out, since current mining activities and global natural reserves are concentrated in South Africa. For some years now, South Africa's energy crisis has caused particular problems for its industrial sector, including its economically significant mining industry (Schnurpfeil 2015). Furthermore, disputes over working conditions and pay led to a series of strikes in the country's PGM[21] mines in 2012. Temporary supply bottlenecks and price hikes were only averted in 2012 thanks to low global demand. In the future, such disputes may resume any time, with potentially significant consequences for mining output. Furthermore, since South Africa enjoys a near monopoly on platinum production, it would be almost impossible to make up for lost production from mines located elsewhere. Strikes of this kind therefore have the potential to directly influence platinum's price and availability (Yager et al. 2013). Nevertheless, recycled platinum now accounts for a growing share of all supply. In light of this and platinum's significant value added, any temporary shortages are expected to be relatively brief.

Summary: Temporary Shortages

In light of their wide range of possible causes, temporary shortages cannot be completely ruled out. The risk of shortages will be highest for lithium (which is not currently recycled and will see the greatest rise in demand) and cobalt (which is mainly located and mined in the DRC, and is also associated with other social risks). There is nonetheless no danger of these temporary materials shortages bringing vehicle production to a standstill; at worst, they may serve to delay the full electrification of the transport sector.

21 Platinum group metals

4.3 Could Extreme Price Hikes Put the Brakes on the Electric Vehicle Sector?

In order to assess the potential influence of raw materials prices on the growth of the electric vehicle industry, in this section we consider the cost of the key materials contained in lithium-ion battery cells. Table 4.1 shows their average prices for the period from August 2016 to July 2017. Alongside lithium, cobalt, nickel and graphite, which are considered in detail in the present paper, we have also included manganese here for the sake of completeness.

In our analysis, we estimated the total costs of the above battery cell materials for a 30 kilowatt hour (NMC) lithium-ion battery in a typical BEV car. We then compared these with the overall battery costs. The absolute costs for all five of the above raw materials run to nearly $1,400 per battery (see Table 4.2)

Figure 4.7 shows the percentage of these total costs accounted for by each of the raw materials.[22] From the chart, it can be seen that lithium and cobalt together make up around 85 per cent of the total raw materials costs, on the basis of current prices.

Overall per kilowatt hour costs for lithium-ion electric vehicle batteries have fallen significantly in recent years, and further decreases are expected in the coming years (IEA 2017). Figure 4.8 shows these raw materials costs as a percentage of total battery costs (currently estimated at $350 per kilowatt hour). The total cost of a 30 kWh battery therefore runs to $10,500, 13 per cent of which is contributed by the key battery cell raw materials. Since battery costs per kilowatt hour are continually falling, however, Figure 4.8 also shows the raw materials contribution for battery costs of $200 per kilowatt hour. Total battery costs would then run to $6,000, around 23 per cent of which would be accounted for by the battery cell raw materials.

Our estimates show that the battery cell raw materials account for a significant though not overwhelming share of total BEV battery costs. In the near future, we can expect battery costs to fall further, when greater economies of scale (in facilities such as Tesla's 'Gigafactory') lead to improved production processes and energy efficiency gains. In all probability, these will (more than) offset any raw materials price rises. Even if our five raw materials were all to double in price, this would only raise the total price of a 30 kWh BEV battery by around $1,400. A reduction in overall battery costs from $350 to $200 per kilowatt hour[23], by contrast, would save $4,500 (assuming raw materials prices remain unchanged). Should raw materials costs double, this would still leave a total net saving of $3,100.

Raw materials costs for the key cell materials in an NMC battery in dollars per kilogram — Table 4.1

Lithium*	10.99
Manganese	2.12
Cobalt	45.40
Nickel	10.08
Graphite	0.80

* Average price per kg of lithium carbonate from August 2016 to July 2017
DERA 2017

Raw materials costs for the key cell materials in an NMC battery (30 kWh, NMC 1:1:1) in dollars per battery — Table 4.2

Lithium	571
Manganese	27
Cobalt	618
Nickel	137
Graphite	39
Total	1392

N.B. Average from August 2016 to July 2017,
DERA 2017

22 A nickel manganese cobalt (NMC) battery in a stoichiometric ratio of 1:1:1.

23 In the long term, battery costs of around $100 per kilowatt hour are expected to be achievable (IEA 2017).

Summary: Price Rises

The above calculations show that raw materials price rises are unlikely to bring the electric vehicle industry to a standstill. Furthermore, the next generation of nickel manganese cobalt battery cells are expected to require less cobalt, which is a relatively expensive metal. The current 1:1:1 stoichiometric ratio is set to be replaced by a 6:2:2 ratio (Umicore 2017). This means costs will be optimised even at the level of battery composition. Nevertheless, the potential influence of raw materials price rises on the competitiveness of electric vehicles cannot simply be brushed aside, since raw materials costs account for a sizeable share of overall battery and fuel cell production costs. This influence would be particularly strongly felt if the prices of a number of key raw materials were to rise at the same time. Recent experience with rare earth elements has nonetheless shown that much can be done to ward off drastic price rises, including investing in technological innovation, developing new production sources, and so on. Ensuring that production is distributed between as many countries and companies as possible will also help to increase competition and counter extreme price rises. It is nevertheless important not to underestimate the potential influence of speculation on raw material prices.

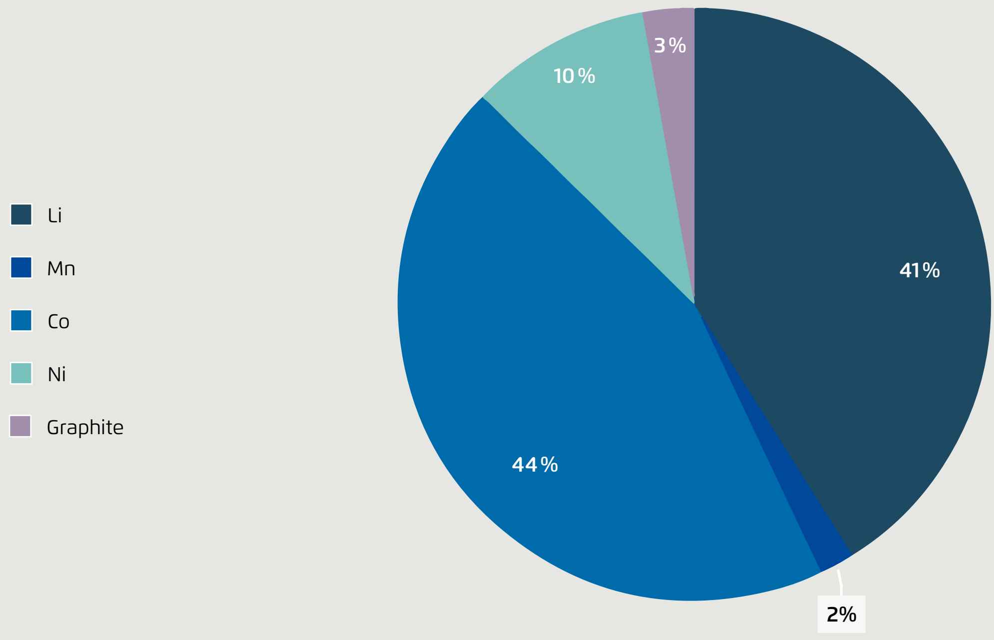
Finally, strengthening the recycling sector will help to diversify supply of all the metals considered here, further reducing the likelihood of extreme price rises.

4.4 Will Increased Primary Extraction Lead to Socio-Economic and Ecological Problems?

In Chapter 3, we saw that the electrification of the transport sector is set to result in significant growth in demand for lithium, cobalt, graphite, platinum and nickel. Only some of this demand can be satisfied through recycled material. The majority will therefore need to

Distribution of average raw materials costs (from August 2016 to July 2017) for the key raw materials for a BEV car battery (NMC-1:1:1-)

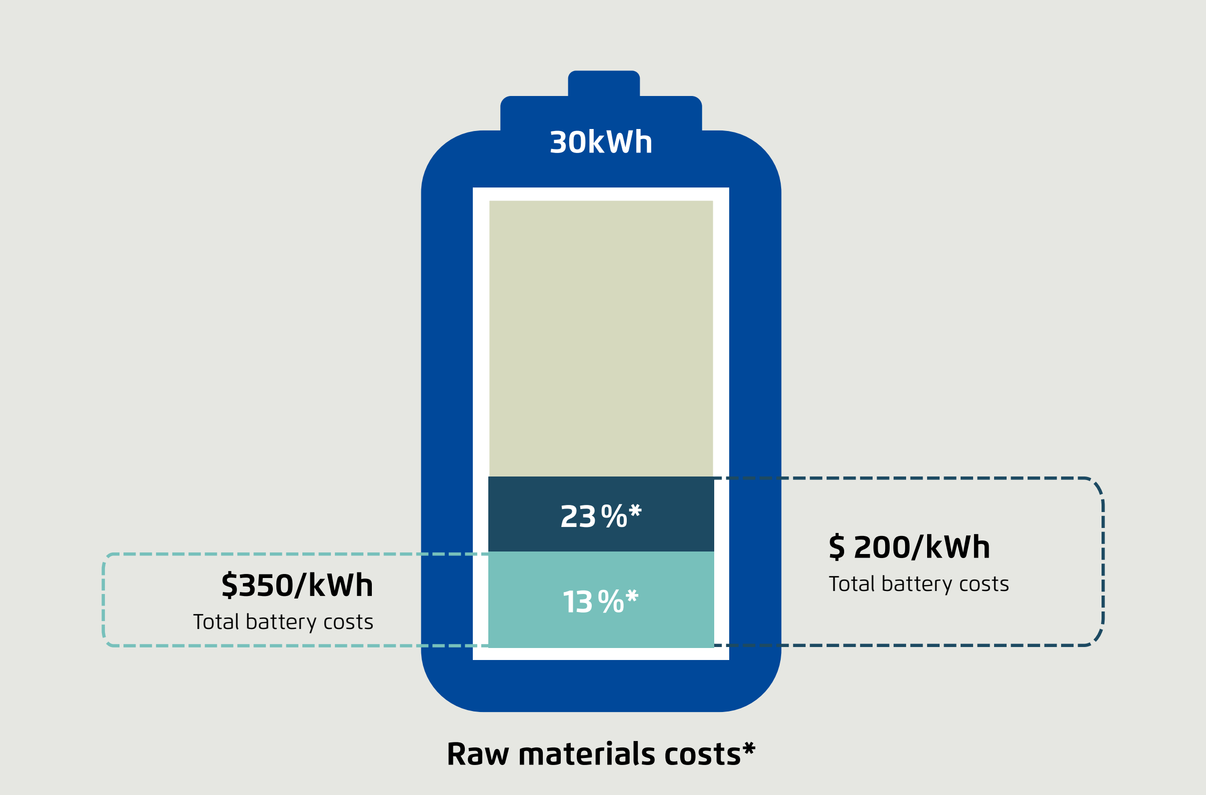
Figure 4.7



Authors' own calculations and visualisation; raw materials prices based on DERA 2017

Key battery cell material costs as a share of variable total battery costs for a 30 kWh NMC BEV car battery

Figure 4.8



N.B. Average nickel, lithium, cobalt, manganese, and graphite prices from August 2016 to July 2017
Authors' own calculations and visualisation.

be met through an increase in primary extraction. The socio-economic and ecological consequences of mining can vary greatly depending on the materials in question, the source country and the standards applied. In Africa, the AU's adoption of the Africa Mining Vision aims to promote those mining projects that can have a positive effect on the continent's overall economic development (African Union 2009). On the other hand, however, the 2010 Dodd-Frank Act[24] highlighted the problem of conflict minerals (Rüttinger, Griestop 2015). The debate around such minerals has spurred a range of initiatives, standards and certification mechanisms that aim to minimise the socio-economic and ecological ramifications of the mining industry. Recent decades have seen the establishment of clearer standards and a growing awareness of the importance of responsible mining. Nevertheless, raw materials mining is still beset by a range of negative social and environmental consequences. In the following, we shall discuss the most significant social and ecological risks attendant on our five key raw materials.

Lithium

Lithium is mined using two principal methods. In the first, lithium is extracted from hard rock mines. A large number of these are located in Australia, which accounts for 45 per cent of global production. In the second, lithium is derived from salt lakes. This method is now widespread in South America, and particularly in Chile, which accounts for a third of all production (See Figure 4.9).

24 See sections 1502 and 1503 of the Act in particular.

More than half of all known reserves are located in Chile. A further fifth are found in China, while Argentina and Australia each possess around a tenth. The majority of lithium is therefore sourced from or located in politically stable countries.

The two different extraction methods involve very different ecological risks. In Australia, the first generally begins with the extraction of spodumene from open pit mines. The spodumene ore is then broken down and ground up in an energy intensive process, before being heated to 1,150°C. It is then mixed with sulphuric acid to form lithium sulphate, which is subsequently concentrated and mixed with sodium carbonate to make lithium carbonate, which is the end product (Evans 2014).

Extracting lithium from salt lakes, meanwhile, involves pumping lithium-bearing brine into evaporation ponds, where the lithium salts are concentrated via natural solar energy. Depending on the brine's chemical composition, a number of different methods can then be applied. Through evaporation and the precipitation of unwanted elements, the brine is gradually reduced to around a six per cent lithium chloride concentrate. It is then mixed with sodium carbonate to yield the end product, lithium carbonate (Evans 2014). On account of the simplicity of the process and its use of solar energy, Grosjeana et al. (2012) classify this extraction method as environmentally friendly.

The two extraction methods may impact the environment and the surrounding population in a range of ways. In Australia, spodumene mining carries the usual environmental risks of any ore mining. It requires significant energy consumption and generates both greenhouse gas emissions and mining waste. Furthermore, sulphuric acid has to be processed carefully after use to prevent it from entering the surrounding environment (BGS 2016). In the brine extraction method, by contrast, what is particularly problematic is the use of large quantities of water, since the salt lakes are usually located in arid regions (Swiss Resource Capital 2016). In the past, conflicts have broken out between local populations and mining companies in areas prone to water stress (FOE 2013). Initial attempts have therefore been made to process lithium-bearing brines from salt lakes without first concentrating them in evaporation ponds. This new method involves pumping the brine out of the salt lakes and then processing it directly. Once the lithium content has been extracted, the brine is then returned to the lake. This approach could help to save water in future (International Mining 2017; Pure Energy Minerals 2017).

Cobalt

At present, cobalt is mainly produced on an industrial scale as a by-product of copper and nickel mining. In the Democratic Republic of Congo, however, artisanal mining accounted for 15 to 20 per cent of the country's cobalt ore production between 2015 and 2016 (Al Barazi 2017). Cobalt mining is socio-economically problematic on account of the tense political situation in the DRC, which accounts for almost half of all global production. The remaining production is relatively evenly distributed across a number of other countries. The DRC also possesses around half of all global cobalt reserves. Australia follows in second place, with around two thirds fewer reserves (see Figure 4.10). It is safe to say, then, that the DRC will play a key role in meeting future cobalt demand.

Nevertheless, direct links have been proven between the financing of armed groups and gold, tungsten, tin, and tantalum mining in Eastern Congo. This is why these commodities have been described as conflict minerals. With the passage of the Dodd-Frank Act in 2010, US companies importing such conflict minerals were required to report to the SEC on their sourcing practices and to ensure they conduct appropriate due diligence (Al Barazi 2017). Prior to the suspension of this reporting requirement in 2017, the OECD introduced a five-stage programme to help companies fulfill their notification duties and minimise risks along the supply chain (OECD 2016).

Although cobalt itself is not a conflict mineral, the fact that 15 to 20 per cent of production is artisanal in nature means that it still carries some risks, which are exacerbated by the broader context of mining in the DRC. Two of these are particularly important to note here: First, artisanal mining is informal in nature and often involves child labour and poor working conditions. Second, weak state state structures and the broader political situation in the DRC are associated with other problems such as corruption and irregular taxation (Al Barazi 2017).

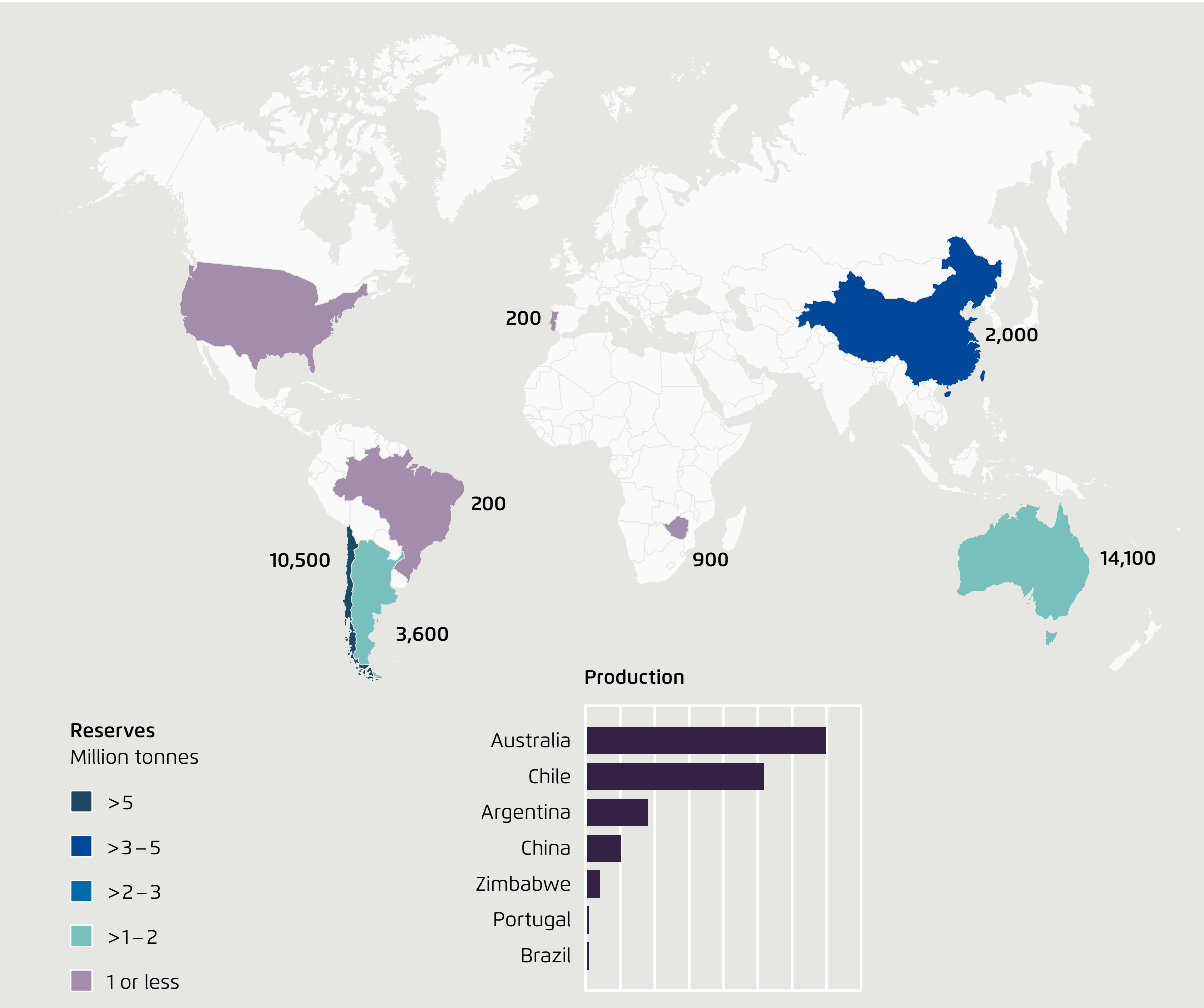
Where the environment is concerned, copper-cobalt deposits are often associated with sulphide minerals and therefore harbour the risk of acid mine drainage,[25] which can be very difficult to prevent. Preventative measures include covering mining waste and residue with membranes or layers of agrillaceous minerals such as bentonite. Alkaline chemicals may also be used, but they do not always prevent acid build-up over the long term. Where acidic pit water has already built up, lime is often used to restore acceptable pH levels (Pozo-Antonio et al. 2014).

25 *AMD:* Sulphide ores can cause - under influence of oxygene and water – sulphuric acid, which releases further heavy metals from the ore and causes long-term damage to the water supply and the surrounding environment.

Nickel

In contrast to the other raw materials considered here, nickel mining is not concentrated in any given region. The Philippines is the world's biggest producer, contributing nearly a quarter of all output. Russia, Canada and Australia, meanwhile, each account for around a tenth of

Global lithium production in 2015 and lithium reserves — Figure 4.9



N.B. Shading represents lithium reserves; numbers annual production.
Authors' own calculations and visualisation on the basis of USGS 2017

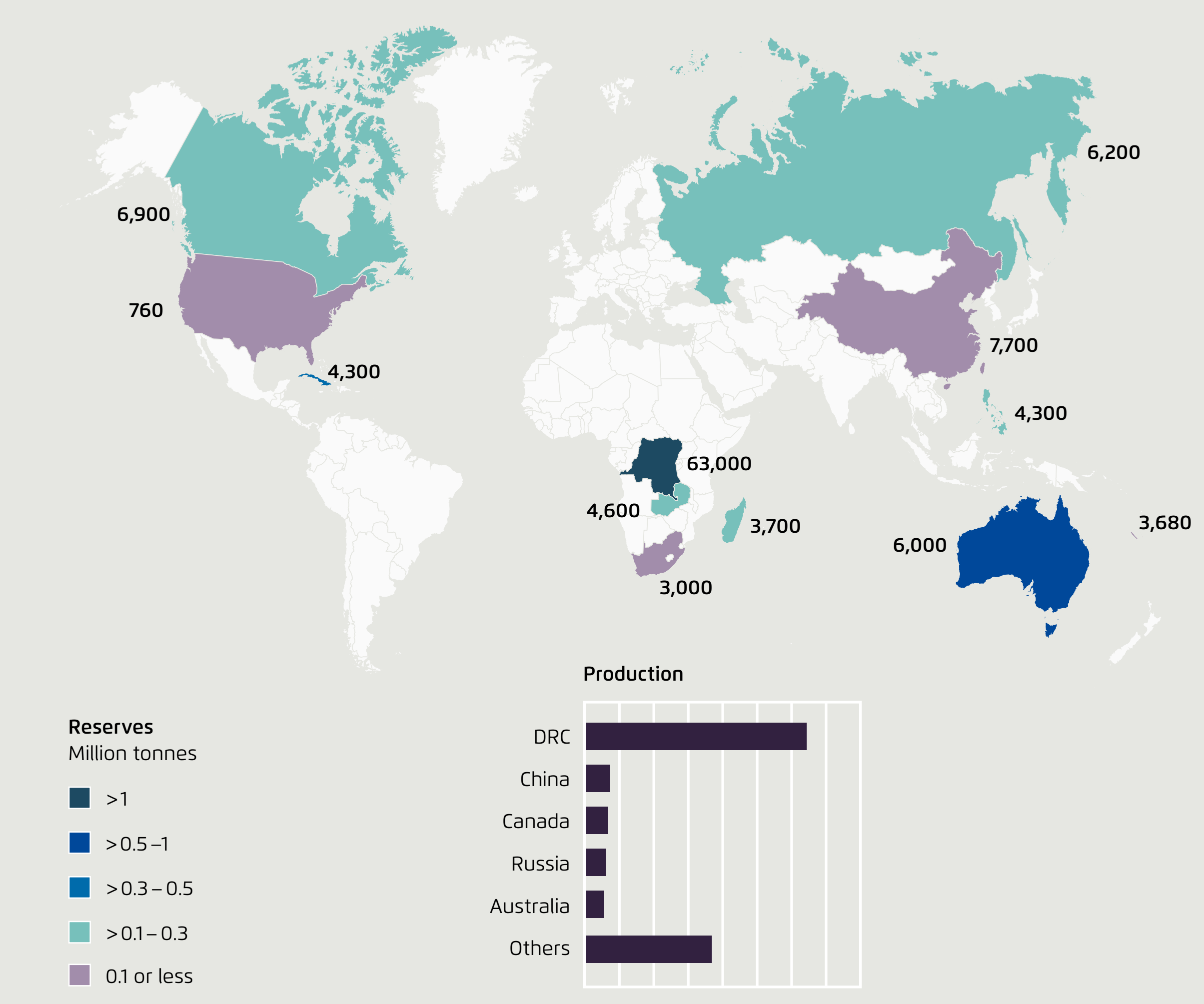
all global production. The remaining nickel production is distributed relatively equally across ten other countries. The situation is similar for global nickel reserves. Australia accounts for almost a quarter of all reserves and Russia and Brazil for around a tenth each. The remainder are spread across a number of countries, each of which possesses between one and eight per cent of worldwide reserves (USGS 2017).

Nickel is extracted in almost equal quantities from sulphide ores and lateritic deposits. Both sources carry a range of environmental risks. Nickel from sulphide ores is generally associated with platinum group metals, copper, and cobalt, and may be extracted either from underground or open pit mines. In both mine types, sulphide ores can cause acid mine drainage, which can have a long term impact on the surrounding soil and water supply.

The majority of nickel reserves are contained in lateritic deposits, which are usually close to the surface and are extracted through open pit mining. Processing lateritic deposits is more energy intensive than processing sulphide ores, partly because the latter are drier. Mining for lateritic deposits therefore generates higher greenhouse

Global cobalt production in 2015 and cobalt reserves

Figure 4.10



N.B. Shading represents cobalt reserves; numbers annual production.
Authors' own calculations and visualisation on the basis of USGS 2017

gas emissions; these currently lie between 25 and 46 tonnes of CO_2 per tonne of primary metal. Mining for sulphide ores, by contrast, generates only 10 tonnes of CO_2 per tonne of primary metal. Both forms of mining release sulphur dioxide, which causes acid rain. Optimising ore processing methods can nonetheless significantly reduce the quantity of sulphur dioxide released (Mudd 2010).

Nickel mining in Canada and Russia has had a range of environmental consequences, including biodiversity losses, acid rain and heavy metal contamination (Mudd 2010). The social consequences of nickel mining usually follow from its environmental impact; they are generally health-related or involve the loss of usable agricultural land.

Graphite

Graphite is both mined and synthetically produced. Almost two thirds of worldwide mining output comes from China. India contributes a further 14 per cent and Brazil almost 7 per cent, with remaining production distributed across ten countries, each of which produces a small quantity of graphite. Graphite reserves are distributed a little more widely, though are for the most part divided between three countries. More than a third of all reserves are located in Turkey, just under a third in Brazil, and around a fifth in China (USGS 2017).

China's significant contribution to global graphite production is primarily due to the lower costs of mining in the country. Its competitive edge nonetheless comes at the price of lower environmental and social standards. As the Washington Post has reported, many Chinese graphite mines emit massive quantities of dust. This dust settles in the surrounding area, affecting the health of local residents. Likewise, local water supplies are often contaminated by mining waste (Whoriskey 2016).

In the future, synthetic graphite production is set to grow, though natural graphite will continue to play an important role in satisfying demand.

Platinum

Platinum is always found together with other platinum group metals (palladium, rhodium, ruthenium, iridium, and osmium) and cannot be mined in isolation. South Africa is the world's largest platinum producer, accounting for almost three quarters of all supply. A further ten per cent is contributed by Russia and around seven per cent by Zimbabwe. Where platinum group metal reserves are concerned, South Africa's share is even higher, at 95 per cent (USSG 2017).

Mining for platinum group metals can cause environmental damage through the extraction of sulphide-bearing ores. This often leads to acid and metalliferous drainage (AMD), contaminating the water supply with heavy metals and reducing pH levels (Gunn 2014). Furthermore, platinum group metals generally only make up 0.002 per cent of these sulphide ores. Platinum processing therefore produces a large amount of waste material. It is also energy intensive and generates large quantities of greenhouse gases (Gunn 2014). In assessing the environmental impact of primary platinum production, it is therefore crucial to take these emissions into account. Some 14,000 tonnes of CO_2 are generated for every tonne of primary platinum. In copper production, by contrast, only 3.4 tonnes of CO_2 are generated per tonne of metal (Hagelüken, Buchert 2008). We should note, however, that global primary platinum production does not exceed 200 tonnes per year.

In South Africa, the government has already initiated a programme to curb the environmental impact of platinum production (Gunn 2014).

The social problems associated with platinum mining in South Africa are largely the result of clashes between mine workers and mine operators. In 2012, disputes over working conditions and pay led to a series of strikes in PGM[26] mines in the country. These culminated in violent clashes between workers and police, in which 78 mine workers were injured and 34 killed. This incident is widely referred to as the Marikana massacre. Conciliation talks held after the massacre resulted in significant pay rises, which brought the strikes to an end (Chetty 2016). Pay and living conditions at the mine nonethe-

26 Platinum group metals

less remain poor, with workers enjoying insufficient access to electricity, water and sanitary facilities. Despite the efforts of the government and the mine operators, improvements in these areas are still slow in coming (Nicolson 2015).

In future, we recommend that platinum recycling programmes be expanded to provide a greater share of all production. As well as offsetting the environmental impact of primary production, this would also help to diversify supply.

Summary: Socio-Economic and Ecological Problems

We have seen that primary extraction of our key raw materials can lead to a range of socio-economic and and ecological problems. Rising demand for these raw materials will make it increasingly important to introduce measures to minimise this impact. In Chapter 6 we present a range of recommendations for action that aim to lay the groundwork for such measures.

We should nonetheless emphasise that, from a sustainability perspective, it is neither expedient nor appropriate to focus only on the socio-economic and ecological ramifications of increased raw materials mining. The ongoing electrification of the transport sector will also bring massive medium to long-term reductions in the use of other raw materials – particularly oil.

Electric Vehicles and Crude Oil Savings

The rapid growth of the electric vehicle sector will not only lead to a rise in demand for strategic raw materials. It will also see demand for other raw materials fall. In the 2DS, for example, 1.6 billion fewer tonnes of crude oil are set to be used in 2050 than on the 4DS.

This will be accompanied by a reduction in the environmental and social impact of the oil industry, and will mean five billion fewer tonnes of carbon dioxide will be emitted in 2050 alone. Furthermore, it will help to reduce the lasting environmental damage caused by the extraction, processing and transportation of crude oil (as has been seen in Ecuador, Nigeria, Alaska, and so on).

In considering the negative impact of rising demand for electric vehicle raw materials, it is therefore crucial to attend to the concomitant reduction in demand for oil and the alleviation of its environmental and social impacts in oil producing countries.

05 | Solutions in Brief

In the previous chapters, we saw how the development of the electric vehicle sector is set to drive significant growth in demand for many strategic raw materials. In order to minimise the negative impact of increased production and to reduce the risk of supply shortages, a number of challenges that will need to be addressed. The present chapter briefly outlines a number of solutions to these challenges.

On the one hand, efforts should be made to reduce demand for natural lithium, cobalt, platinum, nickel and graphite without hindering the growth of the electric vehicle sector. This will partly be achievable through improvements in material efficiency. On the other hand, we should work to develop viable substitutes for the various raw materials in question (except for graphite, which can already be synthetically produced). Today, it is already possible to satisfy a significant share of the demand for cobalt, nickel, and platinum through utilising secondary materials. Primary extraction of these materials can be further reduced by expanding recycling programmes. In the case of lithium, we should seek to achieve a rapid roll-out of recycling programmes over the next few years.

In order to keep up with demand, however, primary extraction will continue to grow. In light of this, it will be crucial to limit its negative environmental impacts in source countries by implementing strict environmental standards – particularly for the four metals in question. Furthermore, the risk of mining-related social conflicts can be reduced by ensuring that corporate due diligence requirements and global production guidelines are adequately upheld. Likewise, there will need to be fair cooperation with source countries to ensure that knowledge is appropriately disseminated and that the necessary growth in primary production takes place in an environmentally and socially responsible manner.

06 | Strategic Recommendations for Action

In light of the risks to the sustainable supply of raw materials for the electric vehicle sector discussed in the foregoing, this section presents seven key recommendations for action. These recommendations, which are derived from the questions elaborated at the outset of our paper, outline key measures required to ensure raw materials availability as well as environmentally and socially responsible raw materials extraction.

Table 6.1 lists the seven recommendations and categorises them according to their potential implementation periods and the stakeholders concerned. Particular focus is placed on national actors who are in a position to initiate international coordination and cooperation processes at the European and global levels.

These recommendations will be discussed in further detail in the individual chapter sections below. The order of their presentation is not intended to reflect their perceived importance.

6.1 Founding a Global Industrial Alliance for Sustainable Lithium

Our first recommendation is to found a global industrial initiative for sustainable lithium.[27] According to our analysis, the expected development of the electric vehicle sector will lead to significant growth in medium to long-term lithium demand (2030/2050). While the concomitant increase in primary lithium extraction may have a number of ecological and social consequences, it will also present an opportunity to improve sustainability and efficiency along the supply chain. The aim of the global industrial initiative is to safeguard the supply of lithium for the rapidly growing electric vehicle sector, and to do so in an environmentally and socially sustainable way.

27 In practice, "lithium" is understood to mean both lithium salts and other lithium compounds.

Solutions and recommendations for action — Figure 6.1

Monitoring

→ Adopting an electric vehicle commodities radar

Reducing demand for primary raw materials

→ Promoting a battery technologies R&D drive
→ Expanding the EU Batteries Directive
→ Establishing a global recycling system for lithium-ion batteries

Improving the social and environmental conditions of mining

→ Founding a global industrial alliance for sustainable lithium
→ Introducing compulsory due diligence requirements for cobalt
→ Fostering international cooperation on sustainable mining

Authors' own visualisation

Overview of our strategic recommendations for action — Table 6.1

Recommendation	Start date	Imple-mentation period	Level	Actors concerned*	National initiators in Germany
Founding a global industrial alliance for sustainable lithium	2018	~ 2025	global	Key industrial actors, global vehicle manu-facturers	Key industrial actors
Introducing compulsory due diligence require-ments for cobalt	2018	~ 2025	EU	European Commis-sion, companies throughout the cobalt value chain	The German government (BMWi)
Fostering international cooperation on sustain-able mining	2018	2020–2026	DE, EU, global	BMZ, EU, World Bank, mining companies	The German government (BMZ)
Expanding the EU Batteries Directive	2018	~ 2020	EU	European Commission	The German government (BMUB)
Establishing a global recycling system for lithium-ion batteries	2018	~ 2025–2030	DE, EU, global	European Commis-sion, G7, G20, OECD, UN, vehicle manufac-turers and recyclers	The German government and industrial players
Promoting a battery technologies R&D drive	ongoing		DE, EU	The German govern-ment, EU, technology companies	The German government (BMBF, BMUB, BMWi)
Adopting an electric vehicle commodities radar	2019	ongoing	DE, EU, global	The German govern-ment, EU, UN	The German government (BMUB, BMWi, BMBF)

*Actors concerned = those to whom the recommendations are directed and who should be responsible for initiating them.

To this end, we advocate the establishment of a global initiative for sustainably sourced primary lithium. Since the electric vehicle sector will account in large part for future global lithium demand, vehicle manufacturers, suppliers and various automotive associations should play a crucial role in the proposed alliance. The alliance should also include lithium mining companies, battery producers, cathode material producers, distributors, and recycling companies. Furthermore, local stakeholders in primary source countries will also need to be involved in the process. The sustainable lithium alliance will require the support of key players in German industry, who will be able to further its aims by involving other national and international actors.

Sustainable lithium is lithium that is extracted according to globally accepted environmental and social standards. The exact details of these standards and the individual criteria and threshold values for sustainable lithium will need to be worked out by the industrial alliance in collaboration with independent experts. In doing so, it will be essential to ensure transparency along the entire supply chain. The impact of the initiative should be most strongly felt in the main lithium source countries (currently Chile, Argentina, Australia, and the USA) and the main processing countries (currently China, South Korea, and the USA).

The alliance will be able to take its lead from schemes such as the Initiative for Responsible Mining Assurance (IRMA), which is currently developing a set of standards through a broad-based, multi-stakeholder process involving both NGOs and international mining corporations (IRMA 2017).

Since it can safely be assumed that demand for lithium will grow rapidly in the next few years, we propose that initial talks on the creation of the alliance should take place as soon as possible in 2018, so that it can be formally established by the middle of the coming decade. [28]

6.2 Introducing Compulsory Due Diligence Requirements for Cobalt

Our second recommendation is to introduce compulsory due diligence[29] requirements throughout the cobalt supply chain, in order to minimise environmental, social and health risks. Our analysis showed that cobalt demand for the electric vehicle sector is set to rise in the coming decades. The sustainability of future supply will largely depend on the world's largest producer, the Democratic Republic of Congo. Rising demand will present significant challenges for the mineral-rich country, since it risks intensifying existing environmental and social conflicts linked to other raw materials.

Mining for conflict minerals in the Eastern DRC has been linked with human rights violations and the funding of armed groups. Against this backdrop, the Dodd-Frank Act was introduced to compel American companies importing conflict minerals (i.e. tin, tungsten, tantalum, and gold) from the DRC and neighbouring states to report on their sourcing practices to the SEC and conduct due diligence along their supply chains. The Act gave rise to a range of initiatives and certification measures, which have brought improvements in standards as a whole. It also led to prices plummeting for non-certified conflict minerals, making it increasingly difficult to use these to finance armed conflicts (Schüler et al. 2016).

Cobalt is not itself classified as a conflict mineral by the Dodd-Frank Act, yet since artisanal mining accounts for around 20 per cent of all cobalt production in the DRC, it nonetheless carries a number of environmental and social risks (Al Barazi 2017). In light of this and the broader context of cobalt mining in the DRC, it will be important to introduce due diligence requirements along the supply chain, on the basis of the mechanisms already in place for conflict minerals. This will help to minimise existing conflicts and prevent them from recurring in future.

Since the due diligence requirements are to be compulsory, companies that work to ensure the sustainability and transparency of cobalt extraction need not worry about losing their competitive edge. The requirements will therefore be an appropriate means of establishing sustainability standards and increasing risk transparency in the sector. In May 2017, the EU adopted a new regulation on conflict minerals, which will come into force on 1 January 2021, after a transitional period (Europäische Kommission 2017). Each of the EU's member states is responsible for appointing its own national authority to administer the regulation. The EU regulation also refers to the OECD's Due Diligence Guidance for Responsible Supply Chains from Conflict-Affected and High-Risk Areas. While this guidance pertains to conflict minerals, its potential applicability to other raw materials is also explicitly emphasised (OECD 2016). In light of the similarities between cobalt mining and conflict mineral mining, we recommend that the EU regulation should be expanded to include cobalt. Furthermore, we propose that environmental factors should also be taken into account in such mineral certification systems.

Though companies will be faced with higher costs as a result of the due diligence requirements, this is unlikely to result in production moving to other countries, since half of all known cobalt reserves are located in the DRC. Such shifts are only likely to occur to a limited extent in the event of rapidly increasing demand. When implementing these measures, it will be essential to help small-scale producers to overcome the obstacles to certification, so that they can continue to enjoy market access.

28 The possibility of expanding this initiative to include other raw materials such as nickel and graphite should also be considered in future.

29 *Due diligence* refers here to a corporate duty of (social and environmental) care along the whole value chain.

The OECD Due Diligence Guidelines already offer an established system to ensure transparency along the supply chain. Furthermore, the EU regulation on conflict minerals indicates a readiness to establish transparent supply chains at the European level too. We therefore recommend that compulsory due diligence requirements be put in place for the cobalt supply chain within the short to medium term, with the European Commission leading the way. Work on expanding the existing regulation should begin as soon as possible in 2018, so that the new rules can be implemented within the first half of the next decade. In Germany, the federal government is the main actor capable of initiating discussions at the EU level.[30]

6.3 Fostering International Cooperation on Sustainable Mining

Alongside the above measures, it will also be important to improve international cooperation between import countries and producing countries, so as to bolster the dissemination of knowledge and technologies crucial to sustainable industrial and artisanal mining.

The foundations for these environmentally and socially sustainable mining practices will need to be laid in those countries where primary production takes place. It is here that responsible standards can be promoted through the active exchange of knowledge and new technologies. The Africa Mining Vision provides for local capacity building in primary source countries. Through increased international cooperation, it aims to create a win-win situation for producing and importing countries: the former benefit from improved environmental and social standards and greater economic prospects, while the latter acquire a reliable and conflict-free supply of raw materials (African Union 2009).

Where artisanal mining is concerned, the Certified Trading Chains Programme developed by Germany's Federal Institute for Geosciences and Natural Resources in collaboration with the Congolese Ministry for Mines represents one attempt to establish responsible standards in this area. The project audits several dozen tin, tantalum, tungsten, and gold mines in the DRC, with the aim of improving working conditions, safety, local community development and the mines' environmental impact, while also ensuring market access for artisanal miners.

In Germany, the federal government has already taken some steps toward strengthening international cooperation via three bilateral raw materials partnerships with Kazakhstan, Mongolia and Peru.[31] In Mongolia, Vietnam, Laos, Rwanda and Myanmar, meanwhile, the Federal Institute for Geosciences and Natural Resources (BGR) has established projects on behalf of the Federal Ministry for Economic Cooperation and Development (BMZ), which provide technical support for local mining supervision programmes.

In the medium to long term, it will be important for donor agencies in the field of development cooperation to support projects promoting the active, long-term exchange of expertise between stakeholders in source countries and import countries. The current indicative programmes run by the European Commission (DG DEVCO),[32] which determine the strategies, goals and priorities of development cooperation, cover the period from 2014 to 2020. At present, these programmes only address raw materials extraction to a very limited extent and then primarily in terms of the financial transparency of mining companies. One of the priorities of the programmes is to assist countries in joining the Extractive Industries Transparency Initiative (EITI). We propose that the next round of indic-

30 In the long term, compulsory due diligence requirements should be expanded to cover all raw materials with similarly problematic supply chains. Applying these requirements to conflict minerals was a necessary first step, and expanding them to include cobalt (from the DRC) would be the logical next step.

31 The aim of these raw materials partnerships is to improve the long-term supply of raw materials to German companies, while assisting mineral-rich countries in developing their raw material sectors. As well as safeguarding the supply of raw materials, these partnerships should also be used to train specialist staff in source countries, to improve working conditions and social standards, and to optimise technological infrastructure. In this way, they can help promote sustainability in the mining industry across the board. The success of these partnerships will also depend on the inclusion of civil society representatives from the various partner countries.

32 Directorate-General for International Cooperation and Development.

ative programmes should be expanded to incorporate projects promoting knowledge exchange and international cooperation in the field of sustainable mining practices. The DG DEVCO should begin to address these areas within the next two years, so that they can be included in the 2020–2026 round of indicative programmes. Other donor agencies should also focus more on projects involving knowledge exchange in the mining industry, such as training programmes for geological authorities in resource-rich countries. Furthermore, the BMZ should work to ensure that raw materials partnerships are expanded to address these areas, while the federal government should use its influence to underscore their significance for the above EU programmes.

6.4 Expanding the EU Batteries Directive

While our first three recommendations are principally concerned with primary production, our recommendation to expand the European Batteries Directive aims to promote recycling of lithium-ion traction batteries and the recovery of strategic raw materials.

The current Batteries Directive does not yet pay sufficient attention to traction batteries for electric vehicles and the strategic raw materials they contain (lithium, cobalt, nickel, and graphite). The ex-post evaluation of the Batteries Directive, however, is currently underway.[33] There is virtual unanimity among those involved that the directive will have to be adapted to take account of current developments in the electric vehicle sector. In our view, this should take place as quickly as possible. Since the new directive will need to be agreed on by the various member states and will only come into force after a transitional period, it is unlikely to be fully implemented before 2020.

In the present Batteries Directive's classification system, lithium-ion traction batteries are subsumed under 'other batteries' in the 'industrial batteries' section. Since lithium-ion traction batteries are set to make enormous inroads into the market in the near future, we recommend that they be treated in a dedicated section of the directive, and assigned their own ambitious collection and recycling targets. These should be individually formulated for each of the strategically significant raw materials in question (lithium, cobalt, nickel, and graphite), in order to facilitate their recovery and re-use. It will be particularly important to develop recycling targets for lithium, since it is currently only recycled on a very small scale. The present Battery Directive's 50 per cent recycling quota (which does not distinguish between individual raw materials) can be achieved without recovering the important raw materials contained in batteries. It is now crucial, however, to establish material-specific recycling targets in consultation with experts from the recycling sector. We recommend that the directive be revised on the basis of an impact assessment of the potential for environmental relief with respect to raw materials, the potential for cost savings and interaction with the growing electric vehicle market, and the resulting potential for greenhouse gas reductions.

33 A report on the results of the evaluation is scheduled for publication in the first quarter of 2018.

The responsibility for the revision of the Battery Directive lies with the European Commission interacting with the Council of Ministers and the European Parliament. We recommend that the German federal government advocate for material-specific recycling targets on the basis of the impact assessment results. A further step would be to evaluate the possibility of re-using traction batteries in stationary energy storage facilities, in line with producer responsibility obligations. At the European level, preparations for the revision of the Battery Directive have already begun. Proposals for its expansion will therefore need to be formulated and presented in 2018.

6.5 Establishing a Global Recycling System for Lithium-Ion Batteries

Building on our proposal to expand existing European battery regulations, our fifth recommendation is to establish a global recycling system for lithium-ion batteries. This system is urgently required to ensure such batteries are collected as efficiently as possible and their raw materials recovered.

In order to reduce demand for primary lithium from the burgeoning electric vehicle sector, we suggested above that 10 per cent of all lithium demand could be catered for via secondary lithium in 2030 and 40 per cent in

2050. If these targets are to be reached, however, it will be imperative to introduce an extensive recycling system for lithium-ion batteries. Here it will be important to foster innovative incentive systems and business models to facilitate the establishment of battery collection programmes (e.g. deposit or leasing schemes) and a recycling infrastructure incorporating collection points and transport networks, in order to ensure that valuable raw materials such as lithium, cobalt, nickel and graphite are recovered as far as possible. The specifications for the collection system will need to be formulated within the next three years, so that existing guidelines can be adapted in time to cope with the large number of traction batteries then coming to the end of their life. As traditional lead-acid battery recycling programmes have shown, putting the right systems in place will allow us to collect a significant proportion of electric vehicle batteries. We recommend that a global recycling system be established on the back of this collection network by 2030. In the key electric vehicle markets of China, Europe and North America, the necessary infrastructure should be put in place by the middle of the coming decade.

At the European level, the revised Battery Directive should give increased momentum to these infrastructural projects (see the previous recommendation). The European Commission, meanwhile, will be responsible for driving them forward, in conjunction with individual member states. At the global level, organisations such as the OECD, the G7, the G20 and the UN (with its Recommendations on the Transport of Dangerous Goods) will play a key role. Furthermore, industrial players such as car manufacturers, battery producers and recycling companies will be crucial to the success of global lithium-ion battery recycling. Germany's federal government should join forces with these industrial actors to actively promote the expansion of recycling infrastructure.

For the EU member states, a global recycling system is also important as a means of diversifying raw materials providers and reducing dependency on primary source countries. Such a recycling system would also help to keep prices stable, as has been seen with platinum.

6.6 Promoting a Battery Technologies R&D Drive

In order to curb demand for primary raw materials and ensure a stable and sustainable source of supply for the electric vehicle sector, our sixth recommendation is to promote a wide-ranging research and development drive in the field of electric vehicle traction batteries. This should address the following areas: improving material efficiency, exploiting alternative materials, optimising battery collection systems, automatising the disassembly process and developing recycling technologies. In addition, greater support should be provided for research and development work to improve the efficiency and sustainability of primary extraction processes. These R&D efforts should explicitly focus on strategic raw materials for the electric vehicle sector.

In recent years, a number of German research and development projects have already been carried out in these areas. These include the BMUB's LiBRi,[34] LithoRec[35] and EcoBatRec[36] projects, and a number of UBA materials substitution projects, such as SubSKrit.[37] These have yielded important insights and helped to kick-start industrial initiatives in areas such as lithium-ion battery recycling. Further R&D efforts will nonetheless be necessary in the short, medium and long-term, particularly in regard to the recycling of high purity, battery quality lithium compounds. In order to ensure Germany remains at the cutting edge of battery technologies and can drive forward new technological innovation, it makes strategic sense for the federal government to continue to promote such research.

34 "Developing an achievable recycling plan for high-capacity batteries in the electric vehicles of the future – Lithium-ion Battery Recycling Initiative – LiBRi" (final report available at: erneuerbar-mobil.de/sites/default/files/publications/abschlussbericht-libri_1.pdf)

35 "Recycling lithium-ion batteries – LithoRec II" (final report available at: www.erneuerbar-mobil.de/sites/default/files/2017-01/Abschlussbericht_LithoRec_II_20170116.pdf)

36 "Demonstration facility for the cost-neutral, resource-efficient processing of used Li-Ion electric vehicle batteries" (project website: www.ecobatrec.de/index.html)

37 "Substitution as a means of reducing raw material criticality for environmental technologies: A report on potential second-best solutions (SubSKrit)"

At the European level, too, there are a range of R&D projects currently underway on material efficiency, material substitution and recycling. The European Commission's Joint Research Centre (JRC), for example, is currently conducting research on alternatives to rare raw materials in traction batteries. The Horizon2020 STRADE[38] project, meanwhile, addresses the issue of sustainable mining. We recommend that further national and international cooperative projects (binational and transnational programmes) be launched in relation to lithium, cobalt, nickel and graphite in lithium-ion batteries. Finally, technology companies in Germany and Europe also have a special responsibility to contribute to technological progress through extensive R&D activities.

6.7 Adopting an Electric Vehicle Commodities Radar

The electric vehicle market is currently developing rapidly. This development is accompanied by huge growth in demand for lithium-ion traction batteries and their essential raw materials. In order to develop appropriate strategies and measures to ensure the sustainable supply of these raw materials in future, it will be crucial to regularly monitor the development of the sector, demand for raw materials and the extent to which the above recommendations have been successfully implemented.

In the present study, our projections for future raw materials demand are based on recent vehicle number predictions (IEA 2016a) and expert views concerning battery technologies and raw materials. There are nonetheless already indications that the IEA's 2016 projections (the 2DS) may need to be revised in light of the particularly rapid electrification of the transport sector. We therefore recommend that the federal government initiate an ongoing monitoring programme to track the development of the sector and its broader impact. This commodities radar should aim to continually update raw materials demand on the basis of current projections for future vehicle numbers, sales and battery technology developments, in order to allow appropriate measures to be formulated and implemented. It should nonetheless not be limited to tracking demand, but should also assess the risk of temporary supply bottlenecks during the development of new deposits. This can be achieved by regularly evaluating mining projects so as to accurately predict primary raw material production levels.

Finally, it should consider the latest research on the impact and risks of primary raw materials extraction and the extent to which current sustainability targets have been reached. In establishing the commodities radar, it will be crucial to ensure the participation of relevant stakeholders from the automotive industry, recycling companies, NGOs, government ministries, suppliers, primary producers and research institutions, so that a range of views and recommendations can be discussed and evaluated. The following Appendix presents raw materials usage and projections for future demand across all areas. Demand for the electric vehicle sector is based on the projections given in Chapter 3. Projected demand for other areas is based only on rough hypotheses.

38 "Strategic Dialogue on Sustainable Raw Materials for Europe" (project website: stradeproject.eu/index.php?id=3)

07 | Appendix

The Appendix also details the battery capacity figures on which our projections are based.

7.1 Raw Materials Usage and Demand across All Areas

Lithium

In 2016, lithium demand for the battery sector accounted for 39 per cent of all lithium demand, exceeding consumption in the glass and ceramics sector (30 per cent) for the first time. In other applications, lithium is also used to produce lubricating greases (8 per cent) and polymers (5 per cent). Lithium usage by area is shown for 2016 in Figure 7.1.

Our projections for lithium demand across all areas are shown in Figure 7.2. These are based on the assumption that demand outside the electric vehicle sector (with the exception of lubrication grease production) will rise by two per cent per year (CAGR[39]). Lubrication grease is used in oil drilling; here we made the conservative assumption that demand will remain constant. The projections do not incorporate secondary material usage.

Cobalt

The battery sector accounts for 42 per cent of all cobalt demand. Cobalt is also used to make superalloys (16 per cent), hard metals (10 per cent), and magnets (5 per cent). Usage by area is shown in Figure 7.3.

Our projections for total cobalt demand across all areas are shown in Figure 7.4. These assume that demand outside the electric vehicle sector will rise by three per cent per year (CAGR).[39] The projections do not incorporate secondary material usage.

39 Compound annual growth rate.

Nickel

In 2010, nickel usage in batteries only accounted for a very small percentage of all demand. In Figure 7.5, which shows usage by area, it is included in the "other" category. Stainless steel production accounts for the majority of all production (61 per cent), followed by nickel-based alloy production (12 per cent).

Our projections for nickel demand across all areas are shown in Figure 7.6. These are based on the assumption that demand outside the electric vehicle sector will rise by three per cent per year (CAGR). The projections do not incorporate secondary material usage.

Graphite

In 2011, battery production only accounted for a relatively small percentage of all natural graphite demand. In Figure 7.7, which shows usage by area, it is included in the 'carbon brushes, batteries' category. Steel production accounts for the largest share of all demand (26 per cent).

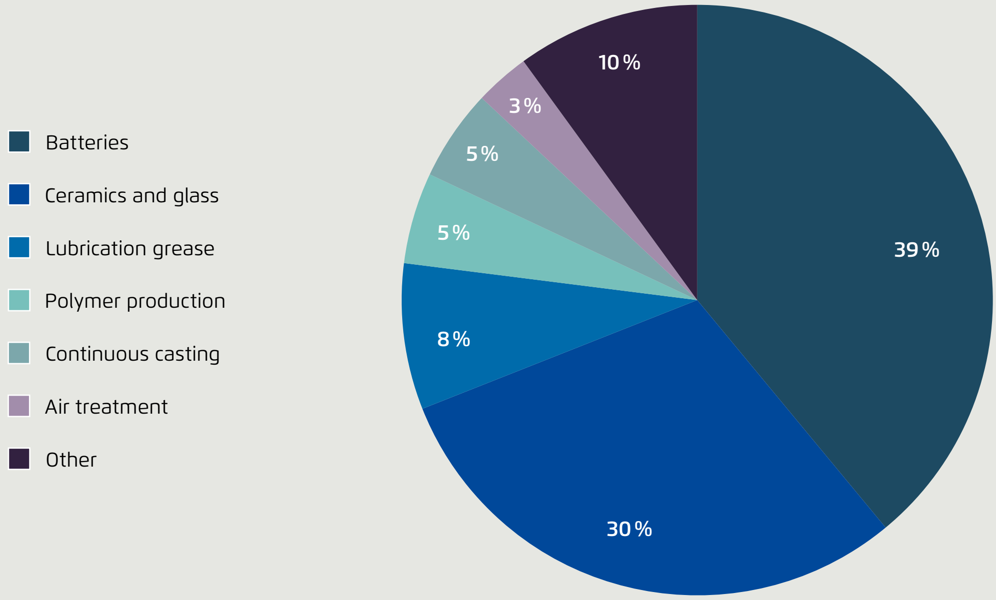
Our projections for graphite demand across all areas are shown in Figure 7.8. These are based on the assumption that demand outside the electric vehicle sector will rise by three per cent per year (CAGR). The projections do not incorporate secondary material usage.

Platinum

In 2013, catalytic converter production accounted for the largest share of all platinum demand (36 per cent), closely followed by the jewellery industry (35 per cent). In Figure 7.9, which shows usage by area, platinum demand for fuel cell production is included in the "other" section.

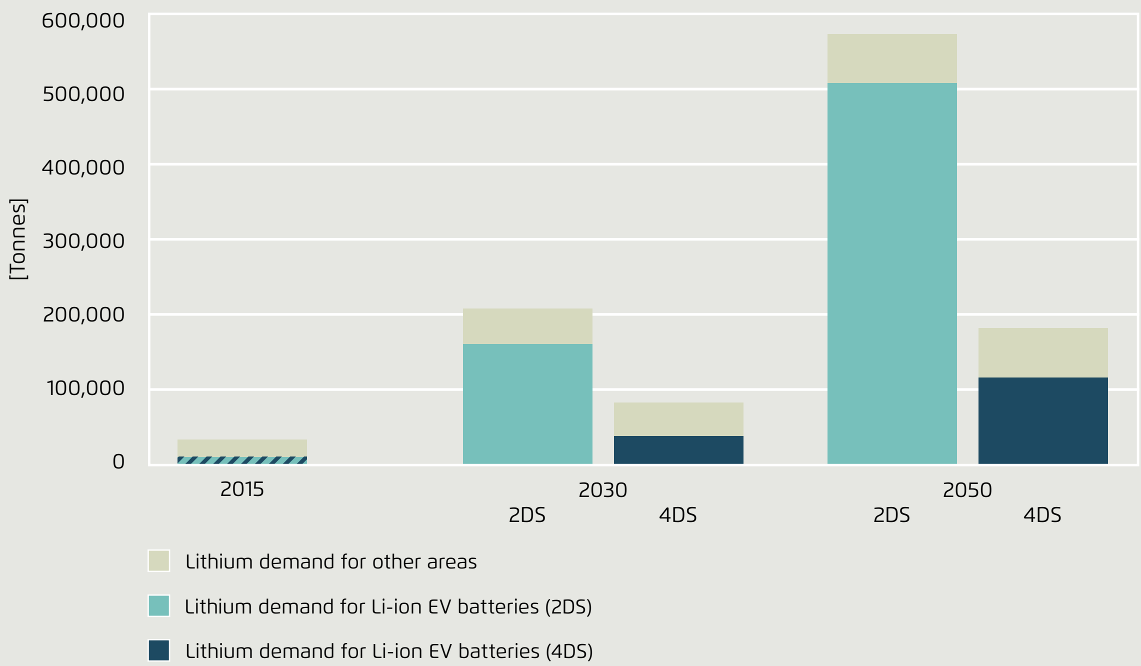
Our projections for platinum demand across all areas are shown in Figure 7.10. The projections assume that demand outside the electric vehicle industry will rise by 1.5 per cent per year (CAGR). The projections do not incorporate secondary material usage.

Lithium usage by area (2016) Figure 7.1



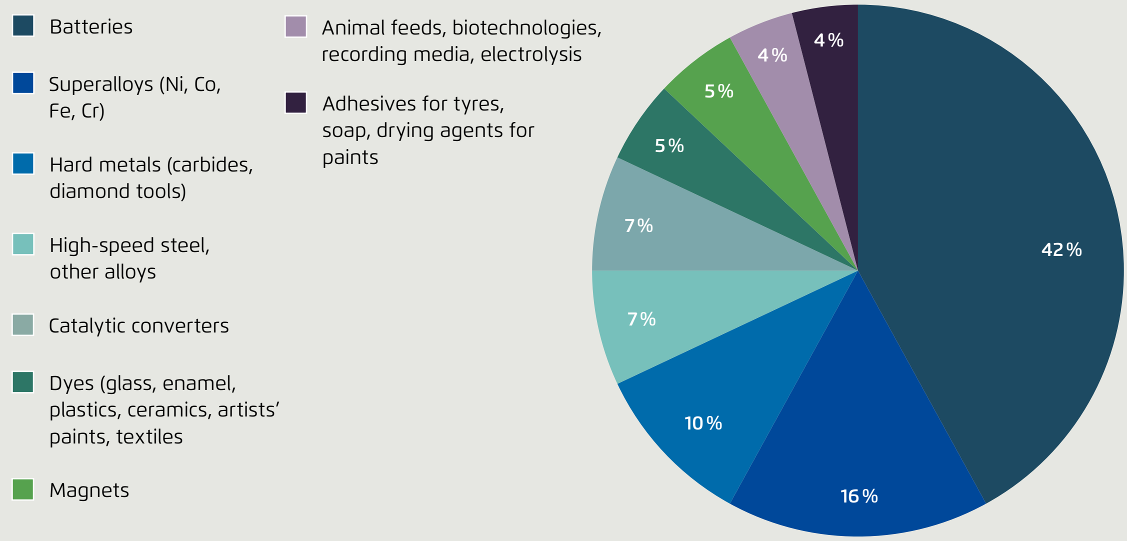
USGS 2017

Projected lithium demand across all areas (not including secondary material) Figure 7.2



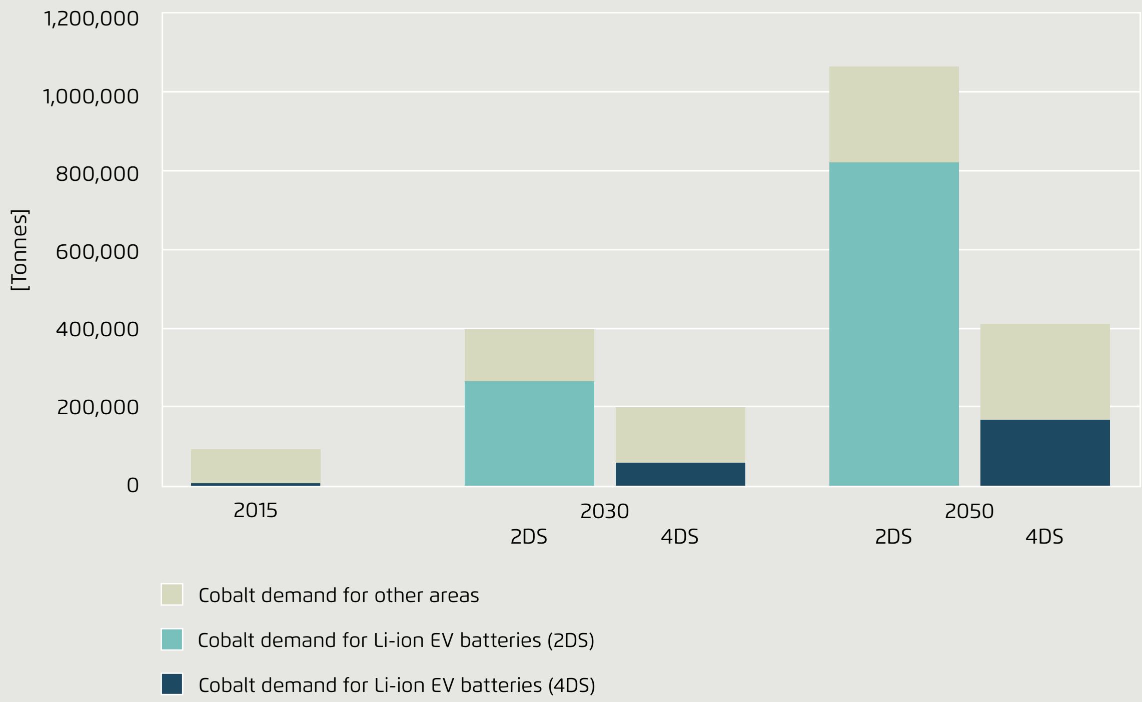
Authors' own calculations and visualisation

Cobalt usage by area (2014) Figure 7.3



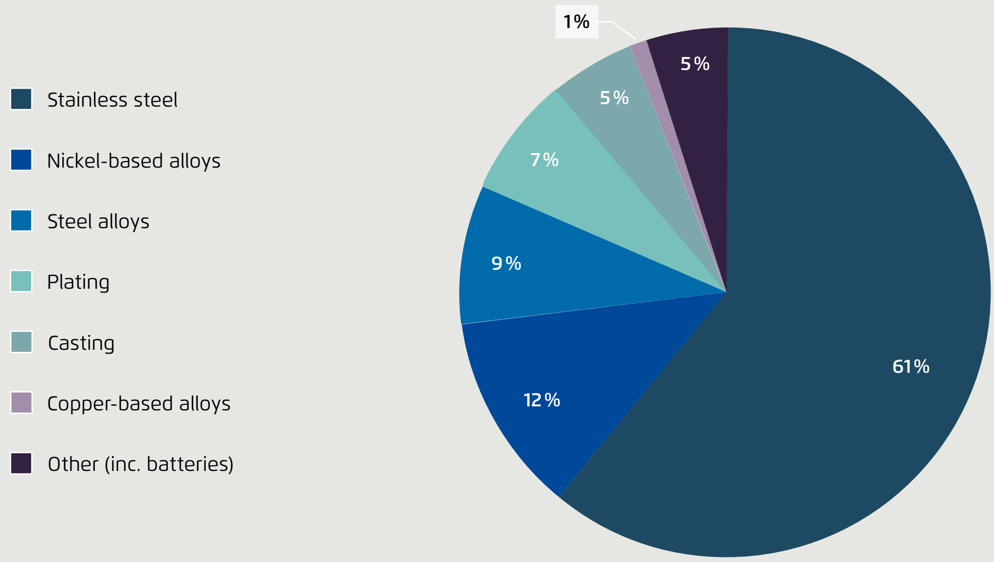
Cobalt Development Institute 2016

Projected cobalt demand across all areas (not including secondary material) Figure 7.4



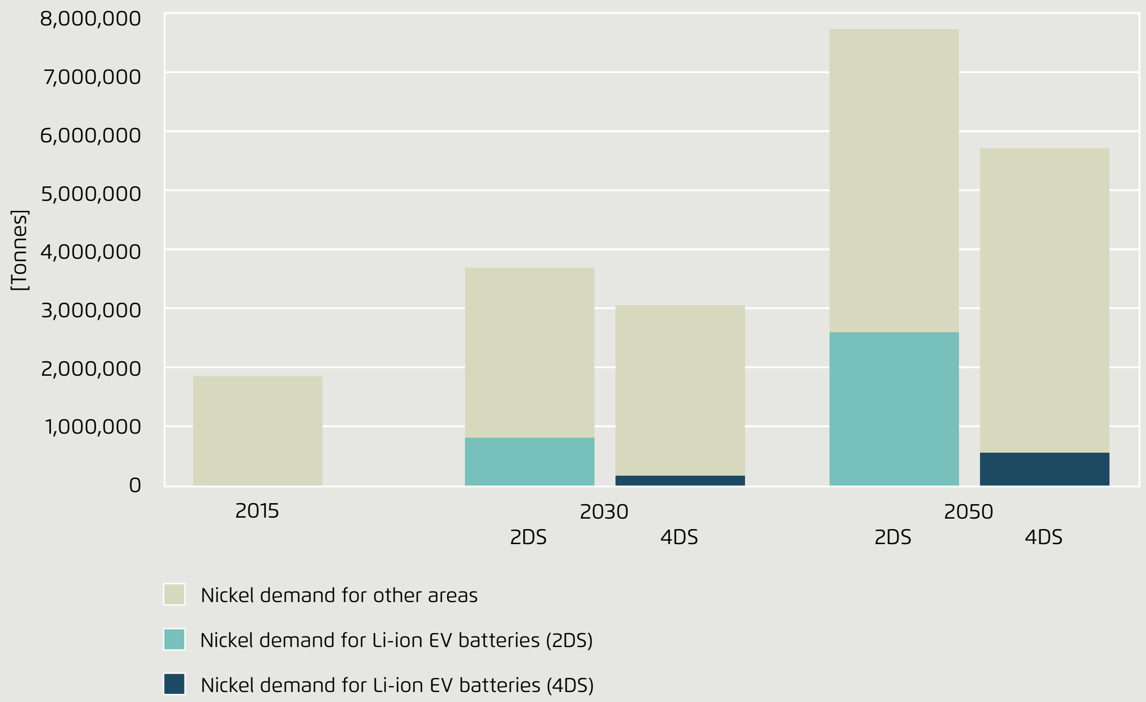
Authors' own calculations and visualisation

Nickel usage by area (2010) Figure 7.5



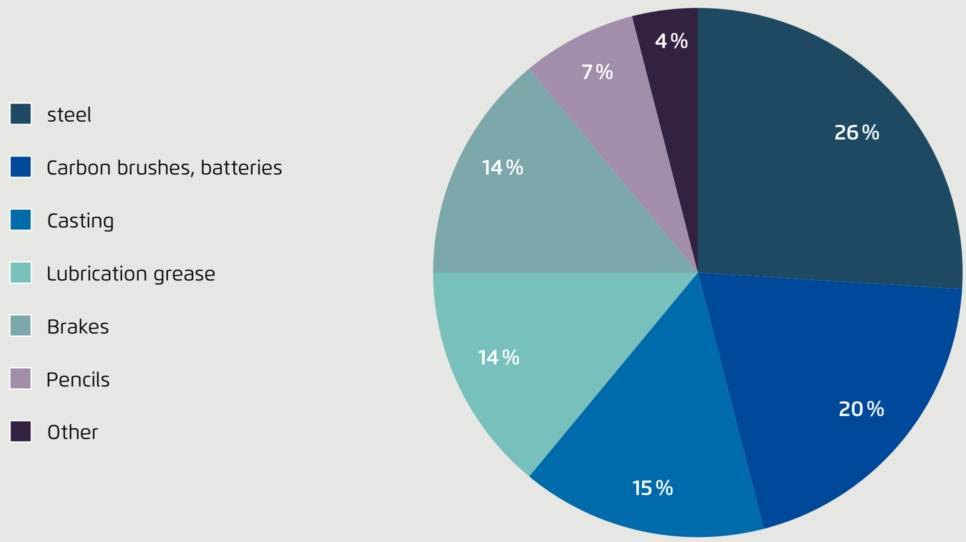
European Commission 2014

Projected nickel demand across all areas (not including secondary material) Figure 7.6



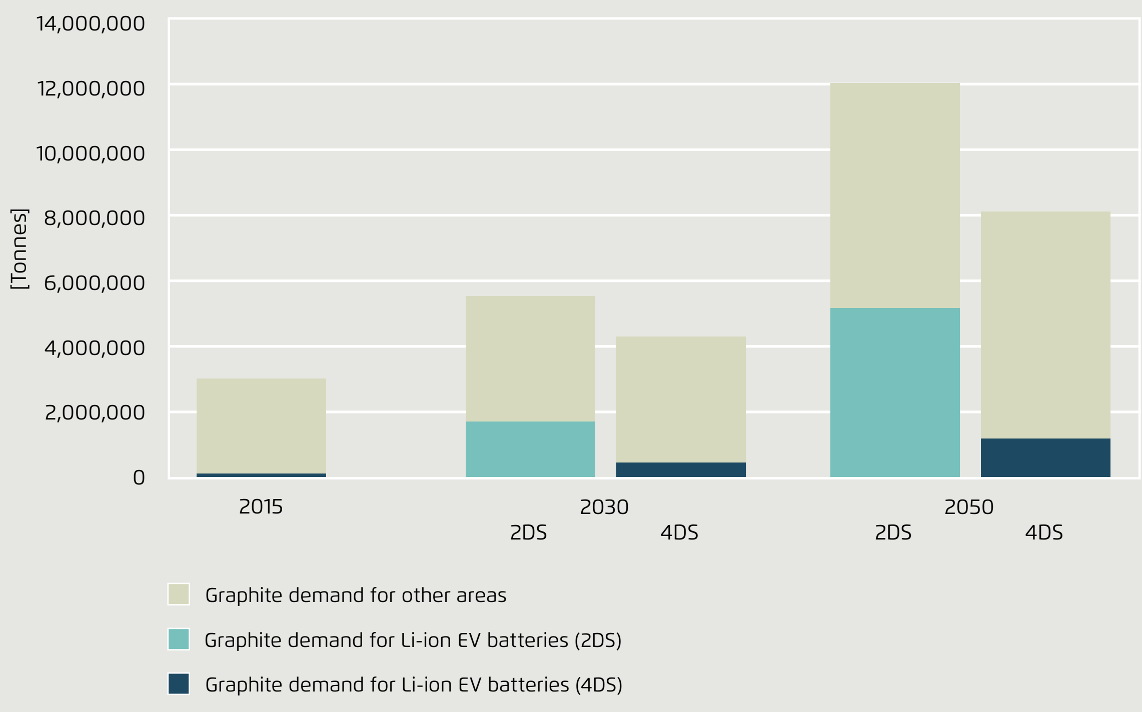
Authors' own calculations and visualisation

Graphite usage by area (2011) Figure 7.7



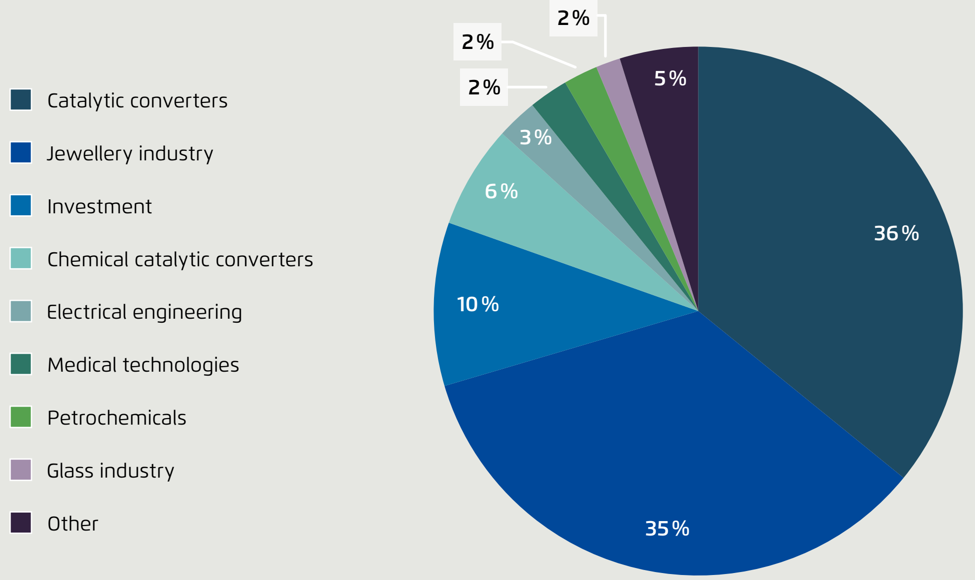
Statista 2017

Projected graphite demand across all areas (not including secondary material) Figure 7.8



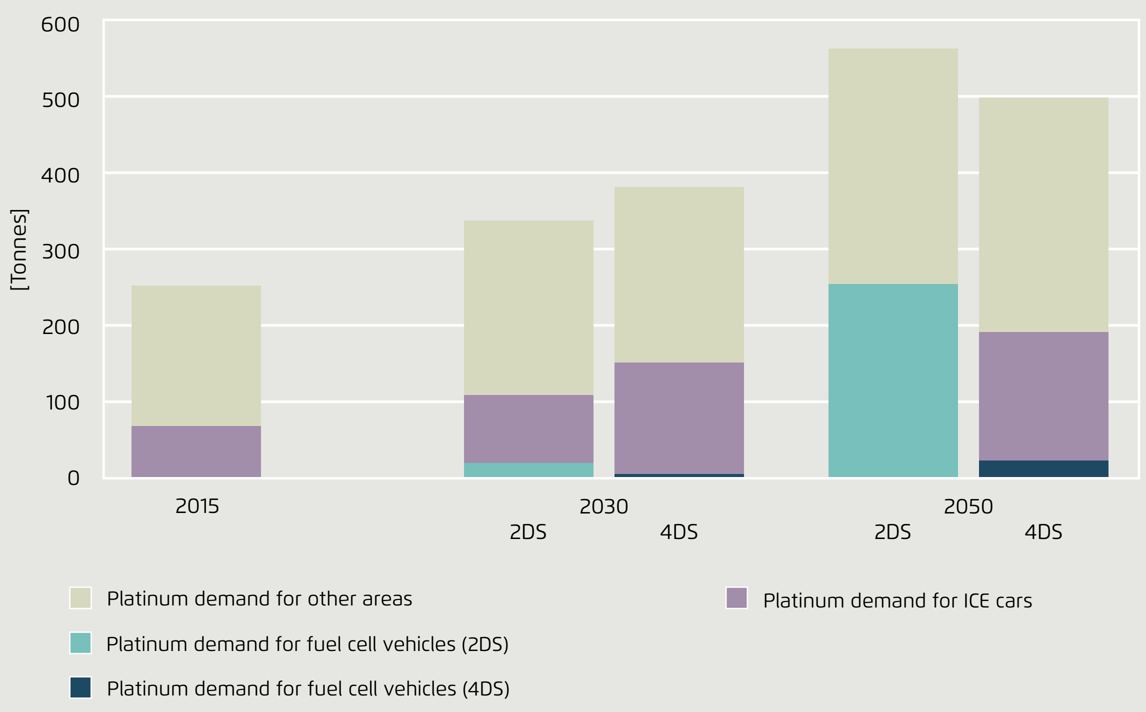
Authors' own calculations and visualisation

Platinum usage by area (2013) Figure 7.9



BGR 2016

Projected platinum demand across all areas (not including secondary material) Figure 7.10



Authors' own calculations and visualisation

7.2 Battery Capacities

Cars: Battery types and capacities — Table 7.1

Cars	2015	2030	2050
BEV	NMC: 30 kWh (1 : 1 : 1)	NMC: 50 kWh (6 : 2 : 2) (90 % market share among BEVs)	NMC: 50 kWh (6 : 2 : 2) (90 % market share among BEVs)
	NCA: 80 kWh	NCA: 80 kWh (10 % market share among BEVs)	NCA: 80 kWh (10 % market share among BEVs)
	LFP: 20 kWh		
HEV	NiMH: 1 kWh	NMC: 1 kWh	NMC: 1 kWh
PHEV	LFP: 10 kWh		
	NMC: 10 kWh	NMC: 10 kWh	NMC: 10 kWh
FCEV	NMC: 2 kWh	NMC: 2 kWh	NMC: 2 kWh
ICE	–	LFP: 0.3 kWh	LFP: 0.3 kWh

Authors' own visualisation

Buses: Battery types and capacities — Table 7.2

Buses	2015	2030	2050
BEV	LFP: 150 kWh	NMC: 250 kWh	NMC: 300 kWh
HEV	LFP: 30 kWh	NMC: 30 kWh	NMC: 30 kWh
PHEV	LFP: 50 kWh	NMC: 50 kWh	NMC: 50 kWh
FCEV	LFP: 20 kWh	NMC: 20 kWh	NMC: 20 kWh

Authors' own visualisation

HGVs Battery types and capacities — Table 7.3

HGVs	2015	2030	2050
BEV MFT	LFP: 100 kWh	NMC: 100 kWh	NMC: 100 kWh
BEV HFT	LFP: 200kWh	NMC: 200 kWh	NMC: 200 kWh
HEV MFT	LFP: 10 kWh	NMC: 10 kWh	NMC: 10 kWh
HEV HFT	LFP: 20 kWh	NMC: 20 kWh	NMC: 20 kWh
PHEV MFT	LFP: 30 kWh	NMC: 30 kWh	NMC: 30 kWh
PHEV HFT	LFP: 60 kWh	NMC: 60 kWh	NMC: 60 kWh
FCEV MFT	LFP: 10 kWh	NMC: 10 kWh	NMC: 10 kWh
FCEV HFT	LFP: 30 kWh	NMC: 30 kWh	NMC: 30 kWh

MFT = Medium Freight Trucks, HFT = Heavy Freight Trucks
Authors' own visualisation

Pedelecs and 2 and 3-wheeled vehicles: Battery types and capacities — Table 7.4

Pedelecs and 2 and 3-wheeled vehicles	2015	2030	2050
Pedelecs	NCA: 0.24 kWh	NCA: 0.24 kWh	NCA: 0.24 kWh
2 and 3-wheeled vehicles (in China)	LFP: 1.6 kWh (4 % of all 2 and 3-wheeled electric vehicles with lithium-ion batteries)	NMC: 1.6 kWh (50 % of all 2 and 3-wheeled electric vehicles with lithium-ion batteries)	NMC: 1,6 kWh (100 % of all 2 and 3-wheeled electric vehicles with lithium-ion batteries)
2 and 3-wheeled vehicles (Rest of the world)	LFP: 1.6 kWh (100 % of all 2 and 3-wheeled electric vehicles with lithium-ion batteries)	NMC: 1.6 kWh (100 % of all 2 and 3-wheeled electric vehicles with lithium-ion batteries)	NMC: 1.6 kWh (100 % of all 2 and 3-wheeled electric vehicles with lithium-ion batteries)

Authors' own visualisation

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List of Abbreviations

AMD	Acid mine drainage
ASM	Asynchronous motors
BEV	Battery electric vehicle
BGS	British Geological Survey
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
BMUB	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (Federal Ministry of the Environment, Nature Conservation, Building and Nuclear Safety)
BMWi	Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy)
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (Federal Ministry for Economic Cooperation and Development)
CAGR	Compound Annual Growth Rate
Co	Cobalt
Cr	Chrome
DERA	Deutsche Rohstoffagentur (German Mineral Resources Agency)
DRC	Democratic Republic of Congo
EESM	Electrically/externally excited synchronous motor
EITI	Extractive Industries Transparency Initiative
EU	European Union
R&D	Research and development
FCEV	Fuel cell electric vehicle
Fe	Iron
FOE	Friends of the Earth Europe
DG DEVCO	Directorate-General for International Cooperation and Development
HEV	Hybrid electric vehicle
HFT	Heavy freight trucks
ICE	Internal combustion engine
IEA	International Energy Agency
IRMA	Initiative for Responsible Mining Assurance
JRC	Joint Research Centre
kWh	Kilowatt hour
LFP	Lithium iron phosphate
Li-ion	Lithium-ion
MFT	Medium freight trucks
NCA	Nickel cobalt aluminium
Ni	Nickel
NMC	Nickel manganese cobalt
OECD	Organisation for Economic Cooperation and Development
OICA	Organisation Internationale des Constructeurs d'Automobiles (International Organisation of Automobile Manufacturers)
ÖPNV	Public transport
PGM	Platinum group metals
PHEV	Plug-in hybrid electric vehicle
RC	Recycling
t	Tonnes
UBA	Umweltbundesamt (German Environment Agency)
UN	United Nations
UNEP	United Nations Environment Programme
USGS	United States Geological Survey

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Agora Verkehrswende works together with stakeholders from the spheres of politics, business, academia and civil society to pave the way for the decarbonisation of Germany's transport sector by 2050. To this end, we assist with the development of climate protection strategies and support their implementation.

Agora Verkehrswende
Anna-Louisa-Karsch-Str. 2 | 10178 Berlin | Germany
T +49 (0)30 700 14 35-000
F +49 (0)30 700 14 35-129
www.agora-verkehrswende.de
info@agora-verkehrswende.de

Agora Verkehrswende is a joint initiative of Stiftung Mercator and the European Climate Foundation.