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WILL METAL SCARCITY LIMIT THE USE OF ELECTRIC VEHICLES?

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INTRODUCTION

The possibility that material scarcity might restrain technologies is an old and complex issue. Arguments have traditionally been from one of two perspectives: one beginning with the fact that the planet is finite, and the other pointing out that both the technologies that supply materials and those that demand them evolve, and thus the economic availability of resources and the capacity of innovation to substitute materials are the most important factors determining scarcity.[1] The real price of most material commodities has dropped in an almost unbroken trend for a century, indicating that most materials are more economically available than ever before[2]. There is therefore a burden of proof on those who would claim that innovation cannot continue this trend. Yet, some materials such as gold and platinum are so rare that it would be unthinkable to use them instead of iron as construction material in buildings and bridges. More sophisticated analysis is required to say anything useful about the possibilities for using a given material for a given application.

Discussions on material scarcity have come back to the forefront of industrial politics and research through issues such as China's current dominance of the rare earth elements (REE) supply. Electric vehicles are one of several applications that make use of a range of the materials discussed.[3] Cars in general contain a

1 For an excellent overview of the arguments, see Tilton, J. E. (2003). On Borrowed Time? Assessing the Threat of Mineral Depletion. Washington, D.C, RFF Press.
2 See Tilton (2003) and Slade, M. E. (1982). "Trends in natural-resource commodity prices: An analysis of the time domain." Journal of Environmental Economics and Management 9(2): 122-137.
3 See for example European Commission (2010) "Critical raw materials for the EU", US DoE (2010) "Critical materials strategy" and Federal Ministry of Economics and Technology (2010) "The German Government's Raw Materials Strategy".

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large variety of materials, and a general trend towards lightweight materials and electronic components is enlarging the roster of metals used. Electric vehicle drivetrains contain a number of additional components using large quantities of metal, such as batteries and electric machines. To achieve a transition to broad usage of electric vehicles, large stocks of some of these metals will need to be supplied at rates far exceeding current extraction, why the speed and timing of such a transition is critical. Recycling will be required for many materials in order to maintain a large societal stock of metals, but achieving this may be a challenge. Finally, the concerns regarding many of the materials, are not a result of either physical rarity or economic scarcity, but arise instead from the reliance of some actors upon a very concentrated supply chain. In order to discuss the possibilities and implications of material scarcity for electric vehicles it is important to achieve better understanding of the factors that may cause concern for a number of materials, as well as the possibility for substituting other materials in their place.

ASSESSING RESOURCE CONSTRAINTS ON TECHNOLOGY DIFFUSION

As implied in the introduction, there is a difference between *scarcity* and *rarity*. A metal that is rare doesn't have to be scarce if the demand for the metal is low. The concept of scarcity implies that there is a demand that somehow exceeds supply. In this chapter we are not primarily interested in rarity, not even in scarcity in general, but in the *availability* of a material for a specific application. To be even more precise, we are interested in the relationship between the availability of a given material for a specific application and the *requirement* of that application for that particular material. If the envisioned *requirement* exceeds the envisioned availability, we may talk about *resource constraints* on technology diffusion.[4] The resource constraint may be global or applicable only to a set of actors with restricted access to the required resource.[5] A *critical* material, in this context, is typically defined as a material which availability is constrained, not only for something (a technology or a set of technologies) that is considered important, but also for someone (a company, a country or society as a whole).[6]

In the previous two paragraphs, we briefly addressed the questions 'How much?' and 'For whom?'. A third equally important question is 'When?'. It is not only the *total available stock* of a material that needs to match the total requirement for the material in a prospective technical system (such as a global fleet of electric vehicles); the *annual availability* and the requirement in different phases of development also need to match. The timing of demand and supply is essential.[7] It should be noted that conclusions drawn in studies with a time frame of the next ten years are of limited value for discussions on longer term constraints, and vice versa. Short term (<10 years), medium term (say 10-40 years) and long term (>40 years) constraints may be qualitatively different.

4 See Andersson, B. A. and I. Råde (2001). "Metal resource constraints for electric-vehicle batteries." Transportation Research Part D: Transport and Environment 6(5): 297-324 and Andersson, B. A. and I. Råde (2002). Material constraints on technology evolution: the case of scarce metals and emerging energy technologies. A handbook of Industrial Ecology. R. U. Ayres and L. W. Ayres. Cheltenham, UK, Edward Elgar Publishing ltd.

5 Similarly, one may analyse limited access to key techniques due to patenting or trade secrets or limited access to key markets.

6 In addition, the concept of critical materials normally also implicate limited substitution opportunities at the level of materials, products and functions.

7 See Andersson and Råde (2001) and in particular Kushnir, D. and B. A. Sandén (2012). "The time dimension and lithium resource constraints for electric vehicles." Resources Policy 37:93-103.

To measure the severity of a constraint we need to put numbers on material requirement and availability, in terms of total stocks as well as annual flows. Estimates of materials requirement have to be made from one or many demand scenarios. Any demand scenario is a product of two factors, the *specific materials requirement*, i.e. the materials demand per functional unit, i.e. per unit of the technology in question, and the *number of units* demanded.

To put a number on the specific materials requirement we need to carefully define which technology we are assessing, i.e. define a functional unit and define how generally the results apply. Indistinctness about technology definition is a common reason for misinterpretation. Examples of this may include when an assessment of 'lead acid battery electric vehicles' in the 1990s was used to make claims about 'battery electric vehicles', which by definition includes vehicles with all kinds of battery chemistries,[8] or when an assessment of 'family sized battery electric cars' are used to make claims also about 'electric vehicles in general', which should include a variety of vehicle sizes and transport modes (see also Chapter 2 and 6). Examples from other technology areas include attempts to defame or raise concerns about 'wind power' (in general) because of the use or rare earth elements in some designs and about 'solar cells' because some designs use indium and tellurium.

In any scenario, assumptions need to be made about how technical development and changing performance characteristics (e.g. speed, range, comfort and safety) for the defined functional unit (e.g. a car) will affect specific materials requirements. Observe that such assumptions should not be viewed as forecasts, in particular if longer time frames are applied. Instead, they form parts of an *explorative scenario* (what-if scenario) that should inform us about something interesting or relevant to upcoming decisions.

The explorative character of the demand scenario is even more evident when it comes to assumptions about the scale of the system, i.e. the number of units (e.g. vehicles) demanded. One can make use of various assumptions about population growth and per capita consumption of a technology. *Extreme scenarios* are often informative. An alternative is to let this parameter be the dependent variable of the study, e.g. by posing a question such as: How many battery electric cars per year can be produced before materials availability constrains production rates?[9]

On the supply side, we need to distinguish between *primary* and *secondary* resources, where the former is virgin resources still in the ground (or sea) and the latter is already processed and used material that is stored in artefacts in use or in waste deposits.

There are many different measures of primary resources. On one hand you have the total number of atoms in the Earth's crust and sea, and on the other, you have the *reserves*, i.e. the amount of discovered resources that are economically recoverable at current prices. For almost all elements the former exceeds the latter by a factor of 1 million to 100 million. Neither of these measures represent a proper

8 Today, not many would consider the lead acid battery EV to be a good proxy for EVs, while this was not uncommon in the 1990s. See e.g. Lave, L.B. et al., (1995). Environmental implications of electric cars. *Science* 268, 993-995.
9 See Andersson and Råde (2001).

estimate of the resources that could become available within a relevant time frame (a couple of decades to a century).

While some elements like silicon, iron and aluminium are abundantly available in ordinary rock, most metals are *rare* and could only conceivably be extracted from the tiny fraction that is concentrated in certain rare minerals (Figure 7.1). One of the few attempts to estimate the size of this fraction suggests that for rare metals only 1-10 ppm of the amount in the crust is available in ores (the major part being diluted in ordinary rock). This conclusion suggests that for some highly exploited metals like copper, actual physical limits on resources may not be that far away despite much more material remaining in the crust.[10] While crustal abundance is not a measure of metal availability in absolute terms, Figure 7.1 indicates that there is some correlation between crustal abundance and annual extraction. Iron is almost one billion times more abundant than ruthenium and, as consequence, can be extracted in volumes exceeding 100 kg per capita per year compared to a few milligrams of ruthenium.

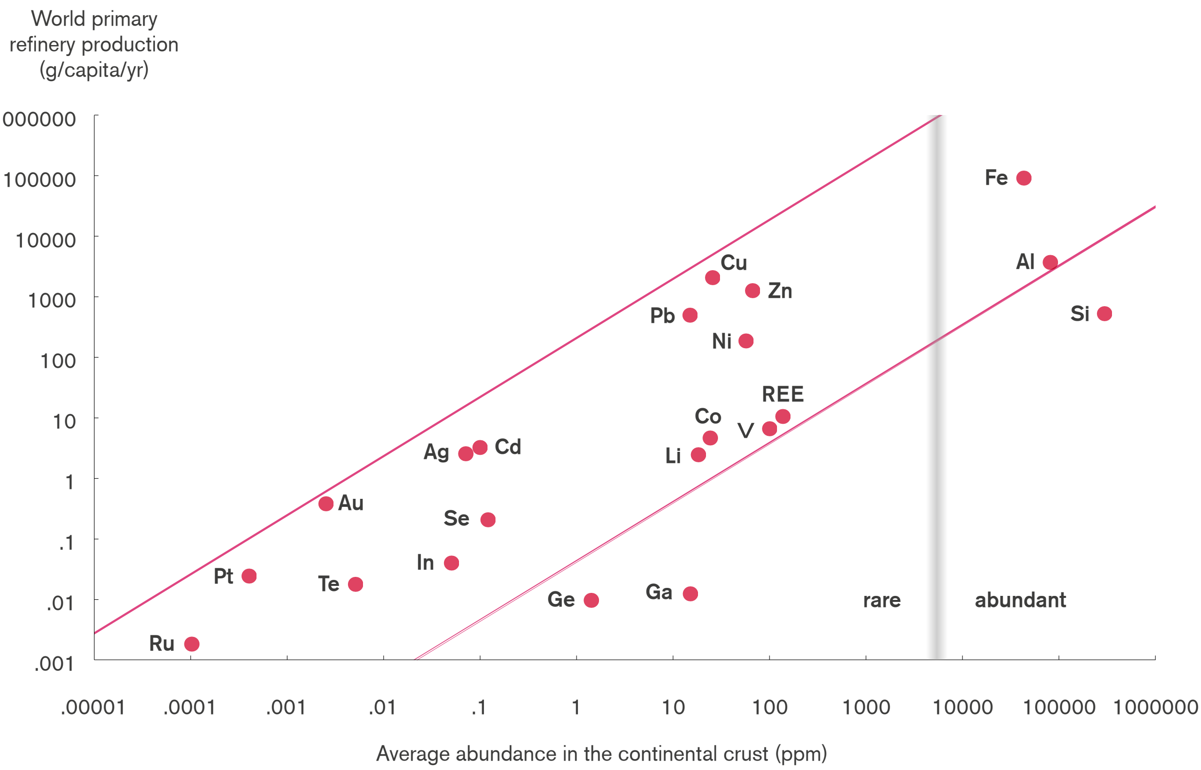

Figure 7.1 A comparison of annual extraction, measured as world primary production per capita, and geological rarity, measured as average abundance in the continental crust. Most of the metals can be capped within a band spanning three orders of magnitude. Towards the upper end of the band with relatively high extraction rates one finds the 'industrially mature' metals like gold, silver, lead and copper. A distinction can be made between abundant elements, such as iron, aluminium and silicon that are building blocks of minerals in common rock, and rare metals that are found in extractable concentrations only in certain minerals in specific locations. Source: Andersson, B. A. and I. Råde (2002). Material constraints on technology evolution: the case of scarce metals and emerging energy technologies. A handbook of Industrial Ecology. R. U. Ayres and L. W. Ayres. Cheltenham, UK, Edward Elgar Publishing ltd. Original data from Wedepohl, K. H. (1995). "The Composition of the continental crust." Geochimica et Cosmochimica Acta 59(7): 1217-1232; and US Geological Survey (2000), Mineral commodity summaries.

10 Skinner, B.J. (1987). Supplies of geochemically scarce metals, in: McLaren, D.J., Skinner, B.J. (Eds.), Resources and world development. John Wiley and Sons, Chichester, pp. 305-325.

The reserves in most cases under-estimate available resources. New discoveries, improved extraction technology, and changed prices will affect what is economically recoverable. On the other hand, environmental and social concerns may limit the full utilisation of resources even if they are considered to be economically recoverable. Furthermore, losses will inevitably occur in the mining and refining of ore. Nevertheless, since reserve data is readily available for most metals, it can be used in initial preliminary surveys that probe for possible resource constraints. When such probing indicates potential mismatches with the scale or rate of a possible application, further investigations can be made. To estimate the availability of a metal for a specific technology the extraction cost from different sources can be compared to willingness to pay for the metal in the application in question. One may also need to assess the likelihood of new major discoveries.

The relationship between the size of primary and secondary resources differ greatly between metals. For some, that we here term 'industrially mature' metals, such as lead, copper and silver, the total historical extraction, and hence the potential secondary resources in the societal stock, are in parity with or even exceed the virgin reserves. Others, that we term 'industrially immature' metals, such as rare earth elements and lithium, have reserves that exceed cumulative extraction by two orders of magnitude.[11] Observe also the relation between extraction and crustal abundance in Figure 7.1, where lithium and REE have relatively low extraction rates compared to crustal abundance while the opposite is true for lead, copper, silver and gold.

The availability of the industrially mature metals to electric vehicles is likely to be constrained by *competition* with already established end-uses. The willingness to pay for a metal will determine how well a certain technology, e.g. electric vehicle batteries, can compete with other applications for the metal, and thus determine the future availability of the metal to this particular application. It might also be the case that the demand from the new application will not take off until we enter a period of increasing general scarcity, which will further increase the fierceness of competition.

In contrast, industrially immature metals could have low current extraction rates compared to the potential annual demand from a growing technology, e.g. electric vehicles. The challenge may then be to scale up extraction rates at pace with the growing technology. Hence, an assessment of the potential for *increased mining rates* is essential. A ramp up of mining and recovery may be constrained by physical limitations at mines, environmental considerations, monopolistic behaviour of producers, lack of investment due to tight capital markets or distrust and limited foresight, accidents and sabotage etc. Some of these factors may in themselves be temporary but still have long lasting consequences from price fluctuations and lack of trust. Most of them increase in likelihood and effect if metal supply is *concentrated* to a small number of producers and geographical locations.

Finally, recycling of used resources will have a profound effect on total resource availability as well as annual availability in the longer term. Efficient recycling systems need to grow at pace with the electric vehicle industry or primary supplies

11 Andersson and Råde (2002)

of many materials may be rapidly degraded. Given the low recycling rates of many metals at present, such a development cannot be taken for granted (Figure 7.2). Instead, the economic and institutional prerequisites need to be assessed for future supply of secondary as well as primary materials.

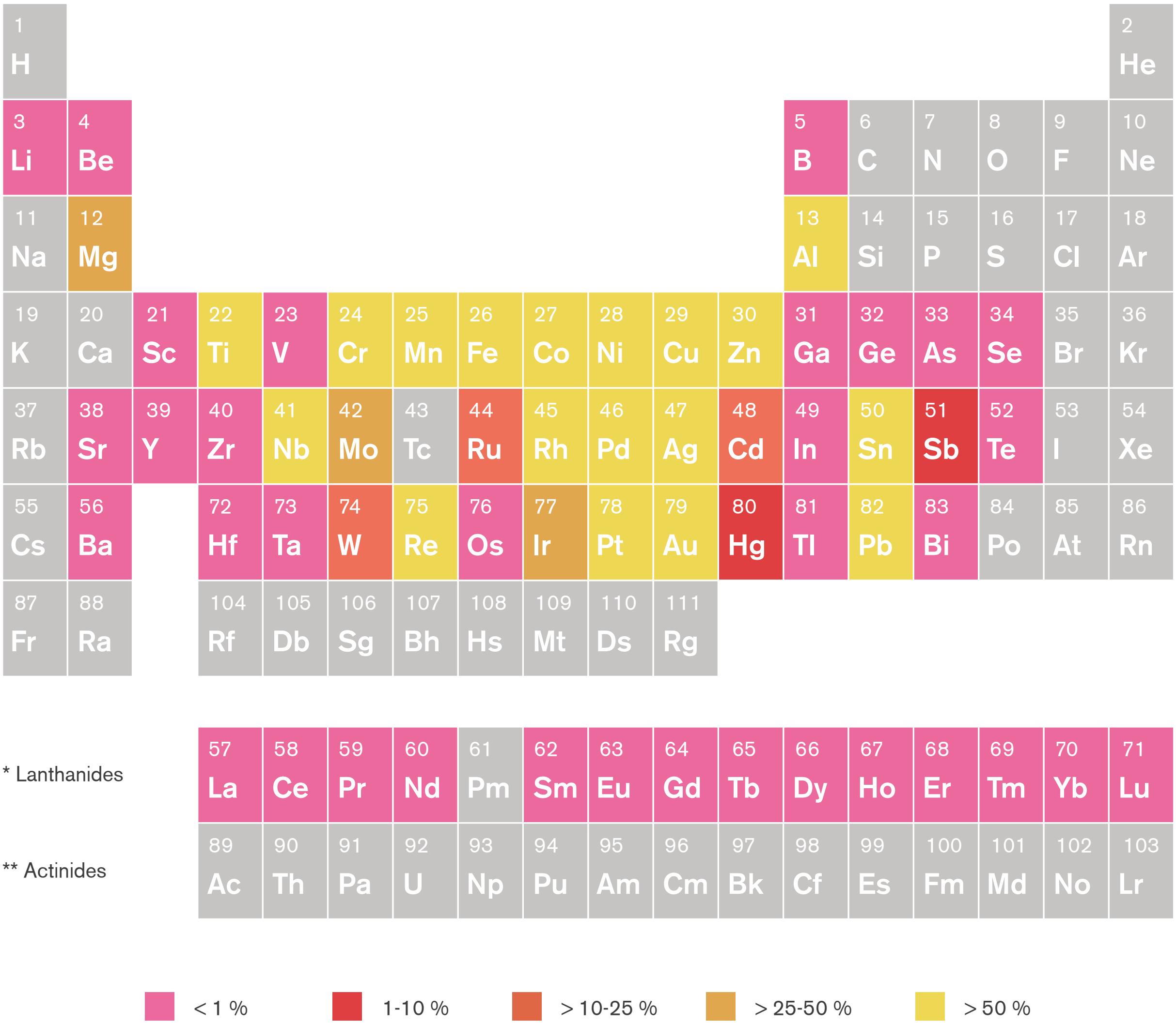

Figure 7.2 Current recycling rates are very low for many metals. Note that even at fairly high recycling rates, the accumulated material losses are substantial after a few cycles. Source: UNEP International Resource Panel (2011) Recycling rates of metals. A status report.

POTENTIAL MATERIAL CONSTRAINTS TO ELECTRIC VEHICLES

Material composition in cars has changed over time. As requirements have shifted and car designs and available materials have evolved, the diversity of materials has increased and new materials have been introduced. Over the years, cars have seen a fundamental shift in composition from wood to steel and further towards higher strength steels, aluminium, magnesium, plastics, composites and other materials, see Figure 7.3.

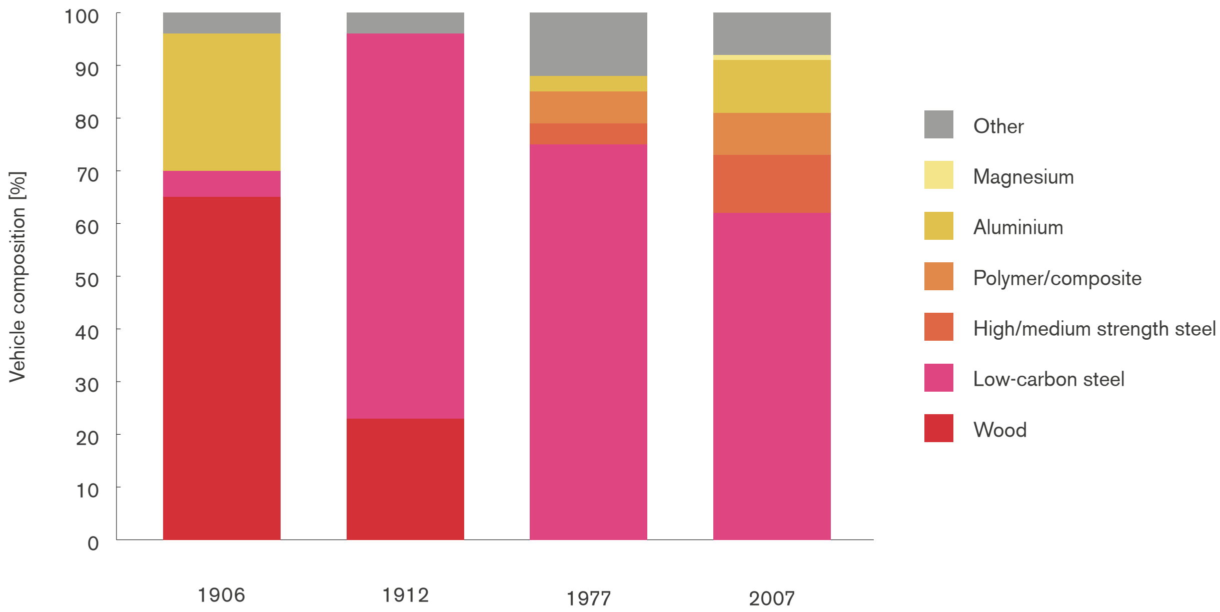

Figure 7.3 Historical shift in car composition by mass. Source: Lutsey, N. (2010) Review of technical literature and trends related to automobile mass-reduction technology, UCD-ITS-RR-10-10, Institute of Transportation Studies, University of California, Davis.

As a consequence of the push for increased energy efficiency of cars, mass-reduction designs with strong and light materials are most likely part of future car trends (Figure 7.4). Increasing the use of magnesium and high strength steels, which might contain niobium[12], means increasing dependence of metals for which concerns of their availability to the EU and US have been raised.[13]

Current material trends for cars in general point at increasing material diversity as well as increasing dependence on rare metals. This chapter focuses on metals for *electric* vehicles, but it may be relevant to ask if there are enough metals for a high global car intensity in general. Regulatory as well as customer driven requirements push the use of rare metals in cars. For example, control of tail-pipe emissions with catalytic converters typically requires platinum group metals (PGM) and REE. Safety and driver assistance features, powertrain control and 'infotainment' typically require the use of automotive electronics containing e.g. gold, silver, PGM, gallium, tantalum and REE.[14]

There are, nevertheless, a number of materials that are particular to electric vehicles. Electric vehicles rely on additional components including batteries, electric machines, high-voltage power electronics such as converters and alternators, battery chargers, and high voltage cables (see Chapter 3). The current designs of these components make use of a number of metals that may warrant further investigation. The rare earth elements neodymium, dysprosium and terbium are used in permanent magnets in electric machines and alternators. Batteries may contain lithium, cobalt, nickel, REE and manganese. Silver is used in electronic control systems and copper in high voltage cables.

12 SSAB (2012) Advanced High Strength Steels For The Automotive Industry, SSAB, Borlänge, Sweden.
13 See for example European Commission (2010) "Critical raw materials for the EU", US DoE (2010) "Critical materials strategy" and Federal Ministry of Economics and Technology (2010) "The German Government's Raw Materials Strategy".
14 Cullbrand, K. and Magnusson, O. (2012) The use of potentially critical materials in passenger cars, Master of Science Thesis, Chalmers University of Technology, Gothenburg, Sweden.

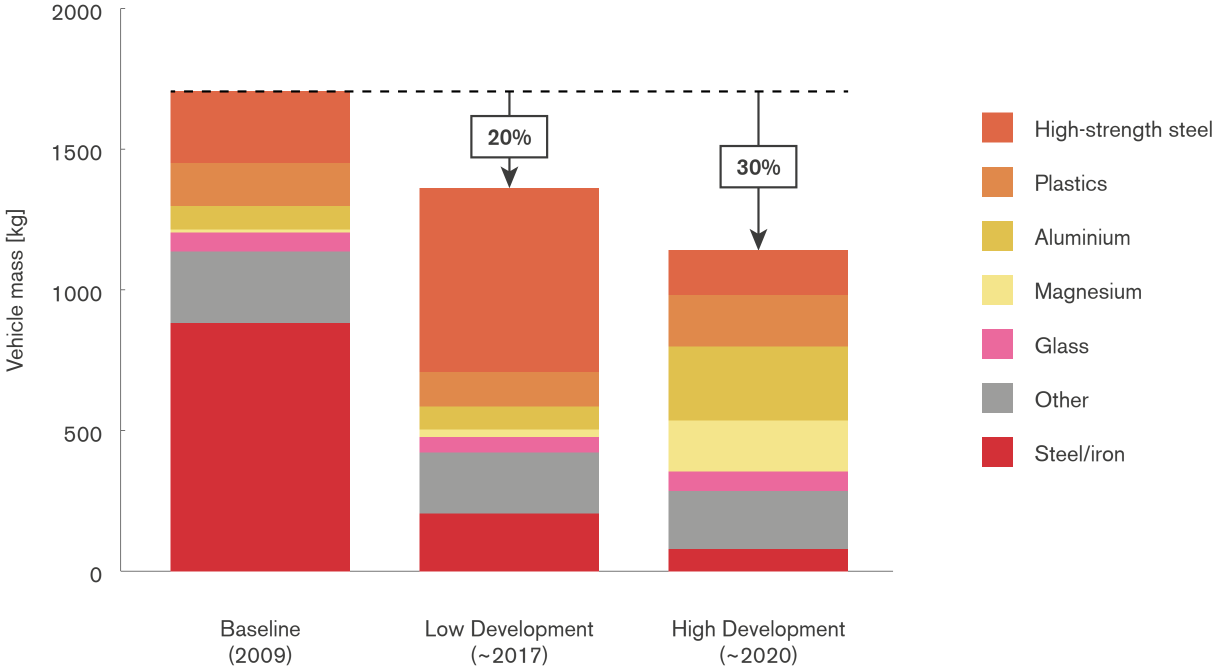

Figure 7.4. The mass by material of the Lotus baseline and mass-reduced car designs. Low and High Development illustrate concepts available for model years 2017 and 2020 commercial deployment. Source: Lotus Engineering, Inc. (2010). An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program as referred to in Lutsey, N. (2010) Review of technical literature and trends related to automobile mass-reduction technology, UCD-ITS-RR-10-10, Institute of Transportation Studies, University of California, Davis.

The materials requirement depends on the type of drivetrain. Plug-in hybrid electric vehicles (PHEVs) demand smaller batteries and electric machines than battery electric vehicles (BEVs), but contain combustion engines and catalytic converters which BEVs do not. A PHEV with Li-ion battery thus typically require less lithium, copper and the rare earth elements neodymium, dysprosium and terbium, but more alloyed aluminium (combustion engine) and PGM (catalytic converter) than a BEV with Li-ion battery. Both PHEVs and BEVs typically require more lithium, copper and the rare earth elements neodymium, dysprosium and terbium, but less aluminium alloys and platinum group metals than Internal Combustion Engine (ICE) vehicles.

The observed requirements of rare metals do not necessarily lead to the conclusion that resource availability will constrain diffusion of electric vehicles. To probe if some of these metals deserve closer attention we make use of two simple indicators. First, we compare the specific materials requirement of one car to the reserves of a set of selected metals. Second, we compare the specific materials requirement to annual resource extraction. The resulting indicators give us (a) the maximum number of cars that the current reserves would allow, and (b) the maximum annual growth rate of the car fleet that the current annual resource extraction would allow, if, hypothetically, each metal would be used only for passenger cars and if there were no material losses (of primary and secondary resources) to maintain the car fleet that has been built up. Figure 7.5 illustrates these indicator values plotted in a log-log diagram for two commercially available cars: one PHEV and one diesel ICE car of comparative size.

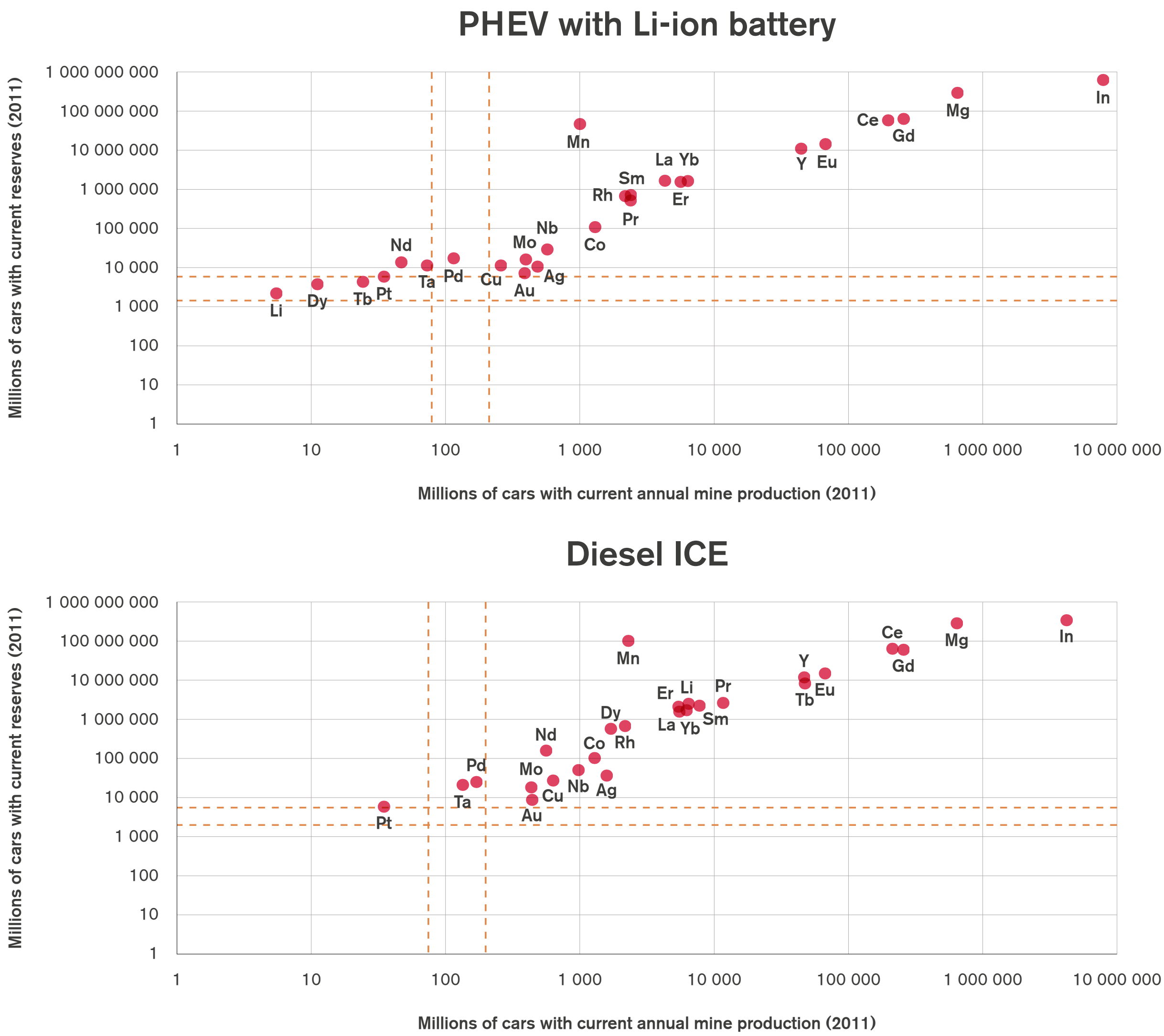

Figure 7.5 Comparison of metal requirements for a PHEV with Li-ion battery and a diesel ICE (both in the executive compact family car segment, see Table 6.2). The diagrams show, for each car, the maximum number of cars that the current reserves would allow (y-axis) and the maximum annual growth rate of the vehicle fleet that the current annual resource extraction would allow (x-axis), if, hypothetically, each metal would be used only for passenger cars and if there were no material losses. Note that reserves data can differ between sources, e.g. REE (a factor of 2) and indium (a factor of 10), and for the purpose of this analysis, low reserve estimates were chosen. Data source for material requirements: Cullbrand, K. and Magnusson, O. (2012), The use of potentially critical materials in passenger cars, Master of Science Thesis, Chalmers University of Technology, Gothenburg, Sweden. Data source for reserves and resource extraction: primarily U.S. Geological Survey (2012), Mineral commodity summaries 2012; complemented by Technology Metals Research (2012), Total code-compliant mineral resources Nov 2012; Alonso et al (2012), Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies, Environ. Sci. Technol., 2012, 46 (6), pp 3406–3414; Johnson Mathey (2011) Platinum, Interim review; and European Commission (2010) Critical raw materials for the EU.

How should this figure be interpreted? The positions of the metals along the y-axis reveal that the included metals are spread over a large range indicating resource constraints at levels from 2 billion PHEVs. *If* we assume a scenario where the PHEV model is introduced to a level corresponding to 0.2 (near future) or 0.5 (western Europe at present) cars/capita globally, and a global population of about ten billion, this results in a fleet of 2-5 billion PHEVs, indicated by the horizontal red lines. From this first rough order of magnitude estimate, it appears that current reserves seem to be sufficient for most of the included metals, even at very high car penetration rates, with the possible exception of lithium, dysprosium and terbium.

The positions of the metals along the x-axis indicate potential constraints on the annual growth of the car fleet due to limited resource extraction. While the resource extraction of several metals allows for production of several hundred million cars per year, again lithium appears at the bottom end with 5 million cars per year. The current production of electric vehicles is not near this number (PHEV and BEV around 70 000 - 100 000 units in 2012, out of some 60 million passenger cars in total), so there does not seem to be any immediate risk of constraints. But *what if* we want to expand the car production significantly over time? If a scenario of a 0.2 to 0.5 PHEVs per capita car fleet is to be reached within say 40 years, due to a ramp-up phase of maybe 15 years, about 80 or 200 million cars need to be produced annually over a period of 25 years. These numbers are represented by the two vertical red lines. In such a scenario, it is clear that the current resource extraction of some metals would have to be increased significantly, in particular lithium but also dysprosium, terbium, platinum, neodymium, tantalum and palladium. Note that the scenario also assumes that there are no material losses so that the built-up material stock in cars is maintained.

With this rough analysis we could not identify any metals as undisputable showstoppers for large-scale introduction of PHEVs. However, the extraction rate required for some materials may produce bottlenecks and thus merit further investigation. Before we continue with such a more in-depth analysis of lithium in the next section, the results presented in Figure 7.5 warrant a couple of additional remarks.

It cannot be ruled out that the seemingly unproblematic metals (those with neither resource nor rate constraints) do not constitute a risk for certain designs of electric vehicles. For example, the industrially mature metals copper, gold and silver are used in a large number of other applications. Although our analysis shows that it is less likely that electric vehicles drive the scarcity of these materials, they might still present other issues. If the competition for these materials is already fierce and increases over time, substantial price increases and even physical constraints on availability could materialise.

The comparison between the PHEV car and the diesel ICE car shows that platinum presents a similar constraint for the two vehicles (Figure 7.5). Lithium, dysprosium, terbium and neodymium are used in the ICE car, but at significantly lower levels. Praseodymium, silver, samarium and copper are also used at lower levels. Tantalum and palladium are among those remaining at approximately the same levels. In a scenario with a global expansion of diesel ICE with the specific material requirements of our design, the current extraction rate of platinum could be a constraint. The main use of platinum in cars is in catalytic converters, why platinum car demand correlates tightly with local requirements on tail-pipe emissions. If global requirements on tail-pipe emissions would reach European levels or beyond and our car design's specific platinum requirement is representative, platinum could pose a risk even at current car production levels (around 60 million cars annually).

IS LITHIUM AVAILABILITY A CONSTRAINT TO ELECTROMOBILITY?

The availability of lithium resources for a large global transition to electric vehicles with lithium-ion batteries has been studied through explorative scenarios by e.g. Kushnir and Sandén (2012).[15] The primary result is that there are many interesting and somewhat overlooked aspects affecting the prospective availability of lithium: primarily limits to the rate at which extraction can be ramped up and the gloomy conditions for recycling. The study also illustrates a variety of factors that can affect resource availability in general, from physical factors, such as material requirements of technologies and geographic concentration of resources, to market concentration, political stability and industrial politics.

The implications of a rapid global transition to EVs is explored through a scenario in which global population will stabilise at 9.3 billion towards the end of the century, global car density will reach between 0.2 and 0.5 cars/capita and EV market penetration will develop along a logistic curve to reach 95% by 2050, with 50% of all vehicles having some sort of battery by 2035. Two size assumptions for batteries bound the study, representing PHEVs and BEVs, both using lithium-ion batteries, at 9kWh capacity and 36kWh capacity respectively. Three different recycling levels (100, 80 and 0%) are assumed. The resulting cumulative lithium demand over the remainder of the century ranges from 4 to 150 Mt, see Figure 7.6.

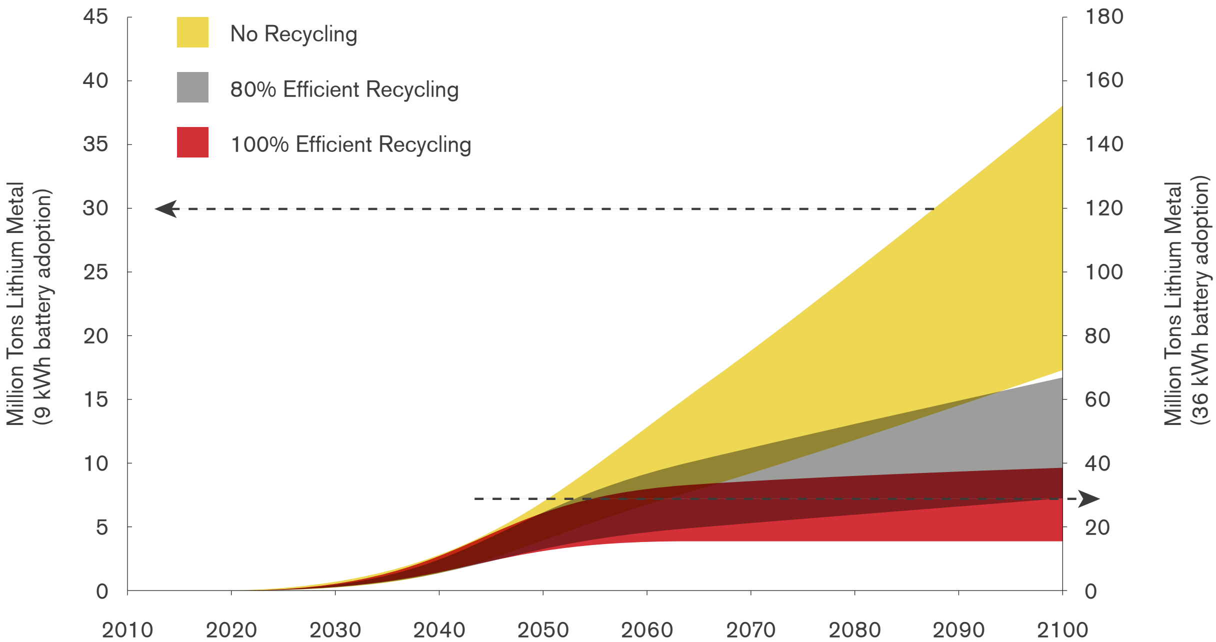

Figure 7.6 Cumulative lithium demand in the scenarios with and without recycling. The figure shows the cumulative virgin lithium demand in million tons (Mt), for growth scenarios of PHEV (left scale) and BEV (right scale). The dashed lines indicate the 30 Mt lithium reserves. The bottom end of each band corresponds to 0.2 cars per capita and the upper end to 0.5 cars per capita. Source: Kushnir and Sandén (2012).

Global terrestrial lithium reserves consist of brine and mineral deposits, which make up 85% and 15% respectively of the estimated reserves (including some marginal resources) of about 30 Mt in terms of recoverable metal. A comparison of these reserves to the cumulative lithium demand in the explorative scenarios

15 Kushnir, D. and B. A. Sandén (2012). "The time dimension and lithium resource constraints for electric vehicles." Resources Policy 37:93-103.

clearly demonstrates that the size of the battery (PHEV or BEV) matter and that efficient recycling is essential, see Figure 7.6.

Ocean resources greatly exceed any conceivable societal need and are theoretically extractable at low energy use, but have not been proven in practice. Established processes for extracting substantial lithium levels from the ocean would require vast surfaces in high insolation areas. The problems and uncertainties surrounding ocean extraction are so large that it should not be assumed for planning of the build-up phase.

The extraction rate may represent a more salient limit to a transition to EVs. Current annual lithium extraction is around 25 kton per year, a rate that will have to increase considerably to meet the demand explored in the scenarios, see Figure 7.7. Two different problems related to annual lithium availability can be pointed out. Firstly, since extraction from minerals is predicted to be constrained at about 100 kt per year (grey area in Figure 7.7)[16] the ability and willingness to expand extraction from a small number of brine sources (concentrated to a few locations and companies in Chile, Bolivia, Argentina and China) will determine the possible timeframe and form of an electric vehicle transition based on lithium batteries. This means that the build-up of a BEV fleet presents a huge challenge, while a PHEV fleet is within reach. Secondly, maintaining the lithium stock in the long run requires a very high recycling rate and a recycling industry of magnificent scale.

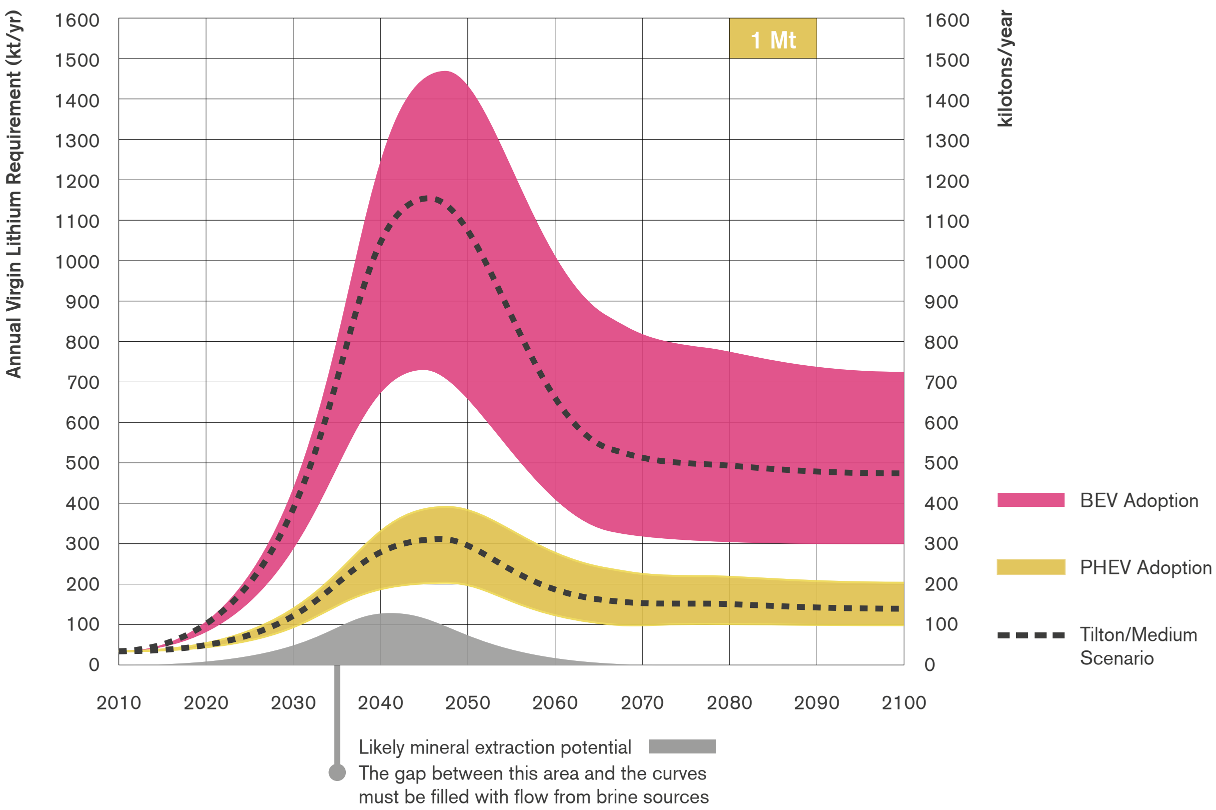

Figure 7.7 Implied annual lithium extraction rates. The demand curves assume 80% recycling. The bottom end of each band corresponds to the 0.2 cars per capita scenario and the upper end to the 0.5 cars per capita scenario. The estimated limited extraction rate from minerals (in grey) indicates the role of lithium from brines and ocean. Source: Kushnir and Sandén (2012).

16 See Kushnir and Sandén (2012) for details.

Despite the importance of recycling, its economics are currently not good and may even degrade as battery material evolves towards less expensive and valuable compositions (such as the removal of cobalt). Due to the assumed exponential growth of initial EV diffusion and the possibility to expand lithium production up to a certain level, it could take a long time until any real shortage of lithium occurs. If this will be case, the market price alone is unlikely to provide incentives for a timely development of the recycling capability and capacity that will be required to maintain a large societal lithium stock, and hence, it will be necessary to design policies to encourage recycling.

In conclusion, it is not enough to look at lithium resource stocks and conclude that there is enough. If recycling does occur, then resource exhaustion does not appear to be a credible threat. Yet recycling is nowhere near economic and will likely require policy support to realise. The time dimension is more important than the resource stock in the case of lithium; issues surrounding the required rate of lithium flows, and particularly their dependency on a concentration of producers and countries, will occur well before any limits to resource quantity. Maintaining the present vision of personal mobility through changing the technology of the car may thus be unrealistic unless the time scale for such a transition is extended.

A worldwide push for lithium batteries risks building up a large, capital intensive stock of cars and associated production systems that are vulnerable to resources more concentrated to a few producers and countries than that of the oil supply system existing today; more than two thirds of the terrestrial resources considered here are concentrated in a small area shared by the three countries Chile, Bolivia and Argentina and possibly to be exported via a single Chilean port. There is currently no battery technology able to compete with lithium for large vehicle batteries, and no concrete indication that this will change in the foreseeable future (Chapter 3). If there are no readily scalable alternative to lithium supplies or alternative vehicle energy technologies, this would be a considerable risk to critical societal infrastructure. This is a strong case for maintaining diversity at all levels of the system. Possible policy responses could be to maintain a portfolio of known lithium resources that are already assessed at the mine feasibility stage in order to minimise the time of any prospective disruption as well as bringing other vehicle and battery technologies to competitive readiness.

CONCLUDING REMARKS

The purpose of this chapter is to discuss the risk that metal scarcity might constrain a large-scale diffusion of electric vehicles. We have tried to show the multi-faceted nature of the materials scarcity issue. It is not enough to answer the question of "how much" of certain materials electric vehicles require in relation to available geological resources. It is also necessary to answer "to whom" are the resources available, as well as "when" can they be supplied.

Cars in general are complex products relying on a large number of metals. Current trends towards lightweight materials, electronic components and tail-pipe emissions control will enlarge this dependence. Electric vehicles are likely to increase it even further with components such as batteries, electric machines, high-voltage power electronics such as converters and alternators, battery chargers, and high voltage cables. Notable examples of such metals are lithium, terbium, dysprosium, neodymium, praseodymium, silver, samarium and copper.

A rough analysis of material requirements for PHEVs did not identify any of these as undisputable showstoppers for large-scale technology diffusion. However, given that lithium batteries are used, lithium is singled out as potentially problematic and clearly warrants some consideration for policy makers. The in-depth investigation of lithium availability clearly demonstrates that a transition to electric vehicles based on lithium batteries is not unproblematic mainly due to concerns about limits to annual extraction and geographical concentration of reserves. Dysprosium, neodymium, platinum and tantalum might also pose a problem concerning the current extraction rate. We also noted that some industrially mature metals such as copper, gold, silver and molybdenum, might present a risk, in the sense that fierce competition from other end uses could lead to substantially higher prices and even physical constraints on availability in the long term.

Another striking result is the role of recycling. Recycling of rare metals in cars is so far neither well developed nor well understood. An example is lithium battery recycling. In all ambitious EV scenarios, extensive recycling will be needed, but currently no lithium is recycled back into battery grade lithium. The dispersive use of many rare metals in cars presents a huge challenge for making recycling happen, in particular on pure commercial grounds.

Finally, we want to return to a fundamental, but sometimes overlooked feature of technology assessments. A constraint to the diffusion of a specific technology does not necessarily imply a constraint to a broader phenomenon. A constraint to some forms of electric vehicles does not imply a constraint to a transition to electromobility in general. Different battery types present different risks and some are less constrained than others. Different car designs offer different opportunities. In terms of material resource efficiency, hybrid electric vehicles might be advantageous in requiring less battery material than pure battery electric vehicles (there could also be other reasons for a smaller battery, see Chapter 10). In addition, smaller vehicles such as electric bicycles, other means to distribute energy such as electric roads (Chapter 2 and 14), and more efficient transport modes are examples of a plethora of substitution opportunities and alternative routes to electromobility. Resource availability will play a role in determining future technological trajectories, but will unlikely be a showstopper for electromobility in general, and even less so, if potential materials constraints are continuously monitored and taken into consideration.