Impulses for the Energy Transition

Criticality and recycling of lithium-ion batteries

Putting the debate on a broader footing

White Paper

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High Performance Battery Technology GmbH based in Bonn, Germany, specializes in the research and development of high tech batteries.

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Content

00 Foreword

The energy transition is an enormous challenge. It touches the physical foundations of our society, affects all areas of life and is in dire need of comprehensive transformation. Society is grappling with balancing current and future energy needs against the need to decarbonize the energy sector. There are many moving parts in the energy transition, but so much is unclear, a work in progress, with science and policy both contemplating where priorities should be focused.

The same can be said about the role of battery storage systems for the energy transition. It is undisputed that they will play a key role in the electrification of transport and the growth of the renewable energy sector. At the same time, it is becoming increasingly clear that the debate on battery storage for the energy transition needs to be conducted more broadly, as there are still many blind spots, pitfalls and unexplored possibilities.

This is where we come in with our Impulses for the Energy Transition.

Our previous White Paper dealt with the sustainability potential of battery rightsizing. We now want to tackle a particularly urgent and complex topic: criticality and recycling of lithium-ion batteries. Both topics already play an important role not only in the field of battery research, but also in the political and public debate. However, the debate must enter a broader footing because their economic and ecological importance will grow further and will affect future generations.

We hope that our White Paper will broaden the debate, and arm the casual and informed reader with useful information and food for thought—and to shed some light on the ways in which the current challenges could be addressed.

Prof. Dr. Günther Hambitzer
Managing Director of High Performance Battery Technology GmbH

Bonn, September 2022

01 Introduction

The first few months of 2022 have dramatically demonstrated our dependence on imported raw materials. Russia's war against Ukraine has prompted many countries to consider banning imports of Russian coal, oil and gas as soon as possible. At the same time, voices are being raised, particularly in the business community, warning of the potentially serious negative consequences of a comprehensive energy embargo for the domestic economy. Energy raw materials, it turned out, are *critical* raw materials: raw materials that are existentially important for national economies and whose security of supply is threatened at the same time.

Current geopolitical developments clearly show us: energy raw materials are critical raw materials.

The concept of criticality has thus entered the mainstream political and public debate. Yet it concerns more than just fossil fuels. Indeed, energy transition technologies also depend on raw materials whose supply is subject to certain risks. Electric motors, for example, which are essential components in electric vehicles, need rare earth metals (also known as 'rare earths') such as neodymium and dysprosium for their permanent magnets. The same applies to wind turbine generators (Erdmann 2021). And batteries, with their numerous fields of application for the energy transition, also rely on critical raw materials. When it comes to batteries the debate has traditionally focused on the metal cobalt, which is essential as a cathode material in battery chemistries with high energy density, such as traction batteries for electric vehicles. But other battery raw materials, such as nickel, lithium, and the anode material graphite, could also prove to be critical (Weil et al. 2018).

This applies not only to fossil fuels, but also to raw materials that are essential for energy transition technologies—such as battery storage systems.

Besides raw material substitution and sufficiency, recycling is seen as a promising way to mitigate criticality in the longer term. Indeed, if we succeed in recovering raw materials from used batteries, we will need fewer new (i.e. primary) raw materials to manufacture new batteries. This could explain why a lot of attention is currently being focused on the development of battery recycling processes and the establishment of a corresponding recycling (or circular) economy. But recycling is important for other reasons as well: in particular, it is to prevent the battery boom from generating huge amounts of waste that could end up in landfill. Recycling also has the potential to decrease energy demand and greenhouse gas emissions—but only if the recycling processes have lower energy and carbon footprints with respect to the primary industry processes. Indeed, it has been demonstrated that the considerable environmental impacts caused by the provision of battery raw materials (Helms et al. 2019) can be reduced by the use

Besides raw material substitution and sufficiency, recycling is a promising factor in mitigating criticality in the longer term.

of secondary materials from recycling (Crenna et al. 2021; Bothe and Steinfort 2020; Xu et al. 2020).

While the importance of criticality and recycling is appreciated from a high level, many questions remain to be answered. For example: Which battery chemistries are actually most susceptible to criticality, and according to what criteria? What are the current barriers to comprehensive recycling of lithium-ion batteries, and how could these barriers be mitigated? What role could second-life battery products play, and can they mitigate critical raw material supply issues for the energy transition? The following chapters aim to shed light on these and other questions—and also to provide impulses for the debate on criticality and recycling.

02 Lithium-ion batteries— Their enormous rise and its enormous consequences

If we look back at the development and history of lithium-ion batteries, one thing is clear above all: there has been a tremendous boom. After their market introduction in the early 1990s, the innovative batteries with their superior performance values gradually replaced nickel-metal hydride batteries in consumer electronic devices and power tools. With the breakthrough of electromobility in recent years, a large new field of application emerged: lithium-ion batteries have since been used as traction batteries in cars as well as in e-bikes and other electrically powered vehicles. While in 2000 their global market was less than 2 GWh, in 2018 the market volume was already over 160 GWh—with 62 percent accounted for by electromobility, 6 percent by industrial storage and 32 percent by all other applications (Avicienne Energy 2019, cited according to Mähliß 2020). This corresponds to a compound annual growth rate of nearly 28 percent.

Lithium-ion batteries have recently experienced a tremendous boom. But this is likely to be only a foretaste of developments in the years to come.

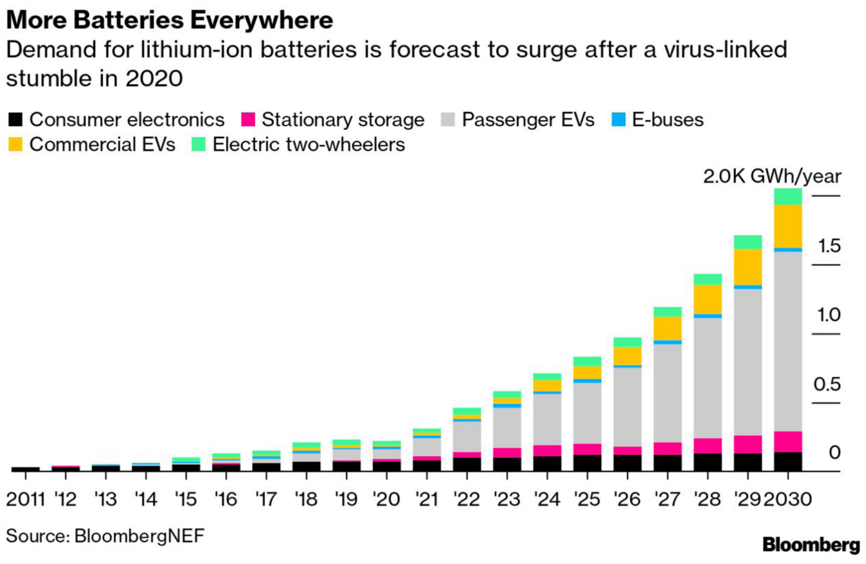

Fig. 1: Demand for lithium-ion batteries—development and forecast
Source: www.bloomberg.com

Despite these impressive figures: the boom of the past is likely to be only a foretaste of developments in the years to come (figure 1). In Germany, the market for electric cars doubled from 2020 to 2021 despite the COVID-19 pandemic, and the market for home storage systems grew by 50 percent—with an estimated 145,000 new installations in 2021 alone (Figgener et al. 2022). On a global level, the electric vehicle amount increased from 7.1 million in 2019 to 10.2 million in 2020, representing a growth of 43 percent. Estimates suggest that this massive growth will continue: in 2025, there could be 46 million electric vehicles on the road worldwide, rising to 125 million in 2030. This would represent an average annual growth of 28 percent over the entire decade (IEA 2021a). In the area of stationary battery storage, the forecasts look similar: the IEA assumes a greater than six-fold increase from 9.6 GW in 2020 to 62.9 GW in 2026—which corresponds to an annual growth of 37 percent (IEA 2021b).

The central driving force behind this development is the political programme called 'energy transition': the shift from fossil and nuclear to renewable energy sources.

The central driving force behind this development is the political programme of the energy transition: the shift from fossil and nuclear to renewable energy sources in all economic sectors and within a comparatively short time. As a concept from the early 1980s, the energy transition initially had a strong resonance in the scientific community. The debate entered the political arena in the 1990s, but it took another 30+ years to fully grasp the urgency of turning away from fossil fuels: on the one hand through Russia's war against Ukraine, which demonstrates the consequences of existing geopolitical dependencies, and on the other hand through the recently published Sixth Assessment Report of the IPCC (2022) and other relevant reports, which warn strongly of the dangers of further progressive climate change.

Batteries will play a central role here, making electrical energy 'mobile' and enabling the integration of fluctuating renewable energy generation into the electricity grid.

The energy transition affects all areas of our lives: energy production and consumption, private households, industry and commerce, electricity, heating and mobility. The necessary measures are correspondingly diverse and their interactions complex. What is certain, however, is that batteries, together with wind and solar power generation, will play a central role in the transition. They make electrical energy 'mobile', and they enable the integration of fluctuating renewable energy generation into the electricity grid. Against this background, it is not surprising that the demand for batteries, as outlined above, has increased enormously and will continue to increase—and that there is a corresponding development on the part of battery production: as Moores (2021) reports, the number of lithium-ion battery gigafactories in the pipeline over the next ten years increased from 4 in 2015 to 118 in 2019 and 181 in 2020. Of these 181, only 16 were based in Europe.

A little more than a year later, it would seem that 38 gigafactories are planned in Europe (Battery-News 2022).

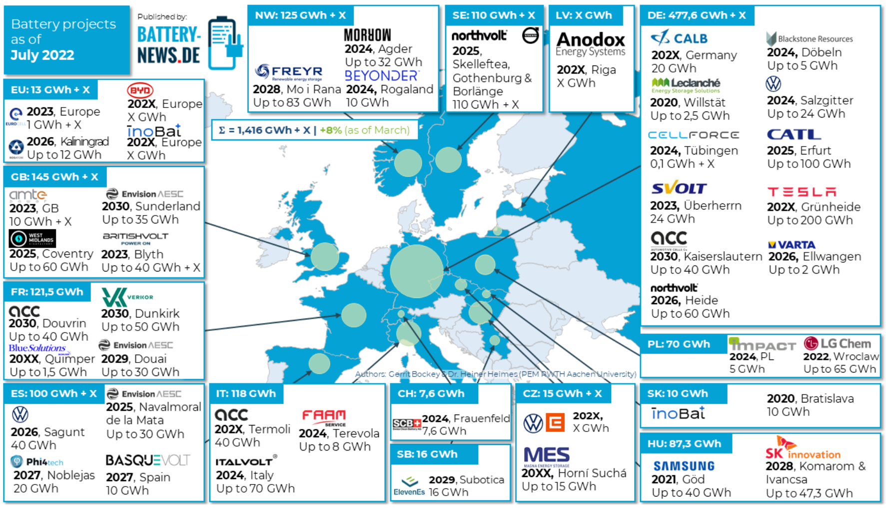

Fig. 2: European battery production projects as of July 2022
Source: Heimes 2022 (map regularly updated at www.battery-news.de)

As their name suggests, each of these factories will produce lithium-ion batteries with a storage capacity on a GWh scale. The plants currently in operation or planned in Europe alone are expected to have a production capacity of at least 1,309 GWh per year (figure 2). If the average lithium-ion battery of 2020 is taken as a basis, this means a raw material requirement of around 1.1 million tons of graphite, 760,000 tons of aluminium, 630,000 tons of nickel, 435,000 tons of copper and steel, 220,000 tons of manganese, 175,000 tons of cobalt, 130,000 tons of lithium, and 110,000 tons of iron—per year (Bhutada 2022).

A key point from a sustainability perspective is that these gigafactories of tomorrow produce yesterday's technology. The reason for this is simple: the technology must be ready for series production, but project planning, construction and commissioning of the sites could take many months if not years. The manufacturing deployment scales are considerably larger than the short-term demand, therefore we rapidly build yesterday's technology rather than waiting for new technology to arrive. Another way to look at it is that battery technology is rapidly superseded in the current climate—what we are manufacturing today could be technologically superseded within a relatively short period of time. The upscaling of battery production that we are currently observing not only includes yesterday's technologies, but also their problems. In addition to over-reliance on critical raw materials such as cobalt, and having to manage and/or mitigate the inherent safety risks associated with these batteries, we must also grapple with their relatively short life.

The battery boom will have enormous consequences on two fronts: resources or raw materials for manufacturing, and management of waste.

Against this background, it is already foreseeable that the battery boom will have enormous consequences on two fronts: on the resource side and on the waste side. Sustainable development is strongly affected by this in several ways: There is a threat of depletion of finite resources, environmental damage along the production chain, generation of large amounts of hazardous waste, and economic dependence on critical raw materials. Therefore, the topics of criticality and recycling are of crucial importance: with a view to the future, but also today—because today's decisions have a major impact on the criticality and recycling problems we will have to deal with in the future.

03

First life, second life, longer life—Different perspectives on the life span of batteries

The emerging consequences of the battery boom are hotly debated. Great importance is attached above all to the resource problem, which calls into question the long-term availability of battery raw materials. The environmental destruction caused by the production of raw materials also features in the debate, whereas the waste problem, which is inextricably linked to the boom, has thus far received limited attention. While the debate on possible solutions rages on, two obvious but powerful approaches that could tackle the root of these problems have been almost completely ignored: namely the longevity and rightsizing of batteries (Dusseldorp et al. 2021). Efforts to find sustainable sources of raw materials are important, but for the time the main focus is on recycling and battery second life.

The different consequences of the battery boom are debated to varying degrees. The same applies to the debate about possible solutions, which has so far focused on recycling and battery second life.

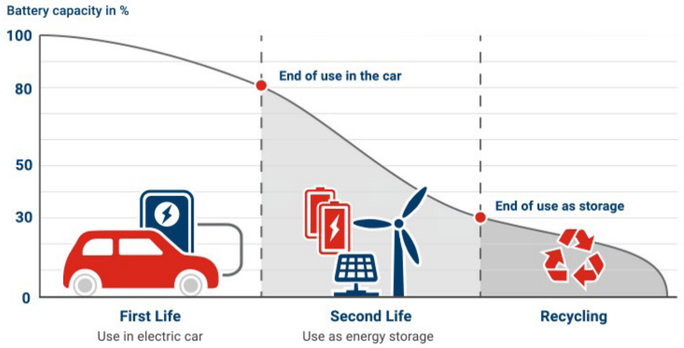

Fig. 3: The concept of battery second life
Source: elektroautomatik.com

The concept of second life (or second use) means that used batteries from electric vehicles are redeployed in stationary or industrial storage applications instead of entering the waste or recycling stream (figure 3). This is possible because the latter applications are far less demanding, therefore batteries that cannot meet the specifications required in automotive applications can still serve the stationary or industrial storage markets. Since stationary applications have lower demands in terms of space requirements and weight of batteries, the degradation from their first life is not a fundamental problem for further use: if higher performance or greater capacity is required, this

Second life means that used batteries from electric vehicles are reused in stationary applications after the end of their first life.

can be achieved by using a larger quantity of batteries. Two fields of application are considered particularly attractive: the provision of primary control power, and domestic energy storage (especially in connection with photovoltaic systems) (Fischhaber et al. 2016).

The main advantage cited in favour of second-life applications is cost: second-life batteries are, for the time being, more cost-effective than new batteries. This could reduce investment costs and increase return on investment, thus promoting applications that accelerate the energy transition. In addition, significant environmental and resource efficiency benefits are associated with second-life batteries: to the extent that second-life batteries replace new batteries, they can reduce greenhouse gas emissions and other pollutants associated with battery production while decreasing our dependency on primary raw materials (Fischhaber et al. 2016). So, according to its prominent role in the public debate, is second life the silver bullet for a sustainable use of batteries?

> The question of cost development is worth a closer look: lithium-ion batteries are becoming increasingly safer and lower cost, so that at some point (and in some territories) the cost of picking a brand new battery off-the-shelf will be lower than the cost of re-deploying a battery in second life. Similar arguments can be made, however, for the second-life market—because discharging, dismantling and re-manufacturing protocols to enable second life deployment will inevitably become more cost-effective and scalable. The bottom line is, that in some territories the second use market will continue to grow and be stronger than in other territories.

Background box 1: Uncertain cost development for new and second-life batteries

First of all, it should be noted: battery second life is not recycling. It does not *replace* recycling, but merely *postpones* the time when recycling becomes necessary further into the future. This has consequences that, on the one hand, are sometimes seen positively: extending the first life of batteries gives us more time to develop effective and economical recycling processes. From a business point of view, it can also be advantageous for companies to shift the recycling costs they have to bear for the batteries they produce to the future. On the other hand, it could just as well be said that second life conceals the fact that the problem of battery recycling, with all its sustainability implications, is far from resolved (Jehle 2021). Indeed, the second-life concept does not answer the question of whether or when effective and economical battery recycling will be possible in the future. It may rather tend to distract from it.

Battery second life does not replace recycling, but merely postpones the time when recycling becomes necessary further into the future.

What about possible environmental and resource benefits of second life use cases? To see more clearly, two cases must be differentiated: if the production of new batteries is avoided through the use of second-life batteries, ecological savings can be assumed. If, however, additional battery storage applications are triggered, the environmental benefit depends on the environmental impact of the applications and of the competing technologies (Fischhaber et al. 2016). This again shows the importance of reflecting on the premises of life cycle assessments (Dusseldorp et al. 2021). Another relevant aspect is the specific resource requirement for a given application: second-life batteries have reduced performance and capacity compared to new batteries. Therefore, 'more battery' is needed for the same application. And 'more battery' implies: more demand for battery raw materials, more energy demand in manufacturing, etc..

Changing the decision-making perspective from 'finding the best possible use for already produced batteries' to 'which batteries to produce in the future' makes a big difference.

The previous questions implicitly presupposed a certain decision-making perspective, namely: finding the best possible use for *already produced* batteries that have had their first life. What happens though when it comes to deciding which batteries to *produce in the future*? Then the situation is quite different. From this point of view, it is important to choose battery technologies from the outset that are characterized by low resource requirements over the entire life cycle and by high recyclability. The concept of second life is then not part of the most efficient solution, but merely mitigates the negative consequences of a poor technology choice. The possibility of second-life applications should therefore not be used as an argument today to justify the future production of batteries based on old technology.

In particular, it makes clear that battery longevity is a particularly beneficial factor for sustainability, alleviating the pressure on recycling while second life only shifts it.

In particular, shifting the decision-making perspective towards sustainable technology choices for the future makes it clear that battery longevity is a beneficial factor for sustainability in many respects. Other things being equal, a battery with five times longer life replaces five batteries without additional energy, raw material or other capital expenditure—in first-life, not in second-life applications. It only becomes a case for second life or recycling after five times as long. This would also mean that fewer batteries would have to be recycled in the end, which goes hand in hand with a significant reduction in energy input, raw material loss and costs associated with the recycling process. So while second life only shifts the pressure on recycling, battery longevity actually alleviates it. It also alleviates the problem of criticality. Finally, long-life batteries avoid the safety risks associated with old batteries based on conventional technology, i.e. with second-life applications.

In the end, it can be summed up as follows: it is a technological deficit, namely rapid battery ageing, that brings the second-life concept into play in the first place—with all its disadvantages in terms of safety and resource requirements. Accordingly, the obvious technological approach to avoid the aforementioned problems is: long-life batteries.

In view of this, not the *second life*, but a *longer (first) life* of batteries should be the focus of the debate, of technology development, technology choice and ultimately also of battery applications.

Not the *second life*, but *a longer (first) life* of batteries should be the focus of battery-related decisions.

04 Battery recycling technologies—A brief overview

At some point, every battery must be recycled—sooner or later, after its first or second life. For the recycling of lithium-ion batteries, different pathways are being discussed, each having its specific advantages and disadvantages. Major differences lie in the technology readiness level (TRL), the ability to handle different cell chemistries (robustness), the recycling efficiencies and the quality and purity of material output of the respective recycling pathways (Chen et al. 2019; Harper et al. 2019; Heimes et al. 2021; Elwert et al. 2016; Velázquez-Martínez et al. 2019). The different technologies can be roughly separated into 3 process types as depicted in figure 4 (Glöser-Chahoud et al. 2021).

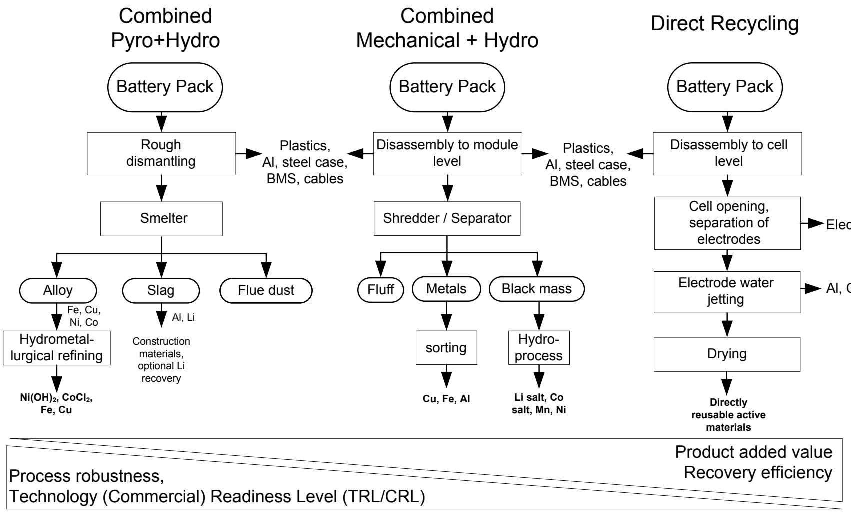

Fig. 4: Recycling process schemes
Source: Glöser-Chahoud et al. 2021, based on Kurz et al. 2021, Elwert et al. 2016

First, there are processes using pyrometallurgical treatment of end-of-life batteries. In these processes, after a rough disassembling to a module level, the entire module is melted down in a furnace. The molten metal fraction may either be used as alloying material in metal production (e.g. for cobalt and nickel containing high performance alloys) or the different metals may be separated by subsequent hydrometallurgical treatment. The entire process usually seeks to recycle the high value cathode materials such as nickel and cobalt as well as copper, while light metals like aluminium or lithium are usually lost or are difficult to recover in battery grade quality. Also graphite, plastics and the electrolyte are simply burnt during the pyrometallurgical process.

For the recycling of lithium-ion batteries, different pathways are being discussed that can be roughly separated into three process types.

A more efficient way of end-of-life battery treatment in terms of recycling efficiency is the combined mechanical and hydrometallurgical treatment. Here, battery packs are disassembled to module level, which allows for a better mechanical separation right at the beginning of the process. Subsequently, all that has not already been sorted out in this first step is shredded and further sorted apart using a series of physical-mechanical separation steps. The black mass (active electrode material) is finally treated in a hydrometallurgical process (Heimes et al. 2021). In advanced approaches of this type, recycling efficiency rates of over 90 percent can be achieved, and all metals, but also graphite, plastics and the electrolyte can be separated and may be reused as secondary materials (not necessarily within battery production) (Düsenfeld 2022).

Pyrometallurgical processing has a rather low recycling efficiency, but should remain relevant to deal with the high variety and heterogeneity of batteries from electronics, smaller vehicles or e-bikes.

Recent research and process development focuses on the direct recycling of active materials. The aim here is to have a very precise separation of active materials from the electrodes to enable their direct reuse in cell production. To this end, a detailed disassembling to the cell level and a cell opening process is necessary to separate the electrode foils covered with the black mass (active materials) without contamination. While the direct reuse of active materials would be the most resource efficient solution, one has to keep in mind that cell chemistries and active materials are continuously modified and improved. It is therefore questionable if 10 years old active materials will be suitable for future cell production. That is why the direct recycling processes seems particularly relevant for (gigafactory) production waste or early returns, e.g. from damaged vehicles. Nonetheless, a more detailed and partly automated disassembling of obsolete battery systems may contribute to higher recycling efficiencies no matter which subsequent processing route is followed.

The more efficient mechanical and hydrometallurgical processes will be used for the treatment of larger traction batteries from battery-electric vehicles or stationary storage systems.

Even if pyrometallurgical processing scores rather mediocre in terms of recycling efficiency, it is expected that it will remain relevant in terms of being able to deal with the high volume, variety and heterogeneity of general end-of-life battery flows from electronics, smaller vehicles or e-bikes. At the same time, the more efficient mechanical and hydrometallurgical processes will be used for the treatment of larger traction batteries from battery electric vehicles or stationary storage systems.

05 What do we want to achieve through recycling? Some trade-offs

When it comes to recycling, it would of course be ideal if all the battery's raw materials could be fully recovered in a safe and economical process that does not require too much energy or materials. As the previous chapter shows, reality does not fulfill this theoretical ideal. Instead, none of the existing battery recycling processes can achieve a near-perfect circularity at low economic and energy cost. On a more general level, there are trade-offs that force us to ask the following question: what exactly do we want to achieve through battery recycling?

When it comes to battery recycling, there are trade-offs that force us to ask the following question: what exactly do we want to achieve through battery recycling?

First, there is a striking connection between battery chemistry and the economics of recycling (Heimes et al 2021). Recycling is economical when the value of the recovered raw materials allows the process to operate profitably. Currently, the most valuable battery ingredient is the cathode metal cobalt, so, in terms of the economics of the recycling process, high cobalt contents are desirable. However, cobalt is also the battery ingredient that has the highest level of criticality (see Chapter 8), along with significant environmental and social issues associated with its extraction. This interrelationship is reflected on the production side: the materials that make battery recycling profitable also make battery production expensive. To put it bluntly, one could say: the decision is between batteries that are cheap to produce and batteries that are profitable to recycle.

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Now, the economic viability of the recycling process is in turn dependent on political framework conditions. These affect, through labor and environmental protection regulations as well as specifications on recycling quotas, the cost of the recycling process, but also possible sources of income for recycling companies. If recycling is a legal obligation, the market prices for raw materials are no longer the central factor for recycling profitability. This means: the recycling of batteries can become economically viable through appropriate regulation, even if the recovered raw materials themselves do not have a sufficiently high intrinsic value. Various national and transnational regulations follow this path of specifying recycling quotas for batteries (see chapter 7 for the EU example). Here, again, it is crucial to be clear about the purpose of recycling and to set corresponding priorities. One reason for this is that regulation can also have undesirable side effects that undermine the sustainability of the overall system of battery use. A second reason is that recycling itself does not come for free in terms of energy and resources.

The economic viability of the recycling process is in turn dependent on political framework conditions.

Therefore, the question must be answered as to what is actually worth recycling. The battery chemistries that have dominated up to now (NMC, NCA, etc.) are based on raw materials that have medium to high criticality values, that are traded at relatively high prices and that would represent problematic materials as waste. In contrast, the raw materials in iron phosphate, which play a central role in LFP chemistry, are 'everyday materials' that have no or at most low criticality, are relatively inexpensive, and are less harmful compared to other common battery ingredients. Considering this kind of differentiation may lead to the result that the complete recovery of all battery ingredients is not worthwhile for all battery chemistries—not only financially, but also in terms of energy expenditure and criticality (or lack of). And it opens the mind to the fact that recycling is a key, but not the only, way to address the resource and waste issues associated with the battery boom.

The complete recovery of all battery ingredients might not be worthwhile for all battery types—not only financially, but also in terms of energy expenditure and criticality (or lack of).

Another important factor has already been mentioned: longevity. Batteries that live longer create less need for replacement, less recycling requirements, and ultimately less waste. In addition, there are other battery properties that can also play an important role for a more sustainable battery use. True fast-charging capability and deep discharge resistance are such properties. When car manufacturers equip their vehicles with large-dimension batteries, it is not least because conventional battery technologies can only be fast-charged within a limited charging corridor (at most between charge levels of 20-80 percent) and because they must always be charged to a certain degree: otherwise the battery chemistry would be irreversibly damaged (Dusseldorp et al. 2021). The use of improved battery technology could help avoid this oversizing—and thus also significantly reduce the raw material and energy requirements during production as well as the recycling requirements at the end of the battery's life.

Besides recycling, there are other approaches to address the resource and waste issues associated with the battery boom. Longevity and other battery properties like deep discharge resistance can also play an important role here.

Another trade-off becomes apparent when we broaden our view by looking beyond the recycling plant: at the collection and recycling infrastructure. When analyzing the cost structure of battery recycling, one concludes that the acquisition, storage and transportation of obsolete batteries play a significant role (Sattar et al. 2020). It is therefore highly important to keep transportation costs low. On the other hand, classical recycling processes (hydro- and pyrometallurgical processing) as common industrial approaches are expected to take advantage of economies of scale with increasing capacities. However, large capacity recycling facilities increase the transportation distances and, therefore, the transportation costs and their environmental footprints. As end-of-life battery treatment always includes disassembly, and battery disassembling enables an early separation of specific battery components such as modules or cells, it might be reasonable to have

Another trade-off is between decentralized plants that minimize transport costs and centralized plants with economies of scale in the recycling processes.

more decentralized disassembly facilities (spokes) for condensing specific waste fractions, while subsequent recycling takes place in large recycling facilities (hubs).

Such a two stage hub-and-spoke system might also be reasonable regarding economies of scale, as the capacity degression effect seems to be lower for disassembly units as compared to recycling processes (see figure 5). This is mainly because battery disassembly lines have limited capacity, therefore an increase in recycling volume would translate into parallelization of different disassembly lines. Hence, a two stage disassembly and recycling network could combine the advantages of decentralized treatment regarding transportation costs and distances with the positive effect of economies of scale for recycling processes. The concept of such a take-back network is depicted in figure 6.

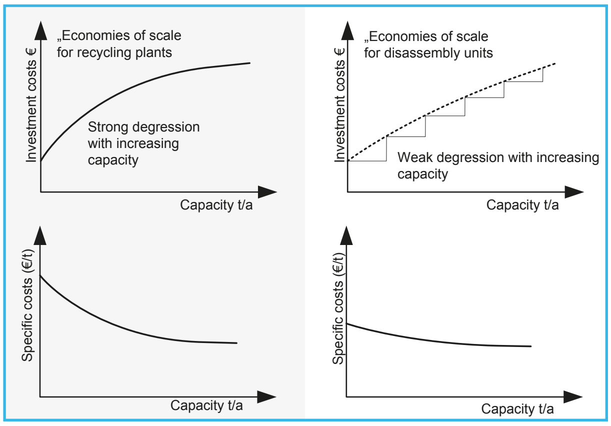

Fig. 5: Expected economies of scale for recycling and disassembly units
Source: own representation

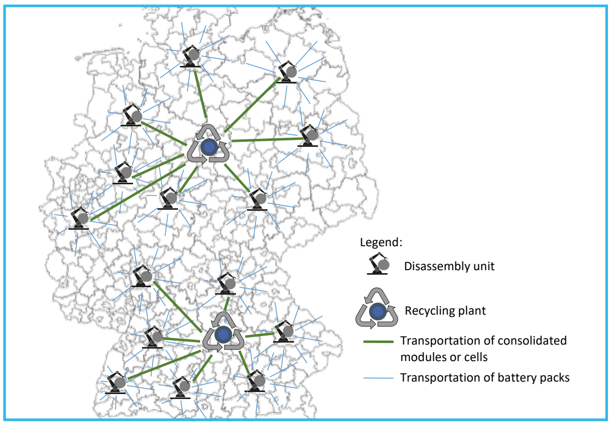

Fig. 6: Two stage reverse logistics network
Source: own representation

This brief overview shows that we need to broaden our perspective on battery recycling when it comes to realizing an overall sustainability-oriented use of batteries for the energy transition. In the end, it is not just about high recycling rates (without, for example, paying any attention to the battery technologies put on the market), but about finding a mix of suitable battery technologies and recycling approaches that meet the requirements of sustainable development as a whole.

In the end, it is not just about high recycling rates, but about finding a mix of suitable battery technologies and recycling approaches that meet the requirements of sustainable development as a whole.

06 Improving the recyclability of lithium-ion batteries

The recycling of lithium-ion batteries is still in its infancy.

Lithium-ion batteries are a comparatively young battery technology. They have become a mass market only in the last two decades. Against this background, it is easy to explain why there is no established recycling industry for them so far. In fact, there is not even reliable data available on the first step of recycling: the collection of used batteries. It is estimated that the collection rate of lithium-ion batteries in the EU is only around 10 percent (Wahlström et al. 2019). This is partly because lithium-ion batteries are often built-in batteries which cannot be disposed of separately by users. Currently, lithium element from waste batteries is not widely recovered in the EU because it is considered to be economically disadvantageous compared to lithium from primary sources (EP 2022). However, numerous projects and initiatives are looking to increase lithium recovery and refining.

This lack of recycling is no longer acceptable, not least because a large number of waste fires are caused by improperly disposed lithium-ion batteries.

The current situation, nevertheless, is not acceptable from a sustainability perspective. The electric transportation sector is rapidly growing, and current recycling infrastructure is not keeping up. Valuable raw materials are at risk of being lost and large amounts of problematic waste could be produced. This is particularly worrying considering the growth projections of the battery market. Geopolitical dependencies as unveiled in the Russian war against Ukraine put additional pressure on the recycling issue. In addition, there are increasing media reports of fires at disposal facilities caused by improperly disposed lithium-ion batteries. It is estimated that around 48 percent of all waste fires occurring each year in the UK are caused by lithium-ion batteries, costing the economy over 150 million pounds annually (Neumann et al. 2022). Against this background, it is clear that we urgently need an effective recycling economy for lithium-ion batteries.

Effective recycling systems are already established for other battery types, lead-acid batteries being the most prominent example.

Yet effective recycling systems are already established for other battery types that have been on the market for a longer time. Lead-acid batteries are certainly the most prominent example here. They were invented in the 1850s, that is before the commercial distribution of electric power which came about in 1882. Nevertheless they happen to be today's most successfully recycled commodity item. Lead batteries are almost everywhere in society. They are used as starter batteries in cars, traction batteries (especially in forklifts), backup power including for medical equipment and emergency lighting, and in stationary storage systems, including renewable energy storage. The European Parliament assumes that 99 percent of all automotive lead-acid batteries in the EU are actually collected and recycled, with recovery rates for lead exceeding 97 percent in most Member States (EP 2022). The overall recycling efficiency, which also covers the other components of the batteries in addition to lead, is estimated at between 70 and over 90 percent in almost all EU member states (Eurostat 2021). In principle, lead-acid batteries are considered almost 100 percent recyclable with today's technology.

How is it that something invented in the 1850s, before global warming, recycling and the circular economy had entered the mainstream, become today's best example of circularity and recycling efficiency? Firstly, all lead-acid batteries have the same basic chemistry. Although each manufacturer uses their own secret recipe in terms of the molecular composition of the battery-active materials (the so-called 'battery paste'), the chemical identity of the materials is more or less the same: lead and sulphuric acid are the essential ingredients, while minor differences such as the separator material do not impact the end-of-life separation or recycling steps. Secondly, as mentioned above, mechanical disassembly and physical separation of the component parts is quite simple, not least because lead-acid batteries are highly standardised: the way they are constructed has not changed significantly over the decades. After mechanical crushing of the batteries in a hammer mill (or similar), the plastic component (mainly the casing) floats in water, the lead burden sinks, and the electrolyte dissolves in water. Thirdly, there are economic reasons: lead, which makes up around 60 percent of batteries by weight, has a high material value, which makes recycling lucrative. Finally, an effective take-back system has long been established which ensures that almost all used lead-acid batteries are actually sent for recycling. All of this allowed for streamlining, automation (to a degree) and scaling up of recycling technologies: turning a battery of the 1850s into the 21st century champion of recycling.

The factors that facilitate the recycling of lead-acid batteries are not present in the case of lithium-ion batteries.

Compared to this, common lithium-ion batteries have a number of disadvantages for effective recycling (figure 7): there is not just one type of lithium-ion battery on the market, but different cell chemistries that differ especially in the cathode materials used (mainly lithium cobalt oxide (LCO), lithium nickel cobalt aluminium oxide (NCA), lithium nickel manganese cobalt oxide (NMC), and lithium iron phosphate (LFP)). Moreover, these chemistries continue to change and to adapt. For example, lithium manganese iron phosphate is currently in the news, lithium sulphur and other competing technologies are in development, and solid-state lithium battery chemistries are also looking to enter the mainstream. There is also hardly any standardization in terms of construction, but three basic types of battery cells—pouch, cylindrical and prismatic cells—that can be assembled in a wide variety of ways to form battery modules and packs. The ingredients only partly have a high material value, with major differences between the different cell chemistries. And effective take-back systems have so far only been set up for parts of the market. In addition, conventional lithium-ion batteries place particularly high demands on transport and occupational safety due to their flammability and explosion hazard. All in all, these are challenging conditions for effective and economical recycling.

	Lead-acid batteries	*Lithium-ion batteries*
Basic chemistry	uniform	very diverse
Disassembly	simple	difficult
Standardisation	high	low
Take-back systems	established	emerging

Fig. 7: Comparison of recycling of lead-acid batteries and lithium-ion batteries

However, some success factors could be transferred to the recycling of lithium-ion batteries, e.g. standardization—at least within certain application fields.

Against this background, we ask whether there are any success factors from lead-acid battery recycling that can be transferred to lithium-ion batteries. Let's start with standardization: the number of fields of application for lithium-ion batteries is immensely higher, which is why standardization is much more difficult here. Nevertheless, it could be increased to a certain extent, for example within individual fields of application such as electromobility or power tools. This would, of course, require agreements between the manufacturers or political guidelines. Moreover, there are new information technology approaches that could compensate for the disadvantage of battery variability to some extent. If batteries were to carry instructions (for example in the form of QR codes) on how to disassemble them, this could enable streamlining of the end-of-life—for example, automatic decisions could be taken in terms of the recycling path or disassembly processes deployed. The same applies to the availability of information from the battery management system (STABL 2021).

Changing consumer demands may lead to a thinning out of the current diversity in battery chemistries. Viewed in this way, consumer behavior may prove complementary to standardization.

What about the field of cell chemistry? Would it be possible to reduce the variety of chemistries used, and thus also the complexity of battery recycling? The types of lithium-ion batteries mentioned above differ considerably in their performance parameters and costs. Depending on the application, appropriate cell chemistries are used—which means that there are (potentially good) reasons for using different cell chemistries. For example, NMC batteries are preferred in applications for which high energy density is desired, while LFP batteries are preferred when cost and safety considerations are key. This means, conversely, that changing consumer demands may lead to shifts in the proportions of battery chemistries used: if safety, cost or resource efficiency play a more important role in future consumption decisions, we could expect a reduction or elimination of less sustainable battery chemistries and thus a thinning out of battery diversity. Viewed in this way, consumer behaviour may prove complementary to standardization.

The 'design for recycling' approach includes construction methods for battery cells, modules and packs which allow batteries to be recycled as simply and as completely as possible at the end of their life.

In general, it would be best to have the recyclability of batteries in mind from the beginning of the development process and in a comprehensive manner. In addition to standardization, this 'design for recycling' approach also includes construction methods for battery cells, modules and packs which allow batteries to be recycled as simply and as completely as possible at the end of their life. Good mechanical disassembly at the beginning of the recycling process plays an important role here. The early separation of different battery components generally favours high recycling rates and qualities because, unlike in shredding, the components do not enter the downstream recycling steps together. Moreover, mechanical disassembly by design favours the usability of batteries in a second life—because here, too, batteries have to be disassembled so that cells or modules in good condition can be selected and brought together for new applications. Finally, the establishment of new take-back systems for lithium-ion batteries is crucial. Here, the development of good business models and forms of cooperation is a factor that can contribute significantly to improving the recycling economy.

Next generation batteries will have other recycling properties.

Although we seek to forecast what recycling of the future might look like, the batteries in question are those of the present—batteries that are already in the market today. What about battery technologies of the future and their recyclability? Solid-state batteries are being considered by many as a potential successor technology to today's lithium-ion batteries. These are characterized by a solid electrolyte and promise advantages in terms of safety, longevity and energy density. When it comes to recycling, there will also be significant differences between solid-state and conventional batteries. The most obvious difference is transport and work safety: in all-solid-state batteries, there is no liquid organic electrolyte. This has important implications because the liquid electrolyte in current lithium-ion batteries is not only flammable but often toxic (however, if in solid-state batteries a liquid electrolyte is used to mitigate ionic conductivity problems, this does not necessarily apply, Bates et al. 2022). Formation of highly corrosive hydrofluoric acid can also be avoided. On the other hand, depending on the specific cell chemistry, solid-state batteries may also pose new challenges for battery recycling in the future. Some solid-state cell chemistries contain metals that are not included in current battery chemistries, such as germanium, titanium or tin. These ingredients can hinder some of today's common recycling approaches (Neumann et al. 2022).

In all of this, it should be a matter of not repeating a central mistake from the past: not worrying about recycling until many years after the market launch of battery technologies. More than with earlier technologies, it is now foreseeable at an early stage that lithium-ion batteries will be produced in huge quantities in the future. Therefore, the development of batteries and the development of associated recycling technologies must be synchronized much more closely. Design for recycling right from the start—a requirement for battery development which cannot be ignored.

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07

Regulating recycling—Well-meant is not necessarily well done

It has already been mentioned that government regulation is a crucial factor for battery recycling. Collection quotas can ensure that a large proportion of batteries placed on the market are recycled at the end of their life. Recycling quotas can ensure that even battery ingredients with a low intrinsic value are recovered. In this way, regulation also affects the economics of recycling, raw material availability and prices, criticality of raw materials, and other facets of the battery economy.

Government regulation is a crucial factor for battery recycling.

The European Union is in the process of creating an ambitious legal framework for the sustainable use of batteries. This is likely to affect policy and debate beyond EU's borders, not least because the battery market is experiencing a global appeal. The new battery regulation is due to be adopted in 2022 and will replace the Battery Directive from 2006—and go significantly beyond it: for the first time, the entire life cycle of batteries will be covered, i. e. production, use and end-of-life. Among other things, the regulation sets minimum requirements for the durability and performance of industrial batteries and general-purpose portable batteries. Battery manufacturers will also be required to ensure compliance with sustainability criteria along the entire supply chain. And a so-called battery passport, as the first digital product passport at European level, is to bring together and make available important information along the life cycle of batteries (BMUV 2022).

The EU is developing a new battery regulation, a major focus of which will be recycling.

Battery recycling will be a focus of the new EU regulation. This starts with the requirement that portable batteries and batteries in light means of transport (LMT) must in the future be completely removable and replaceable by customers or independent suppliers. This, in combination with mandatory battery labelling, is a key prerequisite for high collection rates of end-of-life batteries and for safe recycling, but also for extending the life of the respective devices. The collection quotas are still subject to the ongoing trilogue negotiations between the EU Commission, Parliament, and Council. The latest proposal of the EU Council of Ministers prescribes mandatory collection rates of 45 percent from 2024 and 70 percent from 2030 for portable batteries and 54 percent from 2030 for LMT batteries (DUH et al. 2022).

This includes the requirement for complete removability of batteries from devices as well as collection and recycling rates.

Recycling quotas are another key component of the new EU battery regulation. On the one hand, recycling efficiencies are envisaged: for example, lead-acid batteries must be recycled at least 75 percent by weight by the beginning of 2025 and lithium-based batteries at

65 percent (three years later according to the Council's proposal). These quotas are to increase thereafter, in the case of lithium-based batteries to 70 percent by 2030 according to the Commission's proposal (70 percent by 2026 and 90 percent by 2030 according to the Parliament's proposal). In addition, there will be quotas for the recovery of individual ingredients: cobalt, copper, lead and nickel are to be recycled at 90 percent by 2026 and 95 percent by 2030 according to the Commission's proposal (two years later according to the Council's proposal). In the case of lithium, the proposals differ more: the Commission envisages 35 percent by 2026 and 70 percent by 2030, the Council the same percentages by 2028, while Parliament wants to set 70 percent by 2026 and 90 percent by 2030 (DUH et al. 2022).

> "In the EU, within the EU Batteries Directive (2006/66/EC), a specific 'collection rate' formula is given for portable batteries; no collection rate is required for automotive lead-based batteries.
>
> The collection rate is defined as: 'The weight of batteries collected in the current year divided by the average of the sum of the weight of batteries placed on the market in the current and two preceding years.' In this context, batteries 'placed on the market' refers to the sales volumes of batteries that producers are obliged to report.
>
> However, it is important to note that this methodology was set up for portable batteries and accumulators specifically; hence their use of an average of the three most recent years, corresponding to the lifecycle of portable batteries, which is around three years. […]
>
> In effect, we believe that this 'collection rate' methodology is not suitable for automotive batteries, due to both their longer life expectancy and their greater potential to cross national borders within the EU. Using the collection-rate methodology for automotive batteries would produce less-than-reliable results." (IHS Markit et al. 2014)

Background box 2: Uncertain cost development for new and second-life batteries

Finally, the new battery directive will also set quotas for the use of raw materials derived from recycling ('secondary raw materials') in the production of new batteries. In the opinion of the Commission, this "would encourage market players to invest in recycling technologies that would otherwise not be developed because they are not cost-competitive against the production of primary raw materials" (EU 2020). Regarding these quotas, the proposals of the three EU institutions agree in the numbers (whereas they do not agree on which

The new battery directive will also set quotas for the use of raw materials derived from recycling ('secondary raw materials') in the production of new batteries.

battery types the specifications should apply to at all): 85 percent for lead, 12 percent for cobalt, 4 percent for nickel and also 4 percent for lithium from 2030, and 20 percent for cobalt, 12 percent for nickel and 10 percent for lithium from 2035. This can also include secondary raw materials derived from the recycling of production waste, which in the case of lithium-ion batteries can be a considerable amount. In view of this, NGOs are calling for only recycled material derived from post-consumer waste batteries to be considered (DUH et al. 2022).

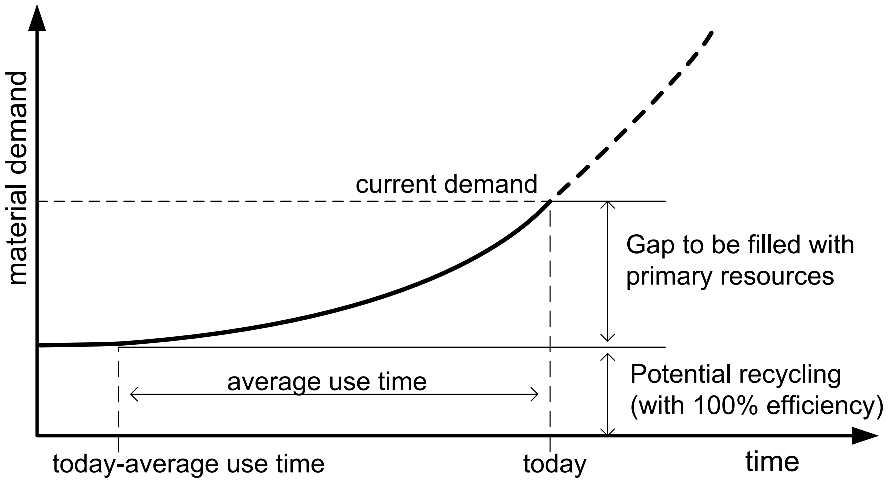

Fig. 8: Availability of end-of-life material flows in emerging markets and the potential contribution of secondary materials to overall supply. As we have a strong increase in the demand for battery raw materials, the current supply situation is weakly influenced by recycling materials from end-of-life batteries. Source: own representation

It is doubtful whether all the selected measures are suitable for achieving the set goals. For example, quotas on recycled content could provide an incentive to produce short-lived batteries.

The regulatory system outlined here, whatever its details, is considered an important step towards a sustainable battery economy. However, it may be questioned whether all the selected measures are suitable for achieving the set goals. For example, it is worth taking a closer look at the quotas on recycled content and asking what developments they are likely to entail. The measure should indeed encourage investments in recycling technologies, as the Commission suggests. But at the same time, it could provide an incentive to produce short-lived batteries. In a growth market, as it is predicted for at least the next decade, the volume of end-of-life batteries lags far behind the volume of new batteries entering the market at any given time (see figure 8). As the share of conventional old vehicles being exported to other (developing) countries outside of the EU is high, it is reasonable to also assume a certain leakage of end-of-life batteries through used electric vehicle exports. Hence, the only way to achieve the quotas might be to rely on batteries with a relatively short lifespan. Longevity, however, is a very central factor for sustainability in batteries. All other things being equal, it reduces the demand for raw materials and energy over the life cycle of a battery application, leads to lower resource requirements and, last but not least, to fewer end-of-life batteries—with less need for recycling and landfill.

Recycling efficiency quotas should also be critically reflected.

Recycling efficiency quotas should also be critically reflected. Comparing lithium-ion batteries with different cell chemistries (such as NMC and LFP), the quotas seem to make very different sense: NMC batteries contain relatively large amounts of ingredients that have a high intrinsic value as well as a high criticality and that are at the same time harmful to the environment or health. The obligation to recycle a large proportion by weight of NMC batteries makes sense in view of this. LFP batteries, on the other hand, contain valuable and harmful ingredients to a much lesser extent. Iron and phosphate, the co-namers of this cell chemistry, are commonplace raw materials that, at least in many compounds, have comparatively harmless environmental and health effects. The benefit of a quota system for recycling efficiency appears to be considerably lower for such a battery type. The quota could indeed lead to a decrease in the comparative price advantage of LFP cells compared to cobalt- or manganese-containing cell chemistries, whereas LFP chemistry tends to bring sustainability advantages, namely: longevity, resource conservation and, not least, greater application safety. And the longevity of the LFP system can in turn take pressure off the recycling system.

Against this background, it is worth considering whether a reorientation of the recycling focus would bring sustainability benefits. If the recycling of LFP batteries were to focus strongly on the contained lithium or other ingredients (such as nickel and graphite) that are worth recycling and not on other (quantitatively dominant, but neither critical nor harmful) ingredients, the recovery of this indeed critical raw material would tend to be simplified without any significant disadvantages.

08 Foresight in dealing with criticality

‘Critical raw materials are raw materials that are existentially important for national economies and whose security of supply is threatened at the same time.’ This definition sounds catchy, but what does it mean? How can we determine which raw materials are of existential importance for an economy and what factors could endanger their security of supply?

There are a variety of factors to assess when it comes to the supply risk of any raw material.

While the basic understanding of criticality formulated at the beginning has changed little since the 1930s, the factors used to assess economic importance and supply risk have become much more diverse over the decades. Initially, the degree of import dependency was the only factor considered to assess the supply risk. Since the 1980s at the latest, several further factors are considered: the concentration of raw material production at country level (see figure 9 for the case of lithium-ion batteries), the political stability of the producing countries, the existence of alternative (e.g. domestic) sources of supply, substitution potential, recycling and savings potential, and the existence of strategic stocks. On the side of economic importance, too, a clear shift has become noticeable in recent decades: while earlier criticality debates focused on the availability of bulk raw materials for military applications, in recent years the focus has been primarily on the importance of raw materials for technological innovations and thus for the entire national economy (Gandenberger et al. 2012).

All of the relevant factors can change over time—sometimes gradually and predictably, sometimes abruptly and unexpectedly.

Now, all of the above factors can change over time. Since the purpose of criticality assessments is to avoid economically significant supply bottlenecks, it is important to anticipate these criticality dynamics— only then can countermeasures be deployed. Some changes in the criticality of raw materials are more gradual and predictable, but others are abrupt and unexpected. The global economic shifts resulting from the Russian war against Ukraine, for example, had not been foreseen at the beginning of 2022. Such low-probability, high-impact events called ‘wild cards’ in foresight studies are very difficult to deal with in criticality assessment. However, many developments can be better predicted with newer methods of dynamic criticality analysis (Glöser-Chahoud 2017).

In this context, the adaptability of demand and the development of material cycles have a considerable impact. The following example may illustrate this: the copper market is characterized by broad use. Especially in the construction sector, copper is used for a variety of building materials. At the same time, there is an abundance of alternative materials that can be used if there are spontaneous price effects or shortages due to, for example, conflicts, export restrictions or natural disasters. Due to its adaptability of demand, the construction sector thus represents an important buffer for managing bottlenecks in overall copper demand. A high recycling rate, which is already being implemented in Europe, also contributes to the reduction of supply risks in the case of copper. In contrast, there is no such buffer for technology metals such as tantalum, indium, rhodium and rare earths, which is why spontaneous events can lead to extreme price spikes with relatively little change in supply (Glöser-Chahoud 2017).

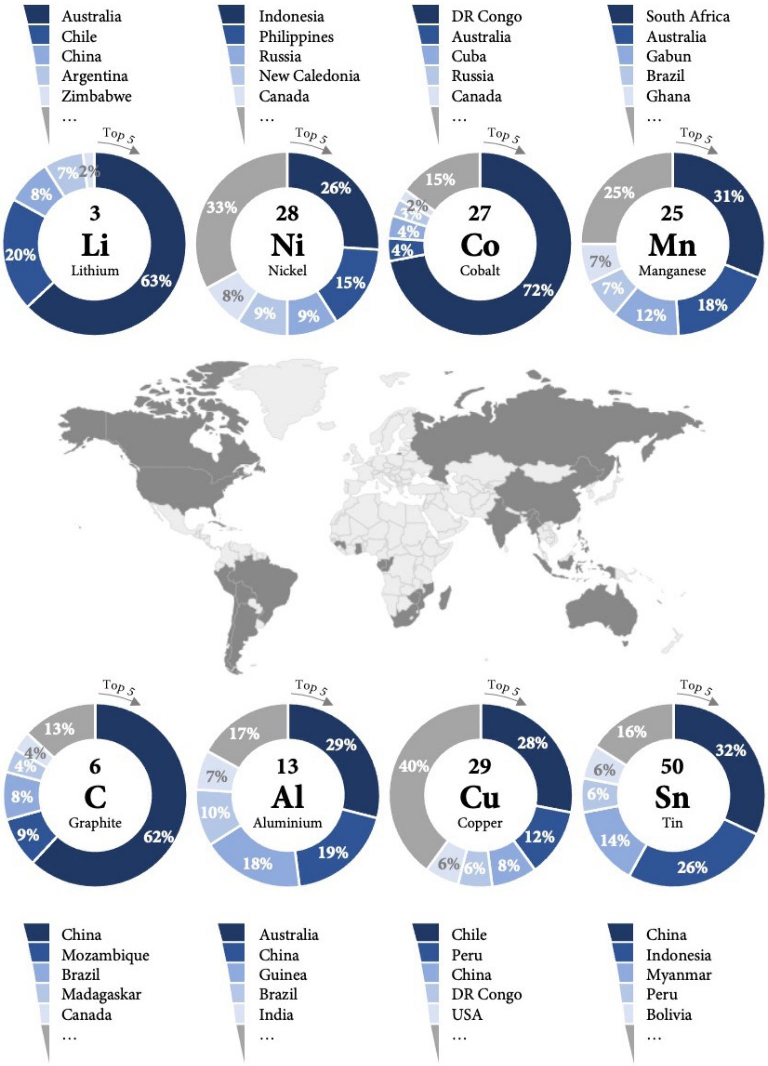

Fig. 8: Criticality of battery raw materials. The market for some key raw materials is dominated by only a few countries, including autocratically ruled states and those with little political stability.
Source: own representation based on GIZ & BGR (2021)

There are different approaches to dealing with criticality: besides recycling, we have sufficiency, substitution of raw materials and diversification of raw material sources.

When criticality analyses show the danger of looming raw material shortages, the question arises: what can we do about it? As shown above, recycling can play an important role in this area. Moreover, there are several other approaches that can help to avoid economic damage caused by raw material shortages. Sufficiency is one of these approaches. It aims to reduce the consumption of the goods or services in question—because less is 'sufficient', as the approach says in its wording. In the context of battery use, less can indeed be sufficient, for example in the field of electromobility (Dusseldorp et al. 2021). This shows that sufficiency and efficiency are closely linked; indeed, the use of batteries that are more efficient can also influence sufficiency by reducing consumption. Another suitable strategy is the substitution of the respective raw material. For example, the cobalt content in battery cell chemistries with particularly high specific energy has been steadily reduced for years, with the nickel-manganese-cobalt ratio changing from NMC 1:1:1 to 6:2:2 and subsequently 8:1:1. This strategy of course presupposes the technical possibility of substitution. It can also include a fundamental change in cell chemistry, for example a switch from NMC to LFP which avoids the use of cobalt altogether, but is accompanied by a lower specific energy. Therefore, when thinking about such changes, the impact on the use cases must be carefully weighed.

Diversifying sources of raw materials is another strategy to alleviate criticality. Here, again, the international sanctions against Russia and their consequences provide a good example: while Germany's dependence on Russian (pipeline) gas is extraordinarily high, the Benelux countries are much less dependent due to their own deposits and LNG terminals. New sources of supply are to reduce dependence on Russian gas in Germany as well. The degree to which dependence can be reduced in the long term depends, of course, on the stability of the newly acquired countries of origin, among other things. Finally, there is the strategy of expanding availability of the raw material concerned. This includes the identification and exploitation of new deposits as well as the improvement of accessibility of secondary raw materials via the waste and disposal industry. Lithium, for example, could also be exploited in considerable quantities in Germany. Projects on raw material deposits and their development in the Upper Rhine Rift point to attractive sources and are an example of such an expansion of availability. As mentioned above, recycling is another lever, especially for countries that rely on raw material imports and have large quantities of waste from end-of-life products.

From the various strategies for dealing with criticality, it becomes clear that the reduction of criticality is a joint task of research, politics and business, but that the responsibility must be assumed by each individual actor within their sphere of decision-making.

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10 Author profiles

Dr. phil. Marc Dusseldorp, Dipl.-Geoökol., has been a Senior Research Scientist at High Performance Battery Technology GmbH since January 2020. There, he is primarily concerned with issues relating to the sustainability of battery storage systems for the energy transition. Previously, he was employed at the Institute for Technology Assessment and Systems Analysis (ITAS) of KIT and at the Office of Technology Assessment at the German Bundestag since 2004, among others as coordinator of an international graduate school on energy futures. Since 2005, he has been a lecturer at KIT. Besides his employment, Marc Dusseldorp works as a freelance scientist. His work focuses on the methodology of sustainability assessments, as in his dissertation on the topic of 'Sustainability Goal Conflicts', as well as on sustainability transformation.

Dr. phil. Athan Fox, PhD in Chemistry, is the CEO and co-Founder of Silicon Fen tech companies Ever Resource and 17Cicada. At Ever Resource, he is mainly focused on the development, scaling up and commercialisation of circular economy innovation—with a specific focus on battery recycling. In May 2022, Ever Resource was awarded the Cambridge Independent 'Cleantech Company of the Year' award. Dr. Fox is also a Board Member at ALGOLiON, an Israeli business which is developing solutions that detect defects in lithium-ion batteries several days before a fire or explosion. He has previously held roles in Technology Transfer at Cambridge, UK, and has worked with publicly listed companies to bring next-generation circular economy innovation into the UK and European markets. He obtained his PhD at the University of Cambridge, UK, where he carried out research into organic and polymer chemistry.

Dr.-Ing. Simon Glöser-Chahoud is industrial engineer by training and holds a diploma degree from TU Berlin. He passed his PhD studies at TU Munich and TU Clausthal in the field of resources management. Before joining the Institute for Industrial Production (IIP) at Karlsruhe Institute of Technology (KIT), he has worked as a research associate and project manager for the Fraunhofer Institute for Systems and Innovation Research (Fraunhofer ISI). In addition to his role as a research group leader in the field of sustainable value chains, he is currently deputy director of the French-German Institute for Environmental Research at KIT. Simon Glöser-Chahoud has been appointed to the chair of corporate sustainability and environmental management at TU Bergakademie Freiberg, where he started his professorship in September 2022.

Dr. rer. pol. Sebastian Heinz, MSSc Human Geography, has been Chief Sales Officer of High Performance Battery Holding AG since June 2018. Previously, he was responsible for the Internet of Things (IoT) in business customer sales at Telekom Deutschland. With his dissertation on market development in a cooperative model, he developed an alternative strategy for the voluntary introduction of smart metering systems in Germany. The approaches developed therein are also suitable for the use of battery storage systems and thereby tap the potential of platform models for the energy industry. In 2018, he also founded the Institute for Innovation and Cooperation Management (Incoom), which specialises in business model development that are sustainable in every respect.

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