COMMISSIONED BY

The Federal Ministry of Education and Research

COUNCIL FOR TECHNOLOGICAL SOVEREIGNTY

Position Paper
Materials Research

Council for Technological Sovereignty

Disclaimer

This publication of the Council for Technological Sovereignty does not necessarily reflect the opinion of the BMBF .

The Council for Technological Sovereignty

The "Council for Technological Sovereignty" is an advisory body of the Federal Ministry of Education and Research (BMBF) and was convened in September 2021. It supports the ministry in identifying technology fields with long-term strategic importance. The council pools broad expertise from science and industry in key technologies and application fields. The members of the Council for Technological Sovereignty are:

Dr. Viola Bronsema	Dr. Stefan Joeres (Chair)
Prof. Dr. Oliver Falck	Prof. Dr. Elsa Kirchner
Prof. Dr. Svenja Falk	Prof. Dr.-Ing. Marion Merklein
Dr. Tim Gutheit	Prof. Dr.-Ing. Hans Dieter Schotten (Vice Chair)
Dr. Christina Hack (Vice Chair)	Prof. Dr. Andreas Tünnermann

Technological Sovereignty

Technological sovereignty is the ability to guarantee access to key technologies that are necessary to implement societal priorities and needs at all times.

This includes the use and further development of technologies and products, taking into consideration available resources and necessary services, making gaps visible and closing them where possible, and helping to set standards in global markets.

Technological sovereignty may also require the independent development of key technologies and technology-based innovations in Europe, and the establishment of own production capacities within the value networks, if this is necessary to maintain the state's ability to act or to avoid unilateral dependencies, taking into account changing geopolitical boundary conditions.

Making these changes requires the ability to understand and evaluate all relevant technological development and manufacturing processes, along with the aspiration to work on an equal footing with strategic partners.

Background of the paper

Material innovations are an essential building block in the (further) development of key technologies. With their recommendations for action, the Council for Technological Sovereignty provides input and suggestions for a new funding programme that focuses on materials research tailored to the needs of Germany and the European Union. Due to the breadth of the topic of materials research, individual aspects of this type of research go beyond the remit of the BMBF, and instead address the Federal Ministry of Economics and Climate Protection (BMWK) and other federal and state ministries.

Executive Summary

Materials research plays a central role in the development of new technologies, and therefore, makes a significant contribution to solving global challenges. From energy generation to medical technology and microelectronics, the targeted investigation and optimisation of materials offers immense potential for creating innovative and sustainable solutions, as well as reducing dependence on critical raw materials through the development of substitutes. In view of the increasing pressure to develop more sustainable and efficient products, materials research is indispensable for progress in science, industry and society. The development of novel materials that exhibit enhanced durability, ease of recycling, and reduced resource utilisation holds the potential to make a substantial contribution to economic and technological sovereignty, as well as to the mitigation of ecological footprints.

Germany's high dependence on raw material imports, particularly for critical materials such as rare earths, induces a need to develop new materials and more efficient recycling methods. While Europe is a pioneer in the recycling of many metals, the recycling rate for rare earths, for example, is low due to inefficient collection, high dismantling costs and a lack of recovery technologies. Overcoming these kinds of obstacles is a major focus of materials research, but there are big economic and technical challenges associated with doing so.

The scaling of innovative research findings into industrial volume production is essential for maintaining and expanding Germany as a production location, for which measures to promote cooperation are essential. Digitalisation is a key to accelerating the development of new materials. Simulations and digital twins in particular promise opportunities to precisely predict and optimise material behaviour and properties even before physical production. Whereas the integration of AI and machine learning into these processes, can potentially provide significant acceleration of new developments.

A comparison of international scientific publications shows that Germany is falling behind the USA and China in the field of materials research. The number of Chinese publications in particular is increasing rapidly. Although Germany is currently still in third place worldwide, the number of publications and students in materials science has been decreasing since approximately 2015. To ensure that this development does not lead to a significant weakening of Germany's innovative strength in the field of materials research in the long term, targeted measures to promote young talent and retain skilled labour are essential.

This position paper emphasises the need for increased support for materials research at national and international level and recommends five specific policy measures:

- In order to secure the required raw materials - without which research would not be possible in many areas - the development of sustainable material substitutes should be prioritised, to minimise dependence on imports and the associated supply risks.
- In product development, consideration of recycling and dismantling options should be encouraged, beginning with the design phase, in order to increase the recycling rate of critical materials and utilise resources more efficiently.
- Ecological aspects, and the recyclability of materials, should be integrated into research programmes, and regarded as important competitive factors, to ensure the marketability of material innovations.
- Scaling is a relevant aspect of material innovation, that should be explicitly considered and promoted, including through dedicated research.
- Interdisciplinary cooperation between materials science and computer science should be strengthened in university education, in order to train specialists with comprehensive expertise in the fields of simulation and materials research.

Table of contents

1. Materials research

Materials form the basis of almost all of our products. Materials research, as a field of research, deals with the scientific principles and technical implementation in the development of new materials, the investigation of material properties, and their potential applications. These aspects make materials research an important driver of technological innovation, by enabling new products with improved properties. The dependence of many products - from everyday goods to medical devices and building materials - on advances in materials research emphasises the fundamental role that material innovation plays in our lives. This dependence even extends to digital content, as the functionality of digital content relies on hardware, which in turn relies on advanced materials, such as semiconductors. Materials research therefore touches our lives more than is commonly perceived.

Due to this fundamental social role, materials research is of great economic and political importance. Many of the materials and raw materials used in our products currently have to be imported – often from countries outside the EU. This is oftentimes complicated by geopolitical conditions and ecological or social problems in local extraction and processing. Materials research has the potential to develop new types of materials that are similar enough to these previously used raw materials such that they can be used as substitutes or otherwise utilised as alternatives. This can reduce dependence on imports - an important factor for technological sovereignty.

This paper presents the current status of Germany's technological sovereignty in materials research and identifies policy options and recommendations for action. It is based on a hypothesis-guided analysis of the scientific and economic status of materials research in Germany and Europe. Due to the diversity of the topic, not all aspects of materials research can be dealt with exhaustively. Recommendations are therefore to be understood as overarching; individual sectors or subject areas may have specific, additional framework conditions that cannot necessarily be considered in this paper.

MATERIAL

Material is the summarising term for all natural and synthetic substances.

RAW MATERIAL

Raw material, in the superordinate sense, is a term for untreated products from the organic and inorganic material cycle of the earth, which usually have to be further processed before they can be utilised. In the narrower sense, a distinction is made between natural mineral products, industrial minerals, energy raw materials and metallic raw materials. Secondary raw materials are processed products from which valuable materials can be recovered through recycling after they have been used/utilised.

(Source: Spektrum.de)

BIO-BASED MATERIALS

The application of biotechnological processes and the utilisation of biogenic raw materials has a major impact on materials research and development. Bio-based materials derived from natural sources or obtained through microbial biosynthesis offer innovative approaches to the production of functional products with higher energy efficiency, and a lower environmental footprint, compared to conventional fossil-based raw materials. The integration of biotechnological processes into material production can not only reduce production costs, but can also promote the development of sustainable circular systems by increasing the efficiency of resources and energy, while minimising the environmental impact.

The topic of "bio-based materials" is dealt with in detail in a separate impulse paper by the Council for Technological Sovereignty.

2. Aspects of technological sovereignty

As outlined above, materials research plays a decisive role in Germany's technological sovereignty. It makes a significant contribution to reducing dependence on raw material imports by developing new, innovative materials, that can substitute scarce or hard-to-access raw materials. In section 2.1, technological sovereignty is discussed using the example of critical raw materials. At the same time, materials research has the potential to increase the recycling of products already in circulation and the materials they contain, thereby reusing valuable raw materials and increasing resource efficiency. The topic of recycling is examined in more detail in section 2.2. Materials form the physical basis for the realisation of all key technologies, which in turn are essential for economic and technological development. The availability of relevant materials is therefore of central importance for the production and use of modern technologies. The specific aspects of volume production are highlighted in section 0, and the role of digitalisation in section 2.4. However, the mere availability of materials is not the only decisive factor: knowledge about the development, production, and processing of these materials also plays an essential role. It is only through comprehensive expertise in these areas, that Germany can ensure its technological independence and maintain its global competitiveness. The issue of skilled labour is discussed in more detail in section 2.5.

2.1. Availability of raw materials

As a country with few natural resources, Germany is is dependent on the importation of (raw) materials. The EU has identified 31 raw materials[1] with high economic relevance and a high supply risk. For example, 93 % of magnesium required in the EU comes from China, and 98 % of the borate used in the EU comes from Turkey.[2,3]

Rare earth elements (REEs) are a group of 17 chemically similar metallic elements (15 lanthanides as well as scan dium and yttrium), and are in increasing demand - particularly due to the increased use of electrical and electronic components. In 2023, China was the world's largest producer and processor of REEs, accounting for 70 % of production and 90 % of processing, while Myanmar was also a major exporter of REEs to China.

The European Commission's "Study on the EU's list of Critical Raw Materials" from 2020 specifies the economic importance of 80 materials (based on the importance for end-user applications and the material's substitution options) and their supply risk (based on various factors that influence the risk of supplying the material, such as import reliability, political situation in the exporting countries, trade restrictions and agreements, etc.). InFigure 1, the materials are plotted according to these two criteria (top). For materials with a high supply risk, the share of recycled material in the total material used is also shown (bottom). This clearly illustrates the very low recycling rates in some cases, particularly for rare earths.

> **METHODS**
>
> The analyses presented here are based on hypothesis-based research. A wide range of sources are drawn upon, including patents, academic literature and various data sets as well as scientific studies on the areas of materials research, key technologies and technological sovereignty. The analyses are underpinned by reports from specialist journals, legal texts and EU Commission strategy papers.

The transition to a green, low-CO_2 economy is contingent on the utilisation of four rare earth elements in the context of permanent magnets: Praseodymium (Pr), Neodymium (Nd), Terbium (Tb) and Dysprosium (Dy). According to current figures from the International Energy Agency IEA[4] , around 60 % of these four rare earths are mined in China, a further 14 % in Myanmar, and 9 % in the USA. [5]

Moreover, these four REEs are almost exclusively processed (i.e. purified, refined, separated or concentrated) in China. The International Energy Agency (IEA) forecasts a decline in the share of the top three countries in production and refining for these four REEs. However, this diversification of production countries will be a long-term development.

In order to reduce dependencies on China and Myanmar in particular, material substitution would therefore be the only option.

However, substituting rare earths has so far been difficult, or even impossible. Particularly when specific material properties are required, there are often no known alternatives. Accordingly, there is, for example, a great need for research and development into new materials.[6] Greater material efficiency and improved recycling are also key levers that can be used to reduce the use of rare earths. This substantial, hitherto untapped reservoir of potential, must be harnessed in the future.[7]

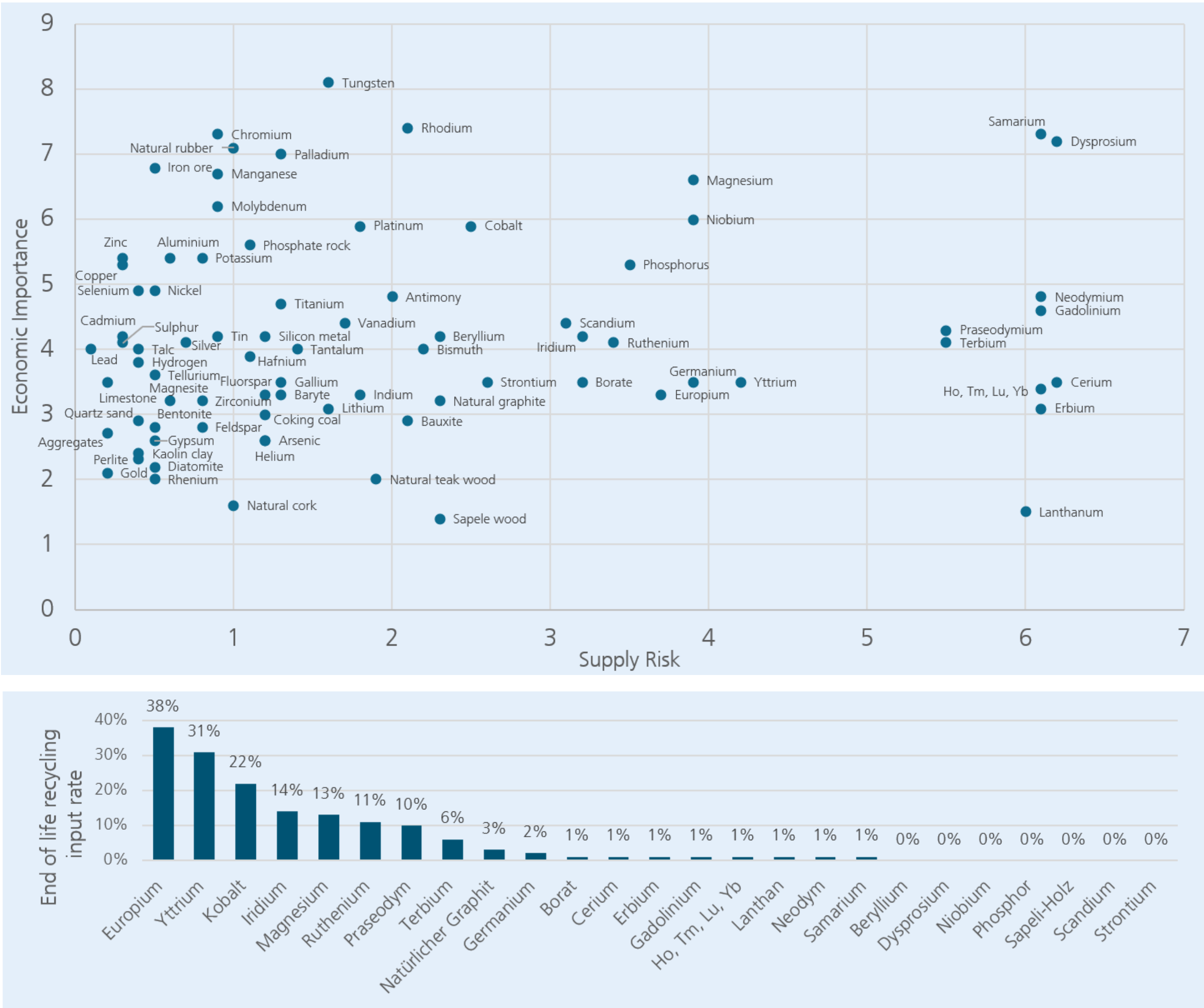

Figure 1 : Top: Supply risk and economic importance of materials according to the "Study on the EU's list of critical raw materials" (2020). Below: Contribution of recycling to covering material requirements (recycling utilisation rate) for the 25 materials with the highest supply risk.[8]

2.2. Recycling and sustainability

The use of secondary raw materials within the EU has already been greatly expanded in recent years. For example, according to the EU Commission, more than 50% of certain metals such as iron, zinc and platinum are recycled. These recycled materials in turn cover more than 25 % of EU consumption. In this respect, the EU can be said to be a global pioneer in the field of recycling. However, the recycling of rare earths from end-of-life (EOL) consumer goods or industrial waste is in the single-digit percentage range, as shown in the section 2.1. However, these materials are particularly needed for renewable energy technologies and high-tech applications.[9]

The barriers to recycling are manifold. For example, collection of unsorted products is inefficient, the dismantling of components to recover contained elements is costly, and there is a lack of cost-effective methods for recovery.[10,11,12,13] Other significant obstacles include the fact that the proportion of rare earth elements in many disposed products is small, and the low yields make it impossible to operate recycling plants economically.[14] For example, a hard drive may only contain a few grams of REE; some products even provide only a few milligrams.

Conventional recycling methods for rare earths require the use of hazardous substances such as hydrochloric acid and high amounts of thermal energy. Extensive research is being carried out in Japan (Tohoku University[15]), Europe (European Rare Earth (Magnet) Recycling Network[16]) and the United States (Critical Materials Institute[17]) to improve the recycling and reuse of rare earths.

The global circular material-use rate (CMUR), i.e. the proportion of material consumption worldwide that is covered by recycled materials, is estimated by the European

Environment Agency at 7.2%, with a decreasing trend. According to the European Environment Agency, the share of the circular economy in the European economy is currently (as of 2022) estimated at 11.5 % based on the CMUR metric. The EU Circular Economy Action Plan, adopted in March 2020 as part of the European Green Deal, aims to double the utilisation rate of recycled materials in the EU over the next ten years. Between 2010 and 2020, there was only an increase of one percentage point (from 10.5 % to 11.5 %).[18]

The recycling of metals and noble metals has great ecological and economic potential. Following the application of separation and sorting technologies, new recycling methods for noble metals are now being used in commercially operated biorefinery plants, where metals are recycled using natural biomass, in addition to traditional chemical, or electrochemical recovery processes.[19,20] However, one challenge for recycling companies, is that electrical appliances are rarely designed for recycling. The utilisation of reusable materials is associated with elevated financial expenditures. For example, devices powered by lithium-ion batteries are responsible for many fires in recycling plants and during collection processes, as they are often glued, encapsulated, or miniaturised, making them difficult to dismantle or unrecognisable as batteries.[21] Another prerequisite for metal recycling is correct disposal by private or commercial consumers.

In a highly regarded study, the International Resource Panel (IRP) of the United Nations Environment Programme (UNEP)[22] defines various metrics for metal recycling. The study covers 60 metals, with only a few exhibiting recycling rates above 50 % according to the three metrics. An end-of-life recycling rate (EOL-RR)[23] of over 50 % is only achieved for 18 metals. The recycled content (RC) reaches a rate of over 50% for only three metals, while the end-of-life recycling rate (OSR)[24] also exceeds this value for 13 metals. The report identifies the inefficiencies inherent in the collection and processing of metal-containing waste products, and the technical limitations of recycling processes. It also highlights the fact that primary materials are not recycled, despite their abundance and cost-effectiveness. These factors contribute to the unattractiveness of recycling from an economic perspective.

For 34 of the 60 elements analysed, end-of-life recycling rates are below 1%, even though they are crucial in technologies such as batteries for hybrid cars and wind turbines. According to the study, the low recycling rates are due to several factors, including inefficient product designs that make disassembly and recycling difficult, poor waste disposal practices and the habit of storing old electronic devices instead of recycling them.

In order to generate a market for sustainable materials and material substitutions, the European Union is currently implementing a number of regulations. For example, the "EU policy framework on biobased, biodegradable and compostable plastics" aims to promote the use and development of biobased plastics.[25,26,27] Another means of reducing emissions is the "Carbon Border Adjustment Mechanism" (CBAM), the pricing of imported CO_2 and products that have caused CO_2, so that the relocation of production abroad ("carbon leakage") is prevented. During a transitional period between 2023 and 2026, the CBAM will only apply to the import of certain goods and selected primary products whose production is carbon intensive and where the risk of carbon leakage is greatest. These are cement, iron and steel, aluminium, fertilisers, electricity and hydrogen.[28,29] In addition, the EU "Directive on packaging and packaging waste"[30] will be updated. This aims to reduce packaging waste and increase its reusability and recyclability, for example by stipulating design criteria and recycling percentages for packaging.[31] Other EU instruments include the "Circular Economy: Packaging and Packaging Waste Regulation[32] and the "European bioeconomy policy"[33] .

The objectives of the Green Deal in particular also have an impact on research policy at European level. The "Materials 2030 Manifesto" defines the strategic direction of European materials research to support the green and digital transformation. The EU initiative "Advanced Materials for Industrial Leadership" (AM4IL)[34] aims to establish Europe as a leading location for the development and application of advanced materials in industry and, in particular, to support the transition to more environmentally friendly, resource-efficient material technologies.

In line with European initiatives, the German government has developed a national circular economy strategy[35] with the aim of promoting the transition to a resource-conserving circular economy. The development of sustainable materials and technologies to extend the life cycles of products and close material loops is a key aspect of this strategy.

In Germany, plastic waste is almost completely reutilised, but over 60 % of it is used to generate energy, i.e. in waste incineration plants. This proportion has grown particularly strongly in the last 15-20 years and is almost entirely responsible for an increase in the recycling rate during this time. A particularly strong increase since 2005 is due to a change in the law, according to which landfilling waste is only permitted, if no other utilisation is possible.[36] Material utilisation, on the other hand, has only increased slightly (see*Figure* 2).

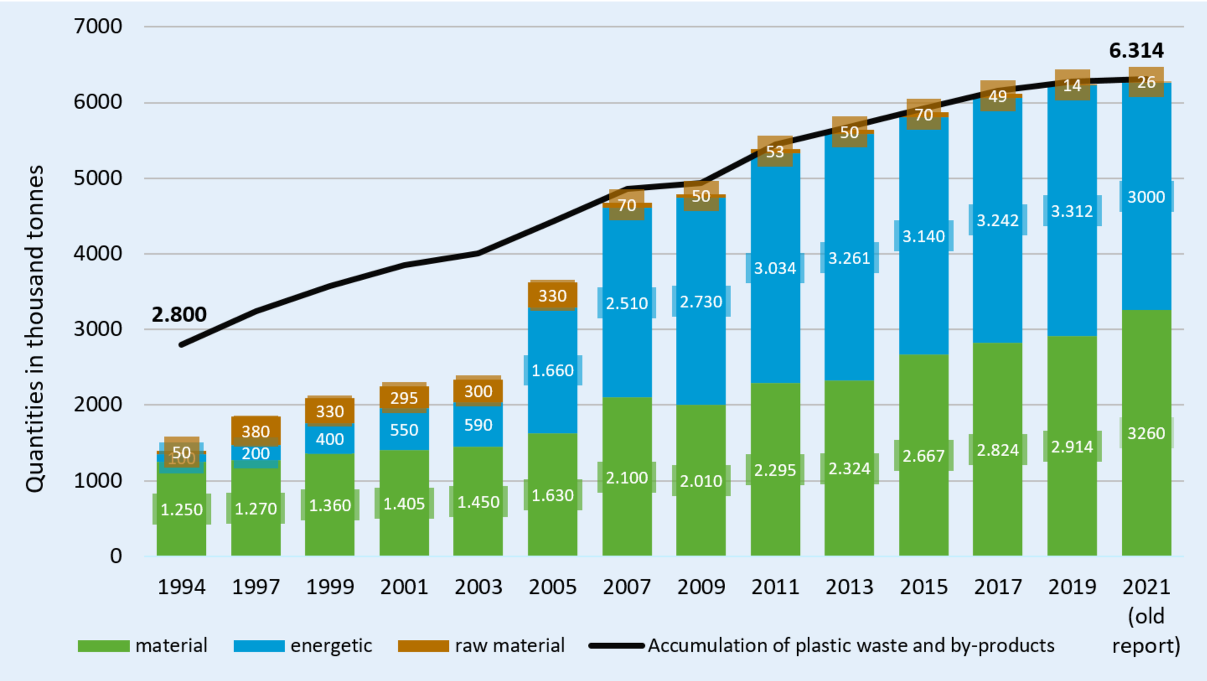

Figure 2: Development of plastic waste recycling. The illustration is based on data from CONVERSIO Market & Strategy GmbH, whereby the previous calculation method was also used for 2021, despite a change in the collection and calculation of the data from 2021 in order to ensure a consistent presentation. [37]

One particular difficulty with plastic recycling is the number of different materials with various properties. *Figure* 3 breaks down the plastics processed in Germany in 2021 by type, illustrating the problems that are exacerbated by the addition and mixing of plastics. Some types of plastic are only present in very small proportions, which makes recovery even more difficult. This often results in mixed recyclates of lower quality. At best, they are processed into products with lower quality requirements (downcycling).[38] For example, only 29 % of plastic waste from households is reused. The rate for industrial waste, which is usually unmixed and uncontaminated, is 38 %.[39]

Although the mechanical recycling of plastics is more sustainable than incineration, it is often associated with technical and economic limitations. For example, not all plastics can be recycled. This applies in particular to plastics that should no longer be put into circulation according to current standards, but are still used in older products. Chemical recycling would be a solution here, but is very energy-intensive.[40]

Biocatalytic recycling of fossil-based plastics is another option. A digital product passport, which lists exactly which materials are contained in a product, would simplify targeted recycling under certain circumstances (see also section 2.4).

2.3. Research for industrial usability

The “Innovationsindikator” (innovation indicator) of the Federation of German Industries (Bundesverband der Deutschen Industrie e. V., BDI)[41] shows that Germany is very well placed in the key technology "new materials and advanced materials". Germany ranks fifth here after Japan, Finland, South Korea and China, while the USA is in eleventh place.

Germany is one of the world's leading nations in basic research in materials science (see also section 2.5). Nevertheless, the successful commercialisation and scaling of innovations developed in research is associated with major challenges. Scaling effects also play an important role in the development of new feedstocks for materials: different challenges can arise depending on the scale under consideration. Examples of such effects can be found in bio-based materials, for example, where the production of certain products can result in residues and/or secondary components in the process that only become visible on a larger scale.

One example of the production of a raw material is bio-based aniline. Aniline is used for the production of polyurethane, and therefore, for many everyday products, and has so far primarily been obtained from crude oil. If scaling

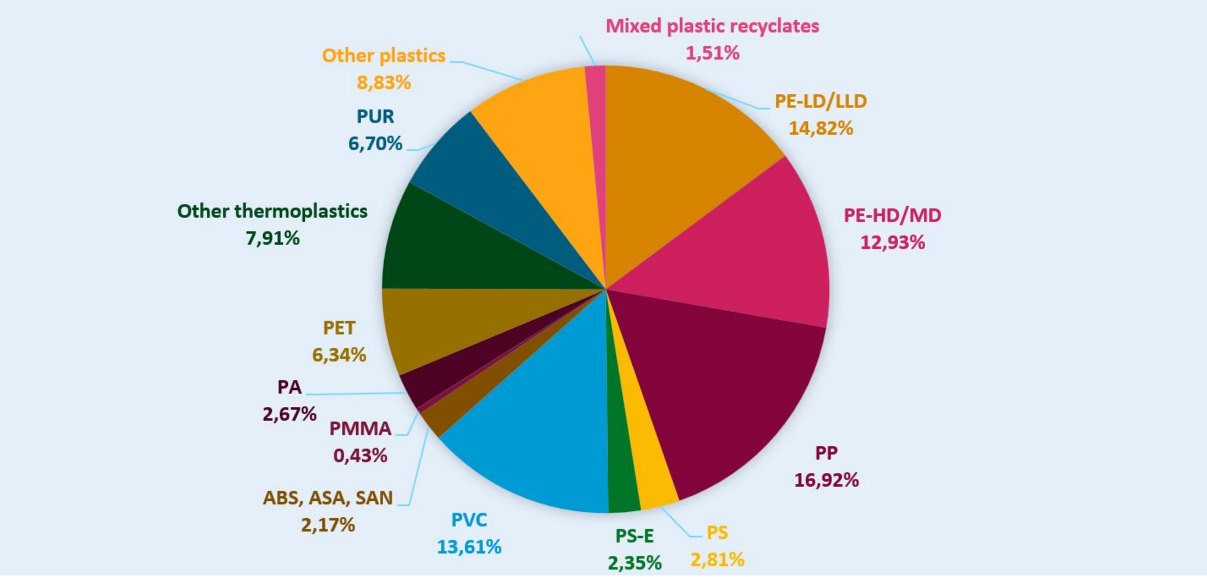

Figure 3: Share of plastic types in the volume of plastics processed in 2021 (virgin material and recyclates). Total quantity: 14.04 million tonnes.[42]

up to production levels is both technically and economically successful, it could also be produced from biomass in the future.[43]

The range of examples extends to applications in microelectronics, where the achievable yield of good chips per wafer is an essential competitive factor given the statistical sources of error in high-volume production, which are difficult to control. Research into scaling processes is, therefore, an important and necessary aspect of materials research.

2.4. Digital approaches in materials research

The simulation and modelling of materials and their properties is an increasingly important aspect of materials research. A text analysis of the relevant scientific literature shows a high relevance of these topics, which has steadily increased over the last 30 years. Around 60-70% of materials research publications contain relevant keywords, and publications from Germany do not deviate from this international trend.

A key aspect of modelling and simulation is information-led design and synthesis automation, which significantly accelerates the development process. By integrating advanced algorithms and machine learning processes, material properties can be precisely predicted and optimised before they are physically manufactured. This not only leads to a significant reduction in development time, but also to a more efficient use of resources. Digital twins of materials also allow flexible and versatile testing options in the development of components and products: The digital representations enable researchers to simulate and analyse the behaviour of materials in detail under various conditions. Since materials must be viewed as highly complex, multi-scale physical systems, whose form and function are interlinked at various levels - from the atomic to the macroscopic scale - the digital twin enables holistic analysis and optimisation.

General advances in machine learning and artificial intelligence also act as driving forces here, provided that AI methods can be adapted and utilised accordingly. For successful digitalised materials research and the use of simulation and AI, it is necessary that information about a material and its processing can be described, stored and processed digitally in a standardised way so that all digital workflows are compatible with each other. Decisive added value only arises when information can be securely exchanged between individual stages along the entire value chain. Preconditions for this are standardised and secure digital data infrastructures, and their coupling with industrial data spaces. This requires appropriate expertise in the form of specialists and experts. Retaining those specialists and experts is thus imperative.

2.5. Research and skilled labour

In an international comparison of scientific publications in the field of materials research (see*Figure 4*), the rapidly growing number of publications with Chinese participation is particularly striking. Since the beginning of the 2000s, China's share has grown disproportionately and in 2013 even overtook the USA, which is also very strongly represented. India is also recording strong growth in the number of publications in materials science and has been

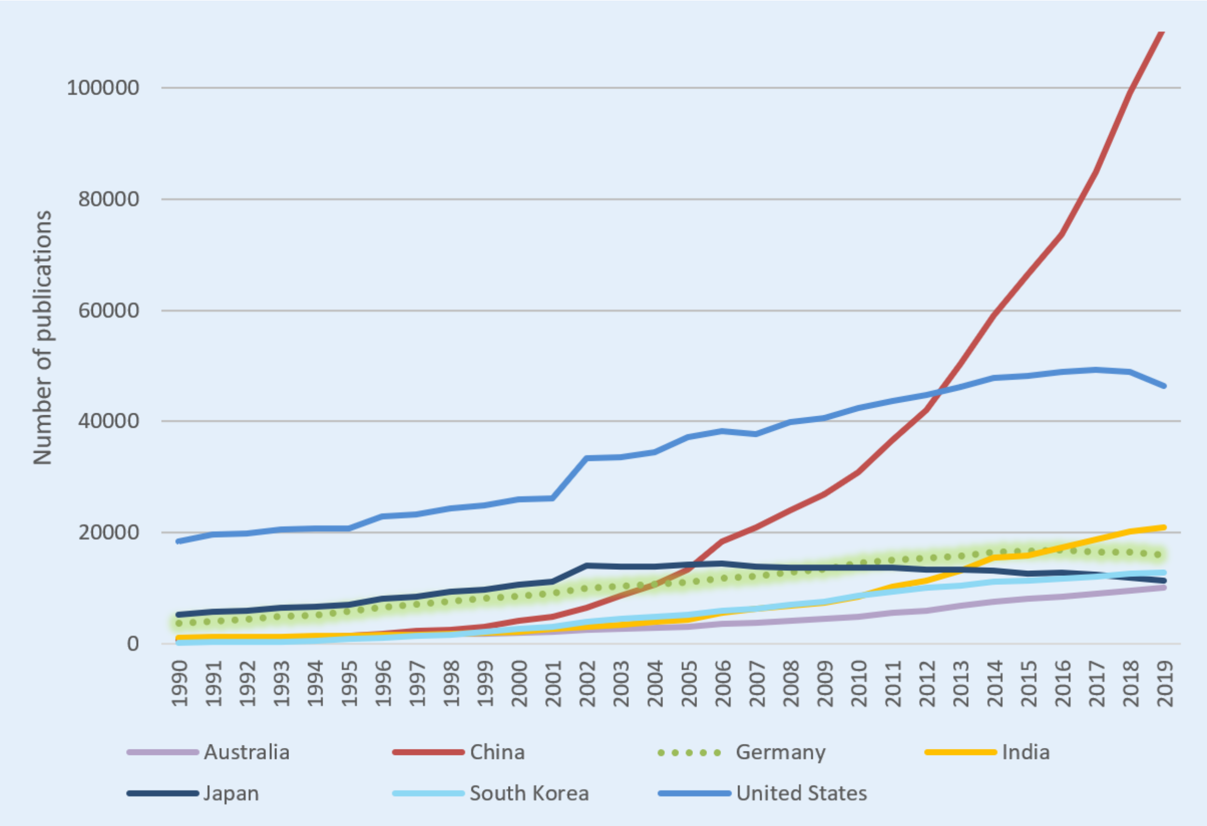

Figure 4: International comparison of scientific publications in the field of materials research. Number of publications with the respective participation of the countries listed (publications with at least 10 citations) Source: OpenAlex

in third place internationally in recent years. Germany follows in fourth place. Despite a rather weak dynamic, Germany is nonetheless ahead in a European comparison. A continuous increase in the volume of publications can also be observed in Australia and South Korea. In Germany, on the other hand, the number of scientific publications has been decreasing slightly since approximately 2015. The number of materials research publications is also stagnating or declining in other European countries.

At the same time, the number of students in the field of materials science in Germany has fallen continuously since around 2015, particularly in comparison to student numbers in engineering in general (see*Figure 5*). The rising student numbers in engineering are mainly due to the strong growth in computer science, while the numbers in the traditional engineering subjects are trending downwards.

A similar trend can also be observed in the number of staff at universities. *Figure 6* shows the relative development of full-time academic staff (e.g. professors, lecturers, research assistants) at German universities in the fields of materials science/materials engineering, computer science and engineering sciences as a whole. While the engineering sciences in general are developing very similarly to the average for all subjects, the increase in personnel since 2019 has been significantly above average in computer science and significantly below average in materials science.

This development harbours the risk of a negative spiral, if increasingly lower student and researcher numbers lead to fewer research results, and therefore fewer scientific publications, which further weakens Germany's position in international comparison.

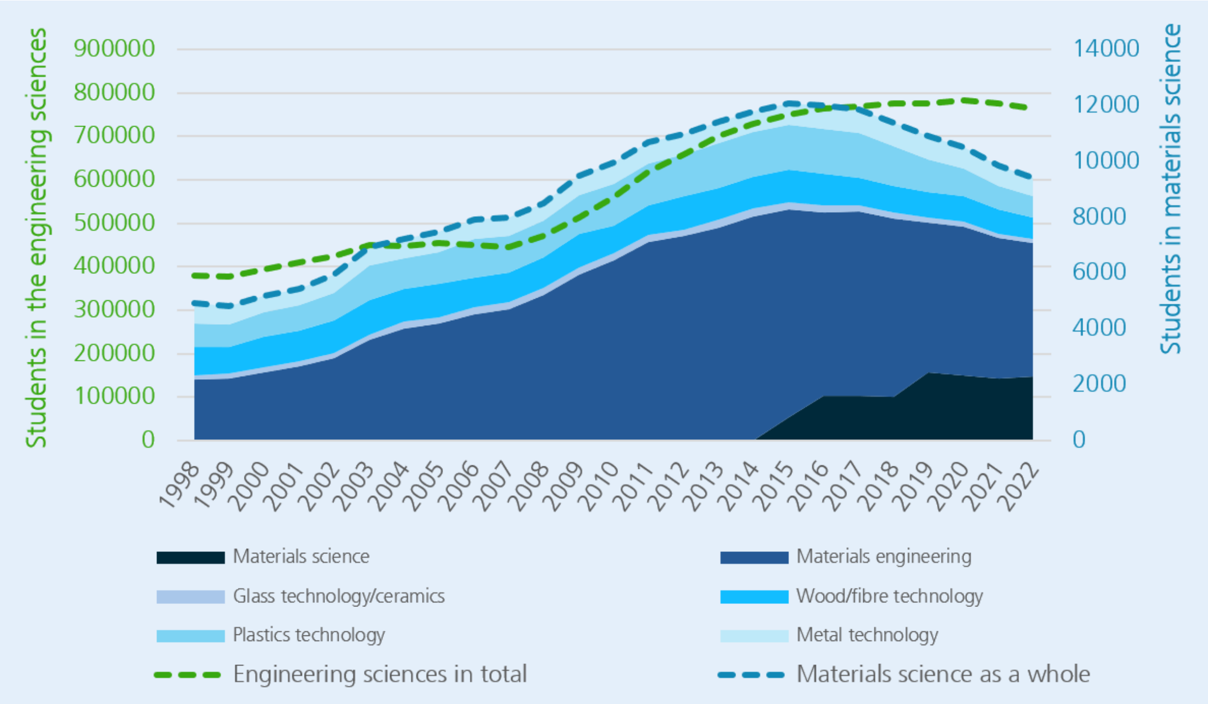

Figure 5: Number of students over time (material sciences broken down into subfields). [44]

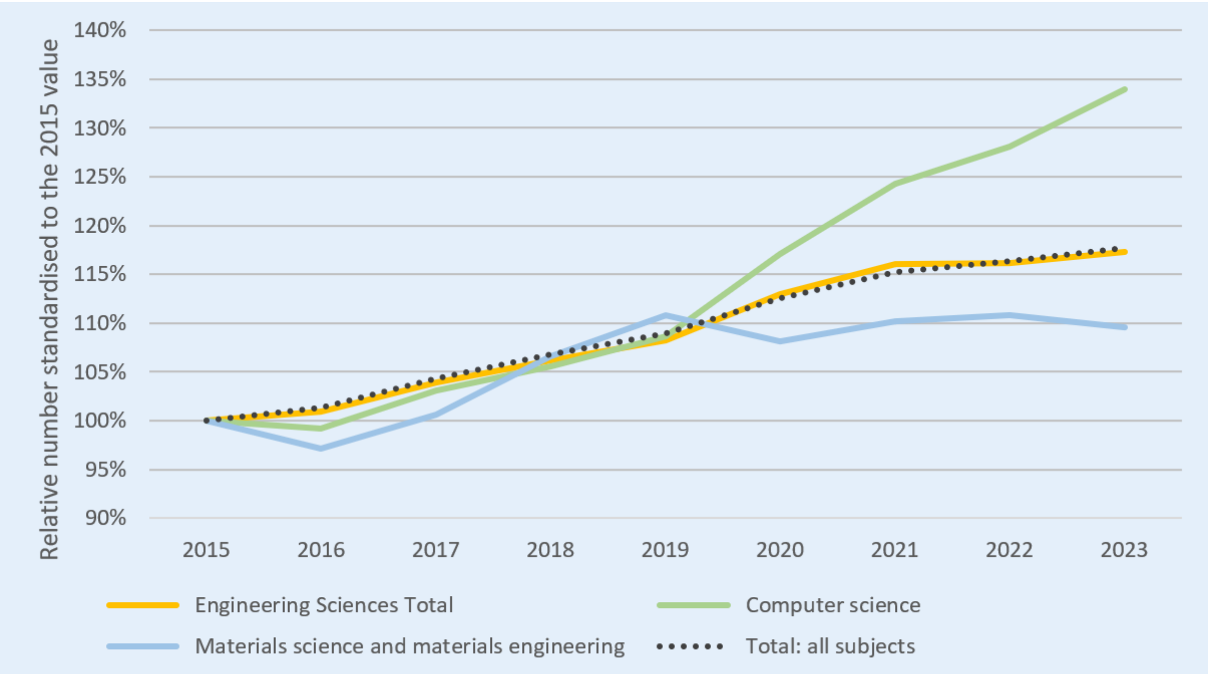

Figure 6: Development of full-time academic and artistic staff at universities in the subjects of materials science/materials engineering and computer science, compared to engineering sciences as a whole and all subjects at universities. The number of staff is standardised to the value in 2015.[45]

3. Recommendations for action

The analyses presented in the previous chapter highlight existing challenges in the field of materials research. From this, opportunities for action can be derived for those involved in public research funding, including the BMBF, as the largest public funder of materials research in Germany.

This position paper emphasises the need for increased support for materials research at national and international level and recommends five specific policy measures:

- In order to secure the required raw materials - without which research would not be possible in many areas - the development of sustainable material substitutes should be prioritised, to minimise dependence on imports and the associated supply risks.
- In product development, consideration of recycling and dismantling options should be encouraged, beginning with the design phase, in order to increase the recycling rate of critical materials and utilise resources more efficiently.
- Ecological aspects, and the recyclability of materials, should be integrated into research programmes, and regarded as important competitive factors, to ensure the marketability of material innovations.
- Scaling is a relevant aspect of material innovation, that should be explicitly considered and promoted, including through dedicated research.
- Interdisciplinary cooperation between materials science and computer science should be strengthened in university education, in order to train specialists with comprehensive expertise in the fields of simulation and materials research.

3.1. Securing required raw materials and developing sustainable material substitutes

As the analyses in section 2.1 show, German and European production in many key sectors is dependent on a large number of raw materials, operating resources and pre-processed materials imported from (non-European) countries. As*Figure 1* shows, for many materials, especially rare earths, high economic relevance goes hand-in-hand with a high supply risk. Recycling of these rare earths is only realised to a very limited extent. In addition to the resulting risks to technological sovereignty, the dependency on rare earth elements is often accompanied by other undesirable circumstances, such as environmental pollution, climate damage, humanitarian hardship or financial support for autocratic states. **In order to reduce dependencies on non-European countries and other undesirable side effects, the development of new materials should be a primary endeavour.** It would therefore be advisable to focus on **recyclability**, the use of **secondary materials** and the development of sustainable **material substitutes**. For this reason, **(raw) materials required in the future** should **be secured today**, if possible. Otherwise, research and development in many research areas will not be possible, as a wide variety of specific materials will be required.

The **European perspective** must play an important role in materials research due to **the availability of resources.** It must be incorporated in the sustainable production of materials of all kinds. The transnational creation of synergies within Europe is of crucial importance, and the necessary instruments should be evaluated from this perspective.

In addition, in materials research projects, the **availability of raw materials and possible risks and problems in the supply chains** should be **considered and documented at an early stage**, with long-term timeframes be considered. To this end, management of the amount of available raw materials should also be considered in the design of research programmes. It should also be noted that research must not be stopped if supply bottlenecks are suspected. Rather, it is important to consider these from the outset and – whenever possible – to define workarounds.

3.2. Recycling rates and dismantling feasibility

An important key to reducing import demands is **increasing the recycling rate of critical and raw materials**. *Figure 1* shows, raw materials such as rare earths, gallium or indium are currently being recycled only to a very limited extent, particularly in the high-tech and renewable energy sectors. In order to increase recycling rates, **the dismantling and recycling of products and goods should be already be considered during development and product design**. The analyses in section 2.2 show the need and the possibilities for increasing the circular use of materials.

In the case of material innovations, this relates in particular to the recyclability of the material itself or the recovery of raw materials. For entire products, **attention must be paid to the separability of the materials used**, for example by **avoiding non-separable compounds and sealants**. The example of plastics (see*Figure 2*) shows that a lack of separability often leads to incineration, and thus to an ineffective utilisation of waste. Material reuse should be prioritised here. **Dedicated research towards energy-efficient separation and recycling of materials** should be promoted. **Digital product passports** are also an important building block.

3.3. Ecological aspects and material diversity

Achieving **ecological goals** is an important mission of technological innovations. By **replacing conventional materials with more sustainable alternatives,** CO_2 for example, can be saved and waste reduced. The European Union is currently planning various measures to increase sustainability, such as a directive to reduce packaging waste, and a framework programme on bio-based, biodegradable and compostable plastics. These measures will establish the framework conditions the European industry, creating significant demand for sustainable material substitutes. This supports the UN's 17 Sustainable Development Goals, to which all member states are committed. Similarly, China has pledged to achieve carbon neutrality by 2060, with initiatives such as the Environmental Protection Law playing a key role in this effort. As a result, there is substantial potential for innovation and development in this area. At the same time, these **forthcoming regulations, and the most diverse endeavours to achieve sustainability,** must be **considered in the research and development of products.** Ecological aspects, such as the recyclability of products, will therefore also become a question of competitiveness.

Fine-grained adjustment of material properties by (permanently) changing the material itself – and the associated creation of a large variety of materials – **makes recycling more difficult**. By closely harmonising the usage and processing properties, costs can be saved and recyclability improved. Materials research should therefore focus on the **development of alternatives**, for example, through reversible, or temporary processes that do not restrict recyclability.

3.4. Scaling

New technological ideas and developments can only unfold their impact when they are put into practice. In materials research, many applications are only profitable or even possible in upscaled production, as the analyses in chapter 0 have shown. **Scaling itself and the improvement of production processes for materials should be research topics worthy of funding**, but which currently receive too little attention.

On the path to scaling**, development stages in which there is still a high level of risk, both technically and financially**, are a particularly important starting point for public funding. **Funding should ensure that the "valley of death" between development and industrial production can be bridged.**

The goal of high-volume production should **be considered as early as possible in the innovation process.** At the same time, **open-ended fundamental research** should be possible at very early TRLs as a seed for future innovations. With regard to material innovations, it is advisable to **promote** not only radically new but **also incremental developments**. These developments benefit in particular from strong volume production in German companies, where expertise is retained and further developed.

The use of new materials in scaled production is a lengthy process. The **robustness and quality of high-volume production** must be **considered** right from the start of the value chain. **Qualifications** (e.g. of vehicles) **in real environments** should also be **carried out at an early stage**

One example of the importance of scaling **is the use of biotechnological processes and methods in materials research.** Due to the use of living systems on an industrial scale, this entails special research topics, such as the development of production organisms, continuous fermentation and cell-free syntheses, as well as regulatory issues, which must be **considered separately.** The topic of "bio-based materials" is dealt with in detail in a separate Discussion Paper by the Council for Technological Sovereignty.

3.5. Specialists and interdisciplinary cooperation

The simulation and modelling of materials and their properties is essential for the realisation of various industrial processes in development and production. These aspects of materials research must therefore be **an important focus of the funding landscape**. This could be realised, for example, through **interdisciplinary research projects** involving, in particular, computer science.

There has been a decline in German research output (patents and publications, see*Figure 4*) in the field of materials research since roughly 2015. The number of students in this area has also been declining since around this time, following a trend that can be observed in many (traditional) areas of engineering (see*Figure 5*). The full-time academic staff in these fields is developing in the same way, with a delay of a few years as expected. This could lead to a negative spiral, which should be prevented at all costs. The importance of technical staff at universities, who are often essential in enabling the practical realization of research in materials science, should not be overlooked. As the complexity of topics, such as the digitalization of materials research, increases, so, too, do the demands placed on this staff. This factor must be considered when securing the necessary specialized personnel. As digital aspects such as simulation and modelling are becoming increasingly important in materials research, **interdisciplinary activities between materials science and computer science** should be **promoted from the undergraduate level**. There is a need for experts and specialists with simultaneous expertise in simulation and materials research-specific knowledge that is currently not being met.

The training of specialists is essential in any area of technology. Even though study programmes and research in the field of materials science are costly, **cuts should not be made in these areas.** On the contrary, the subject should be **made more attractive** by **good and positive publicity**. **Information and dialogue formats** ("Science Year Materials Innovations" etc.) are a conceivable way.

Moreover, society should be made more aware that engineers play a crucial role in meeting the basic needs of people, such as providing everyday items, transportation infrastructure, and mobile communication. This goes hand in hand with the fundamental need for better education across all STEM subjects.

[1] Report of the European Commission on the 2020 Criticality Assessment, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474 .

[2] Rare earth elements (REE) are a group of 17 chemically similar metallic elements (15 lanthanides as well as scandium and yttrium). However, there are only 4 rare earth elements that are important for permanent magnets: Praseodymium (Pr), Neodymium (Nd), Terbium (Tb) and Dysprosium (Dy).

[3] A distinction must be made: Metals in general versus REE in general versus REE that are relevant for permanent magnets (use the term "permanent magnets" instead of "permanent magnets")

- Raw material deposits versus raw material extraction versus refining. Dependencies exist above all in refining.
- Shares of certain countries in production/refining versus EU import quotas.

[4] Critical Minerals Data Explorer of the International Energy Agency (IEA - an autonomous unit of the OECD), https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer.

[5] Praseodymium (Pr), neodymium (Nd), terbium (Tb) and dysprosium (Dy).

[6] “Rohstoffsituation der bayerischen Wirtschaft” (Raw material situation of the Bavarian economy), 2023, https://www.vbw-bayern.de/Redaktion/Frei-zugaengliche-Medien/Abteilungen-GS/Wirtschaftspolitik/2023/Downloads/231211_Rohstoffstudie_final.pdf .

[7] “Mobilisierung der Kreislaufwirtschaft für energieintensive Materialien” (Mobilising the circular economy for energy-intensive materials), 2022, https://www.agora-industrie.de/fileadmin/Projekte/2021/2021_02_EU_CEAP/A-EW_256_Mobilisierung-Kreislaufwirtschaft_exec-sum_DE_WEB.pdf.

[8] Study on the EU's list of critical raw materials, 2020, https://op.europa.eu/en/publication-detail/-/publication/c0d5292a-ee54-11ea-991b-01aa75ed71a1/language-en).

[9] EU resilience on critical raw materials: Charting a path towards greater security and sustainability, 2020, https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:52020DC0474.

[10] Y. Fujita, S. K. McCall,. D. & Ginosar,. Recycling rare earths: Perspectives and recent advances. MRS Bulletin 47, 283-288 (2022), https://link.springer.com/article/10.1557/s43577-022-00301-w.

[11] K. Binnemans, P.T. Jones, B. Blanpain, T. Van Gerven, Y.X. Yang, A. Walton, M. Buchert, J. Clean. Prod. 51, 1 (2013), https://doi.org/10.1016%2Fj.jclepro.2012.12.037.

[12] R. Eggert, C. Wadia, C. Anderson, D. Bauer, F. Fields, L. Meinert, P. Taylor, Ann. Rev. Environ. Resour. 41, 199 (2016), https://doi.org/10.1146%2Fannurev-environ-110615-085700.

[13] S.M. Jowitt, T.T. Werner, Z. Weng, G.M. Mudd, Curr. Opin. Green Sustain. Chem. 13, 1 (2018),

[14] G. Gaustad, E. Williams, A. Leader, Resour. Conserv. Recycl. 167, 105213 (2021),

[15] Institute of Multidisciplinary Research for Advanced Materials (IMRAM),

[16] KU Leuven, http://www.kuleuven.be/research/excellence/materials_energy/binnemans.html.

[17] Critical Materials Innovation Hub, http://cmi.ameslab.gov.

[18] European Environment Agency (EEA) Report 13/2023 "Accelerating the circular economy in Europe: State and outlook 2024".

[19] If there is a high content of plastic with a homogeneous precious metal content, the precious metal is recovered using an acid solution consisting of several components. Electrochemical methods can be used to treat waste containing precious metals with a low plastic content (possibly plastic-free), some of which has an inhomogeneous content. (Precious Metals Recovery & Refining Services | Goldwater Recycling GmbH).

[20] In commercial application: Biorefineries (mint.bio); research e.g: Sustainable and economical: New method for recycling gold from electronic waste (analytik.news)"Nachhaltig und wirtschaftlich: Neue Methode zum Recycling von Gold aus Elektroschrott" (Sustainable and economical: New method for recycling gold from electronic waste) | analytik.news.

[21] "Goldgrube im Schrotthaufen" (Gold mine in the scrap heap) | Handelszeitung.

[22] UNEP (2011), Recycling Rates of Metals - A Status Report. A Report of the Working Group on Global Metal Flows to the International Resource Panel. Graedel, T.E; Allwood, J;Birat, J-P; Reck, B.K;Sibley, S.F; Sonnemann, G;Buchert, M; Hagelüken, C., page 16.

[23] i.e. the percentage of a metal in waste that is actually recycled.

[24] i.e. the proportion of old scrap in the total scrap stream.

[25] Synopsis report on the consultation on the policy framework on biobased, bio-degradable and compostable plastic, 2022, https://op.europa.eu/en/publication-detail/-/publication/85ed8b1e-705d-11ed-9887-01aa75ed71a1/language-en.

[26] Synopsis report on the consultation on the policy framework on biobased, bio-degradable and compostable plastic, 2022, https://op.europa.eu/en/publication-detail/-/publication/85ed8b1e-705d-11ed-9887-01aa75ed71a1/language-en.

[27] Communication - EU policy framework on biobased, biodegradable and compostable plastics, 2022, https://environment.ec.europa.eu/publications/communication-eu-policy-framework-biobased-biodegradable-and-compostable-plastics_en.

[28] Carbon Border Adjustment Mechanism, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.

[29] IW-Report 64/2023, https://www.iwkoeln.de/fileadmin/user_upload/Studien/Report/PDF/2023/IW-Report_2023_Nachhaltigkeit-Wertsch%C3%B6pfungsketten.pdf.

[30] Directive 94/62/EC on packaging and packaging waste, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31994L0062.

[31] European Green Deal: Putting an end to wasteful packaging, boosting reuse and recycling, https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7155.

[32] European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste, http://data.europa.eu/eli/dir/1994/62/oj.

[33] European Commission: Directorate-General for Research and Innovation, European bioeconomy policy - Stocktaking and future developments - Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/997651.

[34] European Commission, Communication on Advanced Materials for Industrial Leadership, 2024, https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/chemicals-and-advanced-materials/advanced-materials-industrial-leadership_en.

[35] Framework conditions for a circular economy National Circular Economy Strategy, Federal Government, https://www.bundesregierung.de/breg-de/aktuelles/kreislaufwirtschaftsstrategie-2323390.

[36] Landfilling, Federal Environment Agency,https://www.umweltbundesamt.de/en/topics/waste-resources/waste-disposal/landfill.

[37] Data from CONVERSIO Market & Strategy GmbH, https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/kunststoffabfaelle, https://www.bvse.de/dateien2020/2-PDF/01-Nachrichten/03-Kunststoff/2022/Kurzfassung_Stoffstrombild_2021_13102022_1_.pdf.

[38] "Kunststoffabfälle – Wie Kunststoff-Recycling in Deutschland besser werden könnte" (Plastic waste - How plastic recycling could be improved in Germany), Deutschlandfunk, 2023, https://www.deutschlandfunk.de/kunststoff-recycling-in-deutschland-100.html.

[39] "Kunststoffabfälle – Unterschiede bei der stofflichen Verwertung" (Plastic waste - differences in material recycling), Federal Environment Agency, 2023, https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/kunststoffabfaelle#unterschiede-bei-der-stofflichen-verwertung.

[40] "Plastikmüll – Wie Kunststoff-Recycling in Deutschland besser werden könnte" (Plastic waste - How plastic recycling could be improved in Germany), Deutschlandfunk, https://www.deutschlandfunk.de/kunststoff-recycling-in-deutschland-100.html.

[41] "Innovationsindikator" (Innovation Indicator), Federation of German Industries (BDI), https://innovationsindikator.bdi.eu.

[42] Data from CONVERSIO Market & Strategy GmbH.

[43] Important chemical based on biomass for the first time, Covestro AG, https://www.covestro.com/en/sustainability/flagship-solutions/bio-anilin.

[44] Students: Germany, semester, nationality, gender, field of study (Table 21311-0003), Federal Statistical Office, 2023, https://www-genesis.destatis.de/datenbank/online/table/21311-0003/.

[45] Full-time academic and artistic staff at universities: Germany, years, teaching and research areas by subject group, gender (Table 21341-0002), Federal Statistical Office, 2023, https://www-genesis.destatis.de/datenbank/online/statistic/21341/table/21341-0002.

Imprint

Publisher
Council for Technological Sovereignty, commissioned by The Federal Ministry of Education and Research (BMBF)

Members of the Council for Technological Sovereignty
Dr. Viola Bronsema
Prof. Dr. Oliver Falck
Prof. Dr. Svenja Falk
Dr. Tim Gutheit
Dr.-Ing. Christina Hack
Dr.-Ing. Stefan Joeres
Prof. Dr. Elsa Andrea Kirchner
Prof. Dr.-Ing. Marion Merklein
Prof. Dr.-Ing. Hans Schotten
Prof. Dr. Andreas Tünnermann

Lead authors of this paper
Marion Merklein, Christina Hack, Viola Bronsema

Cite as
Council for Technological Sovereignty (2025): Material Research

Editor
DLR Project Management Agency

Design
DLR Project Management Agency

April 2025

Contact

DLR Project Management Agency

Society, Innovation, Technology
Strategies for Key Enabling Technologies
pt-ts@dlr.de

DLR Projektträger