ENGLISH VERSION

Circular Flows to Meet Increased Demand for Metals and Minerals

A component report of the IVA's *Roadmap for Metals and Minerals* project

IVA

Royal Swedish Academy of Engineering Sciences

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Published by: The Royal Swedish Academy
of Engineering Sciences (IVA), 2024
Box 5073, SE-102 42 Stockholm, Sweden
Tel. +46 (0)8 791 29 00

IVA publishes various types of reports within the framework of its activities. All reports are fact-checked by experts and then approved for publication by IVA's President.

IVA-M 555
ISSN: 1100-5645
ISBN: 978-91-89181-60-1

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1. Foreword

»This report emphasises the importance of developing circular systems.«

Society in general needs to switch to fossil-free energy sources in order to meet global climate goals. This switch will require the increased use of metals and minerals in, for example, wind turbines, electric cars and solar cells. Demand for metals and minerals is expected to grow significantly, given their essential role both in increasing electrification and in digitalisation.

The purpose of the IVA's *Roadmap for Metals and Minerals* project is to help Sweden and Europe secure long-term, sustainable access to the metals and minerals needed for the transition to a fossil-free society.

This is the second of four reports within the *Roadmap for Metals and Minerals* project. The other three reports are *'Challenges for Meeting Increased Demand for Metals and Minerals'*, *'Increased Demand for Metals and Minerals – Strategies and Conflicts of Objectives and Interests'* and the final report *'Metals and Minerals for Sustainable Development and Strengthened Competitiveness'*.

This report emphasises the importance of developing circular systems, as the transition cannot be achieved sustainably solely through the increased use of primary resources from mining. With an emphasis on materials recycling, the report covers various topics, including:

- The potential for circular flows to secure both short- and long-term access to metals and minerals;
- Identified technological, legal and market barriers, as well as the conditions required for exploiting the opportunities for circular flows; *and*
- Actions needed to realise the potential for circular flows from a Swedish perspective.

This report was prepared during 2023–2024 by an expert group consisting of:

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The expert group has analysed and discussed the conditions, challenges and measures linked to circular flows in relation to the project's objectives. Their conclusions are based on factual reports, scientific articles and their collective expertise.

The expert group supports the report as a whole, but not all individual statements.

Project funders: ABB, Epiroc AB, LKAB, Ragn-Sells, Sandvik AB and Zinkgruvan Mining with support from Mistra (Foundation for Strategic Environmental Research), the Swedish Foundation for Strategic Research (SSF) and Swedish Mining Innovation, a joint initiative of Vinnova, Formas and the Swedish Energy Agency.

Related IVA projects: The IVA has previously undertaken the *Resource Efficiency and Circular Economy* project, which encompassed various sectors including mobility, premises, food, textiles and plastics (IVA, 2020a). The current report illustrates the IVA's ongoing commitment to this field, now with a specific emphasis on metals and minerals.

Stockholm, March 2024

Mikael Dahlgren,
Expert Group Chair

2. Summary and conclusions

»Today, waste is under-utilised as a resource.«

Circular material and product flows are needed in order to secure long-term and sustainable access to metals and minerals in the transition to a fossil-free society. Circular flows, which in this report include extended product life, reuse, remanufacturing and recycling, cannot cover all of the increased needs, but there is great potential for improvement. For example, recycling rates are currently low for most of the metals and minerals classified as critical by the European Union (EU).

In many areas, the design of products makes them complex to repair, and the materials used in them difficult to separate in recycling. There is often a lack of supporting legislation, business models and systems (for example, for dismantling, sorting, processing and refining) for recovering critical metals and minerals from end-of-life products. Good examples exist, and they can serve as role models, but to bring about a major change, the challenges outlined below need to be addressed.

Challenges

Today, waste is under-utilised as a resource that can contribute to the sustainable and secure supply of critical metals and minerals. However, increased use and circularity in general pose several challenges.

Profitability

The lack of profitability is a recurring theme in challenges to achieving circular material and product flows. According to the expert group's analysis, poor profitability has several root causes:

- The principle of 'polluter pays' does not work. Societal and environmental costs of finite resources and emissions are not reflected in the pricing of materials and products;
- Legislation and infrastructure for handling used and end-of-life products are not adapted to a circular economy;
- Recycling systems are small-scale compared to the production of primary raw materials. This challenge becomes especially evident for critical raw materials, which are often used in low concentrations across many different products;
- Society has not invested sufficiently in research and development in secondary material and product streams as, for example, in method development for recycling critical metals and minerals efficiently; and
- Existing producer-responsibility systems are cost-neutral for producers, regardless of whether the product is designed to facilitate circularity or not.

There are, of course, exceptions, with good examples of where circularity is economically profitable. Unlike many other critical metals, copper has a high recycling rate. The profitability of material recycling is influenced by factors such as raw-material prices and volumes, the costs of dismantling and separation, and the recycling technologies that are available. For repairs and remanufacturing, the original price of a product needs to be compared to the costs of labour and spare parts involved in repairing and remanufacturing efforts.

Technical challenges with complex materials and mixed waste streams

Recycling is complicated by the fact that products are made up of many materials – often in low concentrations. For example, electronics scrap contains critical metals such as gallium, rare-earth elements and others. These small amounts are complicated to recover, and today only a limited number of metals are recycled from electronics. Challenges exist at all stages: design, collection, pre-treatment (dismantling, separation and sorting) and final processing. Functional requirements, based on factors such as industrial competitiveness and product energy efficiency, have driven the need for complex materials. The challenge is therefore to find solutions for recycling complex materials, to find alternative less complex materials with appropriate properties, and to agree on standards (in the EU and world-wide) that promote circularity.

Waste is not seen as a resource

There is often separate legislation covering primary resources and waste, with different rules for each; this makes achieving circular flows more difficult. This in turn affects the possibility of developing profitable technologies for increased materials recycling.

- The landfill tax in Sweden hinders the recycling of metals contained in landfills, as some material will need to be re-deposited at high cost. The tax also complicates the intermediate storage of waste, which may be needed in order to collect sufficient volumes of critical metals and minerals to support profitable and efficient recycling. As an example, this could involve storing end-of-life solar panels for recycling until a dedicated facility can be built or upgraded to recycle all their component materials.

- Rules for waste transport within the EU are not harmonised, resulting in significant costs for the recycling industry in terms of administration, storage and uncertain conditions. As a result, the recycling industry faces challenges in, for example, consolidating waste streams from the Nordic market into common specialised facilities. Legislation today is designed to protect human health and the environment in a linear economy – not to facilitate a circular economy.

- A material classified as waste can only be used as a raw material by someone authorised to process waste. This limits the possibility of using these materials as raw materials in production processes. In some cases (such as recycled phosphorus), waste cannot be used as a raw material in products, regardless of its quality. Within the EU's waste directives, there are criteria that must be met for a waste to no longer be classified as such. One such criterion is that there must be a market for the material. This creates barriers for emerging secondary raw materials that could be used by customers who do not have authorisation to handle waste.

Difficult holistic assessments

It is difficult to assess the environmental impact of different choices. It is often the case that the impact within one area must be weighed against impacts in others, and system boundaries play a crucial role in the assessment. Using less material in products is resource-efficient and desirable, but it can also complicate materials recycling. Is it then better or worse for the climate and biodiversity with a resource-efficient design, or with a design that focuses on recyclability? Another challenge may be determining whether materials recycling or the reuse of a particular product is preferable. The climate impact depends on the product's energy consumption and technological advancement, as well as on existing systems such as collection, pre-processing and recycling processes, and the energy mix. Similarly, it can be challenging to determine which strategy best contributes to securing the supply of critical metals and minerals. There is often insufficient global data and decision support within the industry to make better and faster decisions aligned with global sustainable-development goals.

Regulatory framework at the EU level

Within the EU, efforts are under way within a number of regulations to strengthen circular flows. This is positive, but these efforts still present the risk of inadequate coordination, conflicting regulations, and an increased administrative burden. A further issue is the impact that EU legislation will have on European companies' competitiveness in a global market.

Permitting processes

Many companies in Sweden perceive the permitting processes associated with recycling initiatives as time-consuming and unpredictable. This area is dealt with in another part of the current IVA project, and is addressed in the report 'Increased Demand for Metals and Minerals – Strategies and Conflicts of Objectives and Interests' (IVA 2024b).

Several of the challenges described above apply to circularity in general – not just to metals and minerals. The same applies to the proposed actions listed below.

Proposed actions

Long-term rules are needed, as well as a review of the taxes and regulations that currently inhibit circularity. The Swedish Government should make it easier for companies that want to engage in circular activities in the following ways:

Circular governance

Encourage the development of markets for recycled metals and circular product flows through:

- Prioritise general actions aimed at addressing the root causes of low circularity, such as inconsistent rules and absent or incorrect pricing of external costs. Examples of measures with a positive impact on circular flows include the EU Emissions Trading System and the EU's new Corporate Sustainability Reporting Directive (CSRD).
- Increase regulation in selected areas. A mix of policy instruments is needed within the EU to boost both the demand for and the supply of recycled

materials. Ensure that companies and industry organisations are included in dialogue when regulations are being developed, to secure both competitiveness and progress in circularity.

- Develop long-term strategies and support that reduce uncertainties and risks for different actors in the transition to circular business models and the recycling of critical metals. Invest in support for the implementation of new business models/processes and pilot plants to increase the recycling of critical raw materials.

- Invest in standardisation efforts within established industrial forums to promote circular flows. Standardisation work is essential in many areas – for example, in relation to the new EU Regulation on Circularity Requirements for Vehicle Design and End-of-Life Vehicle Management, which includes the reporting of recycled materials. Since current standards do not define how to calculate the amount of recycled material in a uniform way, new legislation needs to clarify this. There is also a need for material standards to which both the processing and recycling industries can relate. Another area of focus is to ensure that product standards allow for recycled materials.

These measures are difficult to implement and require co-ordination at an international level to avoid any loss of competitiveness for the EU's manufacturing sector. Nevertheless, it is important to work on these fundamental areas.

Extended product lifespan

Simplify reuse and remanufacturing by, for example, removing Sweden's chemical tax on imported used electronics and by imposing repairability requirements for more products within the EU. There is also the need for increased circularity in public procurement in Sweden. Investigate and implement various ways of reducing costs for companies that extend the lifespan of different products through, for instance, repairs and remanufacturing.

Regulations and the perception of waste

Change the perception of waste so that it is treated as a valuable resource. Make it easier for recycling companies to collect larger volumes of waste and recycling from landfills, and create incentives for recovering old infrastructure.

Knowledge, skills and expertise

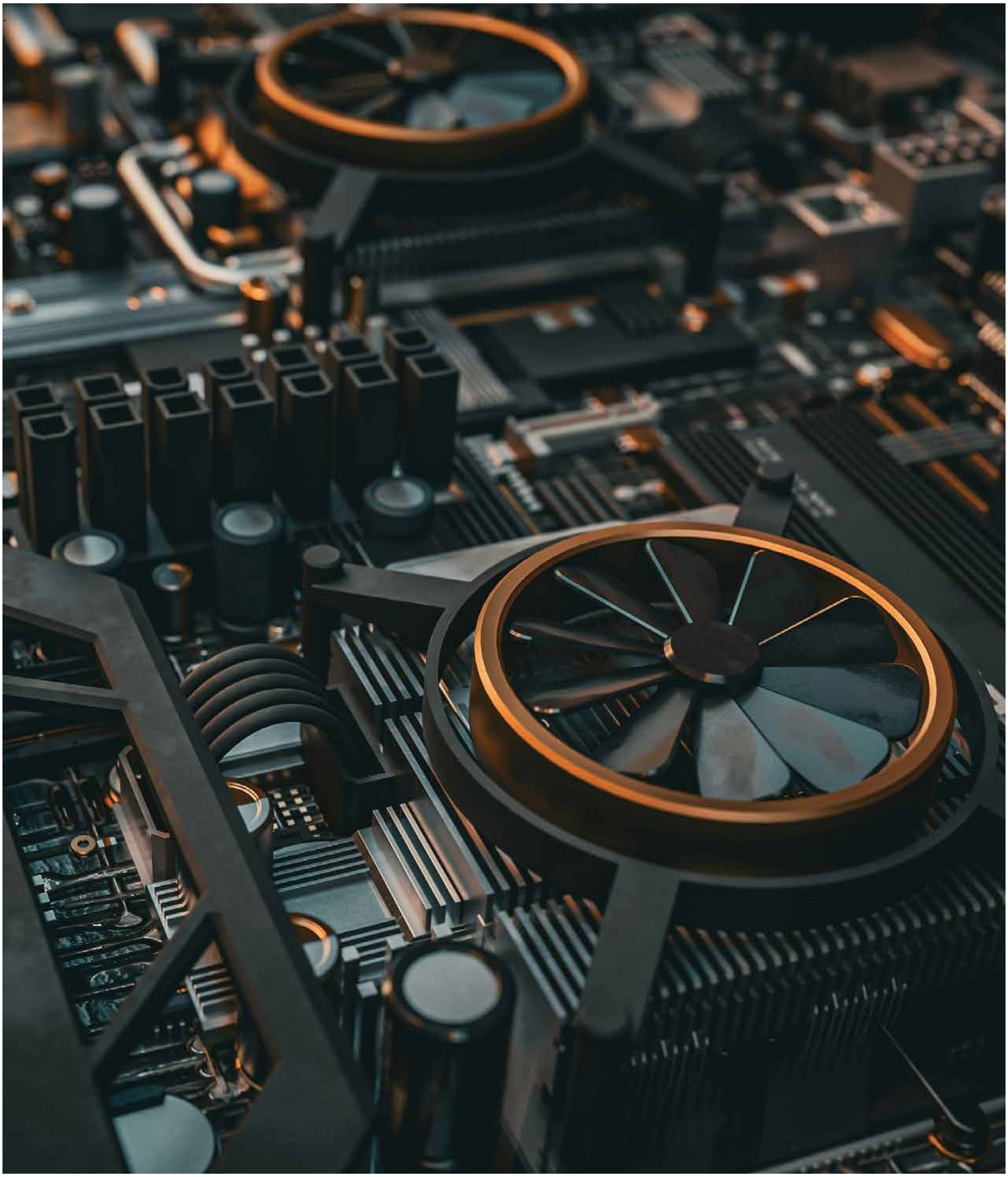
Invest in education, research and innovation in the field, and create platforms for collaboration.

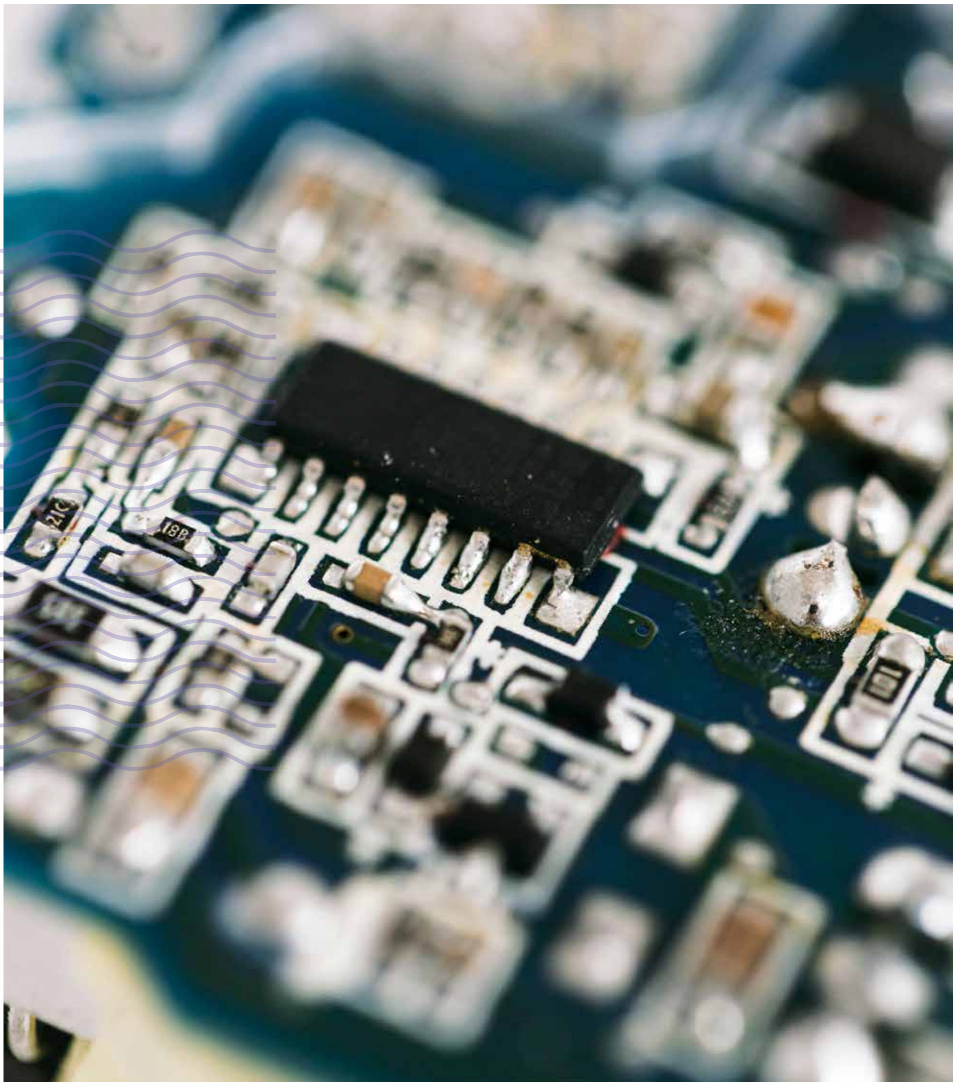
- Better knowledge is needed of how different metals and minerals flow in society. Without understanding these secondary material flows, it is difficult to evaluate what works well, what works less well, and where new business opportunities exist.

- We need more professionals with better knowledge of circular flows, circular business models, circular design, preventive maintenance, specific material recycling techniques and landfill recycling.

- Different methods should be developed, and global datasets collected, to assist in weighing various sustainability aspects against each other. Practical industrial methods need to be developed for assessing the best actions from a resource and climate perspective.

- Collaboration platforms are needed for circular flows. Actors throughout the value chain need to collaborate on new business models. There are potential synergies in materials recycling with the primary extraction of critical metals. The Metals & Minerals innovation programme, part of Sweden's state-funded Impact Innovation initiative, will be crucial in this context. It is important to build up funding for the programme quickly, to enable the financing of research and development within circular material and product flows, focusing on critical metals and minerals.





3. Glossary

Definitions and explanations of technical terms used in the report.

Alloys
Materials composed of a mixture of two or more different metallic elements. Specific combinations yield desired properties such as strength, heat resistance or corrosion resistance.

Circular design
Resource-efficient design that promotes repair, reuse, remanufacturing and efficient recycling.

Circular economy
An economic model that, in contrast to the traditional linear economy based on 'use and dispose', focuses on reducing resource use through resource efficiency, extended product lifespan, reuse and materials recycling. A widely accepted definition of the circular economy is still lacking, but work is in progress on this within the Swedish Institute for Standards (SIS, 2024).

Closed-loop recycling
A recycling system that involves the production, collection and recycling of materials in a way that allows for the continuous remanufacture of the same product using recycled materials. An example of this is the recycling of aluminium cans in Sweden.

Critical Raw Materials (CRM) within the EU
Raw materials with a significant risk of supply disruptions that may have undesirable consequences. In the EU, raw materials are given this classification because of their economic importance in relation to their supply risk. Examples of critical metals in the EU are cobalt, lithium, manganese and rare-earth elements. The EU's list of critical and strategic raw materials is updated every three years, most recently in 2023 (see also Table 1). Raw materials defined as strategic (see the explanation below) are automatically included in the list of critical raw materials.

Downgrading
The process of converting a product or material into a lower-quality or less-valuable form, resulting in the degradation of the material or product.

Electronic waste
A term used in this report to refer to waste from electrical and electronic equipment in a broad sense. In the EU's Waste Electrical and Electronic Equipment (WEEE) Directive, electrical equipment in vehicles and large-scale stationary installations is excluded, as this is managed under other legislative acts.

EOL-RIR (End-of-Life Recycling Input Rate)
A measure of the proportion of materials in the production system derived from recycling 'old scrap', which refers to scrap from end-of-life products. Scrap generated from manufacturing processes is not included.

EOL-RR (End-of-Life Recycling Rate)
A measure of the proportion of materials in waste streams that is recycled.

Industrial waste
Surplus materials, production residues or defective products from industrial processes that are either discarded or recycled.

Life-Cycle Assessment (LCA)
A method for evaluating the environmental impacts of a product or service by analysing its entire life cycle, from a chosen start point to an end point. This includes stages such as raw-material extraction, manufacturing, usage and waste management.

Materials recycling
The system of reprocessing waste into new materials and substances that are not intended for use as a fuel or as filler material.

Metal
Elements are grouped into metals, semi-metals (including semiconductors) and non-metals. Metals are characterised by properties such as high electrical and thermal conductivity, malleability, high density and metallic lustre.

Mineral
Chemical compounds, alloys or pure elements with well-defined chemical compositions, crystal structures and properties.

Modular design
A design principle that divides a system or product into smaller components, known as modules, which can be modified, replaced or interchanged with other modules. This approach promotes repairability and remanufacturing.

Post-consumer waste
This refers to waste generated from end-of-life products. It is produced by end-users, whether individuals or businesses, from items that have fulfilled their intended purpose or are no longer usable. Such waste is often complex and more challenging to manage than industrial waste.

Primary raw material
A raw material that is extracted from a mine.

Rare-earth Elements (REEs)
A collective name for the 15 lanthanides (atomic numbers 57 to 71). Scandium (21) and yttrium (39) are often included as well. REEs are usually divided into two groups — light and heavy — based on their chemical behaviour. They are used in electronics and have special magnetic, optical and catalytic properties. Many REEs have very specific properties that make them difficult to replace.

Raw material
A substance in either processed or unprocessed form that is used as an input in the production of intermediate or final products. This excludes substances primarily used as food, agricultural feed or fuel.

Reconditioning
A process to extend the lifespan of a product. New components may be added, but the product is not restored to an as-new condition.

Recycled (Secondary) raw material
A raw material obtained from previously used products that can be reused through recycling. Recycled raw materials can also come from other sources, such as purification concentrates from air- and water-emission treatment, dust and particles from steel production, and sludge from wastewater treatment.

Remanufacturing
An industrial process where used products are restored. Materials are added, and the product is brought back to an as-new condition or even better.

Repair
A process in which broken parts or products are mended. The remaining lifespan of the repaired item depends on its previous usage.

Reuse
A process where a product that is no longer needed by its owner is taken over by a new user who can benefit from it, instead of it becoming waste. No new materials are added, and the product's technical lifespan is not extended.

Secondary raw material
See 'Recycled raw material'.

Society-critical metals and minerals
This term is used here to refer collectively to metals and minerals classified by the EU as critical or strategic, as well as iron and limestone, which are essential for Sweden's industry.

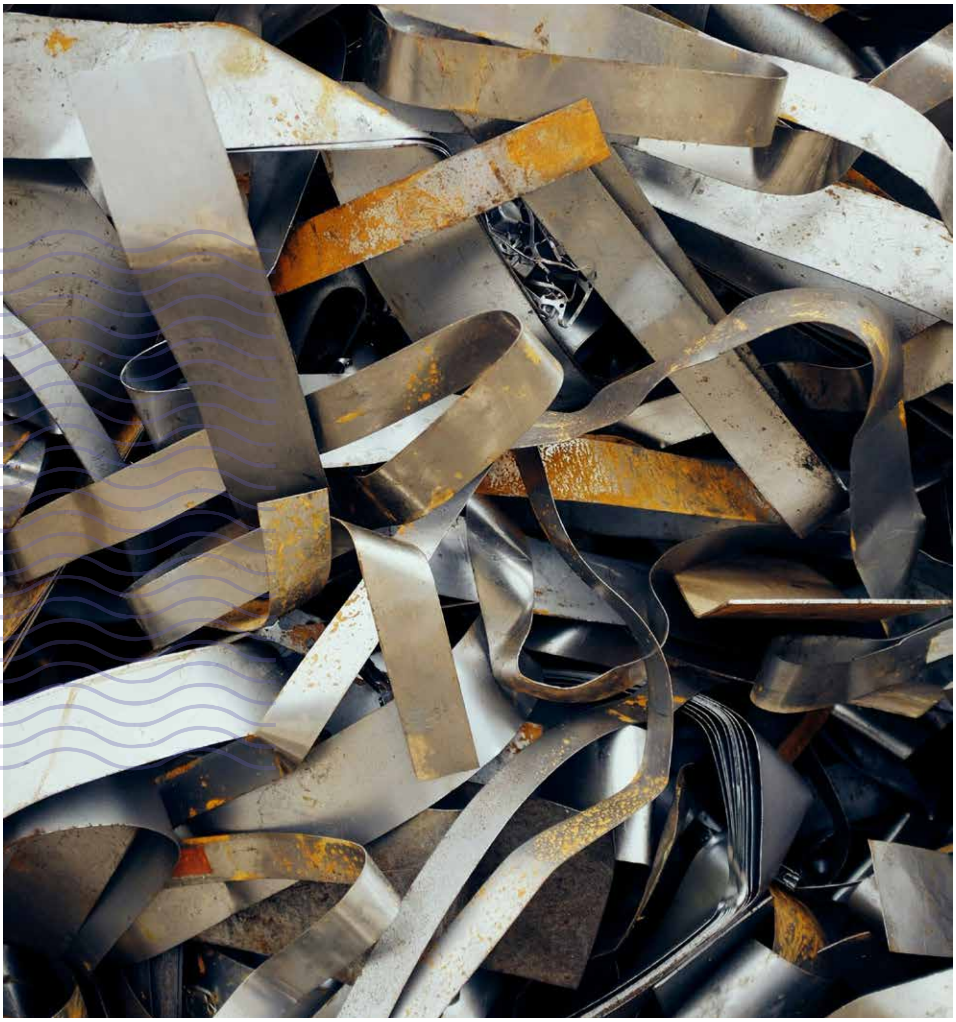
Strategic raw materials within the EU
Raw materials essential for the internal market, particularly for green and digital transition technologies or defense and aerospace applications, with potential supply-demand gaps and limited capacity for rapid production increases due to long project lead times (see Table 1).

Vertical production
A production method where various stages of a manufacturing process are carried out within the same company or facility. This approach can enhance efficiency and provide better control over the production process.

Waste
Any substance or object which the holder discards, or intends or is required to discard (the EU's legal definition).

Table 1: The left column lists raw materials classified as critical by the EU in 2023. The middle column shows those classified as strategic, which have an even higher priority. The right column represents the proportion of the total amount of a material used in EU production that comes from the recycling of post-consumer scrap (EOL-RIR).

Critical Raw Materials in the EU 2023 (European Parliament, 2023, Annex II)	**Strategic Raw Materials in the EU 2023** (European Parliament, 2023, Annex I)	**EOL-RIR (End-of-life recycling input rate)** (Grohol & Veeh, 2023, Annex 11)
Antimony		28%
Arsenic		0%
Baryte		0%
Bauxite/Alumina/Aluminium	Bauxite/Alumina/Aluminium	32%
Beryllium		0%
Bismuth	Bismuth	0%
Boron	Boron (metallurgical grade)	1%
Cobalt	Cobalt	22%
Coking Coal		0%
Copper	Copper	55%
Feldspar		1%
Fluorspar		1%
Gallium	Gallium	0%
Germanium	Germanium	2%
Graphite	Graphite (battery grade)	3%
Hafnium		0%
Heavy and light Rare-earth elements	Rare-earth elements for permanent magnets (Nd, Pr, Tb, Dy, Gd, Sm and Ce)	1%
Helium		2%
Lithium	Lithium (battery grade)	0%
Magnesium	Magnesium metal	13%
Manganese	Manganese (battery grade)	9%
Nickel (battery grade)	Nickel (battery grade)	16%
Niobium		0%
Phosphate rock		0%
Phosphorus		0%
Platinum Group Metals (PGM)	Platinum Group Metals (PGM)	12%
Scandium		0%
Silicon metal	Silicon metal	0%
Strontium		0%
Tantalum		1%
Titanium metal	Titanium metal	1%
Tungsten	Tungsten	42%
Vanadium		6%



4. Background

»The extent to which needs can be met by recycling is influenced by factors such as levels of demand, recycling rates, and product lifespans.«

Increasing demand for metals and minerals, and its drivers

The UNEP-established International Resource Panel notes that total material use worldwide has more than tripled over the past 50 years (from 30,000 Mt to 106,600 Mt) and continues to increase by over 2.3% per year. The Panel also predicts that global raw-material consumption will rise by 60% by 2060 compared to 2020 if no measures are taken. A significant part of this global increase is related to a growing population, rising living standards, urbanisation and unsustainable consumption. The material footprint in high-income countries is six times higher per capita than that in low-income countries. The built environment, mobility, energy and food account for 90% of global material demand (see Figure 1). For metals, the energy transition will lead to a substantial increase in demand until 2050, while the use of fossil fuels should fall (UNEP, 2024).

The increasing need for metals and minerals resulting from the transition

The transition to a fossil-free energy system significantly increases the demand for metals and minerals—a conclusion echoed in numerous reports. According to the International Energy Agency (IEA), the energy sector will have a substantial impact on mineral markets in the coming decades.

For a selection of critical metals, manufacturing an electric vehicle requires about six times more of these metals compared to a conventional car, and an onshore wind power plant requires about nine times more than a gas-fired plant of the same capacity (IEA, 2022a). This is illustrated in Figure 2. The specific metals and minerals needed in the future will depend on the technology chosen.

How much these needs increase also depends on countries' climate ambitions. The IEA has estimated that the demand for minerals in the clean energy sector will quadruple if the goals of the Paris Agreement (Sustainable Develop-

Figure 1: Material footprint for different income groups and the shares of material footprint by five provision systems and income groups. Source: Global Research Outlook: Bend the Trend – Pathways to a liveable planet as resource use spikes, United Nations Environment Programme, 2024.

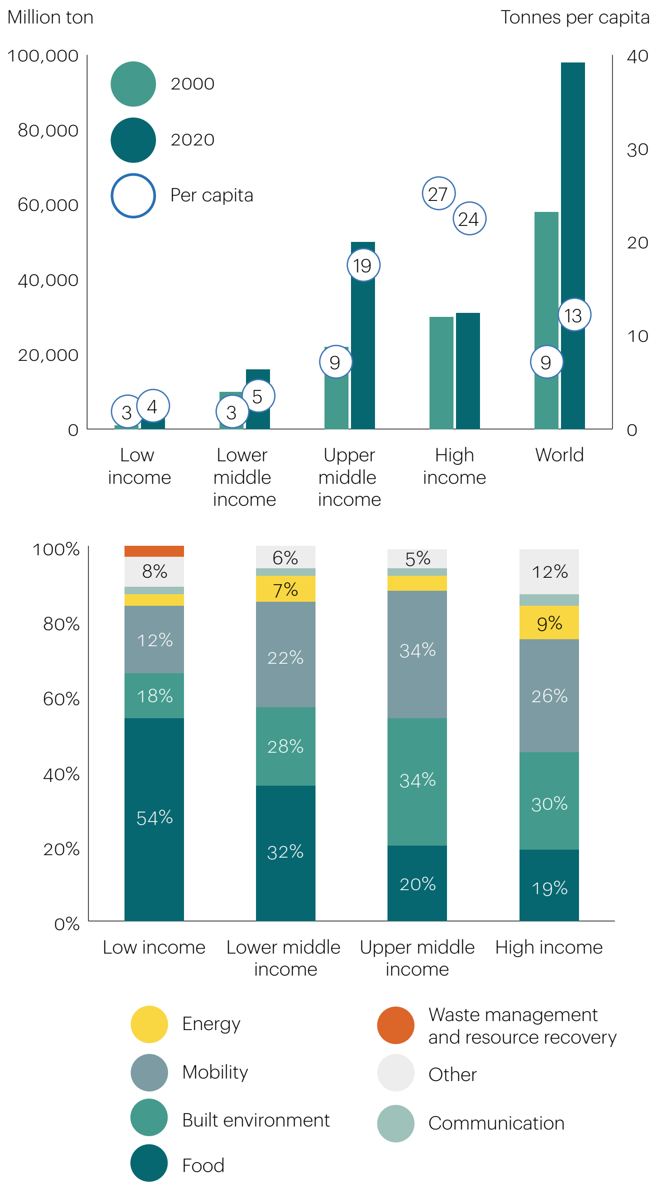
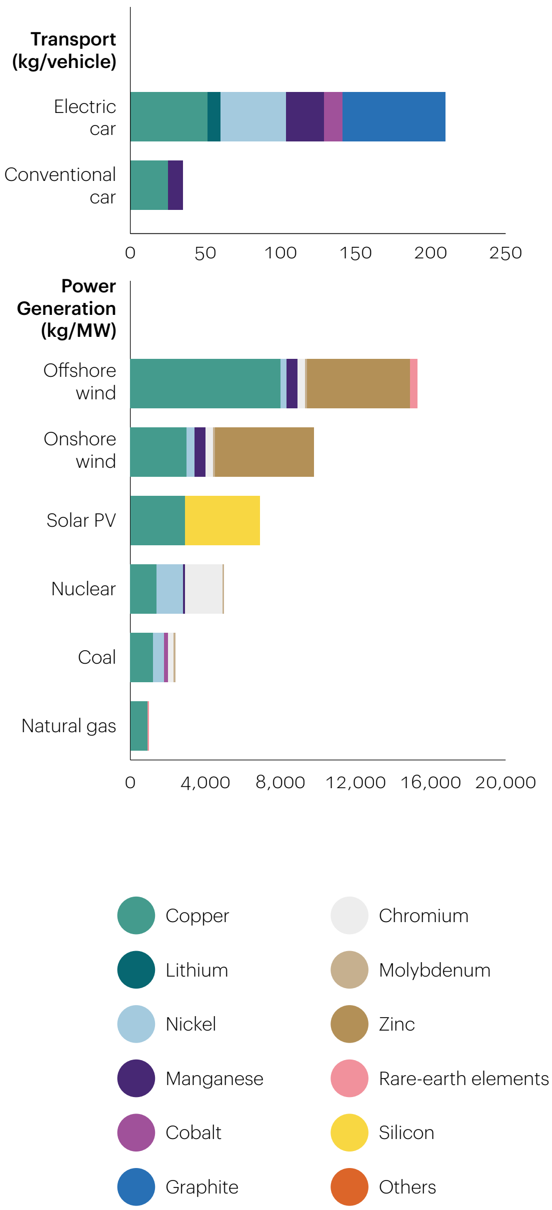


Figure 2: Comparison between a conventional car and an electric car in terms of a selection of critical metals, and the content of various metals and minerals across different power sources. Source: The Role of Critical Minerals in Clean Energy Transition, IEA, May 2021.



ment Scenario) are to be met. In this scenario, electric vehicles and battery storage account for the largest share of the increase. For example, demand for lithium is expected to increase 42-fold between 2020 and 2050 (see Figure 3).

The IEA warns that a shortage of materials could delay the energy transition. With the current expected supply (existing mines and on-going projects) and the ambition to meet the climate goals of the Paris Agreement, the world will have access to only half of the lithium and cobalt needed by 2030. According to the same analyses, we will have only 80% of the copper required (IEA, 2021a).

Predicting future needs is challenging, but the electric-based technology replacing fossil-based systems today is more mineral-intensive. Forecasts indicating a significant increase in the need for metals and minerals are common in several publications, an example of this being a summary by the Joint Research Centre, the European Commission's science and knowledge service (Carrara et al, 2023).

The summary notes that the EU's demand for lithium for batteries in 2050 could be up to 21 times higher than it was in 2020, and global demand could increase by as much as 90 times over the same period. This applies to the report's 'high demand scenario', which reflects ambitious climate policies.

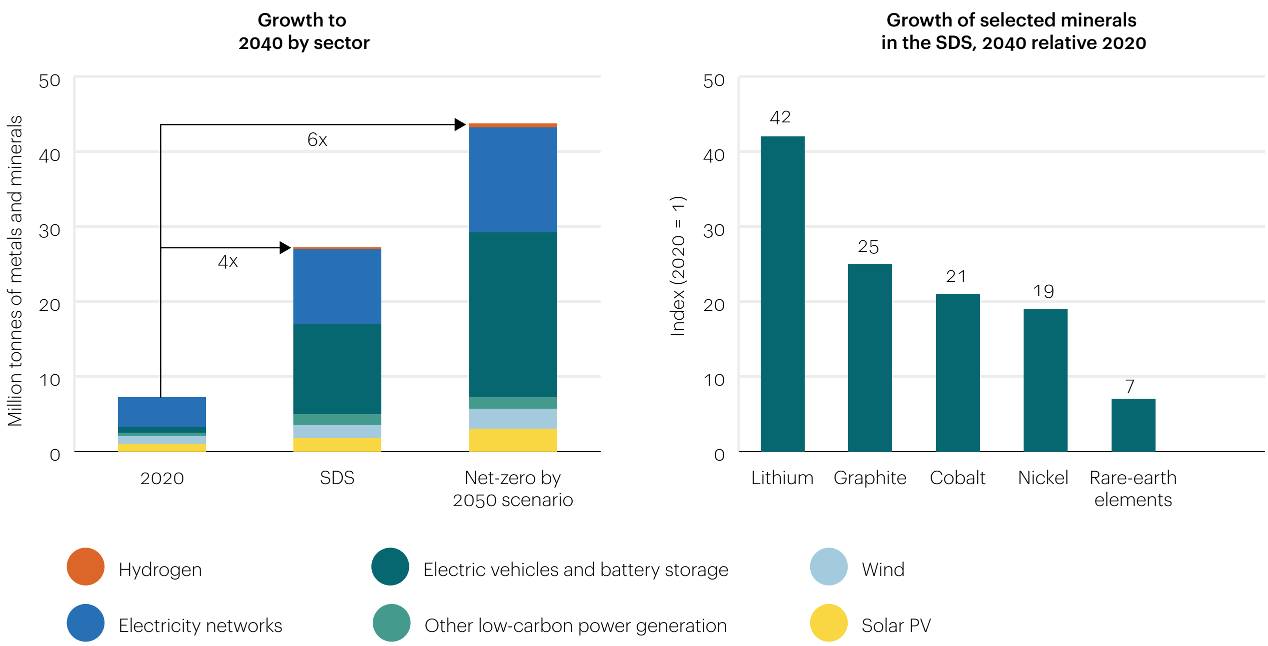
We are using more and more metals

Our knowledge of the properties of various elements, both individually and in combination with other substances, is constantly increasing. In today's society, significantly more elements are used than was the case only a few decades ago. A modern mobile phone can contain some 50–70 different elements.

Technological advances also permit the use of smaller amounts of a specific element in a component, while maintaining functionality. This means that the concentration of, for example, gallium in a product can be very small.

Read more about elements in the Appendix, section "Metals and minerals".

Figure 3: Demand for metals and minerals could increase 4–6 times by 2040 because of the transition of the energy system from fossil fuels to electricity (SDS = Sustainable Development Scenario). The analysis excludes steel and aluminium. Source: The Role of Critical Minerals in Clean Energy Transition, IEA, May 2021.



A few countries control the value chains

Metal and mineral value chains are global, and the energy system's transition is shifting power from oil-producing nations to countries with access to metals. A few countries dominate the production of critical metals and minerals. For example, the Democratic Republic of the Congo (DRC) accounted for 70% of global cobalt production in 2019, and China accounted for 60% of the global production of rare-earth elements that year (IEA, 2021a). China also has a strong position in the subsequent refining stages for many metals. Technological development and its need for strategic metals and minerals are therefore closely linked to geopolitical developments.

Value chains and geopolitics are discussed further in the project's first report *'Challenges for Meeting Increased Demand for Metals and Minerals'* (IVA, 2024a).

RECYCLING – A GEOPOLITICAL ISSUE

The geopolitical perspective is fundamental when discussing the profitability and importance of establishing conditions for circular flows of critical metals and minerals. The price of most critical metals is currently too low relative to recycling costs, and is also highly variable over time (Tillväxtanalys, 2023a). Many critical metals and minerals are mined and processed in countries that pose a supply risk for the EU (IVA, 2024a). Currently, a critical metal recycled within the EU cannot compete in the market because of its high cost compared to the price of equivalent imported primary raw materials. Regulations and policy measures need to be revised in order to increase the recycling of critical metals and minerals within the EU, thereby reducing supply risks – particularly in the long term, when more secondary material is available. See Chapter 6: Recommendations.

Different ways of reducing the need for primary materials

Innovation and new materials

The demand for materials can change and decrease with new technologies and material substitution. The IEA cites the reduction of silver and elemental silicon in solar cells as an example, where technological advances have reduced the amount of these materials by 40–50% in just ten years (IEA, 2021a). At the same time, more material-efficient products can lead to lower prices and thus higher consumption (Carrara et al, 2023). Using smaller amounts of materials in products can also pose challenges for recycling (see also Chapter 5, Challenges).

In some cases, specific metals and minerals can be replaced by alternatives – the process known as substitution. For instance, there are hopes of replacing lithium with sodium in car batteries. Found in table salt, sodium is cheaper and significantly easier to extract. If successful, this would reduce the demand for lithium. On the other hand, the comparatively low energy density of sodium would increase the weight of the battery, which is a disadvantage.

More efficient energy use

Energy efficiency and a more transport-efficient society play a vital role in reducing the need for metals and minerals while simultaneously achieving climate goals. In a transport-efficient society, the focus is on accessibility rather than mobility, avoiding unnecessary transport. A previous IVA report emphasises the importance of avoiding unnecessary transport, coordinating existing transport, and increasing the fill and utilisation rates of transport (IVA, 2020b).

This is also highlighted in the IRP report *'Bend the Trend'*, cited above. Although not discussed further here, efficient use is essential for curbing increasing demand for raw materials.

Extended product lifespan and circularity

Sweden's action plan for a circular economy highlights critical metals and minerals as a priority in the transition towards this (Swedish Ministry of Climate and Enterprise, 2021). Extending the lifespan of products, developing new business models, and promoting circular material and product flows can all help reduce the increasing need for primary materials. This report focuses on these areas with an emphasis on materials recycling.

There are also valuable metals and minerals in existing waste landfills and old infrastructure projects. Estimates show that Sweden's many landfills contain over 350 Mt of material, from which some 7 Mt of iron and 2 Mt of other metals could be extracted. Landfill mining also has the potential to reduce greenhouse-gas emissions as a one-time measure by reducing methane emissions from landfills, and by increasing materials recycling (Frändegård et al, 2013). In a similar context, there is untapped potential in the copper cables left in the ground when replaced by technologies such as fibre optics. For example, there are an estimated 500 t of copper in unused electrical cables in the city of Norrköping alone (Wallsten et al, 2013). If other cities are similar to Norrköping, there could be more than 2 Mt of copper in unused electrical cable within the EU, representing around 10% of current annual global primary copper production (Reichl & Schatz, 2023).

Decoupling material use from growth

To achieve the global sustainable development goals, it is essential to decouple environmental impact and primary resource use from economic growth and human well-being. Current projections indicate an enormous material demand and an unsustainable level of material growth given the Earth's limited resources. Since the extraction and processing of primary resources often have significant impacts on climate and biodiversity, materials must be used sparingly and thoughtfully (UNEP, 2024). The European Environment Agency (2023) notes that the EU is far from reaching the goal of reducing its material footprint by 2030. However, reducing the need for metals and minerals is challenging, especially as new technologies are needed to address the climate crisis and phase out fossil fuels. The circular economy offers strategies for businesses and governments to decouple primary material use from growth through reuse, remanufacturing, sharing solutions and materials recycling.

Mines are also needed

According to current forecasts, in addition to developing circular systems, we will also need more primary sources (mines) to succeed in the transition. For a closer look at this topic, see this IVA project's report *'Challenges for Meeting Increased Demand for Metals and Minerals'* (IVA, 2024a).

Circular systems need to be developed in parallel with increased mining. The new raw materials introduced into the system should, like recycled ones, be produced with minimal environmental and societal impact.

HOW CIRCULAR IS THE WORLD IN GENERAL?

Every year, approximately 100,000 Mt of raw materials are used world-wide. According to the Circularity Gap Report (Circle Economy, 2023), only 7.2% of this is made up of recycled (secondary) material. Despite increased recycling efforts, on a relative basis the global percentage has gradually decreased since 2018. This is because the extraction of primary materials has risen even faster, driven by growing demand. The Circle Economy report emphasises the importance of using less, using products for longer, reusing/recycling, and mimicking natural cycles by phasing out harmful materials and processes and replacing them with renewable resources such as biomass.

The figures above include all resources, with society-critical metals and minerals accounted for as well. Although we frequently discuss the circular economy in Sweden, the country remains largely in a linear system while maintaining high consumption (RISE & Circle Economy, 2022).

Moreover, the extraction and processing of natural resources account for more than 55% of total global greenhouse-gas emissions and over 90% of land-based biodiversity loss. This includes all natural resources, not just metals and minerals (United Nations Environment Programme, 2024).

Recycling today

Recycling rates

Current recycling rates vary significantly from metal to metal. For bulk metals such as iron (steel), copper and aluminium, recycling is already well-developed, although there is still room for improving the quality of the recycled material. For steel, half of global usage could come from secondary sources by 2050 (Material Economics, 2021). The World Bank estimates that 60% of all aluminium will come from secondary sources by 2050 (Hund et al, 2020). The reason that the proportions of steel and aluminium from secondary sources is not higher is largely due to long product lifespans and increased demand (see also the info box on page 27).

For other metals, such as lithium (battery metal), rare-earth elements (used in permanent magnets found in electric vehicles and wind turbines), and indium (used in flat screens and solar cells), there is still a long way to go to achieve effective recycling (see Chapter 5, Challenges). Very little of these metals is currently recycled (Näringsutskottet, 2022).

For many critical metals and minerals, obtaining current statistics on recycling and material flows is challenging (Lindblom et al, 2023). To improve our recycling and material-flow systems, knowledge must be gained about the locations and flows of these materials, both within Sweden and globally.

There are various ways to measure recycling rates, such as:

- The proportion of material recycled from the amount scrapped in a year;

EXAMPLE: THE RARE-EARTH ELEMENTS NEODYMIUM AND DYSPROSIUM

Neodymium and dysprosium are two rare-earth elements used in permanent magnets. Currently, any neodymium and dysprosium that is recycled comes primarily from decommissioned wind turbines, which contain large permanent magnets that are relatively easy to extract. By contrast, cars contain numerous small permanent magnets integrated into various functions, often glued in place to ensure that they remain secure throughout the vehicle's life. Given current market conditions, it is challenging to justify the high costs associated with extracting these magnets, which have to be demagnetised before being transported for recycling. Although recycling processes are available for neodymium and dysprosium sourced from permanent magnets, there are significant challenges, mainly in sorting and handling the magnets before the recycling process (information from Stena Recycling and ABB).

Neodymium is one of the rare-earth elements examined in detail in the report *'Flöden av sekundära kritiska råmaterial i den svenska teknosfären'* (Lindblom et al, 2023). The report estimates that Sweden's secondary flow is currently around 150 t/y, of which about half is estimated to come from magnets, and some 40% from electronics. However, a negligible amount of the neodymium present in Swedish material flows is actually recycled.

The report *'Developing a supply chain for recycled rare-earth permanent magnets in the EU'* (Rizos et al, 2022) discusses the opportunities and challenges associated with increasing the recycling of rare-earth elements from permanent magnets within the EU. Some of the challenges include:

- The lack of clear regulations on how products should be labelled with information about the magnets;
- The high cost of extracting magnets from discarded products because of their design;
- The prices of rare-earth elements are low and/or difficult to predict, making it challenging to compete with primary materials;
- The recycling process involves technical challenges; *and*
- The currently low and uncertain future volume of magnets available for recycling poses significant challenges for scaling-up recycling efforts in the EU.

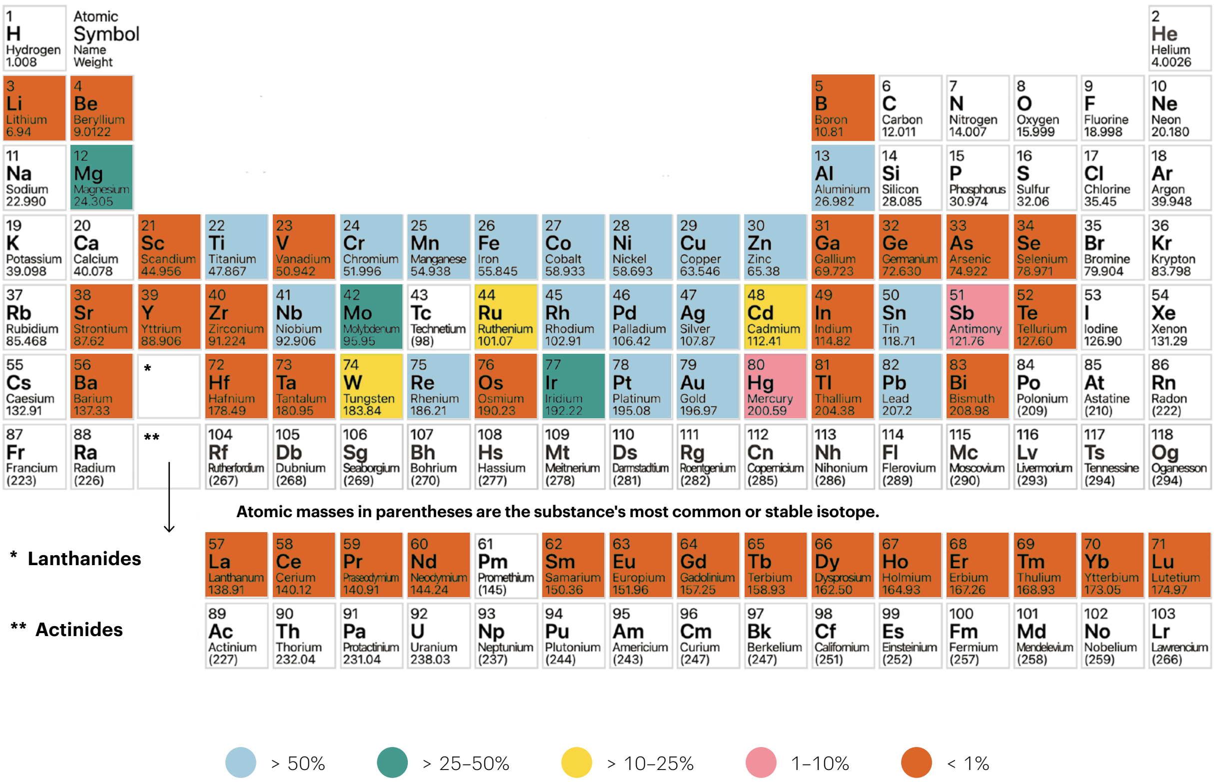
- The proportion of recycled material relative to the total metal consumption for that year or an average per year over a limited timeframe; *or*
- The proportion of recycled material used in production.

Economic growth and product lifespan can cause these measures to vary significantly for a given metal.

In 2011, the UNEP IRP made a global estimate of the amount of metal actually recycled from waste while maintaining quality (see Figure 4). Since then, no equally comprehensive analysis has been undertaken, although the IEA has compiled waste flows for some metals (see Figure 5).

The European Commission has recently attempted to estimate how much recycled material from end-of-life products is used in manufacturing (see Figure 6). The low figures can be attributed to several factors. There are shortcomings in recycling, but they may also be the result of a significant amount of material still being tied up in long-lived products, as well as to increasing demand. A drawback of this measurement method is that it does not account for any

Figure 4: EOL-RR (end-of-life recycling rate) for 60 metals. EOL-RR indicates the proportion of material in waste streams that is actually recycled. Unless otherwise noted, this refers to functional recycling, which means recycling with maintained quality. Empty boxes indicate missing data or that the element was not included in the study. Note that the study is from 2011. Since then, no equally comprehensive analysis has been carried out, although the IEA has compiled recycling rates for some metals, as shown in Figure 5. Source: Recycling Rates of Metals: A Status Report, United Nations Environment Programme & International Resource Panel, 2011.

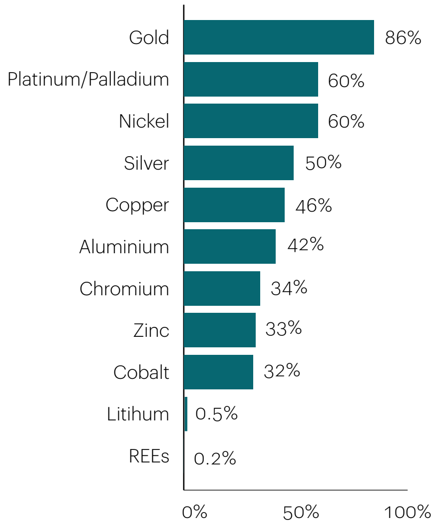


downgrading (material degradation); when this happens, the material can be used in fewer applications. In the long term, this becomes problematic. To maximise a material's utilisation, it should be as pure as possible.

The use of recycled materials in production varies between countries and between industries. Existing industrial standards across various sectors can complicate its use. The higher the purity and quality requirements, the less recycled material is utilised. For instance, the figures may be lower than average in the automotive industry.

Given inadequate data and the difficulties in mapping material flows and recycling rates within Swedish society (Lindblom et al, 2023), it is evident that global recycling rate figures are based on a range of assumptions.

Figure 5: EOL-RR (end-of-life recycling rate) for selected metals. EOL-RR indicates the proportion of material in waste streams that is actually recycled. The figures are somewhat more recent than those from the UNDP (see Figure 4) but are not as comprehensive. The recycling rates shown here are slightly lower. Source: End-of-life recycling rates for selected metals, IEA, 2021.



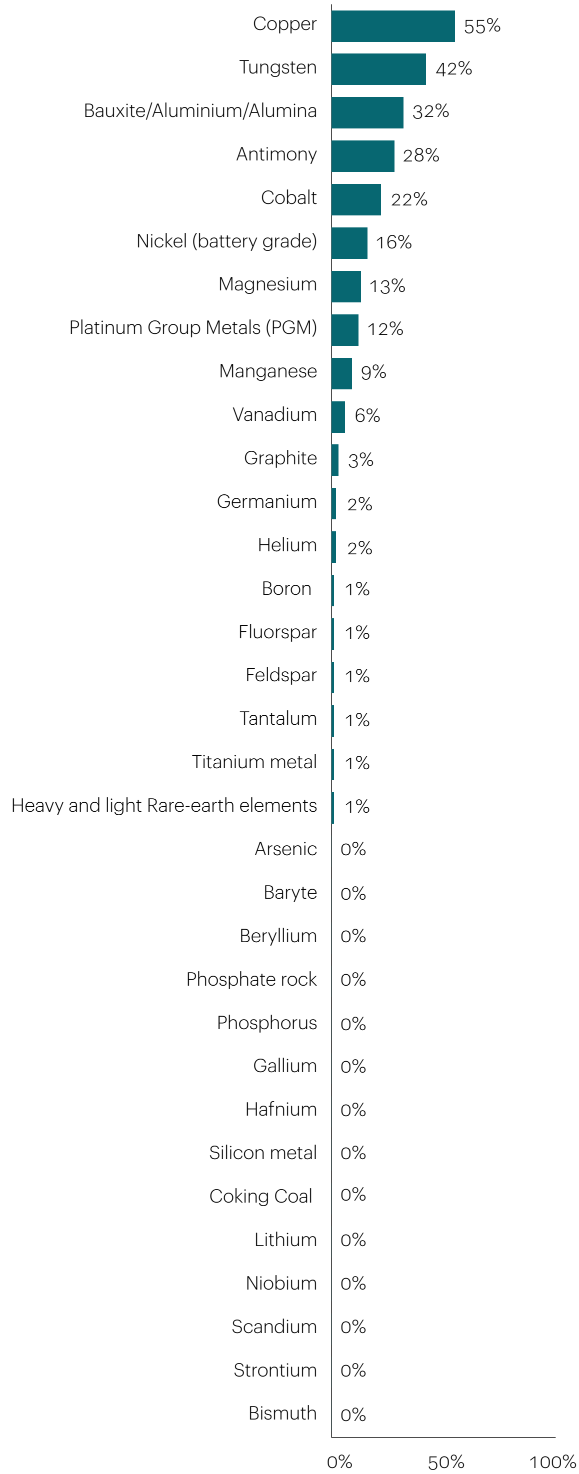


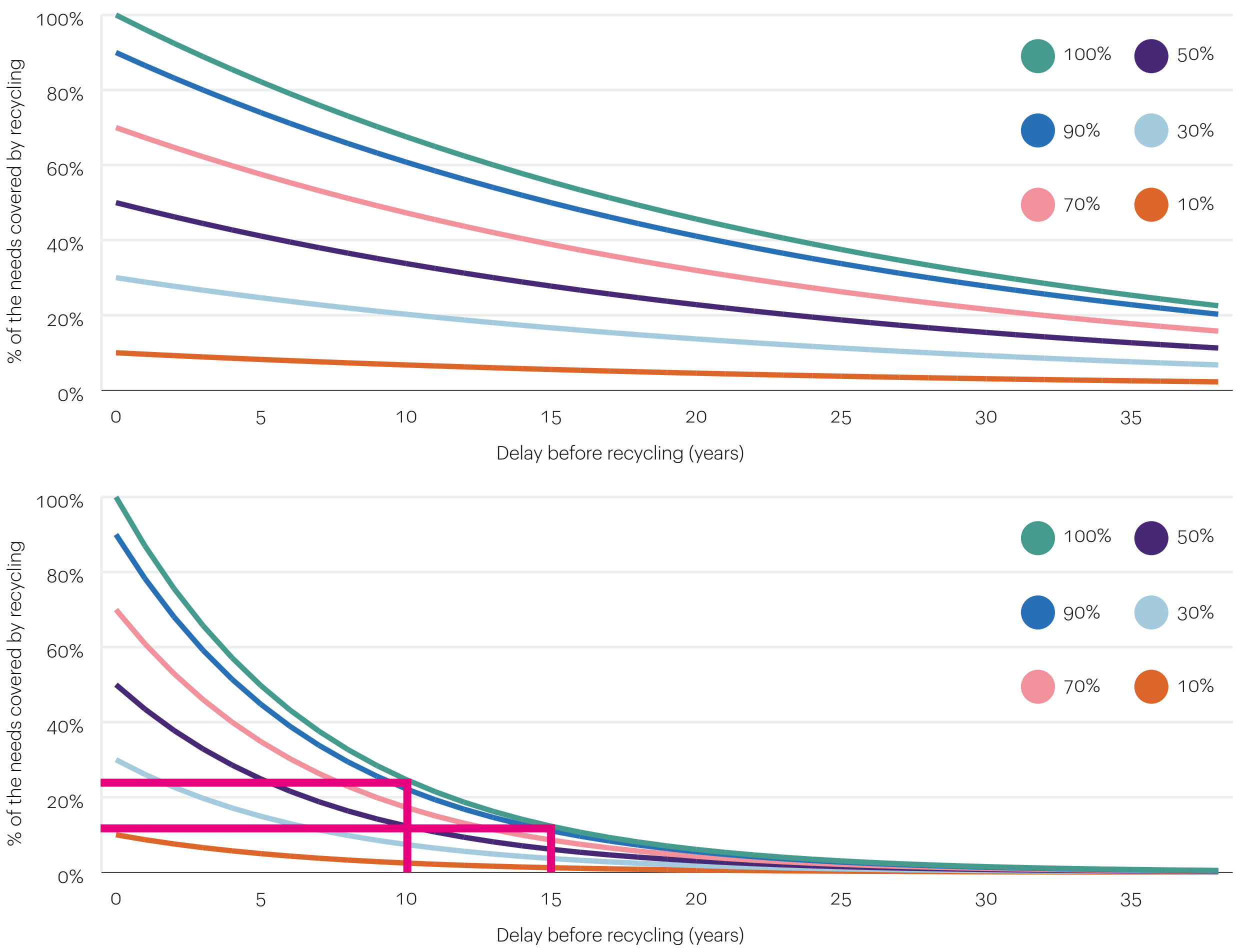
Figure 6: The chart illustrates EU-critical raw materials, and the proportion of these materials within the EU production system that are sourced from the recycling of post-consumer scrap. Scrap from manufacturing processes is excluded. This proportion is known as the end-of-life recycling input rate (EOL-RIR), which differs from the EOL-RR shown in Figure 5. Source: Study on the Critical Raw Materials for the EU 2023, Grohol & Veeh, 2023.

Not enough metals and minerals in circulation

The lifespan of products affects the availability of recycled material. For renewable-energy technologies, the materials from today's installations will be tied up in long-lived products. For example, wind turbines have a lifespan of up to 35 years with proper maintenance, meaning we cannot rely on material recycling to meet the increased demand for new wind turbines. Small volumes of waste from new energy technologies, and lack of profitability, also contribute to the underdeveloped recycling processes for recovering all critical raw materials. To recycle materials effectively as volumes increase, these processes must be developed (Carrara et al, 2023).

Today, approximately 80% of all steel is recycled on a worldwide basis, but only about 29% of newly produced steel

Figure 7: Proportion of demand that can be met by recycling with an annual demand increase of 4% (see upper image) and an annual demand increase of 15% (see lower image). The result depends on the lifespan of the products (x-axis) and the recycling rate (the various curves). For example, in the lower image, it can be seen that if the demand for a metal increases by 15% per year and the product lifespan is ten years, recycling can only cover about 25% of the demand, even if 100% is recycled. If the product lifespan is 15 years instead, recycling can theoretically cover about 12% of the demand. Source: Christian Ekberg, Chalmers University of Technology.



DEVELOPMENT IS UNDER WAY FOR INCREASED RECYCLING AND REDUCED DOWNGRADING

Continuous progress is being made towards increased materials recycling and reduced downgrading, exemplified by the newly implemented (2024) EU Regulation introducing quotas for recycled material in battery recycling (Regulation 2023/1542). Both Northvolt's and Stena Recycling's newly opened recycling facilities for electric vehicle batteries have set very high targets for recycling rates.

comes from secondary metal (scrap) (Material Economics, 2021). This is partly due to the lifespan of steel products and partly because demand is still increasing. For many of the other metals needed for the transition to a fossil-free society, the recycling rate is lower than that for steel, while demand is increasing even faster.

Interaction between demand, recycling rates and product lifespan

The extent to which needs can be met by recycling is influenced by:

- the increase in demand;
- the recycling rate; *and*
- product lifespans.

The report *'Innovationskritiska metaller och mineral – en forskningsöversikt'* (Näringsutskottet, 2022) addresses this issue. It concludes that with a normal growth in demand of 4% per year, a product lifespan of ten years and a 100% material recycling rate, recycling can only cover up to 70% of the need. For critical metals like lithium, annual demand is increasing at much more than 4%. This implies that even if the material recycling rate for lithium were 100%, the recycled material could only cover 25% of the need, again assuming a ten-year product lifespan (see also Figure 7).

As well as this, some material losses are inevitable when recycling complex material mixtures because of technical and thermodynamic limitations. While it is not possible to achieve 100% recycling of metals, there is still significant room for improvement.

Downgrading – Recycled materials often deteriorate

The use of a recycled material is determined by its level of contamination. The more advanced the properties of the material (mechanical, electrical and so on), the greater the demand for purity and precise composition. Several fossil-free energy technologies require particularly high purity in materials. Of Sweden's secondary cobalt flow, 44% is recycled, most of which comes from alloys and is then recycled into new alloys. The small amount of cobalt that is recycled from batteries is also largely used in alloys (Lindblom et al, 2023). It is difficult, and above all expensive, to purify the material enough to be reused in batteries, although this does happen on a small scale. For example, Northvolt's Revolt project has successfully produced a new battery cell from recycled batteries. In cars, there are similar challenges with high demands for pure materials. The challenges of downgrading are further discussed in the next chapter.

Scrap from industrial processes – cleaner flows

Recycling material from manufacturing by-products or surplus materials from by-products or surplus from manufacturing helps reduce waste, conserve raw materials and energy, and lessen the environmental impact of production by minimising the need for new raw-material extraction. For several reasons, recycling scrap from industrial processes is often easier than recycling post-consumer waste. It typically consists of relatively large, homogeneous quantities of material. In contrast, waste from end-of-life products is often more heterogeneous and complex, requiring more advanced techniques and methods for effective recycling.

This report does not focus on by-products from the process industry, but it is crucial that they are not overlooked in process planning.

STEEL

Steel is an iron alloy containing a certain amount of carbon. In this report, iron is categorised as a society-critical metal. Depending on the manufacturing process and the required properties, other alloying elements such as chromium, nickel, manganese and vanadium may also be included. Steel is produced either from iron ore or from recycled steel scrap, both of which are necessary to meet society's steel needs for the rest of this century (Jernkontoret, 2018a). Iron ore undergoes a reduction process to separate iron from oxygen, while steel from scrap is remelted without the need for reduction. Maximising the use of scrap is a key factor for more efficient resource use and for achieving lower emissions.

Steel scrap is collected, sorted into different quality grades, and then remelted into new steel. Sorting is crucial for optimising the use of the scrap's alloy content, and is expected to become even more important in the future with the introduction of more specialised steel grades. A specific challenge is the increasing copper content in the steel cycle, as copper adversely affects steel properties. Although technologies exist today to separate high-copper-content scrap, they are not economically viable. As a result, the automotive industry cannot yet achieve a fully circular flow, meaning that car scrap is not recycled into new steel for new cars. Instead, the material is downgraded and used in other sectors. In contrast, advanced techniques are used to separate different aluminium alloys, with aluminium's higher price making it feasible to utilise more sophisticated sorting methods.

Approximately 75% of all steel products ever manufactured are still in use, with the average lifespan of steel products being estimated at around 30–40 years. Forecasts indicate that steel production in 2050 will be about 50% higher than current levels. While the increase in steel demand is likely to be met by scrap-based production, ore-based steel production will still be necessary for a long time (Jernkontoret, 2018a). In addition, steel recycling generates some by-products, and the steel industry has long been working to develop these for use in other parts of society as a means of contributing to more efficient resource use (Jernkontoret, 2018b). However, there is still potential to explore whether a greater proportion of the critical-metal content can be recycled from these residual flows. Projects are already under way to develop a method for extracting vanadium from the slag produced during steelmaking (Jernkontoret, 2013).

Figure 8: Forecast for steel demand and the proportion of scrap-based versus ore-based production. Source: The steel scrap age, Pauliuk et al, 2013.

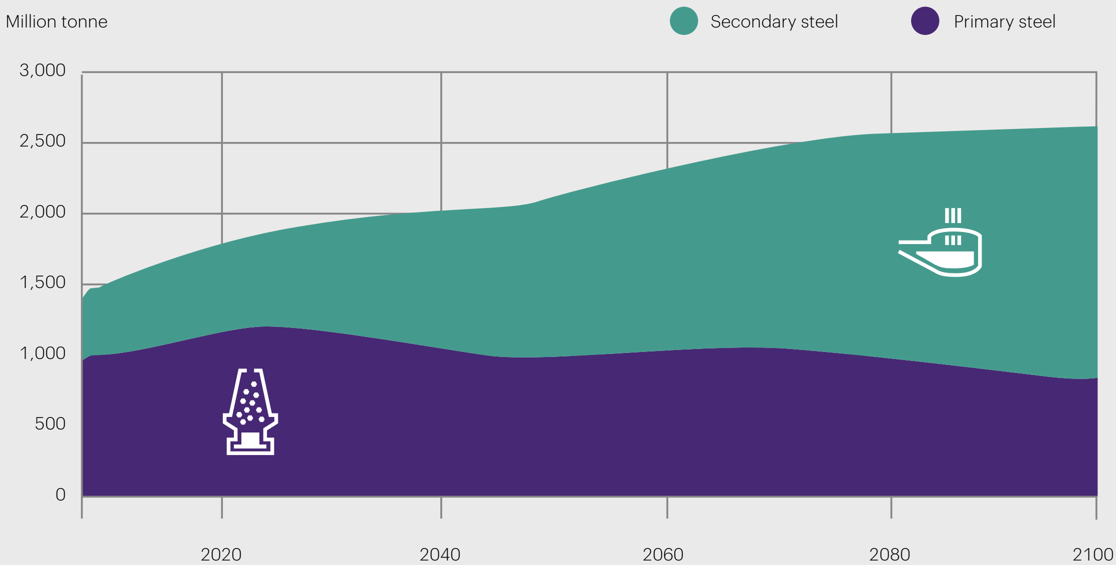


Table 2: Examples of regulations affecting circular materials and product flows.

Regulation	Content	Status
EU Circular Economy Action Plan (CEAP)	The action plan supports the EU's climate neutrality goal for 2050. It outlines various measures to create a clear and consistent foundation for product policy, making sustainable products, services and business models the norm. Batteries, vehicles and electronics are identified as key product value chains.	The EU's second circular economy action plan was adopted on 11th March 2020.
EU Critical Raw Materials Act (CRMA)	The aim of the act is to increase and diversify the supply of critical raw materials in the EU, and to enhance circularity. It sets ambitious benchmarks for the proportion of the EU's consumption of strategic raw materials that should come from recycling. (See info box to the right.)	Entered into force on 23rd May 2024
EU Emissions Trading System (EU ETS) and Carbon Border Adjustment Mechanism (CBAM)	Planned tightening (reductions of the emissions cap) of the EU ETS, combined with the CBAM regulation, raises the price of carbon emissions, which can favour recycling over primary extraction. The CBAM regulation ensures that emissions from certain carbon-intensive goods imported into the EU are priced the same as those produced within the EU.	Decisions on changes to the EU ETS were made on 25th April 2023. On 17th August 2023, the European Commission adopted rules for the implementation of the CBAM transition period, from 1st October 2023 to 31st December 2025.
New EU Battery Regulation	The regulation aims to promote a circular economy and improve the environmental and social sustainability of batteries throughout their life-cycle. It mandates transparency and traceability of batteries, as well as the increased use of recycled materials (quota obligations).	Entered into force on 17th August 2023, and applied from 18th February 2024. Many requirements and targets will take effect later. Delegated acts, known as implementing acts, will be established over time.
EU Taxonomy Regulation	The framework sets criteria that must be met for an economic activity to be considered environmentally sustainable. This aims to direct investments towards environmentally friendly projects and activities.	Adopted in June 2020. Delegated acts are established over time.
EU Waste Electrical and Electronic Equipment (WEEE) Directive	There is a proposal for a new waste-shipment regulation aimed at strengthening the control of waste shipments and increasing digitisation. The proposal mentions that limiting the ability to export waste from the EU can contribute to increased circularity within the EU as the waste remains within its borders.	There is an existing directive, but updates are under way (end date unclear).
Forthcoming EU Regulation on Circularity Requirements for Vehicle Design and End-of-Life Vehicle Management	The regulation will replace, among others, the ELV Directive (Directive on end-of-life vehicles). The proposal covers all aspects of a vehicle, from design and market placement to end-of-life treatment. It proposes rules to improve the design and facilitate the removal of materials, parts and components for reuse and recycling, as well as requirements for exporting used vehicles from the EU to third countries. It also proposes reporting requirements for recycled materials in cars, and minimum levels for recycled plastics. (Minimum levels for metals may be introduced after the regulation's implementation.)	A proposal exists, likely to be finalised in 2024 or 2025.
EU Corporate Sustainability Reporting Directive (CSRD)	Aims to improve corporate sustainability reporting, including increased transparency and more comparable reports. This includes impacts on biodiversity and the amount of recycled materials used by companies. The financial reporting standards will drive the standardisation of all input data.	Comes into effect in 2024.
EU Proposal for Eco-design requirements for Sustainable Products (ESPR)	A framework regulation that will eventually include delegated acts with product-specific requirements related to circularity. It also includes proposals for digital product passports. This replaces the current Eco-design Directive. (See info box to the right.)	Entered into force on 18th July 2024

THE EU'S CRITICAL RAW MATERIALS ACT (CRMA)

The new Regulation emphasises circularity as a crucial aspect of securing access to critical and strategic raw materials (European Parliament, 2023).

- The overarching benchmark for circularity is that by 2030, 25% of the consumption of strategic raw materials should come from recycled materials within the EU.
- Significant improvements in the recycling of all strategic raw materials from waste are to be achieved within the EU. Specific targets for recycling rates of strategic metals from waste streams with sufficient data are expected by 2027.
- The Commission and Member States should also act to promote technological development and resource efficiency to reduce the anticipated increase in demand for critical materials.

Innovation is highlighted as a prerequisite for achieving these goals. In addition, permanent magnets are identified as a priority product, subject to requirements such as providing information on the content of selected materials, and forthcoming quotas for the proportion of recycled content. For the strategic raw materials consumed within the EU, the targets also include that 10% should be mined, and 40% processed within the Union, with no more than 65% of each strategic raw material being imported from a single country. The regulation includes measures such as national programmes for basic geological mapping, and the possibility of applying for designation as a strategic project with time-regulated permitting processes.

ECO-DESIGN FOR SUSTAINABLE PRODUCTS REGULATION, ESPR

The Eco-design for Sustainable Products Regulation (ESPR) came into force on 18th July 2024. The regulation will replace the old Eco-design Directive, which only covered energy-related products. The ESPR is part of the Sustainable Products Initiative (SPI), and is one of several proposals aimed at aligning companies with the Green Deal ambitions and the EU's sustainability goals. The objective is to raise sustainability standards for products and goods sold or released on the European market (with some exceptions). The regulation sets high requirements for product lifespan, and mandates that products be more easily repairable, upgradeable and recyclable. Based on the sustainability and circularity aspects outlined in the Circular Economy Action Plan, the requirements will be further developed by the Commission through delegated acts.

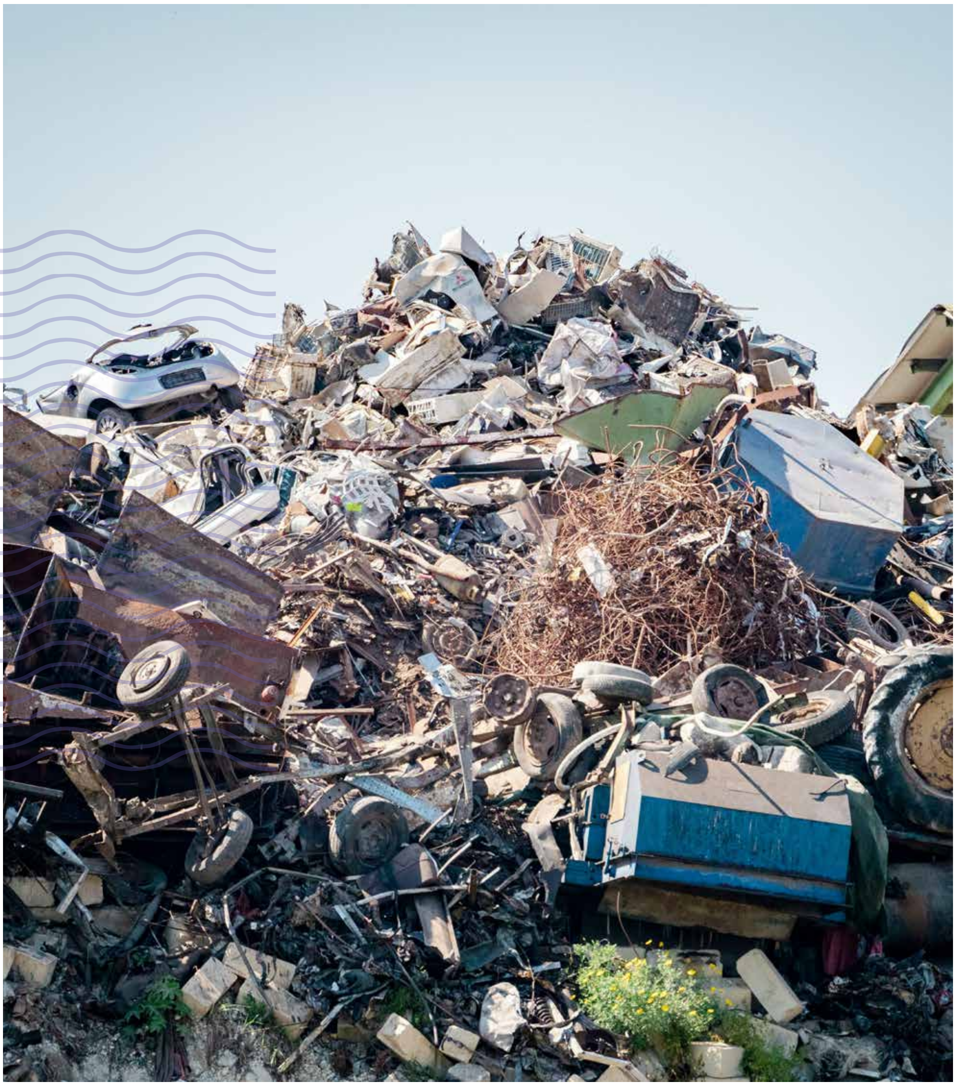
The ESPR also includes requirements for digital product passports, containing reliable data about a product to support sustainability, promote circularity and strengthen legal compliance. These product passports aim to increase transparency and help consumers to make more sustainable choices. Specific regulations for different product groups will be developed through delegated acts that set eco-design requirements for each product. The process will start with a prioritisation exercise, followed by the publication of a working plan that outlines the products and measures to be addressed under the ESPR over a specific period. Stakeholder input will be gathered through an Eco-design Forum. (European Commission, 2024c)

It is crucial that the legislation and the upcoming acts are coherent with other regulations and directives. Decision-makers play an important role in this process. They can also support dialogue between various market actors.

Developments in the EU and Globally

Several newly introduced or forthcoming regulations directly or indirectly impact circular material and product flows, and consequently the availability of metals and minerals. These regulations emphasise various aspects such as climate impact, access to critical raw materials, eco-design, batteries, waste management and more. Table 2 provides some examples of these regulations.

Even outside the EU, there are increasing demands for greater circularity and reduced environmental impact. China is implementing requirements for life-cycle assessments (LCAs) on cars (China Automotive Technology and Research Center Co. Ltd, 2022). In the USA, California is leading with requirements for companies to report direct greenhouse-gas emissions within their own production (scope 1), emissions from consumed energy (scope 2), and soon for greenhouse-gas emissions that occur in a company's value chain but which it does not own or control (scope 3).



5. Challenges

»Today, many products are designed without considering the circular economy and its strategies.«

Profitability

Lack of profitability is a recurring theme in challenges to achieving circular material and product flows. According to the expert group's analysis, poor profitability has several root causes:

- The principle of ‘polluter pays’ does not work. Societal and environmental costs of finite resources and emissions are not reflected in the pricing of materials and products;
- Legislation and infrastructure for handling used and end-of-life products are not adapted to a circular economy;
- Recycling systems are small-scale compared to the production of primary raw materials. This challenge becomes especially evident for critical raw materials, which are often used in low concentrations across many different products;
- Society has not invested sufficiently in research and development in secondary material and product streams as, for example, in method development for recycling critical metals and minerals efficiently; *and*
- Existing producer-responsibility systems are cost-neutral for producers, regardless of whether the product is designed to facilitate circularity or not.

There are exceptions and good examples where circular flows are profitable. Materials recycling is influenced by factors such as the price of raw materials, volumes, the cost of disassembly and separation, and the available recycling technologies. For repairs and remanufacturing, the new price of a product needs to be compared to the cost of repairs and remanufacturing in terms of labour and spare parts. High material or product values, and low costs for quality assurance, are therefore advantageous for circular flows. For example, a high-quality computer or mobile phone can be profitable for reuse companies to repair and resell. In terms of materials recycling, it becomes profitable for valuable metals with well-developed recycling techniques, such as gold, copper and iron (steel). Larger volumes provide economies of scale, which also increase profitability and thereby enhance materials recycling.

For certain specific materials, it can even be profitable for companies to establish their own recycling loops to ensure the quality of the recycled material. For example, Sandvik has initiated a buy-back programme for recycling tungsten from its drill bits (Sandvik, 2023). However, it is often too costly to build proprietary systems for retrieving products, sorting, and developing new processes to recycle a number of metals to a high quality. The capital investment for a new facility with better performance often struggles to compete with the costs of depreciated existing processing plants. In addition, it can be challenging to achieve the scale needed for profitable materials recycling without downgrading.

THE POLLUTER DOES NOT PAY ALL COSTS

The societal and environmental costs of finite resources and emissions are not reflected in the pricing of materials and products. This issue is highlighted by Tillväxtanalys in the report *‘En resurseffektiv och konkurrenskraftig metall- och mineralnäring’* (2023a). The pricing of emissions, and their impact on nature, has been a long-standing topic in economic debate. The entire Emissions Trading System (ETS) is based on creating a price for carbon dioxide emissions that better reflects the actual cost.

COSTLY SEPARATION CONTRIBUTES TO DECREASED RECYCLING

A car contains over 50 metals (Ortego et al, 2020), but in terms of weight, mostly steel, aluminium and copper are recycled. For recycling a higher proportion of the critical-material content to be profitable, the components must be easy to separate, and there must be a demand for the material. For example, extracting permanent magnets (which contain rare-earth elements) from the motor of an electric vehicle is complicated and time-consuming, and is therefore costly. See also the info box on page 22.

Steel is a material with a high recycling rate, but it faces challenges with downgrading (reduced quality) due to contamination. The degradation of material (degree of contamination) is influenced by the feasibility and cost of separating the materials. Although copper degrades the quality of steel, it is not profitable to dismantle circuit boards and all the wiring from a scrapped car to achieve a lower copper content in the fragmented scrap.

Profitability can also vary among different actors in the system. The actor who needs to make the most significant changes to create or contribute to circular flows, such as the one designing and selling products, currently may benefit the least from it.

Product design does not promote circularity

Today, many products are designed without considering the circular economy and its strategies for long lifespan, reuse, high utilisation rates, sharing, remanufacturing and recycling. These products can be difficult to disassemble, making repairs challenging. The design can also make it time-consuming and costly to sort and separate materials into pure fractions for recycling. Innovation in new materials is typically driven by the desire to increase performance and reduce costs, without accounting for recycling rates or the ability to use recycled raw materials in performance

CIRCULAR DESIGN, BUSINESS MODELS AND SYSTEMS

The circular economy provides strategies for companies to enhance resource efficiency practically by extending the lifespan of products, components and materials. This can be achieved through repair, reuse and remanufacturing, and by designing for efficient materials recycling. Effective product and material flow in a circular economy depends heavily on product design. The design should align with a company's circular strategy for a product. In addition, that product's design should integrate with the company's business model, and with the system in which it will be used.

The contribution of products to a circular economy can be analysed from three dimensions: product design, its business model, and the system of processes and legislation that affects the product (Stena Recycling, 2024).

Companies with a linear business model may find it difficult to justify investments in aspects such as longer lifespan and increased repairability. A revised business model, with a greater focus on service and the function that the product delivers, can enable and motivate a more sustainable design.

Deposit systems and returnable bottles exemplify effective business models that incentivise customers to return products. This approach creates a return flow of products to manufacturing, leading to economies of scale and increased profitability. Another business model that encourages product returns is "trade in the old one for a discount on a new one". In addition, sharing solutions represent another strategy to reduce resource consumption.

Functional sales involve selling the service or function a product provides rather than the product itself. This shift in focus moves a company from selling new products to offering long-term utility and functionality. Such a model increases incentives for extending product lifespan.

Company purchasing departments play a crucial role in boosting the use of recycled materials and remanufactured components and products. To facilitate this transition, it helps to have policies aimed at enhancing the use of recycled raw materials and the development of skills within the purchasing organisation.

optimisation. Not only should design align with the intended circular strategy, but all products should aim to be technically feasible and cost-effective to recycle, as they will eventually reach the end of their lifespan and need to be recycled for use in new applications.

In addition to the design itself, supportive business models and systems for handling a product at the end of its life are often lacking, even if the design promotes circularity. Most products are still designed, produced and sold for a single use cycle, and the eco-systems for large-scale remanufacturing, reuse, repair and sharing are often inadequate. Service-based business models involve shifting capital investment from one actor to another, and increase the financial risk for the company that transitions to a service-based model. Read more about circular design, business models and systems in the info box.

Interest and understanding of circular design are increasing, as are positive examples within the industry. Despite this progress, much work remains to be done.

The expert group concludes that expertise and research are limited in several key areas that are needed for the transition to a circular economy. These areas include circular design, circular business models, behaviour changes, material optimisation, logistics solutions, disassembly/separation techniques, maintenance for extended lifespan, automated and faster life-cycle analyses, and traceability throughout the value chain and over time.

Obstacles to increased product lifespan

Extending the lifespan of products, thereby reducing the need for new materials, offers significant environmental benefits (ADEME et al, 2022). However, there are obstacles. Market failures, such as the societal and environmental costs of finite resources, and emissions not being reflected in pricing, make it difficult for companies to achieve profitability in reuse and remanufacturing. As mentioned above, repairing products is often too expensive, despite being environmentally beneficial. Many products are simply not designed to facilitate this.

IT equipment, along with other electronics, contains many EU-critical metals, making it an important product category for extending lifespan. Sweden's chemical tax complicates circular solutions for IT equipment. Companies that import used IT equipment for upgrading, and then selling or leasing it, face increased costs because of the tax. This has been highlighted by the Swedish Environmental Protection Agency, along with several other shortcomings related to the tax's objectives (Naturvårdsverket, 2022).

It is also challenging to get national authorities to include requirements for procurement processes to include circular solutions, as well as to change people's behaviour and preferences to favour reuse.

Producer responsibility can also pose a challenge if products are to have longer lifespans and be used in new applications. The responsibility must be able to be shared or transferred if the product changes its area of use. For example, it is not reasonable for a car company or a car dismantling firm to have producer responsibility for batteries that are remanufactured for stationary applications in the power grid. Since the battery is not designed for that application, battery aging can change, and warranties cannot be given. It is important that legislation is adapted for this. In the EU's new Battery Regulation, ownership responsibility for batteries has been adjusted to account for changes in usage. If a car battery that has become waste is reconditioned, it is considered a new battery, and the producer responsibility transfers from the entity that originally placed the car battery on the market to the company that repaired the battery and uses it in a new application. However, national interpretations of the regulation remain. For example, it is unclear if the same rules will apply to car batteries regardless of their secondary use. What happens, for instance, when a car recycler uses the battery as a spare part in another car? If a car dismantling firm alone has to take full producer responsibility for the reuse of a battery, there is a high risk that fewer car batteries will be reused.

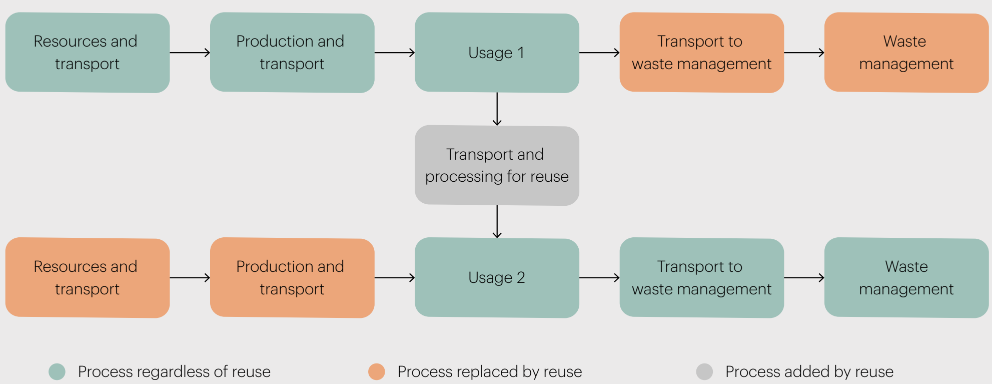
Extending the lifespan of products and thereby reducing the need for new materials often provides significant environmental benefits, but it is not a universal solution. For products used in applications where there is rapid

REUSE AND REMANUFACTURING

Reuse aims to extend the lifespan of products, often yielding significant climate benefits. Recycling the materials in a computer saves 1.44 kg of CO2 equivalents per kilogram of electronic waste, whereas reusing a computer saves approximately 280 kg of CO2 equivalents (Wranne, 2020). Globally, around 80% of a computer's or phone's climate impact occurs during production, highlighting the substantial advantages of prolonging their lifespan (Inrego, 2023). In Sweden, production accounts for an even greater proportion of the climate impact since the electricity consumed during use comes mainly from renewable energy sources (data from Inrego).

If someone chooses to buy a used IT product instead of a new one, it eliminates the need for new production. This generally results in environmental benefits, as new production consumes materials and energy, which have their own environmental impacts. In addition, transport and waste-management process requirements can be reduced or avoided altogether. However, reuse and remanufacturing do have some environmental impacts. Additional transport is needed, and the refurbishment processes, where the product is repaired or refreshed, also have environmental costs. IVL Swedish Environmental Research Institute and Inrego have undertaken a study and developed a database showcasing the climate benefits of reusing several common IT products, effectively illustrating these benefits (Wranne, 2020). See Figure 9 below.

Figure 9: Source: '*Produktdatabaser: miljöfördelar med återbruk Klimatfördelar med återbruk av IT-produkter samt metod för databasskapande*', Wranne, 2020.



technological change, it may be more beneficial for the materials to be used in a new product with lower energy losses or reduced material usage. However, this assumes that the materials-recycling process used is sustainable and efficient. (See also the info box above)

At the same time, a design that supports repairs and remanufacturing also facilitates material recycling, as the products can be disassembled more easily. In other words, there is not always a contradiction between reuse and recycling.

Technical challenges with complex materials and mixed waste streams

Sweden is better at recycling materials such as copper and iron, which have been mined here for a long time, compared to many critical metals used in lower concentrations. However, more and more metals are being used in society, and the complexity of products is increasing. The report *'Förutsättningar för en ökad återvinning av CRM i Sverige'* (Junestedt et al, 2023) specifically examined the recycling of silicon from solar panels, rare-earth elements from wind

REUSE AND REMANUFACTURING (CONTINUATION)

Example: Circular IT
Increasing reuse and remanufacturing largely involves driving behavioural changes. Electronics can be used much longer than many people realise. Forthcoming EU regulations requiring producers to support software updates and provide spare parts for longer periods are expected to contribute to extending product lifespans significantly (European Commission, 2024a).

Behaviours and attitudes have already begun to shift. For example, schools are now prepared to demonstrate their commitment to the environment by buying used computers, which also allows them to invest more in teachers. In the past, buying used items carried more stigma. It was also widely believed that it was economical to replace computers every three years, but during the COVID-19 pandemic, companies discovered this wasn't necessarily true, and many have now extended their usage from three to four or even five years (data from Inrego).

Example: Battery reuse
Similar to IT products, there are environmental benefits to extending the lifespan and reusing batteries. Reusing a battery from an electric vehicle can involve repurposing it for different applications once it is deemed no longer suitable as an EV battery (a so-called second-life application). Lithium-ion batteries retain up to 80% of their capacity at the end of their first life, making them prime candidates for reuse. The lifespan of these batteries could be further extended by deploying them in applications with lower demands for energy density and charge/discharge rates. In addition, safety risks associated with used batteries can be managed through reliable monitoring of their status. However, this approach differs from circular IT, where products are reused for the same function, thereby reducing the demand for newly manufactured IT products. By contrast, the second-life use of car batteries does not reduce the demand for new car batteries, while delaying the availability of materials for recycling.

A recent study on batteries for mining machinery (Helander & Ljunggren, 2023) highlighted the challenge of balancing the maximisation of recycled material availability with the extension of product lifespan. These batteries are rented out, and because different mining machines have varying battery requirements, a battery that has lost too much capacity for one machine can be reused in another. Eventually, these batteries can be sold for other applications when their capacity becomes too low for mining use, or when the number of reusable batteries exceeds the demand. The study showed that, after an initial period, reuse unsurprisingly reduces the need for new batteries for this type of equipment. However, when it comes to reducing the need for new raw materials, it may be more effective for the battery manufacturer to focus on increasing materials recycling rather than reuse, provided the recycling process is efficient. The less efficient it is, the more significant reuse becomes in reducing the need for new raw materials. Selling the batteries for other applications can benefit society but reduces the company's opportunities for increased material self-sufficiency. It is important to note that the study did not examine the environmental impact, but rather how different business models affect the need for primary materials in battery manufacturing. The EU's new battery legislation includes quotas for recycled material. For companies that base their business model on product service systems (PSS) and reuse, these requirements can be challenging.

turbines, and lithium, graphite and cobalt from electric vehicle batteries. Like many others, the report indicates that demand is increasing while only a small portion of these metals is currently being recycled.

Many products contain small amounts of a large number of elements. Low concentrations of elements spread across many products, and complex material mixtures, are often difficult to recycle. It is simply not profitable at the moment.

Collecting sufficiently large volumes of sorted waste containing critical metals to achieve economies of scale is part of the challenge. (See also 'A linear perspective on waste results in lower quality recycled material' on page 38 and 'Product design does not promote circularity' on page 32.)

Recycling materials from complex products requires effective collection, pre-treatment (disassembly and sorting), and final processing (chemical and metallurgical treatment). E-waste is a prime example of this complexity. The report *'Recycling and circular economy—towards a closed loop for metals in emerging clean technologies'* (Hagelüken & Goldmann, 2022) highlights the importance of collection, using the recycling of gold from electronic waste as an example. If the collection rate for electronic waste is 50%, the pre-treatment efficiency for gold is 70% and the final processing efficiency is 95%, then a total of 33% of the gold from electronic waste is recycled. According to the report, this reflects the reality in Europe fairly accurately. For gold, the efficiency in the final step is very high, whereas for other metals it is zero – they are simply not recycled.

For a complex mix of metals, there are thermodynamic limitations that prevent all of the constituents from being recycled to the same extent. The more diluted a substance is, the more energy is required to extract it. In addition, complexity affects recyclability since different processes are needed to optimise the recovery of various metals. Focusing on the maximum recovery of one metal can limit the ability to recover another, as different processes are required (Reuter et al, 2019).

In smelters processing mixed electronic waste, rare-earth elements, for example, end up in different slag phases. These can be managed with solution chemistry techniques, but this is done to a very limited extent because of the lack of profitability, small volumes, high energy consumption, lack of knowledge, and lack of equipment. The substances that remain in the slag after processing often end up in landfills. Rare-earth elements can also report to other material streams, such as contaminants in iron scrap.

Not all available methods are currently utilised in recycling. In Sweden, hydrometallurgical methods are used much less frequently than pyrometallurgy, even though institutions such as Chalmers University of Technology and Luleå University of Technology are carrying out research in this area. A lack of knowledge and the absence of facilities also pose challenges within primary flows (IVA, 2024a).

For products containing metals, such as various forms of electronics, significant product innovation can lead to more complex alloys and rapid changes in material selection. This makes it difficult and costly to adapt recycling processes in time. Technological changes can also result in the material in demand not being the one that is currently recycled. Managing this without impacting technological development is challenging. What is more, a product's contents – and hence the contents of any waste derived from it – are often unknown, further complicating both pre-treatment and final processing.

Table 3: Comparison of dedicated and general recycling systems, simplified classification.

	Dedicated recycling	General recycling
Material	Specialised in a specific material/group of materials.	Optimised for a mixed inflow of materials.
Process	Specific collection and sorting process for the material.	General collection and sorting process for the material.
End product	Focus on higher quality and purity of the end product, such as the recycling system for aluminium cans and PET bottles in Sweden.	Focus on industrial efficiency and the recycling of various materials, including the shredding of complex waste streams in large volumes, such as scrap cars and municipal waste.

A flexible and comprehensive metallurgical infrastructure, capable of handling various types of metal combinations and flows, is required in order to optimise the recycling of critical metals in the future. Product design should also be based on an understanding of metal-separation techniques (Reuter et al, 2019). The focus now should be not only on optimisation, but on initiating measures to start recycling certain metals at all. Both dedicated and general recycling systems are needed, as each has its own advantages and disadvantages (see Table 3).

There is the potential for improvement at all stages: design, collection, pre-treatment (dismantling and sorting), and final processing. However, as previously mentioned, the challenges are often system-dependent. Building more knowledge today about critical metals and recycling techniques to recover these materials, along with measures in other stages, would provide Sweden and the EU with preparedness when secondary material flows increase, or if Europe is faced with an even greater need to be self-sufficient.

Another challenge in recycling complex products is the presence of other substances that can disrupt certain processes, such as chlorides, or substances that cannot be managed and thus risk creating emissions, such as per- and polyfluoroalkyl substances (PFAS).

An immature market with low demand for recycled materials

There is a mature market and established processes for recycling metals such as iron, copper, aluminium and gold. However, the infrastructure and market for recycled lithium and neodymium, for example, are still immature and lack parts of the value chain for processing. The circular flows for components and products intended for reuse and remanufacturing are even less developed and are, in many cases, non-existent.

Using recycled materials in products also presents a challenge. Manufacturing industry currently optimises material selection based on function, quality, cost and sustainability, with few requirements for the proportion of recycled materials. In addition, purity levels cannot be significantly lowered while maintaining standards. To achieve fully circular flows, secondary materials must have the same high quality (and known content) as those from primary sources. There must also be a market for recycled materials.

Recycling targets are often set as a percentage of total weight. According to the EU's current ELV directive, 85% of a car's weight must be recycled, but the regulations do not specify which materials should be recycled or the quality those materials should achieve. Hence there are requirements on the total amount to be recycled but not on the recycling of specific materials. What is measured is the weight of the collected material sent for recycling; the efficiency of the actual process is not regulated. Neither are there quality requirements for recycled materials or standards for recycled content. The new Battery Regulation (Regulation 2023/1542) introduced requirements for the recycling percentage of specific materials. However, there is still a dilemma in that there are no requirements for the purity or quality to which a material must be recycled. The quality determines whether the material can be used for the same type of product again, or if it can only be used as a filler.

Further to that, matters are complicated by the use of different life-cycle assessments (LCAs) and standards to define recycled material and its climate impact (Ekvall et al, 2020). Depending on the chosen methods and interpretations in an LCA, the climate impact of recycled material can vary, influencing its attractiveness.

Export of waste and value chains outside the EU

Retaining materials in Europe is a challenge since, for example, companies in China often pay more than their European counterparts for battery 'black mass' (a mixture of anode and cathode materials) to be recycled. Recycled material for batteries will become a scarce resource as the requirements for quotas of recycled material increase, and it remains to be seen how material flows will develop.

In their report *'Critical Raw Materials for Strategic Technologies and Sectors in the EU — a Foresight Study'*, Bobba et al (2020) noted, amongst other things, that the recycling (collection, dismantling and final processing) of rare-earth elements from small electric motors can be improved within the EU, and that the majority of these 'scrap flows' are currently exported to Asia.

In addition, there is the challenge of illegal waste export or the export of used products that quickly become waste and are not managed in the best possible way regarding environmental impact and working conditions. It is therefore crucial to ensure sustainable and safe recycling throughout the entire value chain – from collection to final processing.

Even if the waste or products containing critical raw materials were to remain within the EU, there is currently insufficient infrastructure to process and recycle all metals, alloys and other materials efficiently from complex products. This is evident from the recycling rates of critical metals. See also 'Technical challenges with complex materials and mixed waste streams' on page 34.

At the moment, there is no comprehensive analysis of secondary flows and value chains for critical metals and minerals from a Swedish perspective. It is also challenging to obtain current statistics on recycling and material flows for many critical metals and minerals (Lindblom et al, 2023). To improve current recycling and material-flow systems, it is essential to understand where these materials are found and how they flow – both within Sweden and globally.

Another aspect highlighted in the project's first report, *'Challenges for Meeting Increased Demand for Metals and Minerals'* (IVA, 2024a), is that the EU needs to ensure complete value chains. If all obstacles were properly addressed, material recycling could contribute more to the supply of critical metals and minerals than it does today. However, there can also be vulnerabilities in the supply chain for semi-finished and finished products. Figure 10 illustrates this with the example of permanent magnets, with 94% of world production occurring in China.

A linear perspective on waste leads to lower-quality recycled material

The current perspective on waste is problematic. Sweden and the rest of the world remain largely in a linear system where waste is not viewed as a valuable resource. Many regulations in Europe focus on managing and mitigating the direct negative effects of inadequate waste management without considering circularity. Unfortunately, this often leads to materials being downgraded or falling out-

Figure 10: The value chain for permanent magnets with the geographical distribution of the different process stages. Source: Developing a supply chain for recycled rare-earth permanent magnets in the EU. CEPS In-Depth Analysis 2022 (Rizos & Righetti, 2022).

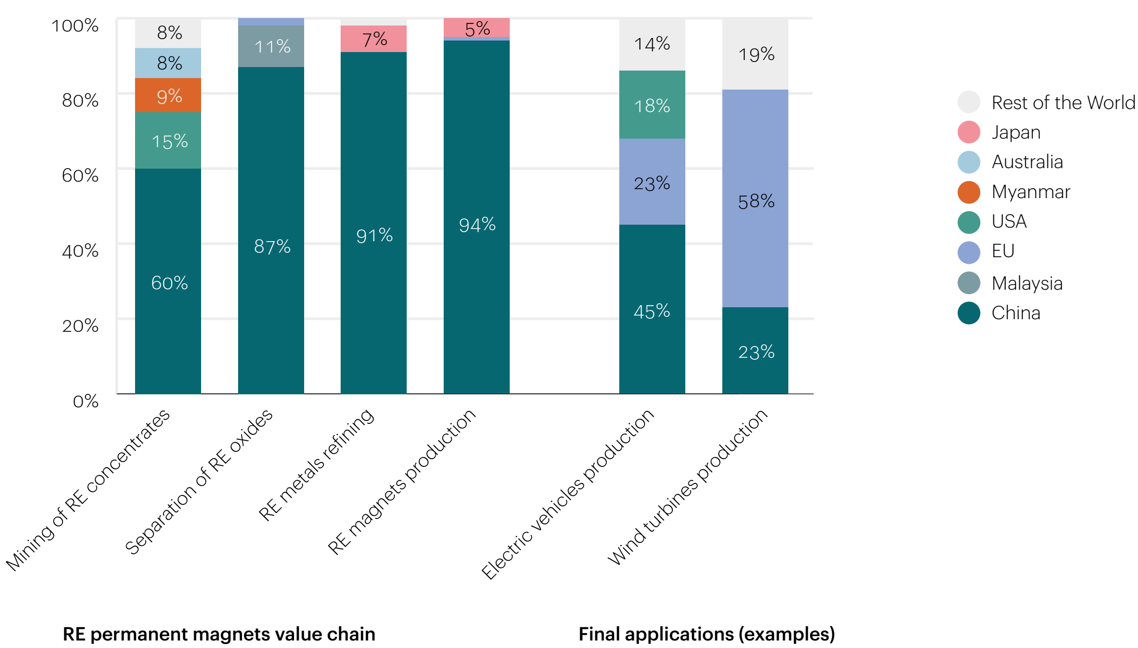
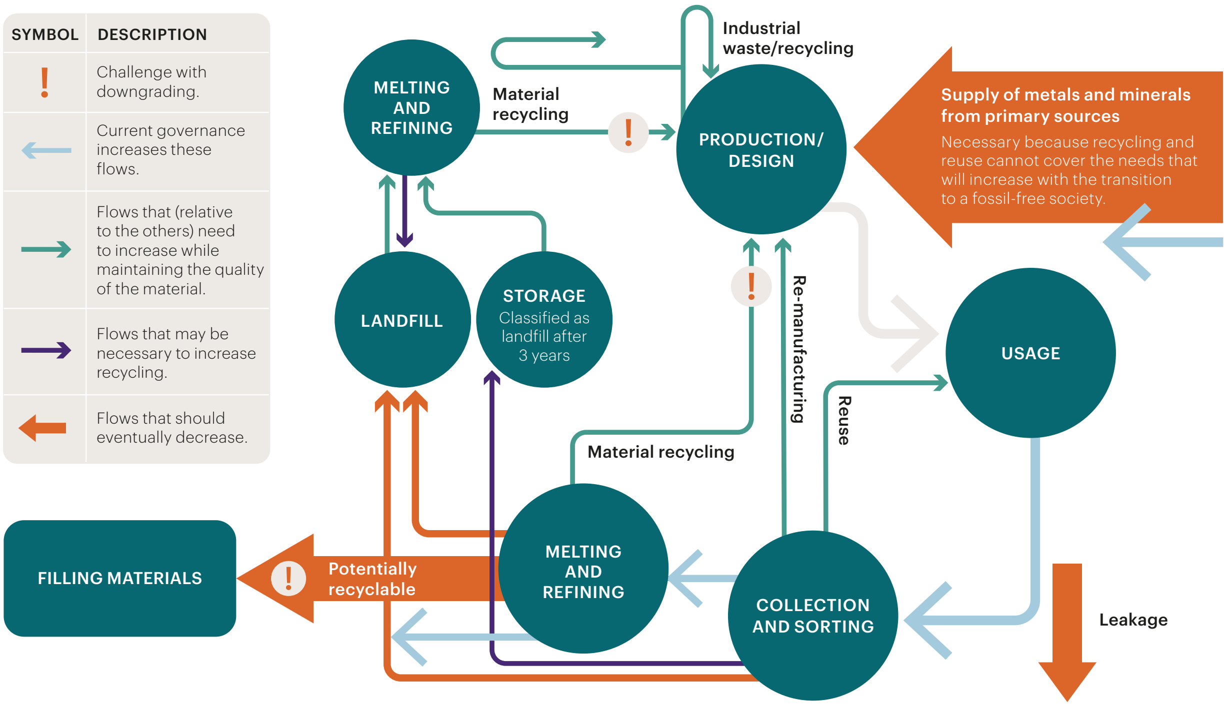


Figure 11: Illustration of system challenges. The figure was created by the report's expert group. The image is simplified, and the challenges, such as downgrading, vary significantly between different metals. In addition, there is a considerable lack of knowledge about the secondary flows of critical metals and minerals, and where they end up when not recycled.



side circular systems. There is also a lack of knowledge today about where critical metals are found in various waste streams and products. As a result, many of these metals end up in residual flows from other metal-recycling processes or waste incineration. They are then incorporated into filler materials beneath houses and roadways, and as noise barriers, or in landfill construction. When waste containing critical raw materials is deposited, it is done in a way that complicates future extraction, partly by mixing waste streams and partly due to insufficient information about where these materials have been put (Bergfald et al, 2024). No stockpiles are created to make the material easily accessible when, for example, material-recycling techniques have improved.

Figure 11 provides an overview of metal and mineral flows, and highlights the challenges in reducing the flow of potentially recoverable materials that currently end up as filler material, thereby increasing circular flows.

Not all filler materials need to be reduced, but waste that is or can become resources in the future, such as waste containing significant amounts of strategic metals, should not be locked into noise barriers, roads, building foundations or in other construction. Moving forward, the focus should be on ensuring that materials extracted by mining can be circulated as much as possible in order to reduce the extraction of finite resources in the long term, while also protecting the environment and human health during waste

EXAMPLES OF CHALLENGES

Waste transport: It took eight months for Ragn-Sells to obtain a permit to transport one ton of sewage sludge ash from Copenhagen to Helsingborg for a pilot project. The company also had to provide a bank guarantee. While the purpose of waste legislation is to ensure that waste does not end up in the wrong place, the current regulations and practices make it very challenging to develop a circular business. If the waste stream is classified as hazardous, the difficulty increases even further (information from Ragn-Sells).

Waste-classified materials: A material classified as waste cannot easily be used as a raw material in production processes because it can only be utilised by entities licensed to process waste. In some cases, waste cannot be used as a raw material in products at all, regardless of the material's quality. Recycled phosphorus is an example. The EU Waste Framework Directive (Directive 2008/98) includes end-of-waste criteria that must be met for a material to no longer be classified as waste. One challenge is that one of these criteria is the existence of a market for the material. This creates barriers for non-established secondary raw materials that could be used by customers who lack permits to handle waste. At the moment, developed criteria exist only for steel, iron, aluminium, copper and glass – all of which are traditional, mature materials with a well-established recycling industry and processes.

management. In addition, materials should not be used as fillers if there is a potential risk that they may require remediation in the future.

It is currently difficult to accumulate sufficiently large volumes, and thereby achieve economies of scale, in the recycling of many critical metals. Storing waste for more than three years may sometimes be justified for accumulating large enough quantities that could be recycled profitably without downgrading when using new methods. This could involve, for example, storing end-of-life solar panels until a dedicated facility can be built or upgraded to recycle all the materials contained in them. The biggest obstacle here is the approach to landfills and storage as a method, and more specifically, the landfill tax in Sweden. The required storage time for a material depends on its value, quantity, and the existing technology for extracting it.

Another way to achieve large volumes is by collecting and combining waste streams from a number of countries. However, regulations pose obstacles. The Basel Convention on the control of transboundary movements and final disposal of hazardous waste is part of this. The challenges are related to the definition of waste and hazardous waste, and the associated regulations. If something is classified as hazardous waste, recycling management becomes more complicated. There are also ambiguities regarding what is required for materials or products classified as waste to no longer be considered as such. While the regulations aim to prevent the dumping of hazardous waste in other countries, they also hinder circular flows. Developing legislation for the circular economy needs to be combined with considerations for environmental protection.

Recycling material from landfills and infrastructure projects

Existing landfills (excluding mining waste)

Extracting materials from old landfills (landfill mining) faces challenges because of a lack of political support, with investment in knowledge and technological innovation needed in order to realise its potential (Krook et al, 2018). The landfill tax further complicates matters. If a waste-management company wants to recover valuable metals or minerals from a landfill or from bottom ash (after waste incineration), they must pay a landfill tax when re-depositing the leftover material. By contrast, when an ore (valuable rock) is mined, leftover material can be deposited without additional cost. This approach favours primary production. If bottom ash is reprocessed into construction material for landfill covering or if old landfills are left untouched, the landfill tax is avoided. But in those cases, the opportunity to recover several critical materials is lost.

The climate impact of landfill mining varies significantly depending on the type of landfill and the technology available. It can lead to both climate benefits and net emissions. At the same time, many studies have been based on assumptions that require further investigation (Laner et al, 2016).

Old (disused) infrastructure

When underground infrastructure systems such as copper cables are decommissioned, they are usually disconnected and left in place because it is not economically viable to retrieve them for recycling. Recycling underground infrastructure is not a priority in Sweden. There are no regulations, and there is no clear allocation of responsibility. Retrieving the material can also be technically challenging, with the risk of damaging functional cables. Meanwhile, the ground is becoming increasingly filled with old cables, which poses an obstacle for new infrastructure projects.

There is also legal ambiguity surrounding the categorisation and definition of disconnected cables, which complicates the application of current waste and environmental laws. Disused cables can be interpreted as a source of pollution, as waste, as a metal resource, or as a spare part (Krook & Wallsten, 2017).

EXAMPLE OF COMPLEXITY

Impact of Different Materials: It is often necessary to balance various sustainability aspects during the design stage. The choice between aluminium and copper, for example, is complex. Aluminium has a larger climate footprint than copper, but copper has a greater ecotoxicity footprint. (Ecotoxicity measures how toxic a substance is to animals and plants in different ecosystems.) Replacing copper with aluminium in electric motors or cables requires a greater quantity of aluminium (Tillman et al, 2020). In addition, mixing steel and copper in products can lead to the downgrading of steel. The amount of copper in steel significantly affects its usability, and copper cannot be removed from steel efficiently and cost-effectively.

Design for recycling or lower weight: Utilising mono-materials in a product facilitates recycling but can increase its weight. This, in turn, can require more fuel, so resulting in higher carbon dioxide emissions. For rare-earth elements, traceability and recycling are challenging, but if they were removed from, say, an electric motor, it would become larger and heavier because more iron and copper would be needed.

Industrial machines: In theory, it is relatively simple to double the lifespan of most machines or components. However, this requires significant compromises that can impact performance and energy efficiency. If machines become larger and heavier, the energy consumption for all moving parts increases, and if they are not as efficient, more machines may be needed to complete the same task. This, in turn, can affect a manufacturer's competitiveness in the global market.

Recycling or extended lifespan: Repairs, reuse and remanufacturing often offer greater environmental benefits than materials recycling and primary extraction. Manufacturing a laptop impacts the climate with 280 kilograms of CO_2 equivalents (Wranne, 2020). Therefore, the longer a product is used, the lower the annual emissions become (Inrego, 2023). However, as previously mentioned, it is not always easy to determine whether recycling or reuse is preferable. This depends on technological development and the actual sustainability and efficiency of the materials-recycling process.

A narrow focus on a single sustainability challenge risks obscuring the overall picture

When society focuses solely on a single sustainability challenge, such as recycling or the climate impact of manufacturing, other important aspects can easily be overlooked. The desire to reduce carbon emissions through material choices can lead to increased emissions during use, or can complicate recycling. See the info box for more examples of this complexity.

However, assessing what is sustainable from a holistic perspective in all situations is challenging. The area is complex, and the decision support available to the industry is perceived by many actors as inadequate. Different priorities and assumptions about future impacts can lead to varying conclusions. Putting the emphasis on supply security and material availability instead of on climate impact can yield different outcomes.

What is considered most sustainable depends on which sustainability issues are included, the time perspective applied, and how the costs of various future environmental impacts are valued – in other words, the alternative costs being compared. These trade-offs will also evolve over time as they depend on external factors and which systems (collection, pre-processing, material recycling processes, and the energy mix, for example) are in place.

Permitting processes

Within the recycling industry, permitting processes are found to be challenging. Predicting the outcome is difficult, and there are differences in application between vari-

LIMESTONE AND CONCRETE

Forecasts generally indicate increasing demand for lime (limestone), particularly given the growing population and urbanisation in many parts of the world. Limestone is the primary raw material in cement, which in turn is a fundamental component of concrete, the most common building material today. Concrete is used not only in buildings and infrastructure but also in wind and hydropower plants. Limestone also has other applications, such as in steel production, mining, agriculture and water purification (Kihlberg & Lagnerö, 2022). In this report, limestone is categorised as a society-critical mineral.

Circular flows can play an important role in reducing the need for primary limestone. The overall demand for new construction materials can be cut by adopting circular-design principles that promote the disassembly and reuse of building materials. Concrete recycling involves crushing and treating old concrete for use as aggregate in new concrete. However, new cement is still required. One way to reduce the need for cement is to use alternative binders such as fly ash and slag from steel production (while also utilising critical raw materials). Improving design and technology is also vital in reducing overconsumption and waste in the construction process.

Political support, technological innovation and education are essential in this area as well. It is crucially important to continue fostering innovation and sustainability initiatives within the construction sector, so as to meet the growing global demand in a resource-efficient manner. At the same time, it is also important to recognise the complexity and diversity of limestone usage across different industries., Circular solutions should therefore be adapted to specific sectors and applications as a way of achieving maximum effectiveness.

The construction and real-estate sector, including construction and demolition waste, is a prioritised material flow in Sweden's action plan for a circular economy (Swedish Ministry of Climate and Enterprise, 2021).

ous counties. Extending an existing permit can also take time. Waste streams change as products continually evolve, necessitating new processes and updated permits, which can also be very time-consuming. Permitting processes is further addressed in the project's sub-report *'Increased Demand for Metals and Minerals – Strategies and Conflicts of Objectives and Interests'* (IVA, 2024b).

Regulations within the EU

There are several challenges associated with the EU's existing and forthcoming regulations in this area.

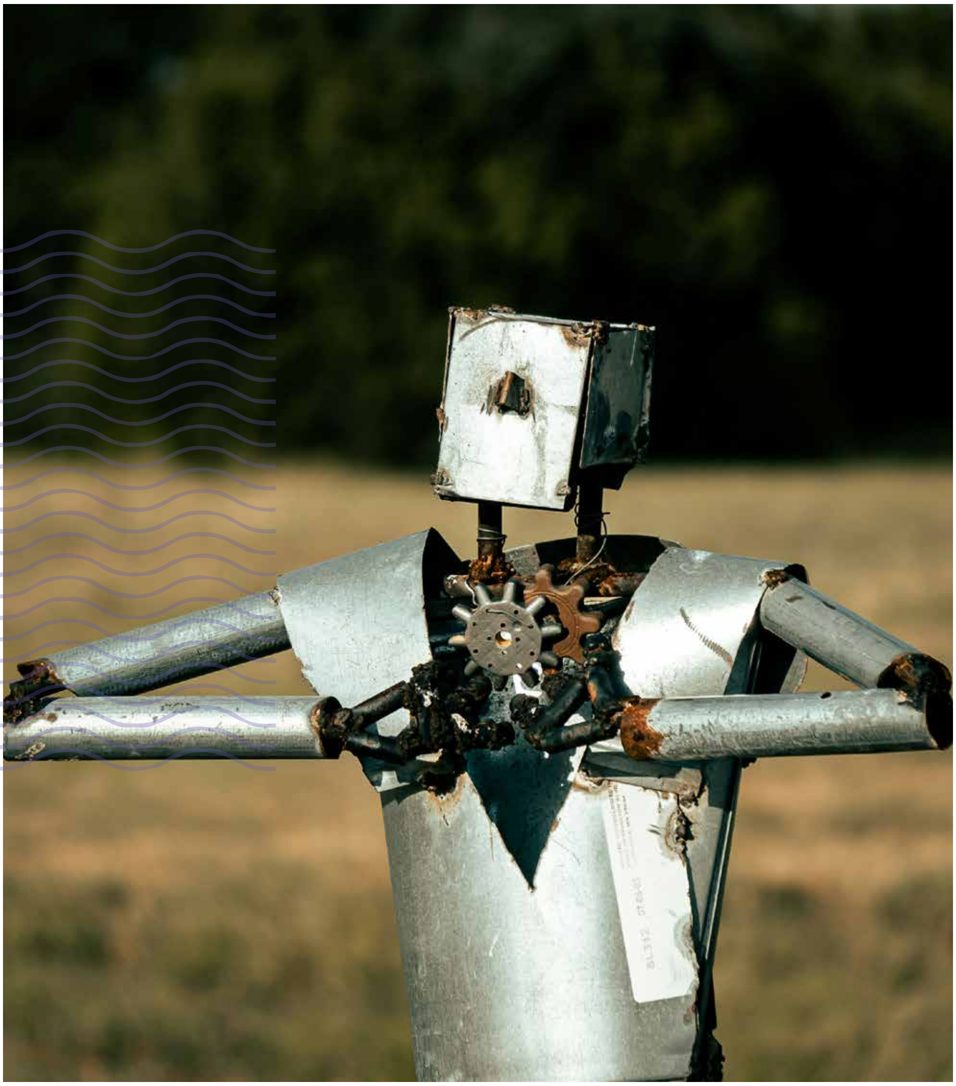
One is that negotiations on several of the regulations have not yet been completed. Even through the Eco-design for Sustainable Products Regulation (ESPR) has now come into force, much work will remain on its associated delegated acts. In other words, the specific requirements for many product groups are far from clear. It is also uncertain whether there will be requirements for reporting critical materials within the ESPR product legislation – something that would be significant for increasing their recycling. A difficult trade-off may arise between the requirements for recycled material in products, and extended product lifespan (which means that the material is tied up for longer). It is essential that forthcoming regulations and directives work in harmony. It must be easy to do the right thing.

There is also concern that the business perspective may not be included sufficiently. This relates to several different aspects:

- There is a risk of a significant administrative burden for companies. Many requirements could become so costly that they would be difficult for small and medium enterprises (SMEs) to manage (Tillväxtverket, 2023);
- There is a worry about potential leakage of trade secrets. For some companies, the product passports and transparency proposed within ESPR are particularly challenging. Its product's content may be what provides a manufacturer with a competitive edge; *and*
- There are uncertainties regarding which actor should bear which costs within a circular system.

Other important issues to address include:

- How can we ensure a level playing field globally so that companies can compete on equal terms?
- How will the holistic perspective and trade-offs between different sustainability aspects be incorporated into the regulations?
- Who holds producer responsibility in the case of reuse or remanufacturing?
- Who ensures that the recycling of exported goods takes place?



6. Recommendations

»There is a need for research and development, a new perception of waste, and updated regulations.«

Circular governance

Summary

Encourage the development of markets for recycled metals and circular product flows through the following methods:

- Prioritise general actions aimed at addressing the root causes of low circularity, such as inconsistent rules and absent or incorrect pricing of external costs. Examples of measures with a positive impact on circular flows include the EU Emissions Trading System and the EU's new Corporate Sustainability Reporting Directive (CSRD).

- Increase regulation in selected areas. A mix of policy instruments is needed within the EU to boost both the demand for and supply of recycled materials. Ensure that companies and industry organisations are included in dialogue when regulations are being developed, to secure both competitiveness and progress in circularity.

- Develop long-term strategies and support that reduce uncertainties and risks for different actors in the transition to circular business models and the recycling of critical metals. Invest in support for the implementation of new business models/processes and pilot plants to increase the recycling of critical raw materials.

- Invest in standardisation efforts within established industrial forums to promote circular flows. Standardisation work is essential in many areas, for example, in relation to the new EU Regulation on Circularity Requirements for Vehicle Design and End-of-Life Vehicle Management, which includes reporting of recycled materials. Since current standards do not define how to calculate the amount of recycled material in a uniform way, new legislation needs to clarify this. There is also a need for material standards to which both the processing and recycling industries can relate. Another area of focus is to ensure that product standards allow for recycled materials.

- Simplify reuse and remanufacturing by, for example, removing Sweden's chemical tax on imported used electronics. Repairability requirements should be imposed for more products within the EU, and there needs to be increased circularity in public procurement in Sweden. Investigate and implement various ways of reducing costs for companies that extend the lifespan of different products through, for instance, repairs and remanufacturing.

Legislation and regulations

Legislation on circularity should be as general and consistent as possible, both within the EU and globally. Stakeholders across the value chain should be empowered to address specific issues independently, provided that recycling or reuse is economically viable.

Good examples of general measures include the EU's Emissions Trading System, which raises the cost of greenhouse-gas emissions and is thus expected to stimulate circularity. Another general measure is the EU's new Corporate Sustainability Reporting Directive (CSRD), which benefits stakeholders using more recycled materials in their value chains by highlighting this in their annual reports.

In certain areas, increased government intervention is necessary to establish markets for circular material and product flows. A blend of policy measures is needed to ensure that the demand for recycled materials increases in tandem with supply. Policies that support improved collection, disassembly and separation should be combined with those that boost demand for secondary materials. Producer responsibility currently focuses primarily on collecting waste from products placed on the market rather than ensuring the use of recycled materials in new product manufacturing. A report from the Swedish Environmental Protection

Agency (2020) indicates that many existing producer responsibility systems do not offer adequate incentives for designing recyclable products. For this reason, existing producer responsibilities and their objectives should be reviewed and adjusted to create EU-harmonised incentives for design that foster circularity. Different solutions will be needed for various types of goods and services. In addition, political governance plays a crucial role in improving the flow of information within markets for secondary materials.

Insights from the new Battery Regulation can and should be applied in the development of regulations for new product groups. In addition, there are valuable lessons to be learned from the historical evolution of metal scrap markets, and of research on political governance in the environmental and natural resource sectors. For instance, focusing on products rather than materials is more effective, and a range of issues and barriers need to be addressed with greater precision (Tillväxtanalys, 2021). See the info box on policy instruments and incentives to the right for more information.

Areas that require stronger governance

More specific political governance is needed in the following four areas:

1. Circular design, recyclability and transparency
Products containing critical raw materials must be repairable and recyclable. Companies need to optimise materials and products to ensure they can be repaired, reused/refurbished and recycled. The design should align with the specific circular strategy being implemented, but all products must be recyclable. When developing a new material, manufacturers must ensure it can be recycled. Examples of practical measures could be that:

- a content declaration (product passport) is applied to the product, similar to the energy label on white goods. Instead of energy usage, it details material choices, such as the content of EU-defined critical materials, the proportion of recycled materials, reparability, and more. Product passports can increase knowledge about material flows, improve conditions for repairs and recycling, and enhance transparency for customers. The product passport should include a comprehensive content declaration and be partially confidential to protect companies from plagiarism. If certain substances are later deemed particularly strategic, capable of causing harmful emissions, or disrupting specific recycling processes, the confidentiality for these substances should be lifted.

- recyclability is ensured through clear, concrete and standardised requirements that can be tracked within the various sustainability reporting standards currently under development (such as the European Sustainability Reporting Standards (ESRS), Science-based Targets and others). This monitoring would enhance the availability of recycled materials.

The ESPR legislative proposal on eco-design requirements for sustainable products includes digital product passports.

2. Recycling rates for specific metals in products, and improved quality of recycled material
It is insufficient to set targets or requirements where the recycling rate is defined solely as the proportion of recycled material by the total weight of the product. Shifting to more metal-specific recycling targets for products would enhance the recycling of several critical metals. This approach is increasingly being incorporated into new EU legislation, such as the Battery Regulation.

There is also a need for regulations to enhance the quality of recycled materials and prevent downcycling. One approach to achieve this could be the development of material standards that increase the availability of high-quality recycled materials.

At the same time, the challenge of increasing complexity must be addressed. Products' complexity grows as they evolve, complicating materials recycling. Resource-efficient design is essential, but to achieve circular material flows without downcycling, complexity needs to be reduced while new recycling technologies are developed and other obstacles are addressed. There is no simple solution, and the Swedish Government can assist by enhancing research

POLICY INSTRUMENTS AND INCENTIVES

In developing and sometimes non-existent markets, it is important to create the right incentives for stakeholders. Policy instruments are complex, and the goals being pursued are not always clear-cut. The design of these goals is critical. Policy instruments should be effective, cost-efficient, feasible, and stimulate technological development. In addition, there must be mechanisms to monitor regulations and ensure compliance. The geographical aspect is also central. Ideally, many policy instruments should be implemented at a global or at least European level, although this is often challenging to achieve in practice.

In its report *'Metallåtervinningens ekonomiska marknader'* (2021), Tillväxtanalys highlights five general lessons for policy: :

- A product focus is needed rather than a material focus. Policy needs to find the balance between measures that improve product design to enable circularity, and measures that improve waste management.
- A mix of policy instruments is needed. There are many different types of barriers, but there is no universal solution that overcomes all of them. The various barriers must be addressed in the most targeted way possible.
- The absence of policy instruments can also create incentives. Voluntary agreements and business models can overcome obstacles unless there are regulations and policies that hinder this. For example, steel scrap recycling has developed over a long period. Voluntary agreements and cooperation exist for catalysts (the chemical and automotive industries) where the industry retains ownership. Consumers may also be willing to pay a premium for recycled materials. Conditions for voluntary agreements are easier in business-to-business (B2B) than in business-to-consumer (B2C) contexts.
- Traditional environmental policy can be the best solution in some cases. More efficient carbon pricing, especially at a global level, will benefit metal recycling.
- The development of new technologies and systems requires targeted policy, partly due to the high investment risks. The state's role here can be to support R&D and innovation, and to stimulate stakeholder collaboration. Policy needs to be based on both technology-neutral and technology-specific instruments.

Source: Tillväxtanalys, 2021

in this area. Hopefully, the next generation of products will be both simpler and better.

3. Proportion of recycled material in new manufacturing

Targets for the proportion of recycled material in products are necessary, but these levels should also be based on factors such as supply, demand, product lifespan, and the climate impact of production. The new Regulations for batteries (Regulation 2023/1542) and vehicles (forthcoming) include quotas for recycled material, sparking entirely new discussions within industries that now need to address this issue, even during periods when the price of primary raw materials is low. This increases the demand for high-quality recycled material and creates incentives for circular design and clean fractions.

4. Ban on certain products

Restrictions may also be necessary for certain products that disrupt recycling processes, such as single-use items with built-in batteries or protective layers of fluorinated plastics.

Discussions on increased regulation in these four areas are already under way within the EU. It is most important that Swedish politicians actively participate in shaping these regulations at a detailed level, and support dialogue between various stakeholders, both before decisions are made and during implementation..

Risks to consider

The EU can lead developments in this area, but at the same time, the Union's manufacturing industry may face reduced competitiveness if requirements differ significantly from those of competitors outside the EU. Equivalent circularity requirements should therefore apply to products imported into the EU, and there should be a plan to ensure compliance. National regulations must also be harmonised in order to create a level playing field for companies within the Union.

Various issues related to trade secrets and circularity should also be addressed when designing regulations, and it is essential to involve relevant companies and industry organisations in this process. At the moment, legislative initiatives in a number of areas are impacting circular flows. This can lead to conflicts of interest, such as between extending product lifespan and meeting quotas for recycled material in new production, or between chemical legislation and recycling targets. It is important to manage these conflicts to ensure that the conditions for circular solutions are not compromised. See also the section "The need for a holistic perspective" on page 51.

Need for transformative measures

Major transitions require long-term strategies and government investment to reduce the uncertainties associated with risk-taking. This approach encourages companies to invest in and transition to circular business models, and to develop recycling for society-critical metals and minerals from various product streams. Long-term commitment is essential, as the lead times for new processes and facilities extend over several electoral terms.

Many initiatives require substantial investment. To support these efforts, the government can facilitate technology development, including demonstration and development projects. One example is Stena Recycling's facility for recycling lithium-ion batteries in Halmstad, which received partial funding from the Swedish Energy Agency.

Tillväxtanalys (2023b) notes in its report *'De ekonomiska förutsättningarna för primär och sekundär metallproduktion'* that during the period 2007–2022, secondary metal production received significantly less support for research and innovation compared to primary metal production, both relatively and in absolute terms, and has therefore been disadvantaged. Increased investment in secondary production should occur alongside strengthened support for the primary production of critical metals and minerals. Both secondary and primary production are essential for Sweden and Europe to secure in a sustainable way long-term supplies of the metals and minerals needed for the transition to a fossil-free society.

Small and medium-sized enterprises may also require specific support or simplified regulations to meet new requirements associated with the forthcoming product passports under the ESPR. This includes covering costs for investment in skills development and IT systems (Tillväxtverket, 2023).

It is essential for various sectors to engage in circularity efforts. The IVL Swedish Environmental Research Institute highlights in the report *'Förutsättningar för en ökad återvinning av kritiska råmaterial i Sverige'* (Junestedt et al, 2023) that there is a lack of dialogue between producers and recyclers, and between recyclers and policy-makers. The government can play a major role in facilitating this dialogue.

Financial support is essential if the recycling target set by the EU's Critical Raw Materials Act (CRMA) is to be met. The goal is for 25% of the consumption of strategic raw materials to come from recycled materials within the EU by 2030. As previously noted, the recycling rate for several strategic metals is currently very low. Given that consumption of these materials is increasing while they are being locked into long-life products, achieving this becomes even more challenging.

Proposals for national measures:

- Allocate a 'Circularity Billion' in Sweden's Research and Innovation Bill, which sets out the government's long-term policy framework for research, innovation and higher education.

- Implement a 'Circularity Leap' like the ones existing for industry and climate.
- Undertake a government investigation to review the existing support system for industrial investments. Recycling initiatives currently struggle to receive support because, although they reduce primary extraction elsewhere, they do not reduce greenhouse-gas emissions within Sweden's borders. Consider introducing a time-limited production subsidy for the recycling of particularly strategic materials.

In parallel, increased initiatives are needed within the EU as these challenges must be addressed collectively. Proposed actions:

- Enable the industrially profitable recycling of critical metals and minerals through financial incentives during the development phase.
- Facilitate waste transport within the EU to allow for large-scale and cost-effective solutions.
- Stimulate the commercialisation and scaling-up of R&D related to circularity.

Repair, reuse, and remanufacturing

There are often significant environmental benefits associated with extending product lifespan, reuse and remanufacturing. Obstacles to these practices should therefore be addressed promptly. Regulations that hinder reuse and remanufacturing should be revised. This could include removing the chemical tax on imported used electronics, imposing EU-wide requirements for the repairability of more products, and incorporating more circular criteria in public procurement.

There is also a need for efficiency improvements and policy measures to make repairing and reuse economically viable for businesses. Potential tools include reduced employer payroll taxes, VAT exemptions, or deductions similar to the ROT scheme (a tax deduction for certain types of construction work in Sweden) for specific business-to-business activities. Like recycling, reuse and remanufacturing become easier if they can be done on a larger scale.

To stimulate remanufacturing, producer responsibility needs to be transferable or shared when products change their use. Swedish politicians can lobby for this within the EU by ensuring it is clearly defined in new product legislation. Regarding the Battery Regulation currently being implemented, the Swedish Environmental Protection Agency should (in consultation with its European counterparts) promptly resolve the remaining issues concerning producer responsibility for reused batteries. This should also be done in dialogue with the industries or sectors involved.

Regulations and the perception of waste

Summary

Change the perception of waste so that it is treated as a valuable resource. Facilitate recycling companies in collecting larger volumes of waste and recycling from landfills, and create incentives for recovering old infrastructure.

The need for large volumes

To remove barriers to circular flows, the perception of waste must change so that it is treated as a valuable resource. This new perspective must then be reflected in regulations. Large volumes of material flows are essential for efficient and profitable recycling that avoids material downcycling. To achieve this, regulations should facilitate the collection of larger volumes of waste.

Current regulations exist for a reason. Changes therefore need to be combined with requirements and supervision targeted at unscrupulous actors, without creating difficulties for legitimate ones.

The expert group has identified the need for changes in the following areas:

- Landfills and landfill tax: Allow waste to be stored where larger volumes are required in order to achieve cost-effective material recycling.
- Transport of waste: Advocate for simplified administration for transporting waste across borders within Europe, and for coordination with nearby geographic regions, such as the Nordic countries.
- Definitions and classification of waste: Update end-of-waste legislation to facilitate the use of waste as a raw material.
- Waste legislation and its implementation should also be harmonised within the EU and the Nordic countries to increase predictability.

These changes would mean that:

- Waste-management companies can transport and consolidate the handling of certain types of waste at specific facilities more easily, thereby achieving economies of scale.
- The recycling industry can maintain inventories of sorted materials and concentrates, which can be stored for future processing when the volume, technology and market conditions are favourable. This could also help to stabilise price fluctuations in raw materials.

Exemptions from the landfill tax have been previously investigated, but as highlighted in the report *'Hållbar utvinning och återvinning av metaller och mineral från sekundära resurser'* (SGU & the Swedish Environmental Protection Agency, 2023), no study has been commissioned to carry out a comprehensive evaluation of the landfill tax's environmental impact and socio-economic efficiency.

As well as this, EU waste codes should be reviewed (Decision 2000/532). Supplementary waste codes could be a viable solution to ensuring that waste containing critical raw materials is directed to the appropriate recycling processes. As the current waste codes are primarily designed for safe disposal rather than materials recycling, they are often too general.

Existing waste landfills

Political support, investment in knowledge, and technological innovation are needed to improve landfill recycling concepts. It is crucial that landfill recycling/landfill mining is acknowledged as a viable option for landfill management within the EU (Krook et al, 2018). Certain landfills should be prioritised based on their climate impact, and guidelines for this need to be established (Laner et al, 2016).

From this perspective, the landfill tax also needs to be revised to allow valuable materials to be extracted and the remaining waste to be redeposited without taxation. Under current legislation, 30–50% of the total costs in a landfill recycling project are tax costs for redepositing waste after the process (Frändegård et al, 2015). To create incentives and conditions for profitable landfill recycling, this must change. However, current taxation is moving in the opposite direction – in 2024, the landfill tax in Sweden increased from SEK 635 to SEK 725 per tonne. In contrast, there is no landfill tax for mining waste such as waste rock and tailings.

Old (disused) infrastructure

Proper guidance is needed in order to ensure that old underground infrastructure (such as copper cables) is recovered during new infrastructure projects. This issue must be prioritised by both network operators and landowners. Development and transformation efforts are essential, along with cross-sector collaboration and negotiations. In addition, there needs to be greater clarity regarding the allocation of responsibilities and the distribution of costs and revenues. At the moment, system owners lack incentives for recycling (Krook & Wallsten, 2017).

Today, many power grids need to be renewed. This presents an excellent opportunity to change current practices. The goal should be to integrate the recycling of copper cables into the strategic planning and execution of infrastructure projects. Recycling copper cables not only recovers valuable metals, but can also offer benefits such as lower costs, reduced climate impact, and decreased future maintenance and installation expenses because space underground has been freed-up (Krook & Wallsten, 2017).

Knowledge, skills and expertise

Summary

Invest in education, research, and innovation in the field, and create platforms for collaboration.

- Better knowledge is needed of how different metals and minerals flow in society. Without understanding these secondary material flows, it is difficult to evaluate what works well, what works less well, and where new business opportunities exist.

- We need more professionals with better knowledge of circular flows, circular business models, circular design, preventive maintenance, specific material recycling techniques and landfill recycling.

- Different methods should be developed, and global datasets collected, to assist in weighing various sustainability aspects against each other. Practical industrial methods need to be developed for assessing the best actions from a resource and climate perspective.

- Collaboration platforms are needed for circular flows. Actors throughout the value chain need to collaborate on new business models. There are potential synergies in materials recycling with the primary extraction of critical metals. The Metals & Minerals innovation programme, part of Sweden's state-funded Impact Innovation initiative, will be crucial in this context. It is important to build up funding for the programme quickly, to enable the financing of research and development within circular material and product flows, focusing on critical metals and minerals.

Education and research

Students need to receive more education in circularity at universities and colleges, as well as earlier in the educational system. The integration of circularity into university curricula needs to progress more rapidly and become a natural part of education to meet future industry needs. It is also important for students from different disciplines, such as economists and engineers, to interact and collaborate.

The expert group has identified the need for educational initiatives and research in several areas, including:

- Circular business models;
- Design that promotes circularity;
- Maintenance for extended product lifespan;
- Behavioural changes;
- Logistical solutions;
- New techniques for disassembly and sorting;
- New recycling technologies; *and*
- Traceability throughout the value chain and over time.

To achieve this, enhanced support is needed for research and innovation in circular flows, focusing on critical metals and minerals. See also the proposals for transformative measures on page 48.

When recycling society-critical metals and minerals, there are significant collaborative benefits between the recycling and mining industries because they use similar methods. Primary and secondary flows are often combined in the recycling process. Ongoing platforms for collaboration are essential. Government innovation programmes can create favourable conditions for this.

Companies require continuing development and dissemination of knowledge across all aspects of circularity, along with specialised training related to forthcoming EU regulations in this field. All stakeholders must enhance their understanding so as to implement new legislation effectively.

The need for a holistic perspective

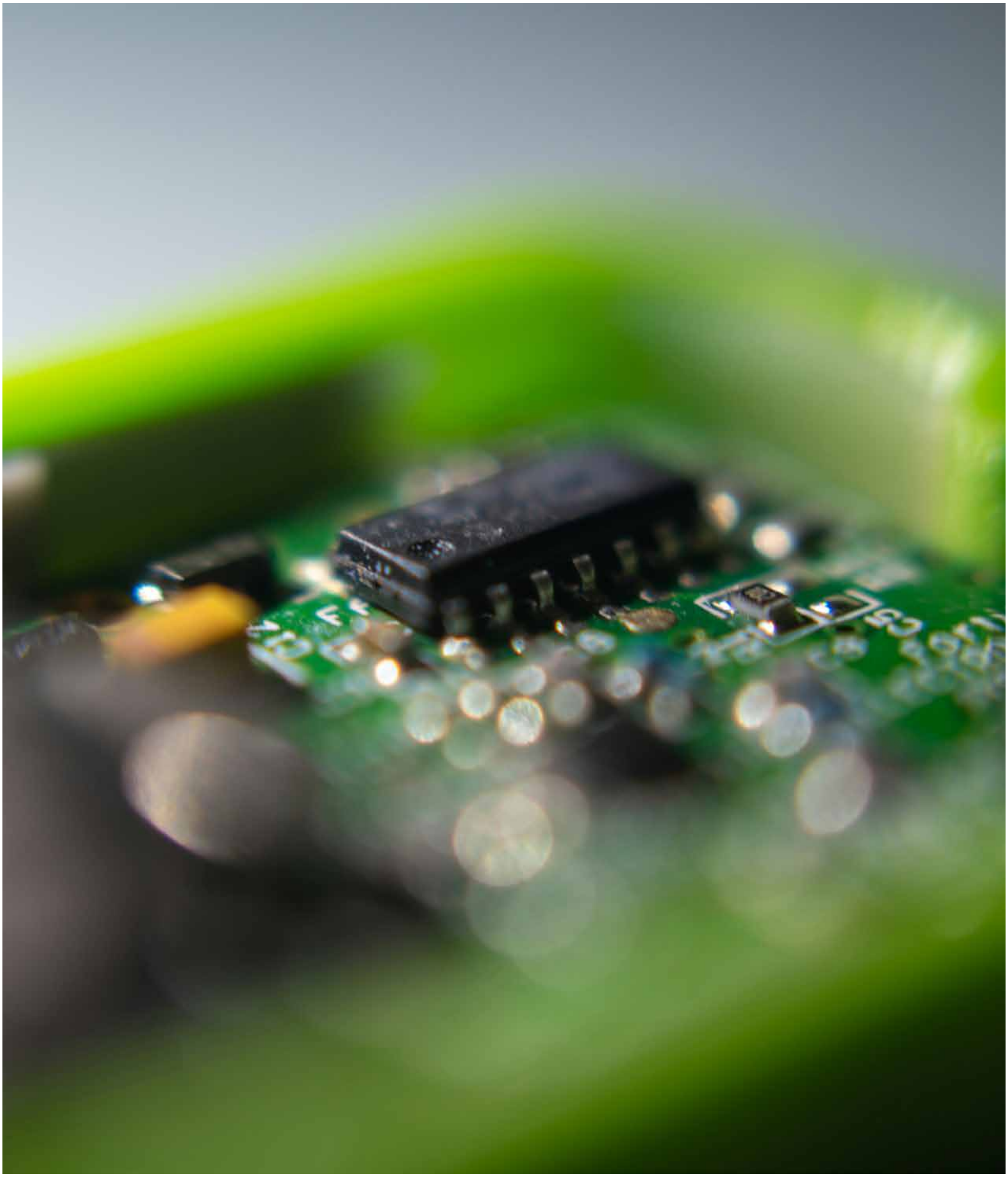
Decision-makers, researchers, companies and organisations must improve their ability to broaden their perspectives and avoid focusing on just one sustainability challenge at a time. It is essential that various sustainability aspects are managed concurrently. In addition, it is crucial to discuss and clarify goals in order to achieve a shared vision of desired outcomes. Clear, long-term guidelines from policymakers are vital in this regard.

To balance different sustainability aspects effectively, global data sets are needed that will allow various alternatives to be compared. Life-cycle assessment (LCA) can be a valuable method for evaluating different business models. When using LCAs, it is crucial to have clear standards and minimal room for interpretation. The implementation of the EU CSRD (European Commission, 2024b), is expected to promote increased clarity within standardisation.

In addition to this, practical industrial methods need to be developed for evaluating the best measures from a resource and climate perspective. Current LCAs are time-consuming, and require specialised knowledge and access to extensive databases, making them unsuitable for providing quick decision support to maintenance and service technicians in individual cases. To enhance efficiency and scalability, simplified methods are needed that can be integrated into existing systems, such as through the use of mobile applications and sub-tools within production and service systems.

Depending on the product category, different tools will be suitable for stimulating circularity in a sustainable way. For long-lived products, given the continuous advance of technology, it may be more effective from both climate and resource perspectives to ensure that certain components containing critical substances can be easily removed and recycled rather than extending the product's lifespan. For other products, extending the lifespan is the best option. This report highlights IT equipment as an example of these. For single-use products and consumables, it is really important that they do not cause problems later in the recycling process, such as containing batteries that cannot be removed or having unsuitable additives like PFAS.

The challenges of balancing different sustainability aspects make it essential to develop regulations with sustainability requirements for various products through dialogue with relevant stakeholders. It is vital to have an understanding of a product’s entire life-cycle.



7. Appendix

»Overall, relatively few components are removed before the car is shredded.«

Cars and Circularity

Modern cars contain many of the elements in the periodic table, with over 50 different metals used in their construction (Ortego et al, 2020). Supply chains are highly complex, with components being sourced from a wide range of suppliers; this often poses challenges for closed-loop recycling. Cars can be likened to other material-intensive products with long lifespans, and the insights from this in-depth analysis can therefore be applied to similar contexts.

When a car is scrapped, some components are removed before the car is compacted and eventually shredded in a hammer mill. After that, some sorting takes place (including iron and steel alloys), but at the moment it is not as easy to separate uncontaminated materials. Plastic is burned for energy recovery.

The parts removed before the hammer mill are those that must be extracted because of regulatory or safety requirements (such as batteries and airbags) and those that are economically profitable to retrieve (such as the catalytic converter, which contains valuable raw materials). The more expensive a material is, the more time is allocated for its extraction.

Overall however, relatively few components are removed before the car is shredded. Most cars being scrapped are around 20 years old and contain smaller amounts of critical raw materials compared to newer models, although they hold significant value in steel, aluminium and copper. Current recycling systems can lessen the motivation to design for enhanced recyclability; there are no incentives to design differently when it is known that components will not be removed before the car is crushed.

Today's systems are designed primarily for steel, making the shredding process less effective for electric vehicles, which contain less steel but more aluminium, copper and other materials compared to conventional cars. Notwithstanding this, continuous advances are being made; as an example, Stena Recycling has developed processes for extracting higher-purity aluminium and copper.

The electric motor contains permanent magnets that contain rare-earth elements. These magnets are deeply embedded within the motor and are glued in place to secure them and to facilitate assembly. Each model has a unique rotor design, making it more challenging to develop efficient equipment for removing the magnets – which requires the entire motor to be disassembled. This is not done at the moment, so the electric motor is crushed along with the rest of the car. However, other components in the motor, such as the bearings, are designed to be removable and replaceable, as they have a limited service life.

To address the challenge of recovering the magnets, designs could be modified to allow the adhesive to dissolve more easily, but this is complex and is unlikely to happen. Another approach would be to improve recycling techniques to allow the recovery of rare-earth elements from the motor in its current form – by simply crushing the motor and extracting the magnets from it. This method has been successfully implemented in Canada (Cyclic Materials (Staub, 2024)) and the EU (Comet). Finding an economical solution for this is very important indeed, as the electric motors contain the largest amount of rare-earth elements used in a car.

The new ELV Directive will seek to address these challenges by mandating the extraction of a comprehensive list of components.

WHAT A CAR MANUFACTURER CAN DO

Car manufacturers can facilitate circular flows in the following ways:

- **Design for disassembly and demand standardised components and modules.** Disassembly must be efficient and cost-effective. Current car designs do not prioritise disassembly. Assembly without pop rivets and using a standard design of screw head throughout would simplify the process. At the moment, different suppliers use different screws for various components. Renault has implemented a disassembly system in France, where they manage recycling, reclaim materials, and have achieved local profitability.
- **Identify priority parts** for replacement and provide high-quality spare parts. Some components wear out more quickly than others, so it is important to have different strategies for 'active components' that undergo frequent wear and rapid technological advancement, and 'inactive components' that are less affected.
- **Optimise material use and select recyclable materials.** Cars contain a wide range of materials. Understanding functional material requirements and how these materials can be recycled within a system fosters opportunities for circularity.
- **Target components that are easily removable** and aim for *closed-loop recycling*. Focus on parts that commonly fail during the car's lifespan.
- **Partner with service providers**, and streamline logistics in different regions. Returning parts replaced during servicing increases costs but reduces scrap-handling expenses. Collaborate with other car manufacturers to develop cost-effective systems. The key is to ensure a steady inflow of parts that are prioritised for reuse or recycling.
- **Select appropriate recycling methods** based on material usage. Chemical recycling may be necessary to restore primary properties, particularly for plastics.
- **Investigate the possibilities of incorporating more recycled materials**, even those typically contaminated with other alloys. Different car parts can tolerate varying levels of contamination.
- Strive for functionality with minimal material use without compromising recyclability, and be willing to **challenge existing functions**.

However, the right incentives are necessary for these changes to take place. See Chapter 6 for proposed measures.

Supply chain

There are many steps between raw material production and a finished car. Most car companies produce few parts themselves and depend on a large network of suppliers. A car manufacturer should be viewed as an assembly company, assembling components produced by others.

A car programme involves more than 300 suppliers, many of whom are unique to a specific programme. To establish closed recycling loops, it is essential to involve a wide range of stakeholders from the very early stages.

IMDS, International Material Data System

The automotive industry utilises the IMDS (International Material Data System) shared data registry, a global system for the entire industry and its suppliers. Providing many benefits, this allows users to access information on various car models, and to identify the materials used in them. However, smaller amounts of certain component materials may be excluded from the reporting.

While the proportion of recycled or bio-based plastics is visible in the system, the proportion of recycled metals is not. Many companies are advocating the inclusion of recycled metal proportions as well.

LCA-challenges

The automotive industry faces significant pressure to reduce carbon dioxide emissions, leading many companies to conduct life-cycle assessments (LCAs) on their vehicles. However, recycled materials are treated differently across the LCA methodologies, of which there are 12 different variants. As a result, different materials can have varying carbon footprints depending on the methodology used. The automotive industry often employs a simple cut-off approach, accounting for 100% of the carbon footprint at first use, while many other sectors consider 50% at first use. The choice of LCA methodology thus influences how advantageous the use of recycled materials is perceived to be from a carbon dioxide perspective.

Standards for what constitutes recycled material

What is considered to be recycled material is open to interpretation. While the automotive industry purchases from the same suppliers, different interpretations are made. The choice of standard – ISO14021, World Steel, or EN45557 – greatly influences these interpretations. Many advocate focusing on waste from end-of-life products, since industrial waste will be recycled regardless, but it is essential for the entire automotive industry to use a consistent approach. At the moment, ISO14021 is widely used, although there is an industry-wide ambition to concentrate more on waste from end-of-life products (consumer waste). Even within a single standard, there is room for interpretation. The grey area concerns industrial scrap that can be easily managed within the same operation (home scrap), which should not be counted as recycled material. This complexity necessitates clear specifications when purchasing materials today regarding the amount of recycled content, the standard used, and the interpretation applied.

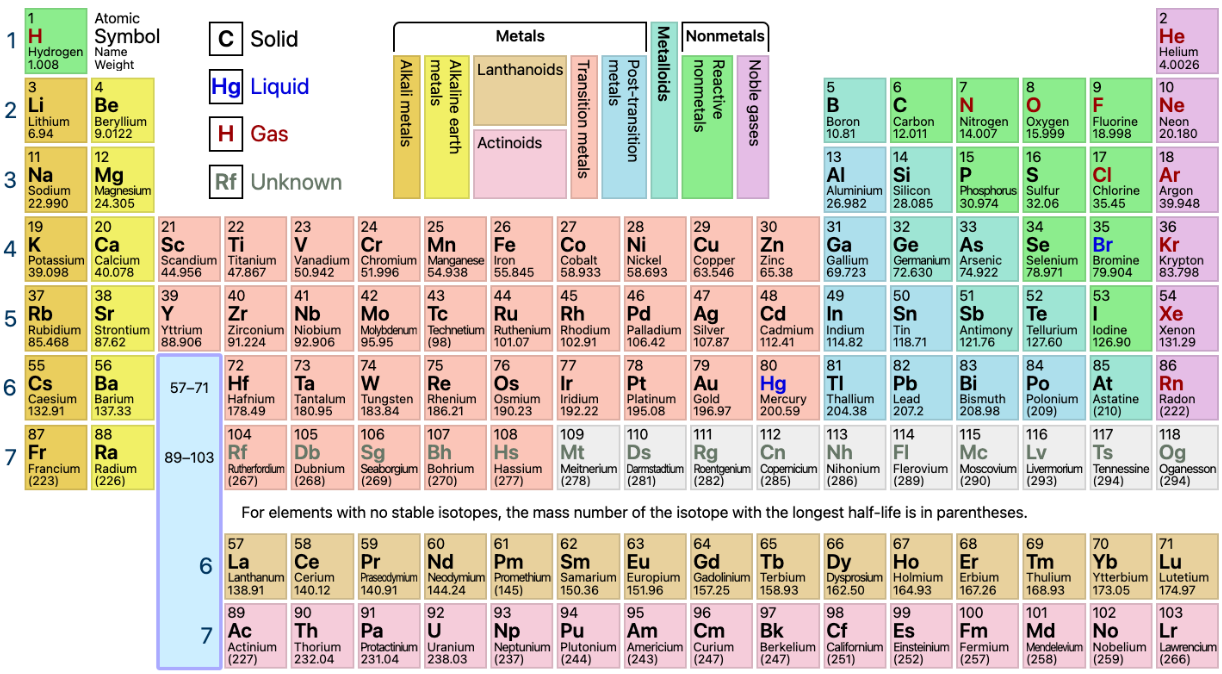
Use of recycled materials (metals from secondary resources)

The industry optimises material choices based on function, quality, cost and sustainability. It is essential to maintain high purity levels to remain competitive. Limiting material options could decrease products' functional value. Moreover, if input materials become more contaminated, the separation problem will only worsen later on.

Another challenge is that suppliers are often reluctant to guarantee a specific percentage of recycled material because of fluctuating availability. For instance, they might promise between 10% and 40%, forcing the buyer (a car manufacturer, for example) to rely only on the lower end of that range to avoid overpromising to their customers. New anti-greenwashing legislation significantly impacts this issue.

A key issue is how to enhance the quality assurance of recycled materials and to increase their market appeal.

Figure 12: The periodic table, a classification of elements by atomic number, and their chemical and physical properties.



Metals and minerals

An element is a substance composed exclusively of atoms with the same number of protons in the nucleus (see the periodic table above). Elements are the fundamental building blocks of everything in the universe and can be categorised according to their properties. Metals are a significant and extensive group of elements, characterised by their specific physical and chemical properties, including excellent electrical and thermal conductivity, lustre and formability.

Minerals typically contain one or more elements with a specific chemical composition and crystal structure. An example of a mineral is chalcopyrite, which consists of the elements copper, iron and sulphur. Minerals, in turn, form various types of rocks.

Different metals have various properties and are widely used in fields such as construction, electronics, medicine and energy production. Well-known examples of metals include iron, copper, aluminium and gold. There has also been a lot of discussion recently about other metals, such as lithium and the group of rare-earth elements. See the info box for more detailed information on these.

EXAMPLES OF METALS

RARE-EARTH ELEMENTS (REES)

The term ‘rare-earth elements’ (REEs) refers to the 15 lanthanides (atomic numbers 57 to 71). Scandium (21) and yttrium (39) are often included as well. Based on their chemical behaviour, they are typically divided into two groups – light (La to Sm) and heavy (Eu to Lu, and Y). Many REEs have very specific properties and are difficult to substitute.

Extraction: China dominates global production.

Refining: China is the leading refiner (IVA, 2024).

Applications: For example, permanent magnets in electric motors and generators.

Recycling rate: Only about 1% of rare-earth elements are recycled today (the figure varies across different sources). The focus is on permanent magnets from wind turbines.

Recycling obstacles: The wide variety of products with different chemical properties complicates recycling. When a product is recycled using pyrometallurgical methods, REEs are often lost in the slag phase. Prices fluctuate as well. Collecting uniform material streams for efficient recycling is challenging.

Ongoing efforts: Several national and international research projects are under way (although they have not yet been adopted by the recycling industry).

The EU Regulation on critical raw materials (the CRMA) specifically addresses rare-earth elements in permanent magnets.

Proposed recycling solutions: Encourage more efficient chemical processes and the collection of relevant material streams that are consistent enough.

LITHIUM

Extraction: Australia is the leading producer, with significant contributions from Chile, Argentina, China, Brazil and Zimbabwe.

Refining: China dominates refining (IVA, 2024).

Applications: Primarily used in batteries (54% of demand). Traditionally, lithium has been used in the ceramics and glass industries.

Recycling rate: Only about 5% of lithium-ion batteries are currently recycled, though this figure may be misleading. Some batteries are classified as exports to China rather than waste. In China, they are reconditioned for second-life applications, such as for use in portable chargers.

Recycling obstacles: Knowledge gaps in the chemical processes involved. More research is needed for sustainable and efficient recycling. The high energy density of lithium batteries poses risks of explosion and fire. The variety of battery sizes, shapes and chemical composition complicates efficient sorting (larger batteries in electric vehicles are more attractive because of their higher lithium content). China holds the largest market share of companies involved in lithium battery recycling. High purity standards in battery applications further complicate material recovery.

Ongoing efforts: The high demand for lithium can make recycling economically viable. Lithium batteries from electric vehicles are especially valuable because of their high lithium content. In cases like this, design research can be productively linked to recycling efforts. Stena Recycling is constructing a facility in Halmstad aimed at recycling 95% of a lithium battery, with battery collection from across Europe. Northvolt also has ambitious recycling goals. Extensive research is under way in Sweden and globally.

The EU’s new Battery Regulation specifically addresses requirements for the recycling of lithium, and the use of recycled lithium in new car batteries.

Proposed recycling solutions: Encourage ongoing research and the scaling-up of recycling technologies.

**The report ‘Innovationskritiska metaller och mineral – en forskningsöversikt’ (Näringsutskottet, 2022) is the main source of information here.*

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