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Recycling Green Technologies of the Future

Scaling by Way of Market-oriented Regulation - the Example of Rare-earth Permanent Magnets

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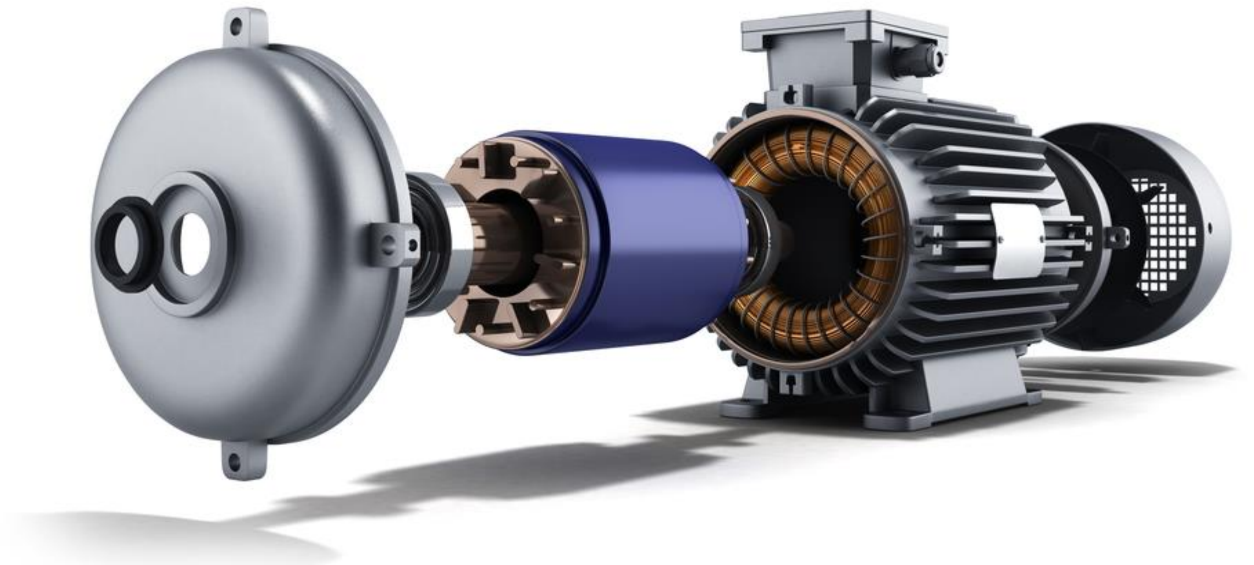

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The switch to low-emission technologies of the future brings Europe's economy into a temporary conflict of interests between sustainability and security of supply. A circular economy for "net zero" technologies provides a promising way out of the dilemma but their development is still in its infancy. Without regulatory impetus, it risks failing due to the chicken-and-egg situation with regard to recycling and infrastructure. Using the example of rare-earth permanent magnets, which will be essential for wind power and electromobility in the future, this cepInput examines the concrete need for action and makes recommendations.

Key propositions:

► To increase the efficiency of collection and dismantling, **targets** should be set for **improving the exchange of information** between actors in the supply chains. In the medium term, efforts should be made to standardise dismantling processes.

► To support the ramp-up of recycling capacities, **a market-oriented bonus system** should be introduced **instead of recycling quotas which drive up costs**.

► The variety of recycling technologies currently being researched offers potential for customised solutions. **Support systems should therefore be designed to be as technology-neutral as possible.**

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1 Context

In addition to the necessary resources and skills, Europe's quest for resilience requires coordination. Aligning the two key strategic goals of climate neutrality and security of supply will only be possible if reliable new supply chains for a whole range of green technologies can be established together with partners. The EU will be jumping out of the frying pan and into the fire if it fails to secure its own competitive production of lithium batteries, electric motors and wind turbines. Secure access to resources, which are both sustainably extracted and affordable, will be an essential prerequisite for this.

The recycling of scarce metals contained in future technologies such as lithium, cobalt or the group of rare earth metals, has all the potential to make an important contribution in this regard. Not only can these raw materials be recycled without quality loss, but recycling is also a sustainable complement to domestic mining, which is fraught with environmental and market acceptance risks. What is more, the treasure trove of raw materials lies right in front of our eyes, in a multitude of production and consumer goods that shape our everyday lives. Enabling green future technologies to transition to the circular economy will eliminate the dependencies inherent in linear manufacturing and become an imperative for strategic sovereignty.

It will, however, take some time to build significant recycling capacity because technologies that are key in terms of their raw material potential, such as wind power and electromobility, are only at the beginning of the scale-up phase and typically have long useful lives. In many cases, the development of recycling processes has not yet reached the stage of market maturity. And a lack of coordination as well as the inadequate flow of information along the supply chains are currently still standing in the way of effective recycling. For future potential to be exploited, the right framework conditions must now be established in Europe to ensure the market ramp-up of a circular economy for green technologies. This includes, but is by no means limited to, forms of direct support. Building an efficient recycling infrastructure requires decentralised cooperation from all actors in the supply chain - with the state acting as a catalyst. The European Commission has recently provided important impetus in this direction with its proposals for a *Critical Raw Materials Act*[1] as well as a *Net Zero Industry Act*[2]. These must be further substantiated, however, and their incentive effect enhanced.

This cepInput identifies recycling potential and existing barriers to green future technologies, with a focus on rare-earth permanent magnets that will be indispensable for wind power and electromobility in the future. Firstly, Section 2 describes the status quo regarding the supply chains for key green technologies, with a focus on the raw material situation and current recycling activities. Section 3 deals generally with the economic barriers to be overcome in establishing a circular economy for green technologies, and presents an overview of possible regulatory instruments. Section 4 looks in detail at the recycling potential of, and barriers to, rare-earth permanent magnet technology. On that basis, it

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[1] European Commission (2023a). Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020 (COM(2023) 160 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160

[2] European Commission (2023b). Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe’s net-zero technology products manufacturing ecosystem (Net Zero Industry Act) (COM(2023) 161 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0161

goes on to develop recommendations for targeted support and finally compares these with the Commission's current legislative proposals.

2 Supply chains of future green technologies

2.1 Strategic "net-zero" technologies

There is general agreement that Europe can only become climate neutral in the long term through the complementary use of a variety of young technologies. Processes for generating energy from renewable sources are only the starting point. In order to be able to use the energy efficiently, technologies are required for transport, intermediate storage and cross-sectoral distribution. The technologies currently under discussion differ as to their stage of development, but also as regards the supply risks resulting from external dependencies and the procurement of necessary raw materials and intermediate products. The extent to which the existence of intra-EU supply chains is of strategic importance in individual cases is difficult to assess.

The European Commission recently presented a list of strategic "*net zero*" technologies with its proposal for a *Net Zero Industry Act*. The total of eight technologies were selected on the basis of three criteria: technological maturity, expected contribution to EU greenhouse gas emission targets, current import dependency. Both the end products associated with a technology and important intermediate inputs in production are covered in each case.[3] The list is subject to the ongoing legislative process and will most likely undergo changes before political agreement is reached. The draft has defined the framework in this regard, however, in that - in addition to the importance of the technologies to the energy system - the criticality of the supply routes will be an essential parameter in the selection process.

Table 1 presents fields of application and input requirements for the technologies selected by the Commission. **What they have in common is a dependence not only on the supply of a variety of knowledge-intensive and capital-intensive manufactured components, but also on mineral raw materials that are judged to be critical**. In the case of individual technologies such as battery storage and wind energy, this involves a whole range of critical raw materials that are currently difficult or impossible to replace in manufacturing. In future, in order to increase the EU's internal manufacturing capacity in these fields, the Commission would like to prioritise projects when it comes to approval procedures and access to public funding.

With respect to the selected technologies, Europe's market position currently looks very varied, both in terms of production and patent activities. Table 2 summarises the Commission's assessment of the market situation. While the EU can (still) be described as the world market leader in the production of wind turbines and biomethane, it has global market shares of significantly less than 10 % in lithium battery and solar module production, for example. In terms of innovative strength, it has also lost ground in relation to some technologies based on the number of patents recorded. The EU is currently only classified as a global technology leader for heat pumps.[4] The complementary use of the

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[3] European Commission (2023b).

[4] European Commission (2023c). Investment needs assessment and funding availabilities to strengthen EU's Net-Zero technology manufacturing capacity. Commission Staff Working Document. SWD(2023) 68.

technologies already makes a loss of competitiveness on a single market potentially critical: underdeveloped areas of technology become a limitation on the overall resilience goal.

Table 1: Characteristics of strategic "net zero" technologies (Commission proposal)

	Output		Input		
Name of technology	**Type**	**Fields of application**	**Main components**	**Critical raw materials**[5]	**Systemic role in the green transformation**
Battery storage	Electrical energy	All sectors	Anode, electrolyte, cathode	Graphite, cobalt, copper, lithium, manganese, nickel, niobium, phosphorus, silicon, titanium	Improved synchronisation of energy supply and demand
Carbon capture, storage and use	Stored carbon	Energy sector, industry	Compressors, pipelines	Cobalt, copper, manganese, nickel	Avoidance of CO2 emissions into the atmosphere, reduction of CO2 concentration in the atmosphere (Direct Air Capture)
Advanced biofuels	Kinetic energy	Transport	Processors, pumps, storage tanks	Copper, nickel	Use of renewable energy sources in the transport sector
Network technologies	Energy transport	Energy sector	Measuring devices, power cables, substations	Copper, nickel	Improved synchronisation of energy supply and demand
Solar photovoltaics	Electrical energy	All sectors	Solar cells	Boron, gallium, copper, nickel, silicon	Low-emission provision of energy
Heat pumps	Heat	Building heating, industry	Compressors, condensers, evaporators	Fluorite, copper, nickel, platinum group, silicon	Expanding the use of renewable electricity by sector coupling
Water electrolysis	Hydrogen	Industry (especially chemicals, steel), transport	Anode, electrolyte, cathode	Graphite, cobalt, copper, nickel, platinum group, rare earth metals (including scandium, yttrium), strontium	Expanding the use of renewable electricity by sector coupling
Wind energy	Electrical Energy	All sectors	Generators, gearboxes, rotor blades	Boron, copper, manganese, niobium, rare earth metals (including dysprosium, neodymium), silicon	Low-emission provision of energy

Sources: European Commission (2023a); JRC (2023)[6]; Marscheider-Weidemann et al. (2021)[7]; Own representation.

Table 2: Market situation for strategic "net zero" technologies (Commission Proposal)

	Production		Innovation		
Name of technology	**Industrial product considered**	**Global share of EU production: Status quo**	**Global technology leader**	**Global share of EU patents: Status quo**	**Global share of EU patents: Trend**
Battery storage	Lithium-ion battery	Relatively low	Japan	Relatively low	Stable
Carbon capture, storage and use	CCS technologies in general	High	USA	High	Falling
Advanced biofuels	Biomethane	World market leader	USA	High	Falling slightly
Network technologies	Smart meters	High	n/a	n/a	n/a
Solar photovoltaics	Solar module	Low	Japan	Low	Falling slightly
Heat pumps	Heat pumps	High	EU	Very high	Stable
Water electrolysis	Electrolysers	Relatively high	Japan	High	Slightly increasing
Wind energy	Wind turbines	World market leader	China	High	Falling

Source: European Commission (2023c); Own representation.

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[5] According to the Commission's proposal for an update of the list of critical raw materials (European Commission, 2023a). Criticality is determined on the basis of two indicator-based criteria: Economic importance and supply risk.

[6] JRC (2023). Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study. Joint Research Centre of the European Union. Luxembourg. doi:10.2760/334074, JRC132889.

[7] Marscheider-Weidemann, F.; Langkau, S.; Baur, S.-J.; Billaud, M.; Deubzer, O.; Eberling, E.; Erdmann, L.; Haendel, M.; Krail, M.; Loibl, A.; Maisel, F.; Marwede, M.; Neef, C.; Neuwirth, M.; Rostek, L.; Rückschloss, J.; Shirinzadeh, S.; Stijepic, D.; Tercero Espinoza, L.; Tippner, M. (2021). Raw materials for future technologies 2021. DERA Rohstoffinformationen 50.

2.2 Status quo regarding recycling activities

Europe's dependence on external sources of raw materials and its limited weight in international technology markets leads us to look at alternative internal supply routes. Recycling processes offer the possibility of using the end products circulating in Europe as a source of raw materials for own manufacturing capacities. Security of supply can thus be increased without having to completely replicate existing international supply chains. In addition, the critical raw materials needed for strategic technologies are predominantly metals whose durability forms the basis for a potentially high level of recycling efficiency.[8]

The Commission also regularly examines the status quo regarding recycling activities in the EU as part of its criticality assessment. As an indicator of this, it uses the end-of-life recycling input rate as an indicator. It is supposed to express the proportion of total EU demand for a raw material that can be met from internal EU secondary sources. Since the level of demand cannot be measured directly using existing surveys, it is measured indirectly as the sum of raw materials used within the EU from EU sources and raw material imports into the EU.[9] The precision of this indicator is disputed[10], but for the critical raw materials used in strategic technologies a clear picture emerges (see Table 3). This shows that the amount of EU-internal secondary production as a proportion of raw material consumption is currently low to very low, with a few exceptions (copper, cobalt, nickel), and is even estimated to be zero in the case of five raw materials (gallium, lithium, niobium, phosphorus, strontium). It is also of virtually no significance in the case of the variously used rare earth metals. The lowest levels of recycling activity are recorded for those raw materials where dependence on imports is also particularly strong. This makes a closer examination of the reasons for the low level of development of recycling systems extremely important.

Table 3: Recycling input rates and import dependency for critical mineral commodities

Raw material	Import dependency[11]	Recycling input rate	Raw material	Import dependency	Recycling input rate
Boron	100%	1%	Manganese	96%	9%
Gallium	98%	0%	Nickel	75%	16%
Germanium	42%	2%	Niobium	100%	0%
Fluorite	60%	1%	Phosphorus	100%	0%
Graphite	99%	3%	Platinum Group	96%	12%
Cobalt	81%	22%	Heavy rare earth metals	100%	1%
Copper	48%	55%	Silicon	64%	1%
Light rare earth metals	100%	1%	Strontium	0%	0%
Lithium	100%	0%	Titanium	100%	1%

Source: European Commission (2023d)[12].

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[8] Hagelüken, C. (2014). Recycling of (critical) metals. Critical metals handbook, 41-69.

[9] Eurostat (2023). Contribution of recycled materials to raw materials demand - end-of-life recycling input rates (EOL-RIR) (cei_srm010) – Metadata. https://ec.europa.eu/eurostat/cache/metadata/en/cei_srm010_esmsip2.htm

[10] Arduin, R. H., Mathieux, F., Huisman, J., Blengini, G. A., Charbuillet, C., Wagner, M., ... & Perry, N. (2020). Novel indicators to better monitor the collection and recovery of (critical) raw materials in WEEE: Focus on screens. Resources, Conservation and Recycling, 157, 104772.

[11] Calculated as: (imports - exports) / (EU production + imports - exports).

[12] European Commission (2023d). Study on the Critical Raw Materials for the EU 2023 - Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

3 A circular economy for green technologies

3.1 Existing market barriers

Recycling the raw materials contained in green future technologies may require a similar number of individual process steps as primary production. The challenges of setting up a recycling system are therefore complex and detailed. The heterogeneity of green technologies leads to highly product-specific problems and makes it difficult to develop a general strategy for the circular economy. Basically, four potential problem areas can be identified across all products: The supply of end-of-life (EoL) products, the collection of EoL products and their transfer to recycling systems, the appropriate sorting and allocation of critical raw materials contained in the products, and the economic efficiency of recycling (see Figure 1). Each of these areas has its own obstacles that can be more or less significant depending on the product. The fact that the recycling steps sometimes involve a highly pronounced division of labour increases the complexity of the regulatory task. To build a sustainable recycling economy, it is not enough to increase the efficiency of the overall system; sufficient individual economic incentives must also be created for all actors in the system.

1. **Delayed supply of EoL products**

The products arising from the technologies under discussion are relatively durable consumer goods. Despite the huge growth in demand forecasted for many of these products[13], some time will pass before this translates into a growth in the supply of EoL products. In the early stages, therefore, recycling can do little to satisfy the rapidly increasing demand which poses a risk that, in the interests of finding a quick solution, capital will initially be channelled relatively unilaterally into other supply routes that rely on primary raw materials. The time lag involved in building capacity could - in the absence of tailor-made support - make it more difficult for recycling technologies to become competitive due to the fixed cost problem (see point 4) and thus also hinder the long-term development of a circular economy for green technologies.

2. **Inadequate collection rates**

The first practical challenge to recycling is securing the products containing future technologies after their use phase has ended. A distinction must be made between consumer products and investment goods that are used in industry or the energy sector. The relevant consumer products are primarily electronic devices (mobile phones, TVs, IT equipment, etc.) and household appliances. On the consumer side, sufficient incentives are needed to ensure the proper disposal of e-waste. The costs to the consumer tend to be higher for electrical equipment than for household waste as additional knowledge is required (location of collection points, recycling centres) and more time is needed.[14] With the WEEE Directive 2012/19/EU, the EU has set Member States the target of increasing the collection

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[13] Cf. Marscheider-Weidemann et al. (2021).

[14] Otto, S., Henn, L., Arnold, O., Kibbe, A. (2015). Die Psychologie des Recyclingverhaltens. In: Recycling und Rohstoffe – Vol. 8. TK Verlag Karl Thomé-Kozmiensky, Neuruppin.

rates[15] for e-waste to at least 65% from 2019.[16] The EU average (46%) fell far short of this target in 2020 with only three Member States (Bulgaria, Finland, Croatia) exceeding the 65% mark.[17] In addition to improper domestic disposal, the illegal export of electronic waste for cheap disposal to countries like China is a major part of the problem.[18] Inadequate collection rates not only directly reduce the potential of recyclates but also help to make the fixed cost problem worse (see point 4). Current research on e-waste shows a stable positive correlation between the amount of waste products collected and the level of recycling in a country.[19]

3. Lack of coordination on substance separation

Following collection, an efficient system of sorting and removal/dismantling is needed that allocates the resource-rich waste to different recycling channels and sorts out non-recyclable material. The separation of components containing critical raw materials may also be necessary to enable their subsequent recovery. The technical hurdles and cost barriers involved in separation are highly product-specific. Diversity in product design and insufficient exchange of information about product characteristics represent uncertainty factors and can drive up the cost of dismantling. Chapter 4 explains the problem in more detail using the example of rare-earth permanent magnets. Insufficient or improper separation can severely impair the efficiency of subsequent recycling processes, both in terms of the type of recoverable resources and their quality/purity level.

4. Technological diversity and complexity of recycling

Variations in product design also impact the chemical composition, and thus the question of which raw materials can be tapped for recycling and by what means. The great variability in the structure of lithium-ion batteries is a good example of this[20] as it renders the standardisation of recycling processes more difficult. In conjunction with the typical cost structure of rare metal recycling processes, this leads to an economic efficiency problem. These processes are typically characterised by high fixed costs (labour, capital), which indicates major economies of scale. The use of this method is only economically sound when large quantities of recyclable materials are involved. [21] Upscaling is also made more difficult by the technological diversity of the recycling processes. The technologies can differ considerably in terms of cost structure and recycling output, as shown, for example, by comparing hydro-metallurgical and pyro-metallurgical processes for recycling lithium-ion batteries.[22] Since many of these technologies are still at an early stage of development with uncertain prospects for future

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[15] The collection rate is defined as the ratio of the total weight of WEEE collected in one year to the averaged total weight of WEEE placed on the market in the three previous years.

[16] European Union (2018). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02012L0019-20180704

[17] Eurostat (2023). Waste statistics – electrical and electronic equipment. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment#cite_note-1

[18] Illés, A., & Geeraerts, K. (2016). Illegal Shipments of E–waste from the EU to China. Fighting environmental crime in Europe and beyond: The role of the EU and Its member states, 129-160.

[19] Boubellouta, B., & Kusch-Brandt, S. (2022). Driving factors of e-waste recycling rate in 30 European countries: new evidence using a panel quantile regression of the EKC hypothesis coupled with the STIRPAT model. Environment, Development and Sustainability, 1-28.

[20] Lander, L., Cleaver, T., Rajaeifar, M. A., Nguyen-Tien, V., Elliott, R. J., Heidrich, O., ... & Offer, G. (2021). Financial viability of electric vehicle lithium-ion battery recycling. Iscience, 24(7), 102787.

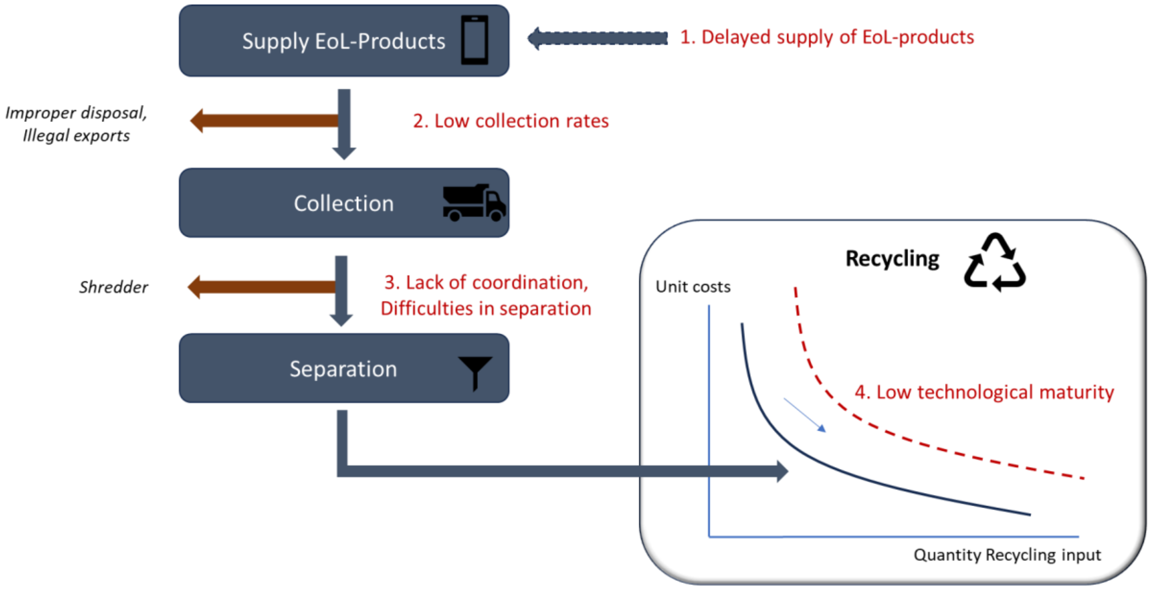
[21] KU Leuven (2022). Metals for clean energy: Pathways to solving Europe's raw materials challenge. Report for Eurometaux.

[22] Lander, L., Cleaver, T., Rajaeifar, M. A., Nguyen-Tien, V., Elliott, R. J., Heidrich, O., ... & Offer, G. (2021). Financial viability of electric vehicle lithium-ion battery recycling. Iscience, 24(7), 102787.

efficiency gains, technology selection involves high information costs. On the revenue side, price fluctuations on the markets for the particularly lucrative rare metals and the risk of material substitution in the medium term (example: trend towards lowering the cobalt intensity of lithium-ion batteries[23]) are particular risk factors for recycling companies.

The problems that exist in the individual stages are in part mutually reinforcing due to the cost relationship. It is the classic chicken-and-egg situation. Without an established infrastructure for the circular economy, insufficient quantities of EoL products reach specialised recyclers, triggering a profitability problem. This in turn inhibits the technological development of suitable recycling processes (low gain in experience, low incentives for R&D investment). Low recycling efficiency subsequently reduces private incentives to build recycling infrastructure. The only possible solution is an external stimulus. This first requires some economic justification.

Figure 1: Hurdles in the recycling chain for EoL products



Source: Own representation.

3.2 Economic arguments for state support

The avoidance of external costs is a key argument in favour of state support for a recycling system for green technologies. These costs directly represent the **avoided environmental damage from the extraction and smelting of primary raw materials**. This applies in particular in the case of critical raw materials such as lithium and rare earth metals. Toxic substances such as arsenic or mercury, which are often associated with the deposits, can pose an environmental risk, especially if contamination of the groundwater cannot be ruled out.[24] In the case of lithium, depending on the geological conditions, high levels of water consumption is an additional problem.[25] Problems identified in environmental

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[23] Ganesh, A., Subramaniam, P., Kaur, A., & Vaidyanathan, L. (2021). Comparison of hydrometallurgical and hybrid recycling processes for lithium-ion battery: an environmental and cost analysis. Working paper.

[24] Kaunda, R. B. (2020). Potential environmental impacts of lithium mining. Journal of energy & natural resources law, 38(3), 237-244. Huang, X., Zhang, G., Pan, A., Chen, F., & Zheng, C. (2016). Protecting the environment and public health from rare earth mining. Earth's Future, 4(11), 532-535.

[25] Bustos-Gallardo, B., Bridge, G., & Prieto, M. (2021). Harvesting Lithium: water, brine and the industrial dynamics of production in the Salar de Atacama. Geoforum, 119, 177-189.

analyses of the Chinese rare earth mining industry include the generation of toxic waste through the use of chemical reactants, the radioactivity of the thorium released, and the emission of CO_2, sulphur dioxide and ammonia.[26] An attempt to convert these multifarious effects into a welfare loss arrives at the equivalent of 4 - 5 euros per kg of rare earth metals,[27] a considerable sum relative to the market price levels of many rare earth elements.[28] The likely damage caused by a possible leak of radioactive material is not even considered here due to the lack of measurability. Studies comparing the environmental impacts of primary and secondary extraction of critical raw materials indicate that in the case of secondary extraction environmental damage is significantly lower.[29]

Another form of avoided social costs that is much more difficult to grasp concerns security of supply. **Promoting a domestic recycling economy helps to reduce dependence on external raw material suppliers**. In many cases, in the area of critical raw materials, such suppliers are monopolistic structures.[30] They make Europe's supply chains in the area of future technologies vulnerable to natural (catastrophic events) and man-made (changes in raw material and trade policies) failures of raw material supplies from individual countries. This default risk, however, is not in itself an external effect because it is directly reflected in the internal risk-return profile of the raw material importers concerned. Social costs do however arise due to the lack of insurability. Many critical raw materials have no possibility of technical substitution in the short term. And market-based insurance by way of hedging instruments will be more difficult for central future technologies due to the macroeconomic effect of supply failures. This implies a strong positive correlation between raw-material-related risks and earnings risks in other sectors.

From a geopolitical perspective, **the goal of strategic sovereignty** could also be brought into play, expressed at the EU level by the concept of "**Open Strategic Autonomy**" as a new guiding principle of EU trade policy. On the one hand, this emphasises the fact that the EU will continue to advocate open and rules-based world trade based on multilateral cooperation. On the other hand, however, it makes clear that the EU must be allowed to defend its strategic interests and values independently and confidently within the world trade order, which explicitly includes measures to increase the resilience and sustainability of its supply chains.[31]

The latter two arguments can in principle also be used to justify the promotion of domestic primary sourcing, i.e. mining within the Union. High environmental standards and strict requirements for the approval of mining projects in the EU should also help to reduce environmental costs by comparison with current mining conditions. However, the fact that the recycled metals can in principle be reused for an unlimited period of time genuinely militates in favour of supporting recycling technologies. While geological deposits are finite and uncertain in their extent in the long term, a circular economy for rare metals promises a never-ending flow of materials.

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[26] Zhou, B. L., Li, Z. X., Zhao, Y. Q., & Wang, S. Q. (2016). The life cycle assessment of rare earth oxides production in Bayan Obo. Journal of Mechanical Engineering Research and Developments, 39(2), 832-839.

[27] Zhou, B., Li, Z., & Zhao, Y. (2017). Evaluation of externalities associated with rare earth exploitation at Bayan Obo. Geo-Resources Environment and Engineering (GREE), 2, 35-40.

[28] SMM (2023). Latest Update in the SMM Rare Earth Metals Market. https://www.metal.com/Rare-Earth-Metals

[29] E.g. Jin, H., Afiuny, P., McIntyre, T., Yih, Y., & Sutherland, J. W. (2016). Comparative life cycle assessment of NdFeB magnets: virgin production versus magnet-to-magnet recycling. Procedia CIRP, 48, 45-50.

[30] Wolf, A. N. (2022). Europe’s position on raw materials of the future, **cepInput** Nr.11/2022.

[31] European Commission (2021). The European economic and financial system: Fostering openness, strength and resilience (Communication from the Commission COM(2021) 32 final). https://data.consilium.europa.eu/doc/document/ST-5487-2021-INIT/en/pdf

3.3 Regulatory instruments

An ideal solution in terms of welfare economics would be to internalise the difference in external costs that exists between the different procurement routes for raw materials. Based on this difference, individual technologies would then be either subsidised or taxed to close the cost gap. Such a project would, however, fail due to the high information barriers (affecting entire supply chains) and methodological difficulties (diversity of cost components). For example, focussing exclusively on the CO_2 price as an existing benchmark would lead to technological distortion, as can be seen in the comparison of hydrometallurgical and pyrometallurgical recycling processes. While pyrometallurgical processes tend to be more CO_2-intensive than hydrometallurgical processes with the current energy mix, the latter are likely to have greater impact on the local environment due to the use of chemicals.[32] In general, a direct comparison between local environmental impacts and the effects of greenhouse gas emissions is virtually impossible due to differences in the duration and geographical dimensions of the effect. Policy makers must therefore look beyond precise compensation of the costs and find more practical solutions to building a circular economy for green technologies.

The measures for a circular economy initiated so far by the EU on the basis of two action plans (2015, 2020) also concern the field of strategic "net zero" technologies.[33] This is certainly true of the recently adopted **recast of the EU Battery Regulation**[34] which contains numerous new regulations for a circular economy for batteries, including lithium-ion batteries, which have been identified as a future technology. On the one hand, these regulations are directed at the battery manufacturers who have been given targets for the collection of spent portable batteries of 63 % up to the end of 2027, and from then on 73 % up to the end of 2030. Separate targets apply to spent batteries from light means of transport (51 % up to the end of 2028 and 61 % up to the end of 2031). Manufacturers of the end products in which batteries are installed must ensure that the batteries can be removed and replaced by the end users. This obligation will apply from 2027. On the demand side, there will also be support for the development of a recyclate market. To this end, the Regulation provides for a mandatory minimum share of recyclates to be used in the production of industrial, starter and traction batteries. This is determined on a raw-material-specific basis and is initially 16 % for cobalt, 85 % for lead, 6 % for lithium and 6 % for nickel. Proof is to be provided by way of mandatory labelling.[35]

The Battery Regulation thus brings instruments into the regulatory system that could be extended to other future technologies in the future. The **common thread is a supply chain-oriented approach**: For the development of a circular economy, all actors - from the battery manufacturer to the end consumer - are taken into account and addressed with specific requirements or incentives. Table 4 lists the instruments currently under discussion according to the actors concerned and the specific objectives. The actual suitability of the instruments for contributing to the aforementioned goals is

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[32] Li, Z., Diaz, L. A., Yang, Z., Jin, H., Lister, T. E., Vahidi, E., & Zhao, F. (2019). Comparative life cycle analysis for value recovery of precious metals and rare earth elements from electronic waste. Resources, conservation and recycling, 149, 20-30.

[33] European Commission (2020). A new Circular Economy Action Plan For a cleaner and more competitive Europe. Communication from the Commissions to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM/ 2020/ 98 final https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF

[34] Council of the European Union (2023). Council adopts new regulation on batteries and waste batteries. Press release, 10 July 2023. https://www.consilium.europa.eu/en/press/press-releases/2023/07/10/council-adopts-new-regulation-on-batteries-and-waste-batteries/

[35] European Union (2023). Regulation of the European Parliament and of the Council concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC. https://data.consilium.europa.eu/doc/document/PE-2-2023-INIT/en/pdf

highly product-dependent. For instance, the introduction of a take-back obligation is only effective for products which have no agreements or standardised procedures for end-of-life recycling. The effectiveness of deposit systems depends significantly on, among other things, the useful life and the market price of the products. In the case of durable, high-priced consumer goods, a deposit would have to be set very high in order to have any influence on disposal decisions. The effect of minimum quotas for the use of recyclates depends to a large extent on the development of recycling efficiency for the raw materials concerned.

Table 4: Overview of regulatory instruments to promote recycling systems

		Intention				Possible areas of conflict		
Instrument	**Addressed Actors**	Increased collection rates	Coordination on recycling	Increased recycling efficiency	Generation of recyclate demand	Competitiveness of downstream industry	Competitiveness of upstream industry	Innovative strength
Take-back obligation	Downstream industry	■						
Deposit systems	Downstream industry, trade End consumer	■				🟥		
Tighter export controls on waste	Waste exporters	■						
Labelling: Composition of products	Upstream industry		■					
Product design specifications	Upstream industry, downstream industry		■	■		🟥	🟥	🟥
R&D support for recycling	Research, recycling companies			■				
Labelling: Origin of raw materials	Upstream industry				■			
Minimum requirements for use of recyclates	Downstream industry				■	🟥		

Source: Own representation.

At the same time, with many instruments there is a risk of conflicting interests. The establishment of deposit systems can put a strain on the competitiveness of manufacturers, both in terms of costs (setting up and managing the systems) and prices (deposit as a perceived price component). Product design specifications aimed at easier abstraction and/or improved recyclability of products could increase manufacturing costs and, in the case of major technological restrictions, also become an obstacle to innovation in the medium term.[36] Minimum requirements on the use of recyclates will also increase manufacturing costs as long as recycling is not cost-competitive with the primary extraction of raw materials. A more precise assessment of the various instruments in their areas of conflict must be undertaken at the product level. As an example, we have chosen rare-earth permanent magnets, which are important for Europe's transformation.

4 Detailed analysis of rare-earth permanent magnets

4.1 Technical description

Permanent magnets are a class of magnets that are capable of maintaining a constant magnetic field without the need for electrical energy. Compared to electromagnets, they therefore have the fundamental advantage of higher energy efficiency. In addition, their construction is technically less complex. Four different classes can currently be identified on the market which differ in their chemical composition and method of production.

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[36] On this: Schwind, S., & Reichert, G. (2022). Ecodesign for Products, cepPolicyBrief No. 10/2022. https://www.cep.eu/en/eu-topics/details/cep/oekodesign-von-produkten-cepanalyse.html

1. Ferrite
2. Aluminium-nickel-cobalt magnets (Alnico magnets)
3. Samarium-cobalt magnets
4. Neodymium iron boron magnets (NdFeB magnets)

The different chemical compositions not only have a strong impact on raw material costs, but also on magnetic force and other process-relevant properties. Ferrites are the most conventional form of permanent magnet. They are made from relatively inexpensive metals (iron, barium) and do not rely on supply-critical raw materials. However, their magnetic force and temperature stability are comparatively low. Alnico magnets score with high temperature stability, but are susceptible to demagnetisation. The other two classes (samarium-cobalt magnets and NdFeB magnets) both have a high level of magnetic force but rely on the use of rare earth metals (samarium, neodymium, praseodymium[37]). **NdFeB magnets are the strongest.[38] This makes them particularly attractive for two types of application technology, both of which are absolutely essential for Europe's green transformation: Wind turbine generators and electric motors**. At the same time, they are cheaper than samarium-cobalt magnets.

In the case of wind turbines, the use of NdFeB magnets allows a significant improvement in the overall efficiency of wind power generation. With a stronger magnetic field there is less need to increase the transmission ratio in the generator via the gear box connecting the rotor and the generator. This limits the energy losses that occur in the process.[39] In the case of electromobility, the high level of magnetic strength most notably meets the need for savings in the required motor energy. Thus, the magnets can be made relatively small and do not add unnecessary weight to the electric motor.[40] In both cases, the widespread use of NdFeB magnets may therefore be a decisive factor for the future economic viability of the technologies - and thus for the success of renewable energy as a whole.

At the same time, NdFeB magnets have other properties that pose a technical and economic challenge for their application and recycling. Firstly, NdFeB magnets are not particularly heat-resistant without alloy additives. To ensure that they retain their magnetic force even at higher temperature ranges, such as when used in electric motors, other substances are added to the basic alloy. Dysprosium is the main element used, and to a lesser extent terbium, both are also rare earth elements. The conditions applicable to their use can vary considerably.[41] Dysprosium, in particular, represents an uncertainty factor for assessing profitability due to its particular rarity and the associated price. Secondly, they are susceptible to corrosion and physical damage, which is why they need to be protected by a shell when in use.[42] There is no industrial standard for this shell; various materials such as nickel, gold and zinc are used in different combinations.[43] This makes the economics of manufacturing sensitive to the price and supply situation of other critical raw materials, in addition to

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[37] Praseodymium is often present in the magnet as an oxide compound with neodymium.

[38] Supermagnetic (2016). Dauermagneten – diese Typen gibt es. https://supermagnetic.de/dauermagnete-magnettypen/

[39] IMA (2018). Wind energy: How to obtain electricity through magnets. https://imamagnets.com/en/blog/wind-energy-how-to-obtain-electricity-through-magnets/

[40] IMA (2018). Applications of neodymium magnets in electric motors https://imamagnets.com/en/blog/applications-neodymium-magnets-electric-motors/

[41] UBA (2019). Seltene Erden in Permanentmagneten. Factsheet – Stand: 15 May 2019. Umweltbundesamt, Dessau.

[42] Fujita, Y., McCall, S. K., & Ginosar, D. (2022). Recycling rare earths: Perspectives and recent advances. MRS Bulletin, 47(3), 283-288.

[43] Cf. Fujita et al. (2022).

the dependence on rare earth metals. The lack of standardisation of the shell is also a barrier to the recycling process, as different techniques may be required to remove and recycle the shell depending on its nature.[44]

4.2 Market development

Permanent magnets are currently only one of many uses of the versatile group of rare earth metals. Various rare earth elements are used, among other things, for doping illuminants, as catalysts for chemical processes, as auxiliary materials in the glass and ceramics industries, as polishing agents and as components of some steel alloys.[45] Globally, according to current estimates, around 35 % of the mass of refined rare earth metals currently goes into the production of permanent magnets. At 90 %, the share in terms of value is significantly higher however[46]. This indicates the huge economic importance of permanent magnet production for the profitability of raw material extraction. NdFeB magnets account for about two thirds of the total production of permanent magnets.

Globally, the production of rare-earth permanent magnets is highly concentrated. According to estimates by the European Raw Materials Alliance (ERMA), China's share of the global market in 2019 was 94%.[47] Apart from that, only Japan managed to record a noteworthy share (5 %), but its market activity is largely limited to the high-grade segment. Japan's total market share was less than 1%. China took over the role of world market leader from Japan in the early 2000s and has massively expanded it since then.[48] The People's Republic has succeeded in increasingly extending the global dominance it has enjoyed for some time in the mining and refining of rare earth metals[49] to include an important downstream part of the exploitation chain. The sale of General Motors' magnet subsidiary to a Chinese-dominated consortium in the mid-1990s is seen as a key turning point in this regard.[50]

The use of NdFeB magnets has also undergone major changes since their invention in the 1980s. According to van Nielen et al. (2023), there have been three waves that have led to an increasingly broad radius of application. In the first wave, consumer electronics was the driving force behind market growth, initially in particular its use as magnetic storage in hard drives and disk drives, and later in loudspeakers, headphones and games consoles. From the mid-2000s, NdFeB magnets started being used en masse in industrial applications such as robots, pumps and vehicle internal combustion engines. With electromobility and wind power (onshore and offshore), the accelerated green transformation of the last few years then spawned a third wave of rapidly growing fields of application.[51] Figure 2 shows Ma & Henderson's (2021) estimates of the distribution of global NdFeB demand by application field in 2019. This shows that vehicle construction accounted for by far the

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[44] Yang, Y., Walton, A., Sheridan, R., Güth, K., Gauß, R., Gutfleisch, O., ... & Binnemans, K. (2017). REE recovery from end-of-life NdFeB permanent magnet scrap: a critical review. Journal of Sustainable Metallurgy, 3, 122-149.

[45] Gaustad, G., Williams, E., & Leader, A. (2021). Rare earth metals from secondary sources: Review of potential supply from waste and byproducts. Resources, Conservation and Recycling, 167, 105213.

[46] Rizos, V., Righetti, E., Kassab, A. (2022). Developing a supply chain for recycled rare earth permanent magnets in the EU. CEPS in-depth analysis 07/2022.

[47] ERMA (2021). Rare Earth Magnets and Motors: A European Call for Action. A report by the Rare Earth Magnets and Motors Cluster. European Raw Materials Alliance.

[48] Ma, D., & Henderson, J. (2021). The impermanence of permanent magnets: A case study on industry, Chinese production, and supply constraints. https://macropolo.org/analysis/permanent-magnets-case-study-industry-chinese-production-supply/

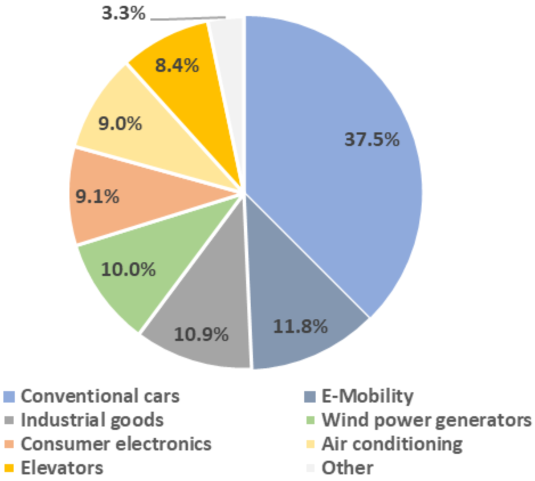
[49] Cf. Wolf (2022).

[50] Cf. Ma & Henderson (2021).

[51] van Nielen, S. S., Sprecher, B., Verhagen, T. J., & Kleijn, R. (2023). Towards neodymium recycling: Analysis of the availability and recyclability of European waste flows. Journal of Cleaner Production, 394, 136252.

largest share of demand, with conventionally powered vehicles (permanent magnets in electric starters) still dominating.

Figure 2: Distribution of global demand for NdFeB magnets

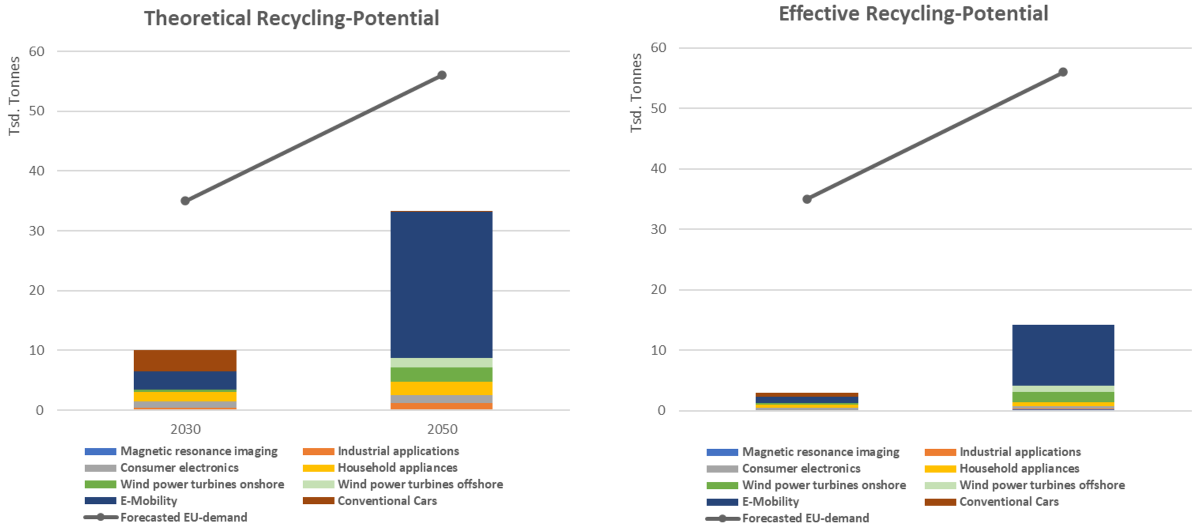


Source: Ma & Henderson (2021); Own representation.

The current dependencies in rare earth supply make the recycling potential arising from the diverse fields of application particularly relevant for Europe. A **distinction must be made between theoretical and effective potential**. Theoretical potential shows the amount of magnets that end their use phase in the respective year. Forecasts for this are based on the development of demand in recent years and assumptions about average lifespans. The theoretical potential therefore says nothing about the state of development of recycling infrastructure and technology. The effective potential measures the magnetic material expected to be recovered from recycling in one year. It results from multiplying the theoretical potential by collection rate, dismantling rate and recycling efficiency. It thus takes into account the material losses that could occur in the collection process (waste exports, improper domestic disposal), during dismantling (no separate recovery, improper removal) and during recycling itself (process-related losses).

The fact that both the size and the installation technology of NdFeB magnets vary significantly from product to product also has a major impact on recyclability. Rizos et al. (2022) have estimated product-specific scenarios for the development of potentials for the period up to 2050 (see Figure 3).

Figure 3: Forecasts for the recycling potential of NdFeB magnets



Source: Rizos et al. (2022) – Forecast scenario: 1; Own representation.

Concerning the amount of theoretically recyclable end-of-life magnets, combustion vehicles will still dominate until 2030. The general trend in the automotive sector towards lightweight construction and vehicle size reduction is also leading to a growing demand for permanent magnets in this segment.[52] Electric bicycles are also a potentially important source at this point, due to a significant increase in demand and a lower average useful life compared to electric cars. Wind generators, on the other hand, will initially still be playing a more subordinate role in 2030, as permanent magnets have only increased in use in more recent models. Also, the expected average useful life (25-30 years) is by far the longest among all fields of application. However, the importance of wind power will increase continuously up to 2050, particularly in the offshore sector. Wind generators powered by permanent magnets are particularly attractive for offshore applications because they require less maintenance.[53] Electric cars are also becoming increasingly important and, according to this forecast, will supply significantly more than half of the total weight of end-of-life magnets in 2050. Consumer electronics, on the other hand, is becoming less and less important as a source, partly because, for some years now, HDD hard disks have been displaced by SDD technology, which does not require NdFeB magnets.[54]

The effective recycling potential is fed proportionally even more by wind power generators and electric cars. In the case of wind generators, this is due to very high collection (90-99 %) and dismantling rates (90-95 %). NdFeB magnets installed in wind generators are relatively large, relatively easy to remove and are disposed of separately from the outset due to their high value. A corresponding infrastructure already exists, at least in rudimentary form. The risk of recycling losses due to mixing with the other waste is therefore low.[55] Dismantling electric cars is more complex, but much less so than for the relatively small permanent magnets installed in the starter motors of internal combustion cars.[56]

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[52] Elwert, T., Goldmann, D., Römer, F., Buchert, M., Merz, C., Schueler, D., & Sutter, J. (2015). Current developments and challenges in the recycling of key components of (hybrid) electric vehicles. Recycling, 1(1), 25-60.

[53] Cf. Fujita et al. (2022).

[54] Cf. Van Nielen et al. (2023).

[55] Cf. Rizos et al. (2022).

[56] Cf. Yang et al. (2017).

Dismantling the magnets therefore represents a significant restriction on the development of recycling potentials. The technical process is complex and error-prone. Removal first requires the removal of the shell (usually made of nickel and copper) and demagnetisation.[57] Adhesive material must be completely removed, as residues can trigger contamination that reduces the efficiency of the recycling process. The magnets themselves are brittle. Contact with air can lead to oxidation, which changes the relevant properties of the magnets.[58] Automation of the individual process steps requires highly specialised machines.[59] If the magnets are not removed but shredded along with the end product, the raw materials they contain are virtually impossible to separate in the subsequent recycling process because the magnetic particles stick to the steel scrap. A considerable amount of rare earth metals thus currently end up in Europe as foreign particles in secondary steel production.[60]

For the efficiency of the recycling process itself, Rizos et al. (2022) assume 90 % (Scenario 1) and 99 % (Scenario 2) across all products. In reality, there is still a great deal of uncertainty in this regard: A wide range of recycling technologies are currently being researched, with significant differences in input requirements and recycling outputs. None of the technologies has yet reached an industrial scale. The future recycling potential of NdFeB magnets will therefore also be largely determined by the outcome of a technology competition.

4.3 Recycling technologies

The recovery of rare-earth permanent magnets can basically start at two stages of the life cycle: the recycling of industrial waste or the recycling of EoL-magnets. Suitable industrial waste is produced during the final stages of primary production of the permanent magnets when the magnets are shaped for the respective application and magnet scrap is produced as waste material. Depending on the shape, this can account for between 6% and 73% of the total production.[61] This waste thus represents a significant source of supply and its key advantage is the immediate availability of the resources in the form required for recycling. No organisational problems arise during collection and dismantling that would reduce the effective potential of end-of-life recycling (see below). The treatment of magnet scrap with copper nitrate is described as a promising technology which allows a mixture of rare earth oxides with a high degree of purity to be extracted. The immediate recyclability ensures economic efficiency and good environmental performance.[62] However, given the current distribution of global production capacities (see section 4.2), this technology will remain of little interest for Europe's supply security in the nearer future.

The recycling of EoL-magnets is much more relevant for Europe's needs. Based on the prioritisation principle of the EU circular economy plans[63], direct reuse without significant processing springs to mind

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[57] Cf. Yang et al. (2017).

[58] Li, Z., Kedous-Lebouc, A., Dubus, J. M., Garbuio, L., & Personnaz, S. (2019). Direct reuse strategies of rare earth permanent magnets for PM electrical machines–an overview study. The European Physical Journal Applied Physics, 86(2), 20901.

[59] Cf. Fujita et al. (2022).

[60] Guyonnet, D., Planchon, M., Rollat, A., Escalon, V., Tuduri, J., Charles, N., ... & Fargier, H. (2015). Material flow analysis applied to rare earth elements in Europe. Journal of Cleaner Production. *107*, 215-228.

[61] Arshi, P. S.; Vahidi, E.; Zhao, F. Behind the Scenes of Clean Energy: The Environmental Footprint of Rare Earth Products. ACS Sustain. Chem. Eng. 2018, 6 (3), 3311–3320.

[62] Chowdhury, N. A., Deng, S., Jin, H., Prodius, D., Sutherland, J. W., & Nlebedim, I. C. (2021). Sustainable recycling of rare-earth elements from NdFeB magnet swarf: techno-economic and environmental perspectives. ACS Sustainable Chemistry & Engineering, 9(47), 15915-15924.

[63] Cf. European Commission (2020).

as the most resource-conserving option. This may involve the use of an entire magnetic ring or its components.[64] However, the diverse product characteristics (magnet properties, chemical composition, dimensioning) and specific demand requirements create major coordination problems for a reuse strategy across supply chains. Direct recycling for use in the same product (e.g. as part of the dismantling of e-cars) is not in every case economical either, due to the length of the use phase and the fast pace of technological development (optimisation of chemical structures, new construction types).[65]

The recycling of magnets, i.e. the reprocessing of the materials in EoL magnets for a new production process, is therefore a much-discussed option. No process has yet emerged as a technological standard. A large number of recycling processes with varying degrees of technological maturity and application fields are discussed in the technical literature. They can basically be divided into two categories. One category is processes for the direct recovery of magnets from the alloys of used magnets ("**direct recycling**"). These technologies, also known as "magnet-to-magnet recycling", do not involve the chemical decomposition of the EoL magnets, but instead serve to directly recycle the old material in an integrated process. A much-discussed specific procedure is hydrogen decrepitation whereby the magnetic material is brought into contact with hydrogen. The small, reactive hydrogen atoms squeeze between the metal grains and thus form microcracks in the material due to pressure, which leads to brittleness and gradual disintegration. This preparatory breaking up of the otherwise very strongly bonded material in turn increases the efficiency of the subsequent milling process, which produces new magnetic powder.[66] During the process, changes can be made to the chemical configuration of the starting material, e.g. by mixing it with additional amounts of neodymium or dysprosium.[67] Compared to "reuse", there is more flexibility in the use options.

The second category of recycling processes is aimed at the chemical decomposition of magnetic alloys. In the case of this so-called "**elementary recycling**", the chemical structure is reduced to the starting materials (partly in the form of oxide compounds), for which an entire range of utilisation options is available in addition to magnet production. Specific processes differ in the means by which the magnetic properties are broken down and in the efficiency with which individual metals are recovered. Basically, a distinction is made between hydrometallurgical, pyrometallurgical and electrochemical processes. [68] **Hydrometallurgical processes** currently have the highest degree of technical maturity. The starting point is leaching the old material using a solvent (usually an acid). The materials are then extracted, e.g. by means of solvent extraction, and the extracted materials are recovered. Depending on the process, the recovered material may consist of a mix of rare earth metals or individual metal oxides. A challenge for leaching, especially with NdFeB magnets, is the high iron content.[69] The strategy of **pyrometallurgical processes** is to use high-temperature processes to separate the rare earth metals from the other magnetic components in various chemical phases. For this purpose, for example, the

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[64] Li, Z., Kedous-Lebouc, A., Dubus, J. M., Garbuio, L., & Personnaz, S. (2019). Direct reuse strategies of rare earth permanent magnets for PM electrical machines–an overview study. The European Physical Journal Applied Physics, 86(2), 20901.

[65] Cf. Elwert et al. (2015).

[66] Habibzadeh, A., Kucuker, M. A., & Gökelma, M. (2023). Review on the Parameters of Recycling NdFeB Magnets via a Hydrogenation Process. ACS omega.

[67] Jin, H., Afiuny, P., McIntyre, T., Yih, Y., & Sutherland, J. W. (2016). Comparative life cycle assessment of NdFeB magnets: virgin production versus magnet-to-magnet recycling. Procedia CIRP, 48, 45-50.

[68] Coelho, F., Abrahami, S., Yang, Y., Sprecher, B., Li, Z., Menad, N. E., ... & Decottignies, V. (2021). Upscaling of Permanent Magnet Dismantling and Recycling through VALOMAG Project. Materials Proceedings, 5(1), 74.

[69] Cf. Yang et al. (2017).

rare earth components are dissolved in molten metals such as magnesium or calcium and separated.[70] Finally, **electrochemical processes** are based on the principle of separating the magnetic compounds by means of electrolysis (i.e. with the addition of electrical energy), for which molten salts are used as electrolytes.[71] These methods are not yet at the stage of commercialisation.

One reason why no clear candidate for commercial scale-up has yet emerged from the multitude of tested methods is their trade-offs. The key factors involved are material requirements, resource efficiency and environmental impact. Direct recycling places the highest demands on the purity of the starting material as foreign substances are not automatically separated via extraction. If the starting material is contaminated as a result of oxidation or faulty disassembly (see section 4.2), this can lead to a loss of strength or of other relevant properties in the recyclates. As a result, the energy efficiency of the corresponding end applications decreases. This is particularly problematic for applications with severe space restrictions in the use of magnets, as is the case with electric motors.[72] The quality requirements for the dismantling process and the resulting economic expenditure are correspondingly high.

In terms of the resource efficiency of the recycling process itself, however, direct recycling has clear advantages over elementary recycling. The EoL-material is used directly to produce new magnets. In elementary recycling, on the other hand, reprocessing takes the longer route of recovering the raw materials, which then still need to be processed into magnets using the usual primary production processes. The lower material and energy consumption of direct recycling also produces a superior environmental balance.[73]

A comparison of the elementary recycling processes also reveals trade-offs. Pyrometallurgical processes require particularly high energy consumption to produce the high-temperature environment. Depending on the role of fossil fuels in the energy mix, this may involve high emissions of greenhouse gases and local air pollutants. In hydrometallurgical processes, on the other hand, the high water consumption and potential environmental damage from the use of acidic solvents are the weak points.[74] With growing decarbonisation of energy production, the environmental balance as a whole could therefore shift in favour of pyrometallurgical processes. This further complicates the forecasting of future market penetration of recycling technologies.

A clear way of visualising the trade-offs is to consider them as different starting points in the production chain (see Figure 4). Elementary recycling goes backwards through a larger number of manufacturing steps. The resources required for the production of new permanent magnets are correspondingly higher. At the same time, the way back also offers more flexibility options: The more basic the recycling output, the broader its scope of application for new end products. This can be a valuable asset, especially with regard to rare earth metals, because rare earth metals with their attractive material properties will continue to be an ideal solution for various applications, some of which we may not yet be aware of, both within and beyond the field of permanent magnets. **From a**

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[70] Cf. Yang et al. (2017).

[71] Kobayashi, S., Kobayashi, K., Nohira, T., Hagiwara, R., Oishi, T., & Konishi, H. (2011). Electrochemical formation of Nd-Ni Alloys in molten LiF-CaF2-NdF3. Journal of the Electrochemical Society, 158(12), E142.

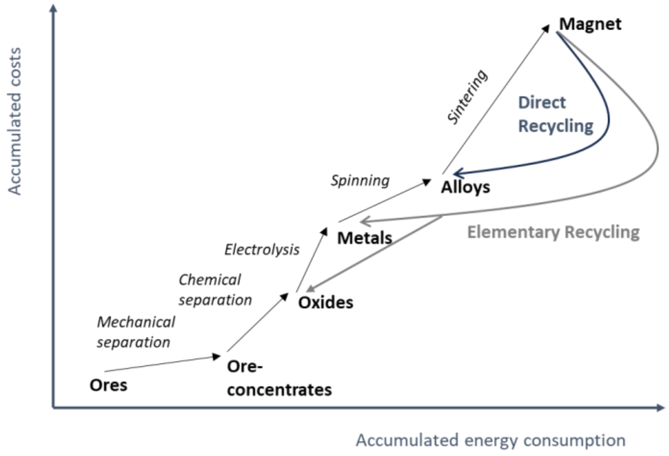
[72] Yang, Y., Walton, A., Sheridan, R., Güth, K., Gauß, R., Gutfleisch, O., ... & Binnemans, K. (2017). REE recovery from end-of-life NdFeB permanent magnet scrap: a critical review. Journal of Sustainable Metallurgy, 3, 122-149.

[73] Ganesh, A., Subramaniam, P., Kaur, A., & Vaidyanathan, L. (2021). Comparison of hydrometallurgical and hybrid recycling processes for lithium-ion battery: an environmental and cost analysis. Working paper.

[74] Cf. Yang et al. (2017).

European perspective, elementary recycling of rare earth permanent magnets promises growing supply security for rare earth metals, without being tied to specific forms of recovery. Thus, on the resource side, Europe will still be in a position to take on a pioneering role in future fields of application and realise first-mover advantages. The price for this flexibility, however, is higher costs in the production of NdFeB magnets and thus less chance of getting a foot in the door against Chinese competition.

Figure 4: Stylised illustration of costs along the supply chain of rare-earth permanent magnets



Source: Own illustration based on Chinwego et al. (2022)[75].

Against this background, a portfolio approach to building recycling capacity is a sensible way forward. In order for Europe to reduce its dependence on permanent magnets "Made in China" and simultaneously participate in future technology waves, it needs direct as well as elementary recycling. Within both categories, funding channels and the underlying conditions for market development should be designed to be as technology-neutral as possible. Which mix of recycling technologies becomes established remains the result of market-related exploration. The decisive factor is entrepreneurial profitability.

4.4 Profitability of recycling

The design of an effective support system needs to be looked at from the investor's perspective. As with other components of the industrial transformation, it is also true for the development of recycling systems that the necessary investments must be marketable. The example of rare-earth permanent magnets shows the complexity of such a consideration. The profitability of recycling processes cannot be looked at in isolation but is tightly linked to the context of the recovery stages, which in this case (at least) include collection, dismantling, reprocessing and final recovery of the recyclates. The extent to which the individual stages can be economically integrated, i.e. concentrated in one company, varies depending on the original product. They can also vary greatly technologically and in terms of cost structures, as is particularly evident regarding dismantling (see section 4.2).

The situation is further complicated by the fact that, due to the early stage of technological development, little public information is available on the material intensities and energy consumption

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[75] Chinwego, C., Wagner, H., Giancola, E., Jironvil, J., & Powell, A. (2022). Low-Cost Distillation Technology for Rare-Earth Recycling. In Rare Metal Technology 2022 (pp. 41-50). Cham: Springer International Publishing.

of the various recycling technologies for rare-earth permanent magnets. The existing data is usually based on highly scaled results of laboratory tests and therefore of somewhat limited value for future commercial production. Used in combination with qualitative considerations and survey results, a meaningful picture can nevertheless be obtained.

On the one hand, this involves comparing the profitability of recycling with that of primary production, i.e. the production of permanent magnets starting with the mining and smelting of rare earth metals. Since the EU in principle wants to rely on both supply routes in its raw materials strategy,[76] the **difference in profitability becomes the decisive factor for the future supply mix**. The general advantage of recycling is the targeted recovery of resources. The content of specific rare earth metals in end-of-life magnets is basically known - apart from variations in the exact proportions and the inclusion of additives. The situation is quite different when the raw materials are extracted by mining: rare earth metals occur in the ores in complex mixture ratios that cannot be determined with certainty in advance. At the same time, rare earth elements not required for production are also unearthed. This increases the yield risk and generates additional costs relating to the necessary separation and storage of the surplus elements. In the market, this results in the characteristic "balance problem" of the various rare earth metals[77], which pushes down the prices for surplus elements and can lead to an inefficient allocation of resources in the economy as a whole. Another advantage of direct recycling over primary extraction is the smaller carbon footprint,[78] which will become an increasing cost advantage as carbon prices continue to rise on the EU ETS.

The economic argument against the recycling of permanent magnets from EoL-products is the high cost of removing/dismantling the magnets from the end products, a stage that is not required in primary production. The variety of sizes and installation techniques of the magnets in the products - and the divergent practices of the manufacturers - make it difficult to automate the disassembly, which can lead to cost-intensive labour, or to a correspondingly high capital outlay for the necessary machines due to low volumes.[79]

On the revenue side, the high volatility of the rare earth metals markets is an uncertainty factor. Due to the low market liquidity and the fact that rare earth oxides are traded on an over-the-counter basis, they are exposed to major price uncertainty. This also applies to the metals neodymium and dysprosium, which are mainly recovered in (elemental) permanent magnet recycling. Dysprosium is produced in smaller quantities, but at the same time is much more expensive due to its particular rarity.[80] As its proportion varies greatly from magnet to magnet depending on the material requirement, it gives rise to particular revenue uncertainty.[81] In addition, the price development of possible further by-products obtained from magnet recycling, especially iron oxides, is a variable factor.[82] In direct recycling, revenue uncertainty mainly concerns the quality of magnet recyclates in

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[76] Cf. European Commission (2023a).

[77] Binnemans, K., Jones, P. T., Müller, T., & Yurramendi, L. (2018). Rare earths and the balance problem: how to deal with changing markets? Journal of Sustainable Metallurgy, 4, 126-146.

[78] Cf. Ganesh et al. (2021).

[79] Cf. Yang et al. (2017).

[80] The market agency SMM estimates a range of 79-81 USD / kg as the price level of neodymium and a range of 371-378 USD / kg as the price level of dysprosium (Status: 4 July 2023). https://www.metal.com/Rare-Earth-Metals

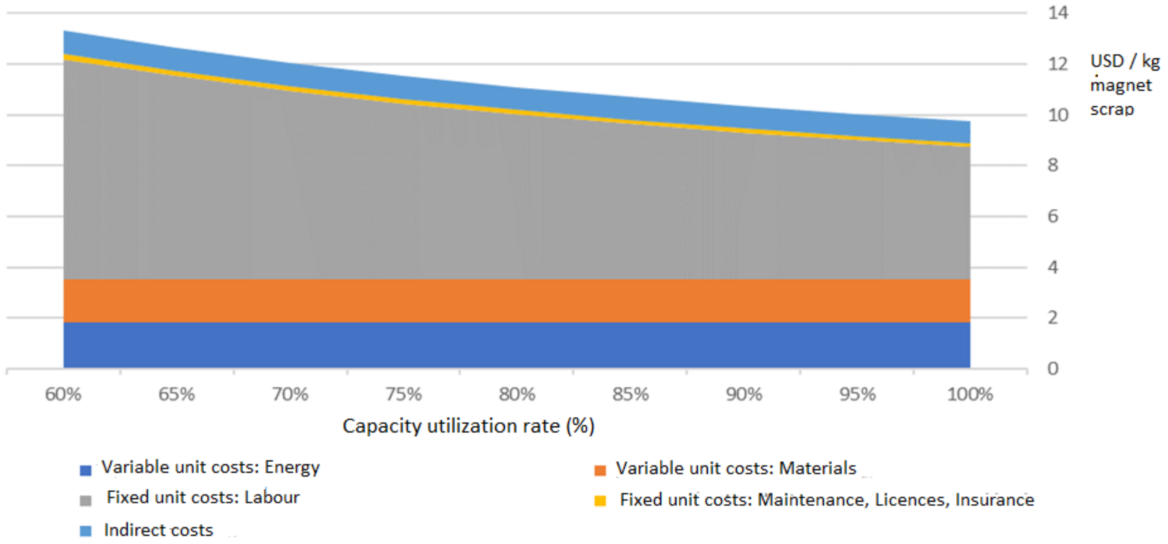
[81] Cf. Chinwego et al. (2022).

[82] Fujita, Y., McCall, S. K., & Ginosar, D. (2022). Recycling rare earths: Perspectives and recent advances. MRS Bulletin, 47(3), 283-288.

the qualitatively highly segmented market for rare-earth permanent magnets. A long-term imponderable for both recycling categories is the future development of market structure. Market entry by European suppliers triggered by support for primary production and recycling could break up the Chinese quasi-monopoly in the long term. It is uncertain how the hitherto dominant providers will react to this. The danger of a price war in rare earth metals and permanent magnets to drive European competitors out of the market is existent.

The costs of the recycling process itself are by nature technology-specific. Chowdhury et al. (2021) estimate that neodymium recycling based on magnetic waste from production is currently already profitable.[83] Regarding the elementary recycling of end-of-life magnets, no complete estimates of the expected capital costs are yet available. Chinwego et al. (2022) present estimated scenarios of the operational costs of elementary recycling of NdFeB magnets based on a hydrometallurgical process, with the USA as a fictitious production site (see Figure 5). The fixed costs associated with labour input clearly dominate over the variable costs of material and energy consumption. Although the material processing stages themselves are automated, material handling between the processing stages (filling the machines, removal and quality control of the process outputs) requires a considerable amount of manual labour.[84] According to the authors, automating these steps as well would significantly increase the capital intensity and only make the process profitable with even larger volumes.

Figure 5: Cost structure of the hydrometallurgical recycling of NdFeB magnets



Source: Own representation. Results from Calculation Spreadsheet (Supplementary Material to Chinwego et al. (2022)).

Relative to the expected revenues (sale of the extracted quantities of neodymium and dysprosium), this would result in a considerable annual operating surplus at current market prices with full capacity utilisation, which drops significantly as capacity utilisation decreases. The annual input capacity of the process can get up to a level of 876 tonnes of magnetic material, and this points at the heart of the economic efficiency problem in permanent magnet recycling: Depending on the scenario, an annual

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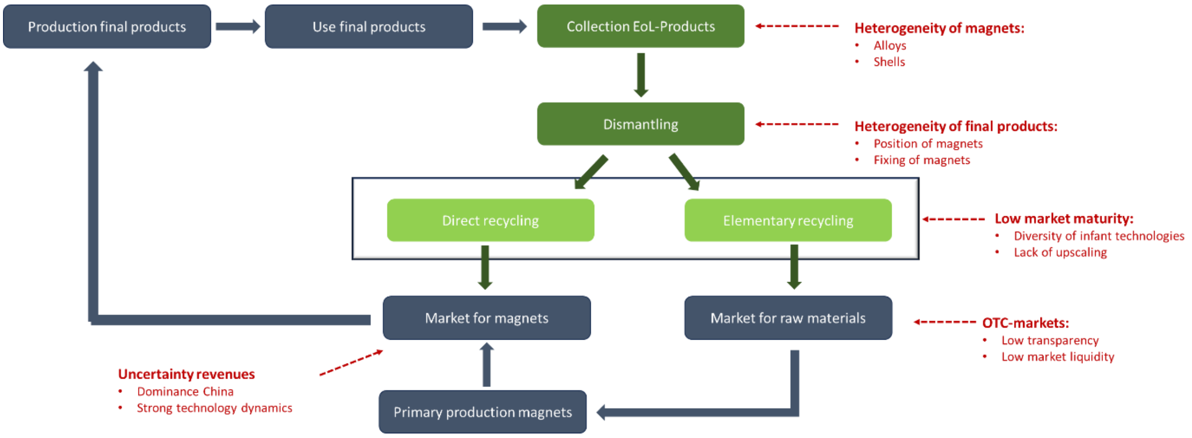
[83] Chowdhury, N. A., Deng, S., Jin, H., Prodius, D., Sutherland, J. W., & Nlebedim, I. C. (2021). Sustainable recycling of rare-earth elements from NdFeB magnet swarf: techno-economic and environmental perspectives. ACS Sustainable Chemistry & Engineering, 9(47), 15915-15924.

[84] Cf. Chinwego et al. (2022).

input quantity of 876 tonnes in a single production plant - correlating to the estimates of Rizos et al. (2022) (see section 4.2) - would represent, about 16 % to 37 % of the total expected supply of EoL-NdFeB magnets in the EU in 2025, and still about 11 % to 16 % of the expected supply in 2030. And even this amount would not be enough to ensure the economic viability of cost-reducing process optimisation by way of automation, according to Chinwego et al. (2022). In light of the portfolio concept (see section 4.2), concentrating capacities on a single plant and technology to such an extent would not be desirable from an economic point of view. Other, possibly more resource-efficient recycling processes such as direct recycling would be hindered in their market penetration.

The decisive impetus for rapid capacity building must therefore come from the input side of the system. In order to achieve the material flows necessary for economic operation in the near future, a significantly steeper increase in the amount of available EoL-magnets is required than currently expected. The two keys to making the necessary adjustment are collection and dismantling rates. Given the wide variation in these rates between end-uses (see section 4.2), a product-specific approach is appropriate. Figure 6 summarises the profitability barriers along the supply chains.

Figure 6: Recycling barriers for permanent magnets



Source: Own representation.

4.5 Approaches for targeted support

The analysis of the supply potential and economic efficiency of permanent magnet recycling has shown that it is essential to look at the technical details of recycling in order to set up an efficient recycling system. Financial support for recycling capacities alone is not sufficient as a policy approach. Regulation must focus on the entire processing chain, from the collection of EoL-products to the final use of recyclates. The diversity of magnet types and installation techniques means that no regulatory "one size fits all" solutions are appropriate. Instead, there is a need for product-group-specific rules without lapsing into micromanagement or blocking innovation pathways. The decisive yardstick should be the ratio of the overall economic potential volume of recyclates to the costs imposed on industry and consumers.

A crucial element will be the improvement of coordination between the actors along the processing chains, some of which are highly fragmented.[85] Information on magnet-specific properties and requirements must be exchanged in a timely manner. This starts at the level of primary production of

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[85] Cf. Van Nielen et al. (2023).

the magnets with information about the exact chemical composition (weight proportions of substances in the alloys, materials used for the magnet shells). This will allow recycling companies to assess revenue potential more accurately and optimise their technologies. Where magnets are recovered at the end applications, knowledge about the location and type of installation is important. This will reduce costs for dismantling companies and thus the risk of magnets being shredded along with other product components and lost in the metal scrap for reprocessing.

For their part, dismantling companies should be obliged to regularly submit information to a digital central register on the stocks of end-of-life products which they hold that (potentially) contain permanent magnets. This is important to close the existing information gaps regarding secondary raw material supply (see section 2.2). More accurate knowledge about the amount of untapped recycling potential will allow for an improvement of recycling indicators and thus better policy targeting. Finally, producers of recycled permanent magnets (i.e. direct recycling) and, in general, permanent magnet producers using secondary raw materials, should provide certified information to their buyers on the type and amount of recycled materials and the recycling technology used. This will open up the possibility for manufacturers of end products containing permanent magnets to exploit the use of recycled materials as a positive signal on the market.

The establishment of such a supply-chain-wide information system is costly and out of proportion to the expected recycling yield for some applications of permanent magnets. At least in the initial phase, it should therefore be limited to the particularly high-potential future applications of wind power generators and electric vehicles.

Beyond the exchange of information, concrete steps must also be taken to reduce recycling costs in order to build capacity quickly. **In order to reduce additional costs resulting from the variety of applications, specifications for technological standardisation may be a way forward in the medium term.** By means of (product group-specific) standards for the installation of permanent magnets in the end applications, process steps for disassembly can be standardised allowing cost-reducing automation processes to be initiated. Higher dismantling efficiency will in turn bring more used magnets into the recycling plants and enable cost reductions in recycling through economies of scale (see section 4.4). Standardisation thus promises a double dividend. At the same time, however, wide-ranging standardisation risks becoming an obstacle to innovation in the long term. And without its own innovative strength in permanent magnet production, Europe will not be able to reduce its cost disadvantage vis-à-vis China in this green technology. Legally defined standards should therefore be limited to the parameters relevant to the dismantling process and exclude chemical magnet properties relating to manufacture.

At the level of the recycling process, efforts should aim at rapidly increasing the technological maturity of the solutions currently being researched. **In line with the portfolio approach (see section 4.3), government research funding should be as diversified as possible and not favour individual recycling technologies from the outset.** The existence of economies of scale in recycling - combined with a major delay in the growth in supply of EoL magnets - also justifies transitional financial support beyond R&D. **In order for Europe to take advantage of the expected surge in supply of end-of-life magnets in 15 to 20 years, the structures for gradually increasing recycling efficiency must be put in place now**. This can only be done by scaling. Public ramp-up financing is the key to bridging revenue shortages in the initial period and thus increasing private investment incentives in the present.

To avoid undermining the necessary technology competition, as well as the creation of capacities without market prospects, the subsidy should take the form of a competition-based bonus payment. The European Hydrogen Bank, which is currently in the implementation phase, is a possible model for this. **According to this principle, the expected market revenues from the sale of recyclates would be supplemented by a state-financed, volume-based bonus, with the amount being determined by a bidding process among recycling companies**. If the bidding procedure is designed in a competitively efficient way, the level of the bids should correspond to the necessary compensation that the recycling companies need to cover the initially high fixed average costs. As the supply of end-of-life magnets increases over time and economies of scale are realised, the necessary cost compensation and thus the bonuses earned in the bidding process will decrease. In order to prevent recycling technologies with a currently still low degree of maturity from being hindered, the *pay-as-bid principle* could be applied to the bidding process. Thus, young technologies that are currently still relatively expensive would have the chance to receive higher bonus payments, provided that the companies' bids remain below a certain threshold.

One advantage of such a bonus system over alternatives such as state price guarantees or the development of specific recyclate markets is the preservation of the price steering effect. Beyond the award of the bonus, recycling companies' earnings depend on price development on the international raw material and magnet markets. The level of the bonus also partially compensates for this current earnings risk, but it does not eliminate the dependence of future earnings on price developments. Potentials and risks in connection with the substitution of raw materials through technological change or the conquest of new areas of application thus remain part of the rationale.

Such a system would also be resilient to politically induced adjustments in market expectations, most notably future changes in China's trade and industrial policies. This would generally reduce the risk of state subsidies unintentionally causing a technological lock-in for Europe in the recycling of raw materials. In addition, in contrast to procurement requirements for companies (see section 4.6), there would also be no immediate cost risks for European downstream industries in global markets. This is also an important factor against the backdrop of competition with China, because real security of supply for Europe can only be achieved with integrated supply chains. At the same time, the state's cost risk can be limited by fixed budgeting of tenders.

One challenge for the practical design of all types of funding instruments in this area is the diversity of the recovered recyclates. With the bonus system, tenders would basically have to be raw material-specific. The raw-material-specific target recycling targets of the Commission's proposal for the Critical Raw Materials Act could serve as a benchmark for allocating quotas for the individual bidding procedures.[86]

Finally, the expansion of European production capacities for permanent magnets is also an important long-term task because raw material recycling only serves to achieve the goal of resilience to the extent that Europe has its own capacities for further processing. Exporting huge amounts of subsidized recyclates to third countries will not solve the supply problem and could also drag the EU into anti-dumping conflicts. **Against this background, the prioritisation measures proposed for projects in the field of strategic "net-zero" technologies (see section 2.1) should also be applied to the production of rare-earth permanent magnets, as an important upstream stage.** If not, there is a risk that the

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[86] Cf. European Commission (2023a).

establishment of supply chains will fail despite extensive funding, due to long approval procedures or inadequate spatial planning.

4.6 Permanent magnet recycling in the Commission's legislative plans

In its proposal for a Critical Raw Materials Act, the European Commission envisages various measures to support recycling capacities that also or exclusively relate to rare-earth permanent magnets.[87] General measures include the envisaged obligation for Member States to develop and implement national circular economy programmes for critical raw materials. These do not specify specific types of regulatory instruments, but lists the sub-goals for which measures are to be taken.[88] Two of the specific problem areas identified in Section 4.5 are also addressed. Measures shall be taken to increase the quantity and quality of recyclable waste streams going into recycling facilities. The maturity of recycling technologies shall also be increased. Both would be important steps to reduce costs and increase recycling output.

Articles 27 and 28 of the proposed law explicitly address the problem of permanent magnets. In it, the Commission provides for the introduction of mandatory labels for a number of products, indicating whether the product contains permanent magnets and, if so, which of the four basic classes (see section 4.1) they correspond to. The scope of application is quite broad. The products mentioned include not only capital goods with particularly high magnet potential (wind power generators, electric motors and industrial robots), but also consumer goods such as tumble dryers and vacuum cleaners. The aim is to establish a more efficient collection and sorting system for EoL products with a view to recycling permanent magnets. Since the presence of such magnets in the products cannot be seen from the outside and in many cases is not technologically imperative, this information obligation would be a first important step. A uniform labelling system is a prerequisite for automating the sorting and subsequent recycling processes, and thus for moving towards scaling.[89]

In addition, further relevant information shall be stored on data carriers on or within the products concerned. This includes the weight and exact chemical composition of the permanent magnets contained therein, as well as information about the nature of their shells and the adhesive material. Precise instructions on the proper procedure for dismantling shall also be included along with the individual work steps. The measure is aimed at dismantling companies and will enable a better assessment of the economic viability of separating the magnets in the recycling process. At the same time, the efficiency of dismantling is likely to be increased and the risk of quality losses due to improper removal to be reduced. In the absence of (product-specific) standards for magnet installation technology, this is a sensible suggestion to avoid the loss of valuable magnet material when shredding discarded products.

Further information requirements relate to the proportion of recyclates in the raw materials used in magnet production. This not only involves rare earth metals, but also other critical raw materials which could potentially be present such as boron, cobalt and nickel. This disclosure obligation shall apply if the total weight of the permanent magnets present exceeds a threshold of 0.2 kg. The information will

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[87] Reichert, G., & Wolf, A. (2023). Critical Raw Materials, cepPolicyBrief No. 8/2023. https://www.cep.eu/en/eu-topics/details/cep/critical-raw-materials-ceppolicybrief.html

[88] Cf. European Commission (2023a).

[89] Burkhardt, C., Lehmann, A., Podmiljsak, B., & Kobe, S. (2020). A systematic classification and labelling approach to support a circular economy ecosystem for NdFeB-type magnet. Journal of Material Science and Engineering A, 10, 125-133.

be made available to the general public on a website. Since it is not the manufacturers or distributors of the permanent magnets themselves who will be affected, but the suppliers of a wide range of products containing permanent magnets, this could result in a considerable information burden for the downstream segment.

In addition, the Commission wants to reserve the right to set minimum quotas for the use of recyclates in the production of permanent magnets for the period from 2031 onwards (by delegated act). These requirements shall apply not only to internal EU production, but to all permanent magnets traded on the internal market. A clear model is the corresponding provision in the new version of the EU Battery Regulation (see section 3.3). The aim is to create demand for recyclates via the minimum quotas, which will enable any additional costs of secondary production to be passed on to the buyers. Our analysis so far makes the effectiveness of such a measure very doubtful. It has been shown that limits to building up recycling capacities for permanent magnets are essentially on the supply side, in the area of the collection and especially the dismantling of old magnets. And the introduction of recycling quotas will not speed up the long-term increase in the supply of end-of-life magnets necessary for the green transformation. Setting an ambitious minimum quota risks either simply not being achievable or leading to high scarcity pricing.

If the quota system is also applied to imported products, there is the chance of a level playing field at least for the domestic market, but even this is only true provided the EU is not left behind by countries like China in the expansion of recycling capacities. China in particular is also investing heavily in the area of secondary production.[90] Thanks to the possibility of using the magnetic waste produced en masse in primary production, the People's Republic also has a resource advantage in this segment right from the start. Support primarily targeted at the demand side thus threatens to thwart the European Commission's industrial policy goal of building up competitive capacities in the downstream segment (production of permanent magnets, wind turbines, electric motors).

5 Conclusion

A circular economy for green technologies is the missing piece of the puzzle called Europe's Green Deal. It could represent a long-term solution to the conflict between climate neutrality and security of supply by sourcing the raw materials necessary for green technologies in an environmentally friendly way. These sources are internal to the EU and will theoretically never run out. When competing with powers that rely on resource exploitation and global transport networks, a recycling economy is a crucial economic and geopolitical asset for Europe. But the EU will need a lot of endurance to reach this goal. So far, the recycling capacities and infrastructure for the critical mineral raw materials concerned exist only in rudimentary form, and some of the raw materials are not yet recycled on a commercial scale at all.

Against such a background, this cepInput analyses recycling potentials and existing obstacles, with a focus on the rare-earth permanent magnets that will be crucial for wind power and electromobility in the future. We argue that supply-side factors are the key obstacles to the rapid development of recycling markets for permanent magnets. This is due, on the one hand, to the long lifespan of the end products, which will only start to provide a significant supply of EoL-magnets after some years, despite a strong current increase in demand. Another problem, which varies in importance depending on the

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[90] https://www.yicaiglobal.com/news/china-jl-mag-to-build-usd100-million-rare-earth-magnet-recycling-facility-in-mexico

product, is the technical difficulty and lack of transparency of the dismantling process. Finally, recycling technologies themselves pose an obstacle to rapid scaling due to their currently still uncertain development path and high fixed costs.

Our key recommendations to the EU are, on the one hand, requirements to ensure the rapid introduction of mandatory information interfaces between the actors in the supply chains. This will reduce the uncertainty about product properties (especially chemistry and positions of magnets) and thus help to increase collection and dismantling rates. In the medium term, this could become the basis for standardisation processes that reduce dismantling costs. Furthermore, we recommend the establishment of a new type of bonus system that compensates recycling companies for the initially high fixed unit costs of recycling in a transitional phase. The system should take the form of competitive tendering in order to limit costs and promote the selection of sustainable recycling processes. In contrast, generating demand for recyclates by means of procurement quotas, the approach envisaged by the Commission, involves a cost burden which threatens the global competitiveness of important European downstream industries and thus counteracts the goal of supply security.

In general, the portfolio concept should always be the focus of government support for recycling technologies. The solutions currently being developed and tested display clear trade-offs between cost efficiency, flexibility and environmental impact at local and global level. This becomes most evident in the comparison between direct and elementary recycling processes. It is therefore unlikely that a single ideal solution will emerge in the technology race. Thus, technology openness in the design of support systems is also a crucial requirement for permanent magnet recycling.

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