TEXTE
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Substitution as a Strategy for Reducing the Criticality of Raw Materials for Environmental Technologies

Summary

For our Environment

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Substitution as a Strategy for Reducing the Criticality of Raw Materials for Environmental Technologies

Summary

by

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Abstract

The research project, entitled Substitution as a Strategy for Reducing the Criticality of Raw Materials for Environmental Technologies, was conducted by the Oeko-Institut and the Institute for Futures Studies and Technology Assessment on behalf of the German Federal Environment Agency (UBA) within the scope of the Environmental Research Programme of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB). It started in August 2014 and ran until February 2018. The project involved the development of a roadmap for critical raw materials substitution in environmental technologies. The roadmap aims to make an important contribution to the implementation and further development of Germany's national raw materials strategy and resource efficiency programme as well as to provide input for the national and international policy debate.

115 environmental technologies were identified from recent studies and key policy documents and were subjected to a multi-stage selection process. As a result of this assessment, 40 environmental technologies were identified as significant and were therefore analysed in more detail. A scenario approach was used to determine the raw material requirements for a business-as-usual and a green economy scenario for the years 2025 and 2050. Out of a total of 64 raw materials investigated across the 40 selected environmental technologies, 38 will play a part in satisfying raw materials requirements. The criticality of the raw materials used in environmental technologies was ranked using a methodology comprising the following three dimensions: supply risk, environmental implications, and strategic significance.

In order to select the 20 priority environmental technologies for screening of substitution options, the raw materials ranking was applied to the environmental technologies.

Substitution options were identified for a number of key environmental technologies. Relevant substitution options are mainly available for the following technologies: electric motors, solar energy, lighting and storage technologies. The broad spectrum of measures, but also the resources required for their implementation, show that the roadmap can only be implemented through concerted action by manufacturers, users, policy-makers and the scientific community.

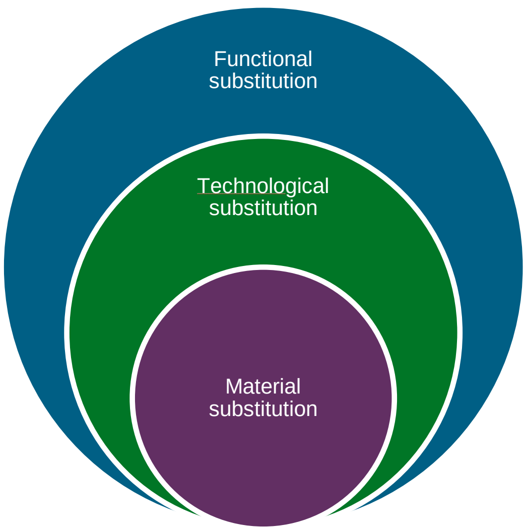
Summary

Substitution: A resource conservation strategy

The expansion and use of innovative environmental technologies are among the most important factors for improved resource efficiency, resource conservation and the transition to a green economy. Many environmental technologies rely on the use of specific raw materials for which there are already various supply risks. These materials are referred to as critical raw materials. The European Commission regularly compiles lists of these materials[1]. A study conducted on behalf of the KfW Group investigated risks to the supply of critical raw materials to German industry[2]. It identifies various critical raw materials of key significance for many environmental technologies, particularly for the transition to a sustainable energy system and sustainable mobility. It is currently foreseeable that efficiency and recycling strategies will not be sufficient in themselves to markedly decrease the criticality of these materials, nor to ensure a far-reaching expansion of significant environmental technologies, not only in industrialised countries like Germany but also globally. A forward-looking focus on substitution strategies is also necessary.

There is a substantial need for further research in this area within the German Government's Resource Efficiency Programme (ProgRess). Measures that support and facilitate substitution, i.e. the replacement of rare and strategic metals with raw materials that have lower environmental impacts, is the key in this respect. In order to meet Germany's particular interests as a consumer, producer, exporter and technology leader, the Federal Government will systematically invest in research on substitution and will develop and implement a strategy on substitutes for critical raw materials in environmental and other technologies[3]. In any analysis of substitution options, it is important to examine resource efficiency potential and possible additional negative impacts on the environment. For example, wind turbines built without rare earths require significantly more copper, which is associated with substantial environmental impacts. A comparative assessment of technologies is therefore extremely important. Here, the type of substitution is significant. It may simply involve the replacement of a single factor input at a material level, but it may also result from changes in the mix of factor inputs or the introduction of new technology and functions[4]. No matter what form it takes, substitution also has an impact on quality, affecting economic, environmental or technical performance to a greater or lesser extent (see Figure above).

Types of substitution



1 European Commission 2017: List of Critical Raw Materials for the EU, http://www.etrma.org/uploads/Modules/Documentsmanager/20170913---2017-list-of-critical-raw-materials-for-the-eu.pdf

2 Erdmann, L; Behrendt, S.; Feil, M.: Kritische Rohstoffe für Deutschland, KfW, Berlin 2011

3 BMUB 2016: https://www.bmu.de/publikation/deutsches-ressourceneffizienzprogramm-ii-programm-zur-nachhaltigen-nutzung-und-zum-schutz-der-natue/

4 Ziemann, S. et al. 2010: Substitution knapper Metalle–ein Ausweg aus der Rohstoffknappheit? / Substitution of Scarce Metals – A Way out of Resource Scarcities?, in Chemie Ingenieur Technik 2010, 82, No. 11.

The SubSKrit project

The research project, entitled Substitution as a Strategy for Reducing the Criticality of Raw Materials for Environmental Technologies (SubSKrit, project code (FKZ): 3714 93 316 0), was conducted by the Oeko-Institut and the Institute for Futures Studies and Technology Assessment (IZT) on behalf of the German Federal Environment Agency (UBA) within the scope of the Environmental Research Programme of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB). It started in August 2014 and ran until February 2018. The project involved the development of a roadmap for critical raw materials substitution in environmental technologies. This roadmap aims to show which substitution measures can substantially contribute to enabling a future expansion of environmental technologies – also against the background of rising supply risks for raw materials, taking into account the long lead times, barriers and favourable factors influencing development from the research stage to market maturity and diffusion. The roadmap aims to make an important contribution to the implementation and further development of Germany’s national raw materials strategy and resource efficiency programme as well as to provide input for the national and international policy debate. To that end, key stakeholders and instruments – as well as relevant measures – were identified and external experts were involved in the project.

Which environmental technologies was the focus of the project?

The term “environmental technologies” refers to technologies, goods and services which “can avoid, mitigate or overcome environmental problems and aid the recovery of already damaged environmental functions, thus contributing to more sustainable management of natural resources”[5]. In line with the BMUB’s Environmental Technology Atlas for Germany (2014)[6], the environmental technologies were subdivided into the following six lead markets (see Table below). In accordance with the methodology, 115 environmental technologies were identified from recent studies and key policy documents and were subjected to a multi-stage selection process. As a result of this assessment, 40 environmental technologies were identified as significant and were therefore analysed in more detail. As the selection of these technologies was based on a broad literature survey which included key reference documents, it may be assumed that good coverage of the range of environmental technologies was achieved overall.

5 Schippl, J. et al. 2009: Roadmap Umwelttechnologien 2020, ITAS Karlsruhe.

6 BMUB 2014: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, *GreenTech made in Germany 4.0 – Environmental Technology Atlas for Germany*, Büchele R. et al., Roland Berger Strategy Consultants, Berlin, July 2014

Table 1: The 40 selected environmental technologies, classed by lead market

Power generation	Energy efficiency	Resource efficiency	Mobility	Waste management/ recycling	Water management
Lithium-ion energy storage Concentrating solar power (CSP) High temperature superconducting (HTS) generators Reluctance generators Combined cycle power plants Thin-film solar cells Tandem cells Crystalline silicon solar cells Storage power plants Permanent magnet generators for wind turbines Externally excited synchronous generators for wind turbines Externally excited asynchronous generators for wind turbines	Compressors RFID White light emitting diodes (LEDs) Organic light emitting diodes (OLEDs) High-performance permanent magnets for industrial applications Green data centres Chlor-alkali electrolysis with oxygen depolarised cathodes	Aerogels Nanocoating Lead-free solders Industrial catalytic converters Celitement Precision farming	Pedelecs Electric traction motors Bodywork Lightweight construction (titanium and scandium airframe) Vehicle catalytic converters Lithium-ion batteries for vehicles Highly efficient aircraft engines Hybrid motors	Automatic substance separation processes Slag and sludge treatment Phosphorus recovery	Water efficiency technologies Reverse osmosis (highly permeable membranes) Decentralised water treatment

How will the material requirements for environmental technologies develop?

The dynamics of the environmental technology markets play an important role in the analysis of raw materials' criticality. Broadly, it may be assumed that rising global demand for environmental technologies will further expand their market volume. However, the pace of growth may vary, depending on how the general and environmental conditions evolve in future. The analysis of the criticality of raw materials for environmental technologies was therefore based on two scenarios: firstly, business-as-usual (BAU), which extrapolates current trends, and secondly, a scenario based on much more dynamic development of markets for environmental technologies, predicated on the assumption that the green economy (GE), which is already regarded by many international organisations and countries, including Germany, as the guiding vision for the 21st century, becomes established. The trend scenario would then be the scenario with the higher probability of occurrence. The GE scenario is a more optimistic scenario, enabling analysis of the development of the raw materials requirement in a radical transition to a green economy.

Looking ahead, it is clear that out of a total of 64 raw materials investigated across the 40 selected environmental technologies, 38 will play a part in satisfying raw materials requirements (see Table). For 21 raw materials, global demand exceeding 3% of total primary production in 2013 (baseline) was identified for at least one of the scenarios (BAU or GE), meaning that these raw materials are strategically significant for market development and diffusion of the relevant environmental technologies.

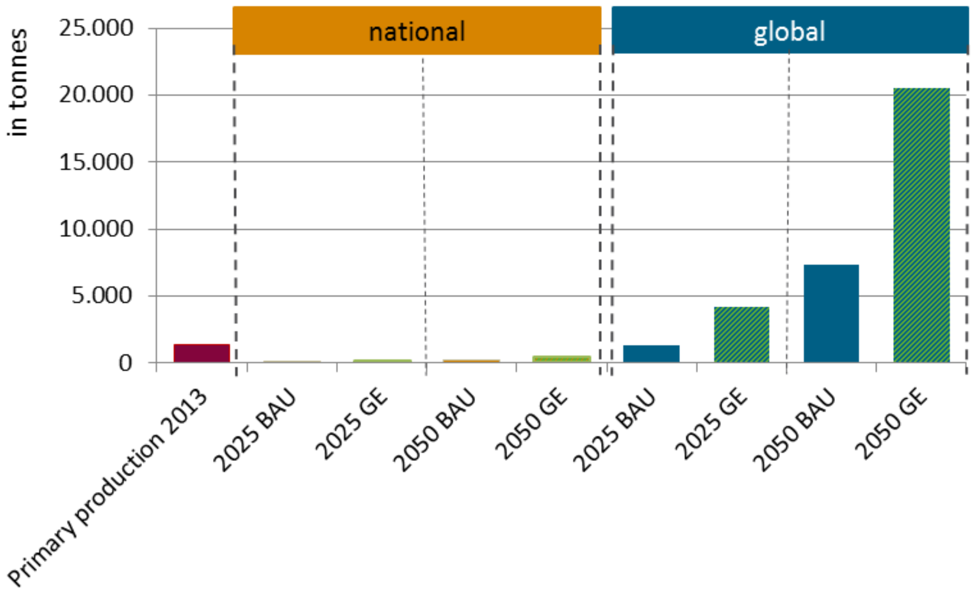
As an example, the figure below shows the scenario results for dysprosium, a rare earth metal, across all 40 environmental technologies studied. Dysprosium is used almost exclusively in neodymium-iron-boron (NdFeB) magnets; it is added to these magnets so that they can be used in high temperature applications. The addition of dysprosium is extremely important for the functional longevity of these permanent magnets at high temperatures. The dysprosium requirement for all 40 environmental technologies studied is shown in relation to the baseline, i.e. primary production in 2013. As is evident from the figure, solely for the environmental technologies investigated in this project, a

Raw materials requirement across all environmental technologies in the green economy scenario for 2025 in relation to global primary production in 2013

Raw material	Percentage
Palladium	423%
Ruthenium	409%
Rhodium	331%
Dysprosium	304%
Iridium	289%
Lithium	247%
Terbium	238%
Platinum	153%
Tin	82%
Neodymium	81%
Praseodymium	67%
Gallium	63%
Silver	58%
Indium	32%
Cerium	15.5%
Titanium as TiO_2	12.5%
Magnesium	11.7%
Copper	11.2%
(Metallic) silicon	5.0%
Manganese	4.8%
Gold	3.3%
Titanium (metal)	2.6%
Yttrium	2.6%
Selenium	1.3%
Europium	1.0%
Gadolinium	0.4%
Cobalt	0.4%
Zirconium	0.3%
Molybdenum	0.3%
Nickel	0.3%
Germanium	0.2%
Chromium	0.3%
Natural graphite	0.2%
Zinc	0.03%
Tantalum	0.03%
Vanadium	0.01%
Lead	0.01%
Phosphate	0.001%

global business-as-usual scenario results in a dysprosium requirement of almost 1,300 tonnes in 2025, close to the 2013 primary production baseline (approx. 1,400 tonnes), while the requirement in a green economy scenario far exceeds this baseline, amounting to more than 4,000 tonnes.

Figure 1: Absolute material requirements for dysprosium [in tonnes] compared with primary production 2013



Source: Authors' own graphics

BAU = Business-as-usual scenario; GE = Green economy scenario

The dynamic development of the global dysprosium requirement for 2025 is driven primarily by the sustainable mobility lead market (90 % in the BAU / 96 % in the GE scenario). In the global GE scenario for 2025, 73 % of the dysprosium requirement for the sustainable mobility lead market relates to electric motors for battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV), with hybrid cars accounting for 26 % and pedelecs 1 %. The projected dynamic development of electromobility is thus the key factor driving the dysprosium requirement, notwithstanding the assumed reduction in the percentage dysprosium content of neodymium-iron-boron (NdFeB) magnets as early as 2025.

Criticality of environmental technologies

The criticality of the raw materials used in environmental technologies was ranked using a methodology comprising the following three dimensions:

1. Supply risk
2. Environmental implications
3. Strategic significance

For each dimension, a separate methodological basis was used in order to facilitate characterisation. A final ranking was then produced for each raw material. In addition, a ranking for each dimension was produced at the raw material level, which was then applied to the environmental technologies.

The **supply risk** dimension of criticality was assessed using the methodology described in *VDI-Richtlinie 4800 Blatt 2 Ressourceneffizienz – Bewertung des Rohstoffaufwands*[7]. This Guideline is based on a system of 13 indicators subdivided into three groups. The indicators are listed in the table below.

Table 2: Indicators according to VDI Guideline Series 4800 No. 2

Geological, technical and structural indicators	Geopolitical and regulatory indicators	Economic indicators
Ratio of reserves to global production	**Herfindahl-Hirschman index of reserves**	**Herfindahl-Hirschman index of companies**
Degree of coproduction / by-production	**Herfindahl-Hirschman index of primary production (countries)**	**Degree of increase in demand**
Distribution of functional EoL recycling technologies	**Political country risk**	**Technical feasibility and profitability of substitutions in main applications**
Profitability of storage and transport	**Regulatory country risk**	**Annualised price volatility**
Degree of distribution of natural resources / growing regions		

Source: VDI 2016: Verein Deutscher Ingenieure (VDI): Richtlinie VDI 4800 Blatt 2. Ressourceneffizienz - Bewertung des Rohstoffaufwands. Gründruck. Berlin 2016.

The **environmental** dimension of criticality was assessed using the data and methodology described by Graedel et al. in the paper *Criticality of metals and metalloids*[8]. In this paper, Graedel calculated the environmental implications of the various elements using the Ecoinvent databases (versions 2.2 and 3) and the ReCiPe impact assessment method[9]. Ecosystems and human health were used as endpoints in determining the environmental implications.

The **strategic significance** dimension of criticality was calculated using the scenario results for material requirements for the various environmental technologies. Here, strategic significance was determined on the basis of the global requirement across the 40 ETs in the green economy scenario for 2025 in relation to the baseline, i.e. global primary production in 2013.

Each of the three dimensions of criticality was assigned a rank, with rank 1 denoting the element with the highest criticality and rank 21 the element of least criticality. In order to apply the raw materials results across all three dimensions to the environmental technologies, the elements' three criticality scores were aggregated in order to produce a final ranking. This was performed by adding and then averaging the individual scores. Rhodium, for example, is ranked 5 for supply risk, 1 for environmental

7 VDI 2016: Verein Deutscher Ingenieure (VDI): Richtlinie VDI 4800 Blatt 2. Ressourceneffizienz - Bewertung des Rohstoffaufwands. Gründruck. Berlin 2016.

8 Graedel et al. 2015: Graedel, T. E.; Harper, E. M.; Nassar, N.T.; Nuss, P.; Reck, B.K.: Criticality of metals and metalloids. Proceedings of the National Academy of Sciences, Volume 112, Issue 14, 2015, 4257 - 4262. (http://www.pnas.org/content/112/14/4257.full.pdf?with-ds=yes).

9 ReCiPe 2013: Goedkoop M.J., Heijungs, R.; Huijbregts, M.; De Schryver, A.; Struijs, J.; van Zelm, R.: ReCiPe 2008 - First Edition. Report I: Characterisation - May 2013. Amersfoort / Leiden / Nijmegen / Bilthoven 2013 (www.leiden-univ.nl/cml/ssp/publications/recipe_characterisation.pdf).

implications and 3 for strategic significance. Added together, this produces a score of 9 and an average of 3. As this is the smallest average, rhodium is placed first in the final ranking, meaning that it has the highest criticality across all three dimensions. This procedure was repeated for all the other elements. The averages were then placed in reverse order (i.e. the lower the score, the higher the criticality). The element with the lowest score is ranked first, while the element with the highest score, denoting the lowest level of criticality, is ranked in last place (21).

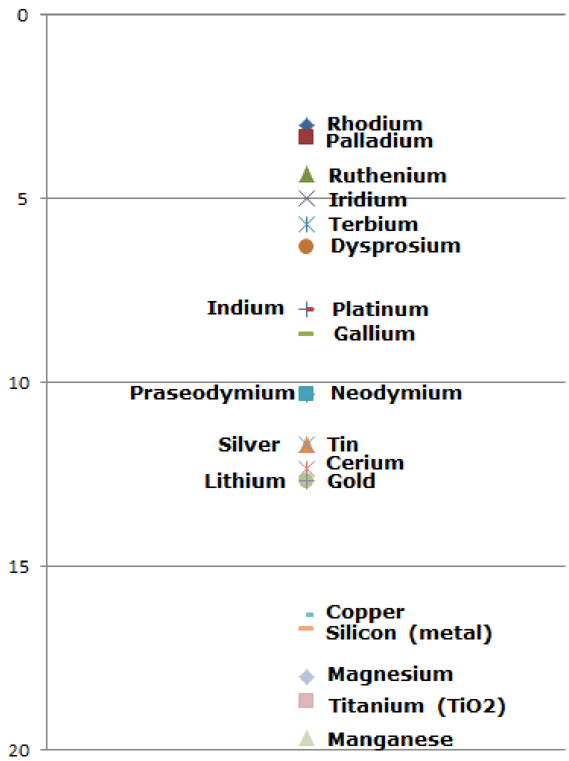
The final ranking is presented in the table below. The platinum group metals rhodium, palladium, ruthenium and iridium are the top-ranking elements (1-4), followed by the heavy rare earth metals terbium and dysprosium (5 and 6). Indium and platinum share seventh place. In 10th place are light rare earths neodymium and praseodymium, with silver and tin placed joint 12th and gold and lithium joint 15th. At the bottom of the table are copper (17), silicon (18), magnesium (19), titanium dioxide (20) and manganese (21).

Figure 2: Final ranking of the raw materials

Ranking and scores

Material	Rank	Value
Rhodium	1	3.00
Palladium	2	3.33
Ruthenium	3	4.33
Iridium	4	5.00
Terbium	5	5.67
Dysprosium	6	6.33
Indium	7	8.00
Platinum	7	8.00
Gallium	9	8.67
Praseodymium	10	10.33
Neodymium	10	10.33
Silver	12	11.67
Tin	12	11.67
Cerium	14	12.33
Gold	15	12.67
Lithium	15	12.67
Copper	17	16.33
(Metallic) silicon	18	16.67
Magnesium	19	18.00
Titanium dioxide	20	18.67
Manganese	21	19.67

Average across all three rankings



Source: Authors' own graphics

As the next step, in order to select the 20 priority environmental technologies for screening of substitution options, the raw materials ranking was applied to the ETs. The following four relevant variables were used for this purpose.

1. Highest individual raw material ranking in the environmental technologies
2. Average across all raw materials and areas of criticality for the environmental technologies
3. Number of relevant raw materials in the environmental technologies
4. In marginal cases: mass requirement for the key raw material for each environmental technology.

The most critical raw material for each ET is the first sorting criterion as this is always the limiting factor. The second sorting criterion is the average across all raw materials and areas of criticality, as this ensures that ETs with the same most critical raw material are sorted further. The third criterion is the number of relevant raw materials. In marginal cases, if the first three sorting criteria have still not produced any differentiation, the mass requirement for the key raw material is used.

This methodology produces a logically well-founded ranking of the ETs and thus achieves the objective, i.e. the selection of 20 priority ETs. The ranking produced a group of 17 ETs, which are clearly located at the top of the table. They include environmental technologies such as catalytic converters, permanent magnets, solar cells, white light emitting diodes (LEDs), green data centres, lead-free solders, RFID and oxygen depolarised cathodes. The results are robust, as a sensitivity analysis shows. With changed weighting of the criteria and changed evaluation of the criteria, the order of the criticality assessments of the raw materials also changes, but the basic criticality assessment for the environmental technologies remains the same.

The 20 environmental technologies selected, with relatively high criticality, can be clustered in the following technology groups:

- Electronics: lead-free solders, green data centres
- Catalytic converters: automotive, industrial
- Permanent magnets: pedelecs, hybrid motors, electric vehicle traction motors, high-performance permanent magnets for other applications, permanent magnet generators for wind turbines
- Solar technology: thin-film solar cells, tandem cells, concentrated solar power (CSP) technology
- Storage technologies: lithium-ion batteries for plug-in hybrid electric vehicles (PHEV), lithium-ion energy storage
- Without permanent magnet generators: synchronous generators, asynchronous generators in wind turbines
- Other technologies: RFID, oxygen depolarised cathodes, white LEDs, gas/combined cycle power plants.

Substitution options

For the environmental technologies studied, the following conceivable options for critical raw materials substitution were identified.

Table 3: Substitution options

Environmental technology	Material level	Substitution options Technology level	Functional level
Electronic			
Lead-free solders	Tin-bismuth alloys	Sintered silver Friction stir welding	Molecular electronics
Green data centres			
Catalytic converters			
Automotive	Replacement of platinum by palladium	Rhodium by platinum in a HC-SCR Rhodium by $V_2O_5/TiO_2/W$ in a SCR	Electromobility with BEV Electromobility with FCEV

Environmental technology	Material level	Substitution options Technology level	Functional level
	Replacement of platinum by multi catalytic converters in diesel-powered vehicles Partial replacement of platinum by gold Replacement of platinum by silver in diesel particulate filters Replacement of palladium by platinum	Rhodium by zeolites (with copper or iron) in SCR Cerium by another type of air control system	
Industrial			
Permanent magnets			
Pedelecs - motors	REE-free motors	Reluctance motor	
Hybrid motors	Samarium-cobalt magnets Cerium and cobalt for neodymium and dysprosium	Asynchronous motor (ASM) Asynchronous motor with high revolutions per minute (ASM with high rpm) Externally / electrically excited synchronous motor (EESM) Other permanent magnets Switched reluctance motor (SRM) Transversal flux motor (TFM) NdFeB magnets without heavy rare earths	
Electric vehicle traction motors for BEV and PHEV	Samarium-cobalt magnets Cerium and cobalt for neodymium and dysprosium	NdFeB magnets with reduced rare earth content ASM ASM with high rpm EESM Other permanent magnets SRM TFM	
High-performance permanent magnets for other applications	Samarium-cobalt magnets	Three-phase asynchronous motor Low voltage motor (Synchronous reluctance motor)	

Environmental technology	Material level	Substitution options Technology level	Functional level
Permanent magnet generators for wind turbines	Dysprosium by terbium FeCo- or FeNi-based materials	Nanocomposites Nanostructures Externally excited generators HTS generators	
Without permanent magnet generators			
Synchronous generators in wind turbines		Reluctance motor	
Asynchronous generators in wind turbines		Reluctance motor	
Storage technologies			
Pedelecs – batteries	Copper by aluminium		Fuel cell
Lithium-ion batteries for vehicles		Nickel metal hybrid battery	Fuel cell Double-layer capacitor
Stationary lithium-ion energy storage		Sodium sulphur battery Redox flow battery	Power-to-gas (hydrogen)
Solar technologies			
Thin-film solar cells	Indium by gallium, Gallium by indium Indium-free TCOs	CZTS cells	
Concentrating solar power	Aluminium mirrors		
Tandem cells in concentrating PV	Indium-free TCOs Aluminium mirrors		
Other technologies			
Combined cycle power plants	Copper by aluminium	Ceramic matrix composites (aluminium oxide) C-C composites	
RFID	Copper by aluminium Copper by silver	Manual sorting Mechanised process technology Optical sensors, software	Waste prevention Deposit schemes
Chlor-alkali electrolysis with oxygen depolarised cathodes	Substitution Ag by Ag(I) or Ag(II) oxides	Deacon/Sumitomo processes (chlorine)	Substitutes for chlorine products
White LEDs	MOF Quantum dots Cadmium-free quantum dots	White OLEDs Foil-based flexible wOLEDs	

Ag: Silver; AlNiCo: Aluminium-Nickel-Cobalt; ASM: Asynchronous Motor; Au: Gold; BEV: Battery Electric Vehicle; C-C Composites: Carbon-Carbon Composites; CZTS cells: Copper Zinc Tin Sulphide; EESM: Electrically / Externally Excited

Synchronous Motor; FCEV: Fuel Cell Electric Vehicle; HTS: High Temperature Superconductor; LED: Light Emitting Diode; MOF: *Metal-Organic Frameworks;* OLED: Organic Light Emitting Diode; PHEV: Plug-in-Hybrid Electric Vehicle; Q-Dots: Quantum Dots ; RFID: Radio Frequency Identification; rpm: Revolutions per Minute; SCR: Selective Catalytic Reduction; SRM: Switched Reluctance Motor; : TCO: Transparent Conducting Oxides; TiO_2: Titanium Dioxide; TFM: Transversal Flux Motor; V_2O_5: Vanadium Pentoxide, W: Tungsten

The substitution options identified have reached varying stages of maturity. For example, substitution options for neodymium-iron-boron (NdFeB) magnets in electric motors for BEV with asynchronous motors, externally electrically excited synchronous motors (EESM) and motors with reduced rare earth content are already available on the market. Sintered silver, as a substitute for lead-free solders, has already entered the commercial phase as well. In niche applications, synchronous reluctance motors can be used as a substitute for high-performance permanent magnets in industry.

Other substitution options are not yet competitive on price; an example is the use of organic light emitting diodes (OLEDs) as a substitute for white LEDs.

For six environmental technologies – green data centres, industrial catalytic converters, pedelec motors, synchronous generators in wind turbines, asynchronous generators in wind turbines, and gas/combined cycle power plants – no foreseeable substitution options were identified within the project framework. These technologies were therefore excluded from further analysis.

As regards the individual environmental technologies studied, it is clear that for some environmental technologies, substantial reductions in the relevant raw materials requirement can be achieved through substitution. It should be noted that not all the raw materials of relevance to the environmental technologies are replaced with substitutes. For the following environmental technologies, a substantial reduction in the relevant raw material requirements can be achieved through substitution, as compared with the green economy scenario. The percentage, shown in parentheses, states the reduction potential that can be achieved in a substitution scenario, as compared with the green economy scenario, for each raw material used in an environmental technology.

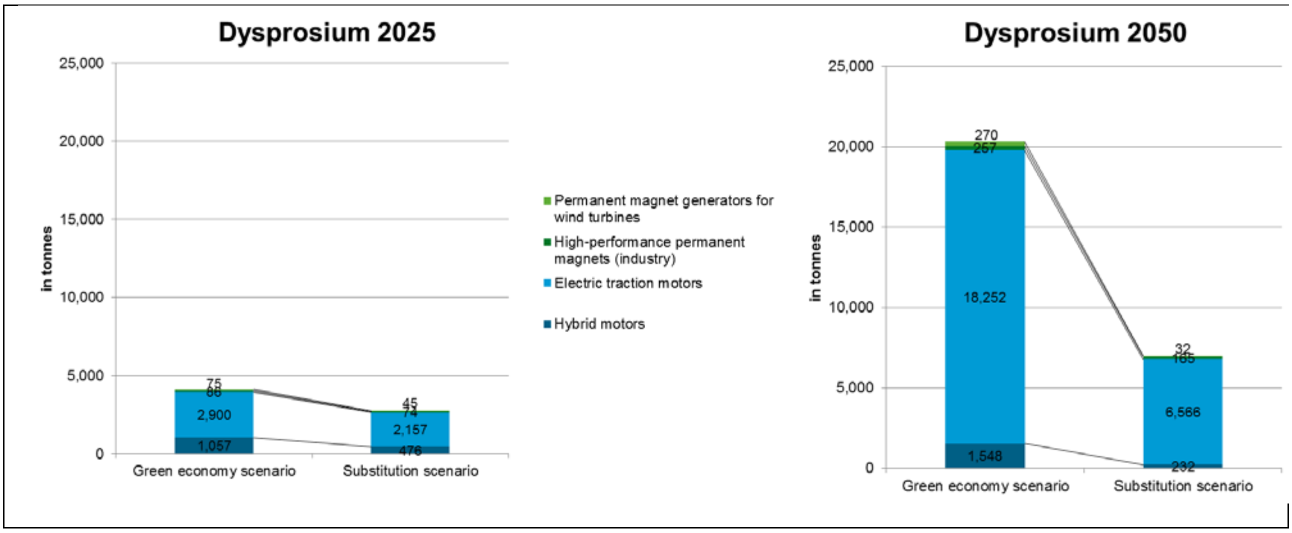
- RFID (radio frequency identification): substantial reduction in copper and silver in 2025 (-96 %) and 2050 (-100 %)
- white LEDs: substantial reduction in cerium in 2025 (-60 %)
- hybrid motors: substantial reduction in dysprosium and terbium in 2025 (-55 %)
- electric motors for BEV and PHEV: substantial reduction in dysprosium, neodymium, praseodymium and terbium in 2050 (-64 %)
- permanent magnets in wind turbines: substantial reduction in dysprosium in 2025 (-40 %)

With other environmental technologies, potential for resource conservation through substitution can only be identified to a limited extent. The use of substitutes may also lead to an increased requirement for other relevant raw materials. This applies, for example, to thin-film photovoltaics, where the slight decrease in gallium, indium and silver in 2025 (-5 %) is accompanied by an increased requirement for zinc and tin in the substitution scenario.

The results for the raw materials across all 40 environmental technologies studied reveal that the raw materials requirement for these ETs changes considerably in the substitution scenario compared with the green economy scenario. Marked changes were identified in relation to silver, gold, palladium, rare earths, lithium, tin, gallium, titanium dioxide, manganese and platinum. This mainly consists of a reduction in the raw materials requirement in the substitution scenario. An increase in the raw materials requirement was observed only in relation to platinum. The effects are illustrated below with reference to dysprosium and platinum.

For dysprosium, the reduction potential in the substitution scenario for 2025 amounts to 33 %, i.e. approximately 1,300 tonnes (see Figure below, left). The most substantial reductions can be achieved in electric motors for BEV and PHEV and in hybrid motors, amounting to 742 tonnes and 50 tonnes, respectively. In 2050, the reduction potential in the substitution scenario amounts to 66 %, i.e. 13,300 tonnes (see Figure below, right). In 2050 too, the most substantial reductions can be achieved in electric traction motors and hybrid motors, amounting to 11,700 tonnes and 1,300 tonnes, respectively.

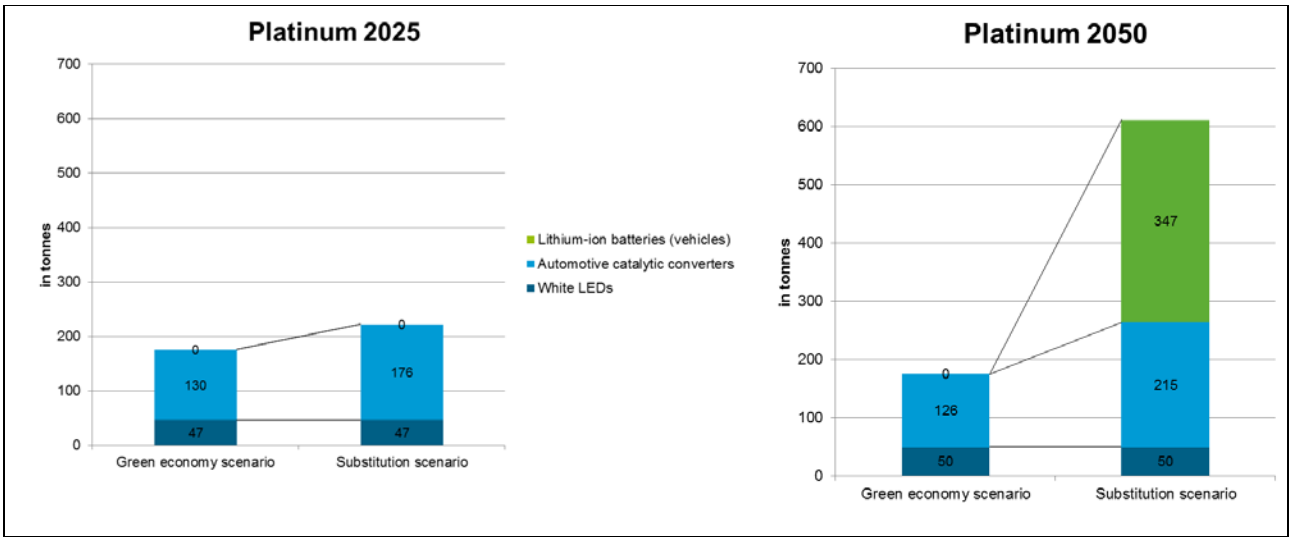
Figure 3: Dysprosium requirement for the environmental technologies studied in the green economy scenario and substitution scenario in 2025 (left) and 2050 (right)



Source: Authors' own graphics

With platinum, a different picture emerges. The requirement for platinum increases in the substitution scenario both in 2025 and in 2050 compared with the green economy scenario. In 2025, the increased requirement in the substitution scenario amounts to 26 % / 46 tonnes (see Figure below, left). This additional requirement arises from the partial substitution of platinum for palladium in automotive catalytic converters. In 2050, the increased requirement for platinum in the substitution scenario amounts to almost 250 % / 436 tonnes (see Figure below, right). Again, this additional requirement relates to automotive catalytic converters and amounts to 89 tonnes (partial substitution of platinum for palladium). However, the largest increase in the requirement in 2050 arises in relation to lithium-ion batteries for vehicles, with the use of fuel cells as a substitute (almost 350 tonnes).

Figure 4: Platinum requirement for the environmental technologies studied in the green economy scenario and substitution scenario in 2025 (left) and 2050 (right)



Source: Authors' own graphics

Roadmap: Tapping substitution potential

The roadmap shows where action is needed, and what form it should take, in order to utilise the identified substitution potential. Reflecting this need for action, practical measures were identified in four areas: technological development, market launch, diffusion through awareness-raising and exchange, and legal/regulatory frameworks.

Technological development

Research and development are required primarily in respect of those substitution options for which a relatively small market share is projected to 2025. Here, a number of disadvantages and obstacles have to be overcome for utilisation of this substitution potential. In many instances, it will be necessary to resolve ongoing technical challenges (lower power density, higher costs) for substitution to become competitive. Copper zinc tin sulphide (CZTS) solar cells, for example, are not yet competitive and the efficiency levels being achieved are relatively low. Further research is therefore required to improve efficiency. Moreover, laboratory efficiency must be achieved in commercial systems as well. With regard to indium-free TCOs (transparent conducting oxides) problems affecting large-scale manufacturing have to be addressed. With white organic light emitting diodes (wOLEDs), it is important to improve their physical and technical properties in the short to medium term. At present, their lifespan is still too short for practical use and they are less energy-efficient than white light emitting diodes (wLEDs). Further research and development are required in order to make inexpensive white organic light emitting diodes (wOLEDs) ready for use in products aimed at the consumer market.

There is also a substantial need for research on high temperature superconducting (HTS) generators for wind turbines. This is a relatively new technology with the potential to achieve very high levels of efficiency in high power ranges using lightweight nacelles. Although some demonstration projects already exist, it is currently impossible to predict when HTS generators are likely to be ready for use in wind energy systems. The first step is to improve the efficiency and reliability of the systems as a whole. With regard to generators for wind turbines, the development of FeCo- or FeNi-based materials, nanocomposites and nanostructures appears to be a promising approach. All these materials are still being developed on a laboratory scale and seem unlikely to achieve the power densities of market-standard permanent magnets even in the medium term. Current research should therefore mainly aim to identify promising material combinations and ways of improving their magnetic properties. Here, the focus is emphatically on R&D, with support for market launch coming later.

Market launch

Many substitution options are already at a very advanced stage of development but are only found in niche markets. This applies, for example, to substitutes for white LEDs, low voltage motors with high-performance permanent magnets in industrial applications, and hybrid and electric traction motors. Here, the main priority is to expedite market launch and diffusion. With regard to white LEDs, conversion of lighting technology will have fairly major implications for value chains. Furthermore, the use of area (instead of point) light sources can cause problems in terms of compatibility with lighting systems in the existing building stock. In order to bring these products to market, entirely new lighting concepts for both indoor and outdoor areas will have to be developed. With regard to diffusion, production costs will have to be reduced for some substitution options. Support is required, for example, in order to scale up demonstration and pilot systems (e.g. OLEDs, sodium sulphur batteries, tandem cells) to commercial production and to reduce costs. Support could also be provided for process development, gathering of experience and economies of scale in manufacturing.

Diffusion through awareness-raising and exchange

In many cases, utilisation of substitution options can be supported with awareness-raising and exchange. With electric traction motors, for example, various technological options, such as asynchronous motors and synchronous motors with reduced rare earth content, are already available in some battery electric vehicles now on the market. Further diffusion should be supported with awareness-raising and confidence-building measures. With asynchronous motors, it is mainly the motor manufacturers themselves who have an interest in establishing their product in the market. Nevertheless, efforts should also be made by the German Government and ministries (e.g. BMU, BMWi), networks and associations (e.g. VDMA, VDA, ZVEI, VDI ZRE) and the EU (e.g. Joint Research Centre, EU Framework Programme for Research and Innovation/Horizon 2020) to develop information offers on the substitution of the asynchronous motor for the synchronous motor. With permanent magnets, too, further diffusion is required, which should be supported by broad-scale awareness-raising, starting right away.

The NdFeB permanent magnet with reduced rare earth content is already available on the market as well. Strong in-market implementation is assumed by 2025 (60%) and 2050 (83%). Further diffusion should be supported by structural policy networks which cluster the knowledge of technologies, needs and conditions for the development and implementation of innovative substitution solutions. Information offers are needed for other environmental technologies as well, such as selective catalytic reduction (SCR) technologies (vanadium pentoxide/titanium dioxide/tungsten SCR or zeolites). Some practical progress has already been made here; however, further improvements and an information campaign to support diffusion are essential to achieve the potential market shares identified, i.e. 5%, for selective catalytic reduction (SCR) technologies. In order to reduce the cerium content in catalytic converter systems, the sensor technology used must be improved or replaced. There are already some promising findings on high frequency-based load sensing in catalytic converter systems, which have already been brought to maturity in the laboratory and should now be installed and tested in vehicles. An information campaign on commercialisation should then follow in order to fulfil the diffusion potential.

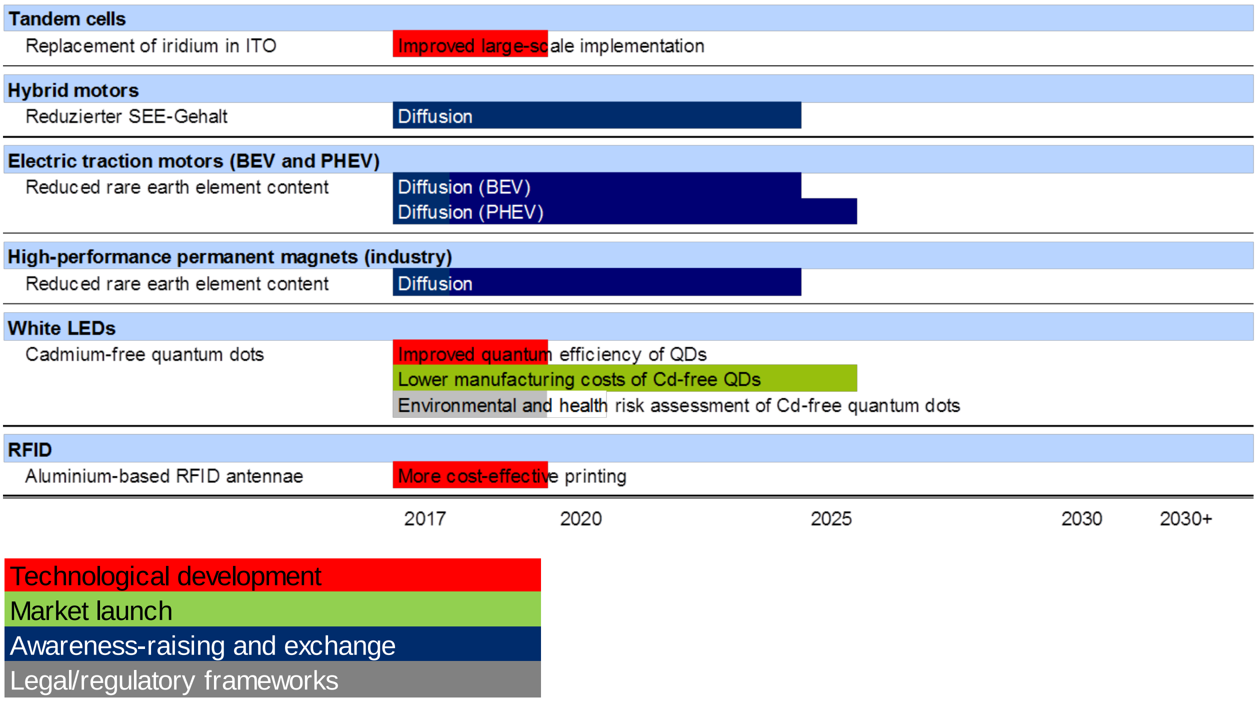
Legal/regulatory frameworks

In addition to technological development, market launch and diffusion through awareness-raising and exchange, legal and regulatory measures have a significant role to play (e.g. in relation to white OLEDs). Innovation should be accompanied by studies on the environmental and health impacts of cadmium-free quantum dots, with a particular focus on the manufacturing of quantum dots and the safe disposal/recycling of the lighting products. In addition, the utilisation of substitution potential should be supported through standardisation to ensure compatibility of white OLED lighting products, including appropriate measurement and quality standards.

The following table shows the environmental technologies and substitution options whose projected potential market share in 2025 exceeds 15%.[10]

10 A comprehensive analysis and overview of the measures relating to the individual environmental technologies, with their key stakeholders, can be found in Work Report 6.

Figure 5: Environmental technologies and their substitution options with a possible market share > 15% in 2025



Source: Authors' own graphics

Conclusions and outlook

The methodology developed and first used within the project framework, comprising systematic screening, monitoring and prioritisation of environmental technologies and substitution options, has proved its worth and received positive feedback from stakeholders at technical workshops. Substitution options were identified for a number of key environmental technologies. Relevant substitution options are mainly available for the following technologies: electric motors, solar energy, lighting and storage technologies. The broad spectrum of measures, but also the resources required for their implementation, show that the roadmap can only be implemented through concerted action by manufacturers, users, policy-makers and the scientific community. The roadmap further reveals that for the utilisation of the identified substitution potential, targeted efforts are required in the innovation system from policy-makers (e.g. through research, innovation and diffusion funding), research institutes (e.g. Fraunhofer, industrial collective research (AiF), universities, major research centres, etc.), industry and associations. In addition to the strategies for implementation of the roadmap, more far-reaching recommendations for action must be pursued:

1. Embed a forward-looking approach in practical action. This can be achieved through regular monitoring; the environmental technologies and raw materials should be assessed for criticality and substitution options every four years.
2. More intensive moves towards efficiency and substitution should be initiated before raw materials become scarce and critical. Systematic screening and early review of criticality are essential.
3. The substitution options with high market potential should be analysed in more depth with a view to utilisation of this potential.
4. There is scope to provide support for substitution research: by opening up the German Government's Resource Efficiency Award to include substitution by launching a separate BMBF

Substitution Research Programme, focusing on lighting, solar and storage technologies, as part of the resource efficiency funding programmes.

In future, a more far-sighted approach should be adopted towards the issue of critical raw materials substitution in order to minimise the impacts of scarcity on the economy. As the raw materials markets are extremely volatile and the extraction of some raw materials is limited to a small number of countries, price shocks with dramatic short-term impacts may occur more frequently in future. It is vital, therefore, to establish continuous monitoring of environmental technologies which make use of potentially critical raw materials and to introduce regular reviews of substitution options for these technologies.