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Substitution of critical raw materials in low-carbon technologies: lighting, wind turbines and electric vehicles

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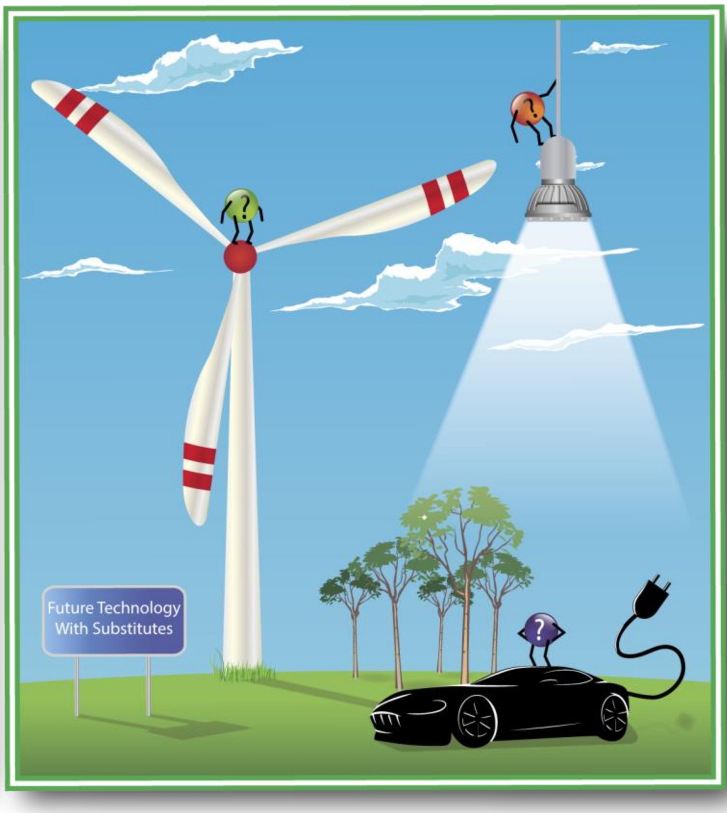

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Substitution of critical raw materials in low-carbon technologies: lighting, wind turbines and electric vehicles

Abstract:

This report evaluates the substitution options of nine critical raw materials (CRM) (Eu, Tb, Y, In, Ga, Ge, Nd, Pr and Dy) required in lighting, wind turbines and electric vehicles applications. Substitution has been considered from many perspectives from reducing the use of CRM via improved material efficiency to substitution at material and component level.

Despite many years of research, the direct and complete replacement of the critical raw materials in phosphors, LEDs and permanent magnets by other more readily available and less critical materials is still not commercially available. However, substitution has the potential to reduce the future demand for CRM in the low-carbon technologies sector by improving material efficiency and component substitution.

In the lighting sector, markets have begun to shift from fluorescent to light-emitting diode (LED) technology. This transition will lead to a decline in the demand for terbium, europium, yttrium and germanium by 2020, although demand for gallium and indium seems to be increasing. In organic-LED (OLED) technology, critical raw materials (with the exception of indium) are substituted by organic compounds. It is expected that OLED technology will widely penetrate the general lighting market after 2025, thereby further reducing the demand for phosphors and critical raw materials in lighting.

Due to concerns over the supply of rare earths, some wind manufacturers have started to develop, adopt or switch to alternative turbine technologies which rely on less rare earth or none at all. In parallel, research has made relevant progress in reducing the amount of heavy rare earths, such as dysprosium or terbium, in wind turbines. Most current wind turbines operate via traditional technologies without any rare earths. The future market share of different turbine types will depend to a large extent on the development of the price and technological advantages of rare earths. For offshore applications, a sector in which the EU is the leader, the direct drive permanent magnet synchronous generator (DD-PMSG), which contains rare earths, has demonstrated a number of advantages especially in terms of efficiency and lower maintenance. In order to maintain its leadership and competitiveness in the offshore wind sector, the EU should continue to invest in rare earth substitution while also adopting other measures to secure the supply of rare earths.

Currently, the permanent magnet synchronous traction motor (PSM) which contains rare earths is the technology of choice for electric vehicles. Alternative rare earth-free electric motors (e.g. asynchronous or electrically excited synchronous machines) exist for battery electric vehicles (BEVs). The lack of component substitution for PSM in the serial production of hybrid electric vehicles represents a major challenge because these models dominate the EVs sector today. However, there are a lot of substitution options available in R&D or pilot phases.

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Executive summary

Ensuring a secure and undistorted supply of raw materials is crucial for the competitiveness and future growth of the entire EU economy. Special concerns are related to the supply of certain raw materials, defined as *'critical' raw materials* (CRM). These materials are fundamentally necessary to meet the deployment goals of low-carbon energy technologies in view of the European transition towards a low-carbon economy and climate resilience policy. Previous JRC studies have found that certain technologies, including fluorescent lighting, wind turbines and electric vehicles, could be at risk due to potential bottlenecks in the supply chain of several CRM.

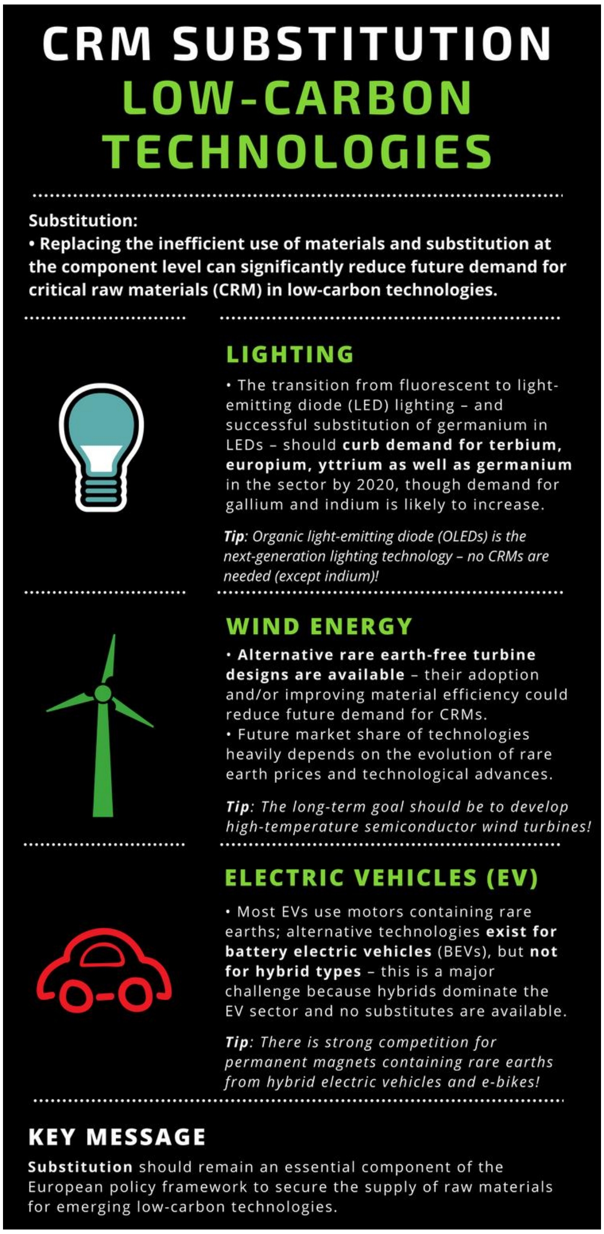
The EU is taking action to secure reliable and unhindered access to raw materials. In this context, the European Commission set up a robust policy framework, e.g. the European Innovative Partnership on Raw Materials, the 7th and Horizon 2020 research framework programmes, etc., to promote innovative solutions and accelerate market take-up of innovations in the field of raw materials. Substitution has been recognised as an essential element of the integrated EU strategy to secure raw materials supply. It could contribute to reducing the EU's dependency on imports of raw materials, among various measures (e.g. improving domestic supply conditions, diversifying supply sourcing, and improving resource efficiency, including recycling).

This study evaluates the substitution options of nine CRM, namely Eu, Tb, Y, In, Ga, Ge, Nd, Pr and Dy, in three low-carbon technologies: lighting, wind turbines and electric vehicles. It also analyses the potential of reducing the demand for these materials in the short term (2020) in relation to the widespread adoption of the technologies.

An assessment of the state of the art of substitution revealed that a complete and direct (one-by-one) replacement of all CRM by other more readily available or less critical materials in phosphors and LED as well as in permanent magnets is still not possible at large scale despite many years of research. A promising approach which, in the short-term, would allow for full substitution of these CRM at element level is also missing. High-functionality features prevent the direct substitution of CRM in high-performing compounds.

As a consequence of uncertainties concerning CRM supply, price volatility, sectorial competition for the same materials, etc., some manufacturers have adopted other solutions. They have made progress on the better use of some CRM (e.g. improved material efficiency) and developed alternative technologies which use either a limited amount of CRM or none at all.

Improvements in material efficiency and the substitution of critical raw materials at component level have the potential to reduce the demand for some CRM.



Component substitution is possible in all the above-mentioned low-carbon technologies. Alternative lighting devices, electric traction motors or turbine designs are either at pilot scale or even are available commercially, through trade-offs between economic and technical performances. Other technologies will probably be developed after 2020 (e.g. OLED technology in lighting, high-temperature semiconductors in wind turbines, and switched reluctance motors in electric vehicles).

The future market share of different low-carbon technologies will depend to a large extent on the evolution of raw material prices and the development of technological advantages for these products, alongside regulatory frameworks and the effectiveness of energy policies. The current low prices of CRM and readily available supply offer no incentive to switch to CRM-free technologies unless they become more cost-effective for equivalent performance. The lighting and wind power sectors as well as the battery electric vehicle sector are well prepared to respond to a potential CRM supply shortage thanks to progress made on improving the material efficiency and availability of CRM-free technologies. However, unlike the wind and lighting sectors, the emerging hybrid electric vehicle applications will remain largely reliant on critical raw materials, particularly on rare earth elements (REEs).

Key findings of this study are summarised below:

- **Lighting sector**: this foresees a technological evolution towards high-energy efficient LED lighting. LEDs do not require terbium and the amount of europium and yttrium required is much less (up to 20 times) than in fluorescent technology. Moreover, germanium has been successfully substituted by gallium in LED lighting. However, the transition from fluorescent to LED lighting is bringing new challenges to material research, such as finding substitutes for gallium and indium which remain key elements in current LED and display applications. In parallel, more research is needed to accelerate the market take-up of OLED in general lighting applications. With the exception of indium, OLED technologies do not need CRM.
- **Wind energy**: although most wind turbines currently operate with traditional technologies without rare earths, the direct drive permanent magnet synchronous generator (DD-PMSG), which does contain critical rare earths, is expected to significantly penetrate the large turbine (more than 5 MW) market and offshore wind sector. Due to concerns about the supply of REEs, some wind manufacturers have developed alternative turbine designs. Adoption of these alternatives and progress on lowering the content of dysprosium in PMSG can contribute to reducing the pressure on the supply of rare earths in the wind power sector. Any potential supply disruption and price increase in rare earths will have a negative effect on the EU's wind industry, due to the lack of domestic production, and its leadership in offshore market, in which DD-PMSG has many advantages.
- **Electric vehicles**: currently, most electric and hybrid vehicles are using permanent magnet synchronous motor (PSM) technology. The demand for rare earths used in neodymium magnet (NdFeB) production is likely to increase significantly in the near future following the global deployment target for EV sales. Significant competition from other similar sectors (e.g. HEV, e-bikes, vans and even heavy-duty vehicles) is adding to the pressure on the supply of rare earths in electric road transport applications. Despite the fact that rare earth-free technologies are already successfully applied for battery electric vehicles (BEV) and notable progress has been made towards improving the material efficiency and developing REE-free motor prototypes for hybrid car types, substitution of rare earths in electric vehicles should remain a priority in European research programmes.

In conclusion, substitution can contribute to mitigating a potential CRM supply bottleneck in low-carbon technologies, as European industries have the innovative capacity to develop and implement substitutes at different scales. Looking ahead, integrating a security of supply policy for CRM must also consider, alongside substitution, access to resources (e.g. through trade policies, and production from EU sources) as well as recycling as potential solutions in the longer term.

1. Introduction

1.1 EU initiatives on raw materials

The EU is highly dependent on imports of certain raw materials, which are crucial for the efficient and sustainable development of the European economy as well as for improving its citizens' quality of life. The growing global demand for certain minerals and metals, price volatility and market distortions imposed by some producing countries have contributed to raising concerns about the secure access and cost-effective supply of raw materials.

In Europe, this situation was recognised by the European Commission (EC), which has pursued specific policies for safeguarding the supply of raw materials. In 2008, the EC adopted the 'Raw Materials Initiative' (RMI) which set up an integrated strategy at EU level aimed at responding to different challenges related to access to non-energy and non-agricultural raw materials [EC, 2008]. Ensuring a sustainable supply of raw materials is essential for the competitiveness and growth of the EU economy and to meet the objectives of the Europe 2020 strategy[1].

The RMI's strategy entered its implementation phase in 2013 through the 'European Innovation Partnership (EIP) on Raw Materials' [EC, 2013]. The EIP brings together companies, researchers and NGOs from all the Member States to promote innovation in the raw materials sector. All stages of the value chain are implicated, from exploration, extraction and processing to recovery and recycling as well as innovation in the area of substitution. It also plays an important role in meeting the objectives of the Commission's flagship initiatives – the Innovation Union and Resource Efficient Europe – by sustaining the supply of raw materials to the European economy. The EIP is not a funding instrument but it facilitates collaboration in the Horizon 2020 framework programme and assists in the coordination of research in other EU policies and programmes.

The European Institute of Innovation and Technology (EIT) also supports EU initiatives in the field of raw materials. The recently funded Knowledge and Innovation Communities (KIC) is focusing on sustainable exploration, extraction, processing, recycling and substitution of raw materials. As one of the strongest consortiums ever created in the field of raw materials, EIT RawMaterials has the ambitious vision of turning the challenge of raw materials dependence into a strategic strength for Europe.

The European Commission carries out criticality assessments at EU level on a wide range of raw materials, and regularly publishes a list of critical raw materials (CRM). They are defined as those raw materials that combine a high economic importance to the EU with a high risk associated with their supply. The latest assessment has identified 20 raw materials as critical from the list of 54 candidate materials (Box 1.1) [EC, 2014a].

Box 1.1: Critical raw materials for the EU economy, 2014

Antimony	Beryllium	Borates	Chromium	Cobalt	Coking coal	Fluorspar
Gallium	Germanium	Indium	Magnesite	Magnesium	Natural graphite	Niobium
PGMs[#]	Phosphate rock	REEs[*] (heavy)	REEs[*] (light)	Silicon metal	Tungsten	

[#]Platinum group metals; [*]Rare earth elements

An analysis of the global primary supply of CRM shows that: (i) the EU is notoriously lacking in production; and (ii) the supply is concentrated in a few countries, particularly China (Fig. 1).

[1] Europe 2020 is the European Union's ten-year jobs and growth strategy to create the conditions for smart, sustainable and inclusive growth. Five specific targets have been agreed to be achieved by 2020, covering employment, research and development, climate and energy, education, social inclusion and poverty reduction.

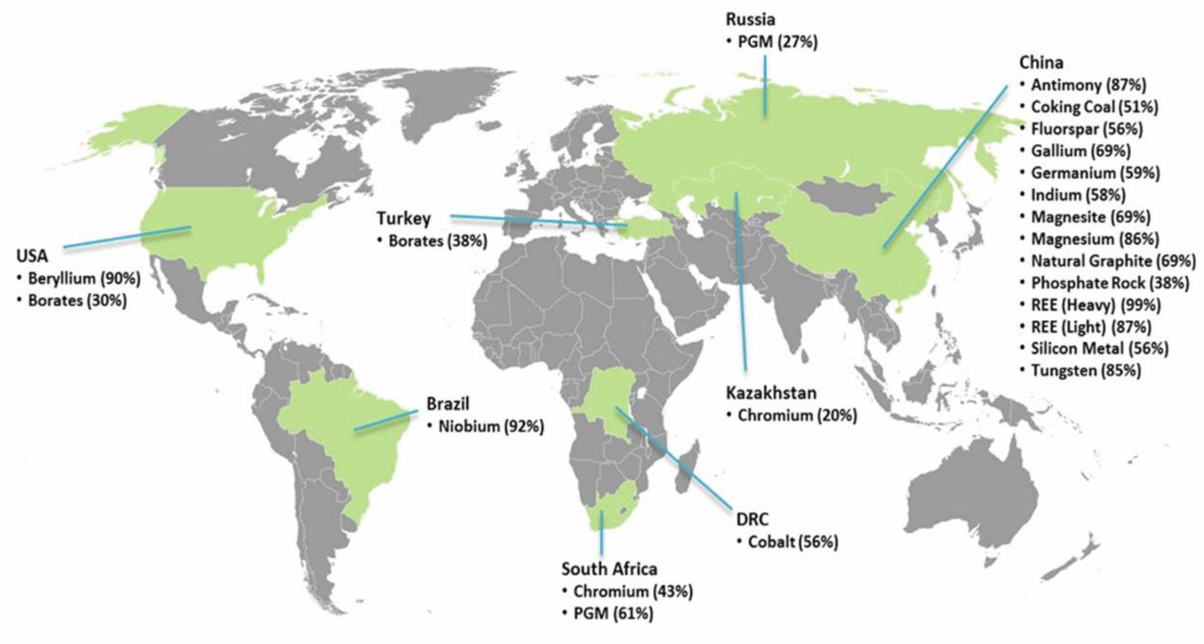


Figure 1: Overview of the primary suppliers of the 20 CRM [EC, 2014a]

Recently, the European Commission's Joint Research Centre (JRC) has contributed to a revision of the criticality methodology and a new assessment is currently ongoing. The new list of critical raw materials is expected to be published in 2017.

1.2 Raw materials as a potential bottleneck to future deployment of low-carbon energy technologies

The transition to a low-carbon economy is a central priority for the EU to tackle climate change and ensure sustainable growth and prosperity for its citizens [EC, 2015]. Energy production and use are responsible for about two-thirds of total greenhouse-gas (GHG) emissions worldwide [IEA, 2015a]. Therefore, the energy sector has a crucial role in addressing climate goals through renewable energy, greater efficiency, sustainable energy management and 'smart' transmission. While the EU is already on track to meet the 2020 goal of 20 % renewable energy in its energy mix, a new ambitious target of 27 % for the share of renewable energy consumed was set for 2030. The EU 2020 climate and energy package sets two additional targets for 2020: a 20 % cut in GHG emissions (from 1990 levels) and an improvement in energy efficiency by 20 %. Under the 2030 climate and energy framework, EU countries have agreed to increase these targets to at least 40 % cuts in GHG emission (from 1990 levels) and improving energy efficiency by at least 27 % by 2030.

Among various technological, financial, market and policy challenges, the large-scale deployment of low-carbon energy technologies will lead to a significant increase in the demand for raw materials. Concerns about the supply of raw materials being insufficient to meet the growing demand of these technologies have increased considerably in the past few years. Previous studies conducted by the JRC have shown that several low-carbon energy technologies could be at risk because of potential bottlenecks in the supply chain of certain raw materials [JRC, 2011, 2013]. The recent JRC report entitled 'Critical metals in the path towards the decarbonisation of the EU energy sector' identified 32 materials that are significant in terms of amounts requested compared to their global supply. When market and geopolitical factors were taken into account, eight of them were given a high criticality rating, namely: dysprosium, europium, neodymium, praseodymium, terbium, yttrium, gallium and tellurium (Fig. 2).

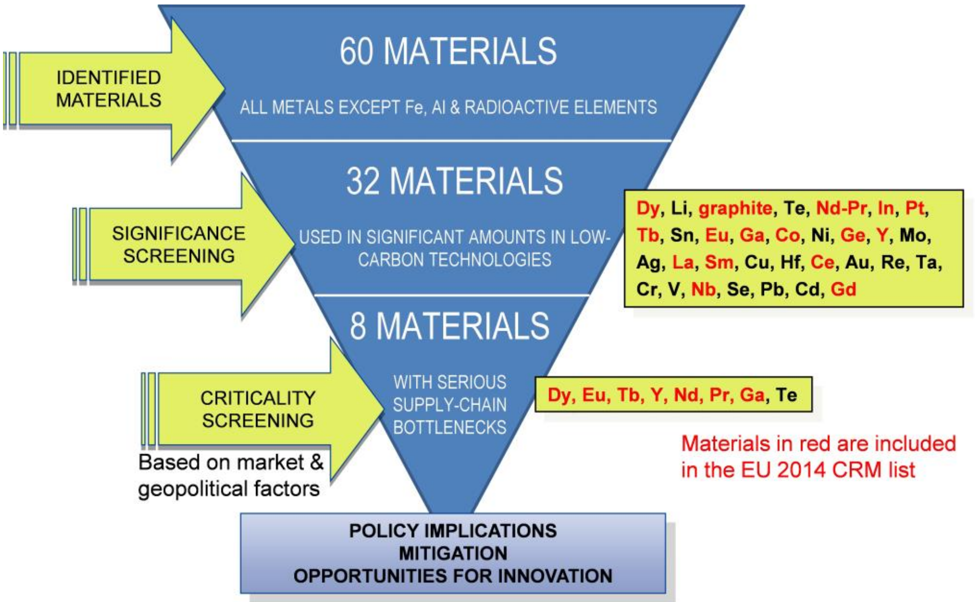


Figure 2: JRC assessment for the identification of raw materials as a potential bottleneck in the future European energy system [JRC, 2013a]

Furthermore, six additional materials are considered to have a medium-to-high risk and should be monitored closely: graphite, rhenium, hafnium, germanium, platinum and indium. Similar challenges to the material supply that may affect the US' clean energy technologies in the short to medium term were found by the Department of Energy [DOE, 2011a].

The technologies of particular concern to the most critical materials listed in the JRC report were as follows: fluorescent lighting, wind energy, electric vehicles, and solar photovoltaic (Fig. 3).

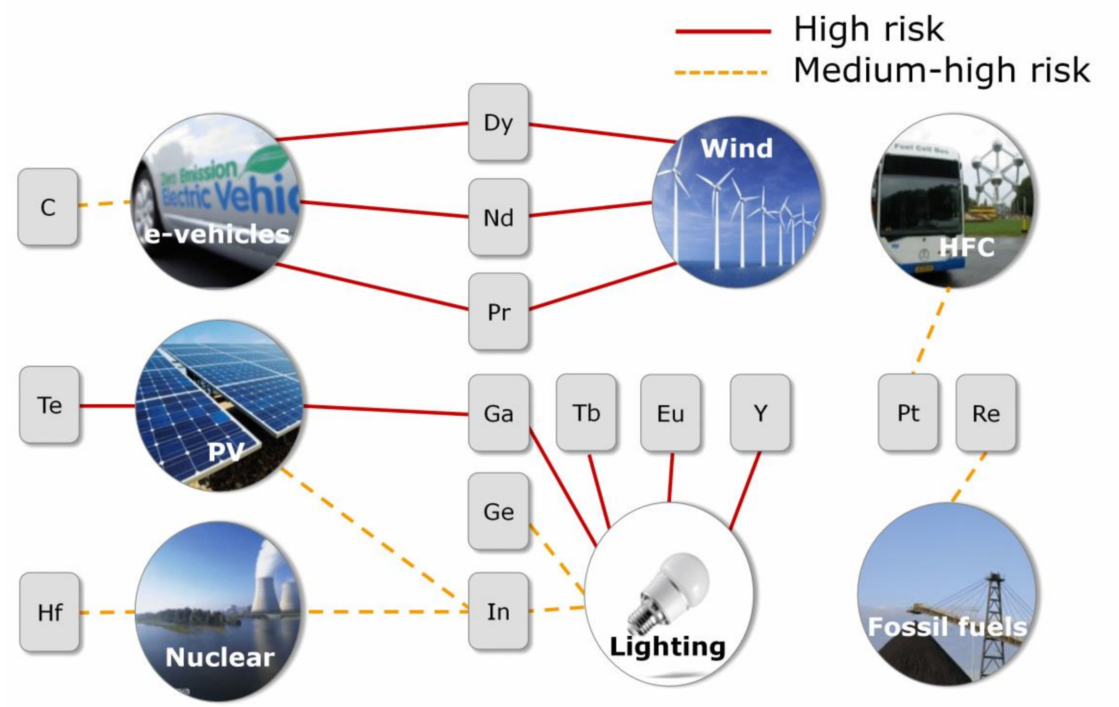


Figure 3: Low-carbon energy technologies at risk due to potential bottlenecks in the supply chain of critical raw materials [JRC, 2013a]

Both the JRC and RMI studies recognise that problems in the supply of raw materials could be alleviated by adopting different strategies in parallel, such as: increasing domestic primary production, securing resources from third countries, better resource efficiency (recycling, eco-design, etc.) and substitution. Nevertheless, these strategies have been frustrated by technical, financial, regulatory and political issues that make any solution extremely difficult in the short term. Of the various mitigation options, substitution has received the most attention and would appear to be feasible, in particular in cases when a new component, system or technology are the substitutes.

1.3 Scope of the study and approach

Although previous JRC and EC reports highlighted the principal strategies for mitigating the supply chain risks for critical raw materials, a complete assessment of the substitution of CRM in low-carbon energy technologies is currently not available.

In relation to mitigating potential bottlenecks in the supply of critical raw materials to the European energy system, the aim of this study is to evaluate the substitution options for nine critical raw materials used in the following low-carbon energy technologies (i.e. applications):

- **Efficient lighting**, which requires: europium (Eu), terbium (Tb), yttrium (Y), indium (In), gallium (Ga) and germanium (Ge) in phosphors and light-emitting diodes (LEDs);
- **Wind energy and electric vehicles (EVs)**, which require: neodymium (Nd), praseodymium (Pr) and dysprosium (Dy) in permanent magnets (i.e. neodymium-iron-boron magnet).

In addition, this report provides background information on current and future technologies, ongoing R&D activities focusing on alternative materials and components, the main key players and other relevant economic, technological or political factors.

The main research questions the study proposes to address are:

Q1. *What are the most feasible substitution options for the critical materials Eu, Tb, Y, In, Ga, Ge, Nd, Pr and Dy in lighting, wind energy and electric vehicles?*

Q2. *To what extent can substitution alleviate demand for these CRM by 2020*?

The study is based on a holistic approach, and thus considers all substitution possibilities starting from primary (one-by-one material) substitution and expanding the search to other opportunities, such as reducing use through better material efficiency and component/system substitution. The feasibility of substitutes was assessed through the so-called 'technological development status', which takes two factors into consideration: technical performance of the substitute, and the economic consideration (Fig. 4). For instance, the technologies widely used or in serial operation are marked in green boxes. In contrast, red indicates those technologies with current niche applications or prototypes, whereas grey-marked technologies are in an earlier R&D stage. The smaller boxes at the right of each substitution path indicate if critical materials are completely substituted or reduced in amount (e.g. CRM-free or CRM ↓). Further information is given on the performance level of the substitution option. The symbol '≈' represents solutions with similar or slightly lower performance compared to the CRM. The symbols '+' and '-' stand for considerably better or lower performance respectively, whereas '?' indicates the substitution technologies with unclear evaluation of their performance due to being in an early R&D stage.

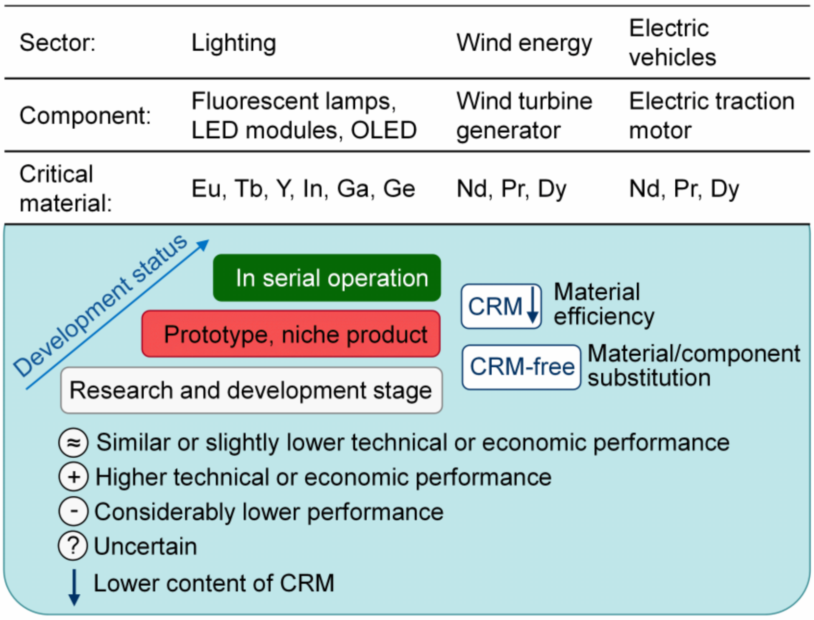


Figure 4: Indicative substitution approach followed in this study

The research and information analysed within this report were collected during 2015/2016 from a wide variety of sources, including the European Commission's reports on critical raw materials, academic articles, relevant documents and reports, industry publications, etc. In some cases an exhaustive analysis of the most recent technological developments was difficult to carry out because of the high degree of confidentiality. This is especially true for the research carried out by industries, which arises from strong global competition and the substantial investment required for developing new products. For these reasons, it is possible that some research activities have yet to be disclosed by the relevant industry. In this study, however, we have integrated the best available information with additional information gathered from interviews with material scientists, technical experts from industry, and academics who, in most cases, requested to remain anonymous. The potential and feasibility of using new or alternative non-critical materials in the three sectors were discussed in a dedicated workshop in which various experts participated and which conveyed the key findings and conclusions presented in this study.

The study also evaluates the short-term global demand for the nine CRM in the three sectors and the role of substitution. Such future demand is based on several assumptions and is designed to show the development trend in order to identify potential bottlenecks and the need for action.

This report comprises the following chapters:

- Chapter 1 provides the background to the study by linking critical raw materials and low-carbon energy technologies;
- Chapter 2 highlights the role of substitution in mitigating the possible constraints in the supply of raw materials and presents the EU initiatives on substitution;
- Chapter 3 discusses the substitution opportunities for critical raw materials in the lighting sector;
- Chapter 4 looks into the rare earth-based permanent magnets and evaluates the paths for reducing or completely replacing rare earths with other less-critical elements;
- Chapters 5 and 6 analyse the substitution options of permanent magnets in wind turbines and electric vehicles, respectively;
- Chapter 7 gives an estimation on future global demand for the nine CRM in the three sectors and the impact of substitution;
- Chapter 8 presents the conclusions of this study.

2. Substitution as a mitigation strategy to overcome the potential disruption in the supply of critical raw materials

In recent years, safeguarding a sustainable supply of raw materials for the European economy as a whole whilst ensuring the transition to a low-carbon, secure and competitive economy has become a priority for the European Commission. Several critical raw materials, including those investigated within this study, are key ingredients of many products used in high-tech applications and low-carbon technologies. These applications and their material constituents are relevant for many industries in Europe, such as renewable energy production, electronics, automotive, etc., which in turn guarantee economic development, safeguard jobs and growth in Europe, and contribute to reducing greenhouse gas emissions (GHG).

As previously mentioned, four principal sustainable strategies are required at the same time to mitigate supply chain risks for CRM within the EU [Schüler, 2015]:

- Increasing primary supply, e.g. by opening new European mining production or by-product extraction;
- Ensuring access to resources from third countries;
- Reuse, recycling and waste reduction;
- Substitution, including better material use.

Sustainable primary production within the EU represents one of the three pillars of the RMI. This is a challenging goal for the EU because mining takes place in a highly competitive global market, often with insufficient environmental and social standards in many mining countries. Currently, the global mining business related in particular to CRM is dominated by non-EU countries. Many barriers prevent the implementation in the short term of the sustainable primary supply of raw materials from European deposits (about 8-10 years elapse between the discovery of deposits and production at the mine).

Likewise, large volumes of secondary raw materials are not expected in the short term since many end-of-life products will enter the recycling circuit after decades (e.g. wind turbines reach the end of their service life in about 30 years), and recycling is not economically viable for many materials. Consequently, recycling is an important long-term strategy to ease the EU's dependence on raw materials, but not an appropriate instrument to cope with potential short- and mid-term supply shortages.

2.1 Policies and initiatives directed towards CRM substitution

2.1.1 Overview of the initiatives supporting substitution

In these circumstances, substitution becomes an essential part of the integrated strategy to reduce the EU's import dependency on certain critical raw materials in the short term. This is sustained by the strong innovative capacity of European industries, which is fundamental to successfully developing and implementing substitutes. Moreover, the development of new substitutes might open new market opportunities in various high-tech and energy-related sectors, thereby facilitating the transition towards sustainable production and a resource-efficient EU economy.

A survey of the policies and instruments supporting the substitution of CRM at the EU and Member State level was carried out by the European Parliament [EP, 2012]. This report highlights four main drivers for substituting critical materials: flexibility in materials supply, potential cost savings, a weakened monopoly power of suppliers, and environmental benefits.

Fostering the substitution of critical raw materials is one of the implementation actions set up by the European Commission in its RMI. For instance, it is addressed within the Strategic Implementation Plan (SIP) of the EIP on raw materials, which has as its objective, among others, the development of substitutes for critical and scarce raw materials in at least three applications [EIP, 2013]. Four synergetic specific actions are proposed in the low-carbon technologies field to promote innovative and sustainable solutions for decreasing the use of CRM or substitution of these materials in permanent magnets, batteries, catalysts and photovoltaic materials.

In Europe, the substitution of critical raw materials is also sustained through the Framework Programmes for research and innovation, e.g. FP7 and Horizon 2020 (H2020). An overview of relevant research projects funded by EU research programmes is presented in the next section. Raw materials represent a new research field under the H2020 programme as part of 'Societal Challenges 5' that support reaching EIP targets, including finding substitutes for critical raw materials. Other programmes under the Horizon 2020 may also promote the substitution of CRM. The most relevant of these is 'Future and Emerging Technologies' which aim to boost Europe's bid to take the lead in sustainable future technologies and nanotechnologies, advanced materials, innovative manufacturing and processing and biotechnology (NMBP). It supports the development of new technologies underpinning innovation across a range of sectors.

Substitution strategies in five priority applications (i.e. electronic components, permanent magnets, batteries, high-value alloys and photonics) were recently analysed by the FP7-funded project 'Critical Raw Materials Innovation Network (CRM_Innonet)'. Based on a transition theory approach, the project proposes five distinct roadmaps that describe the most promising pathways for reducing or eliminating CRM over the next 10 to 15 years [CRM_Innonet, 2015]. The project concludes that through substitution it is possible to reduce Europe's demand for several critical and scarce materials, however implementation of substitution strategies by industry will be achieved only if the pressure from the landscape on supply increases and access to these raw materials is no longer guaranteed.

Another initiative launched by the EC at the request of the European Parliament is the European Rare Earth Competency Network (ERECON). This project aimed to create a network of excellence and cross-disciplinary exchange to increase knowledge of the most efficient use of critical rare earth elements and their mining, refining, recycling and substitution. The working group proposed various policy priorities for consideration by European policy-makers and concluded that substitution of rare earths can help to mitigate pressure on supply, although it is not the only solution to rare earth challenges.

At the national level, a selected number of EU Member States, e.g. France, Finland, Germany, Sweden, the Netherlands, the UK, etc., presented specific strategies related to critical raw materials. While in principle these national strategies promote trade and regulatory policies, development co-operation, improving conditions for mining raw materials, provision of supporting infrastructure, etc., little is said about reducing the primary supply through substitution.

Other non-EU countries, such as the USA, Japan and the Republic of Korea, are actively acting to secure the supply of raw materials, and in general their approaches are similar to those in the EU. The USA and Japan have developed specific programmes for promoting advanced research on the substitution of critical materials across various industries, including the energy sector. For instance, the US' DOE supports the implementation of its Critical Materials Strategy by the Critical Materials Institute (CMI), a hub led by the Ames National Laboratory and a team of research partners. The CMI addresses in principal the challenges associated with critical materials used in clean energy technologies through diversifying supply, developing substitutes and improving reuse, and recycling. Since 2011, trilateral workshops between EU-US-Japan have promoted a dialogue on different policy areas related to critical raw materials at all stages of the value chain from exploration, mining and refining to end-use.

Besides national/regional programmes, international initiatives on raw materials are undertaken through the G8 Research Councils Initiative on Multilateral Research Funding. This joint funding initiative is a coordinated effort which supports multilateral partnerships working on research topics of global relevance. A specific call has already been dedicated to materials efficiency and the sustainable use of raw materials.

2.1.2 The EU landscape and funding programmes on the substitution of CRM

In support of the RMI, stakeholders are encouraged to take joint actions to achieve the EIP's objectives. Substitution of critical raw materials is one of the EIP priority areas, which involves various pan-European and national authorities, industry, academia and other relevant organisations. These partners are brought together on a voluntary basis in the so-called 'Raw Materials Commitments' (RMCs). There are currently 123 RMCs, eight of which are linked to the SIP's priority area 'substitution of raw materials' (Table 1).

Table 1: EIP's raw materials commitments (RMCs) linked to the priority area: substitution of raw materials

Commitment	Material for substitution	Overall objective
Critical Raw Materials Innovation Network (CRM_Innonet)	Several	To create an integrated community driving innovation in the field of substituting critical raw materials for the benefit of EU industry
European NAtural Rubber Substitute from Guayule (EU-NARS-G)	Natural rubber	To develop a basis for commercial guayule cultivation in European countries, implementation of plant extraction pilots, economic feasibility study to provide the basis for a larger-scale extension
New affordable stainless steel for extreme conditions (NASSCO)	Titanium, cadmium, chromium	To develop substitutes for CRM-based alloys with improved performance and longer lifetime in aerospace applications
Raw elements substitution in electronic and optoelectronic technologies (RESET)	Rare earth elements, indium	To create an efficient platform dedicated to the sustainable substitution of rare earth elements in photodevices and substitution of indium in transparent conductive layers
Recycled carbon fibres substitute for natural graphite and industrial applications (CARBOCYCLE)	Graphite	To scale up and bring to market a substitute such as carbon-fibre-reinforced plastic for natural graphite
Substitution of CRM – place for graphene in EIP on RM (SUBGraph)	Graphite, rubber, magnesium	To develop a graphene-based elastomer and polymer composite for a wide range of applications
Sustainable substitution in extreme conditions (SUBST-EXTREME)	Tungsten, cobalt, niobium, ruthenium	To identify and develop substitutes for CRM in metal alloys and hard materials used in energy, aerospace and mining industries
Critical raw materials: their role in nanotechnology-based value chains. Nanotechnology as a vehicle for substitution (RAW-NANOVALUE)	Several	To investigate how nanotechnology can foster the substitution of CRM in the main EU industrial value chains

The outcome of these commitments is monitored annually. Delivering innovative products, processes, services, technologies, business models or ideas on the sustainable supply of raw materials will contribute overall to reducing import dependency and putting Europe at the forefront of the raw materials sector. Although an RMC is an undertaking without any legally binding, and even though the EIP as such is not a funding instrument, it has the potential to facilitate access to finance from various sources.

The achievement of EIP's targets and, in general, implementation of the raw materials policy is sustained at a more practical level through funding programmes in line with the EU's strategy for research and innovation. The most relevant action contributing to ensuring a sustainable supply of non-energy and non-agricultural materials is the inclusion of raw materials in the Horizon 2020 programme as part of the Societal Challenges 5: 'Climate action, environment, resource efficiency and raw materials'. Total funding for all actions included in Societal Challenge 5 will reach EUR 3081 million, of which around 20 % is dedicated to raw materials. The main focus of the raw materials calls is on securing the supply of minerals and metals through innovative technologies for primary and secondary materials, as well as providing alternatives for supply. There is potentially substantial funding for CRM substitution through multiple actions and programmes (e.g. Horizon 2020). Several projects are ongoing while others have finished. It is beyond the scope of this report to analyse how these projects address the issue of critical materials. Instead, we only briefly describe those projects that are pertinent to CRM substitution, the intention being to highlight a series of concrete actions undertaken by the EU in this field (Table 2).

The EU has been funding and continues to fund priority research into developing CRM-free materials and technologies in key technology areas, including energy applications. Eighteen research projects were identified that address the substitution of critical raw materials, with a total budget of EUR 77.2 million, 78 % of which is the EU contribution. The majority of projects (61 %) aim at developing alternative materials or technologies for rare earth materials in permanent magnets, catalysts and lighting applications. Additional projects focus on the substitution of other critical materials (e.g. PGM, indium, gallium, tungsten, cobalt, etc.) in electronics, alloys and hard materials.

Besides research projects, the EU is sustaining the building of integrated communities to drive innovation and the transfer of knowledge in the field of critical raw materials and their substitution (i.e. CRM_InnoNet, COBALT and ERECON projects).

Apart from the projects described in Table 2, additional research and innovation actions are currently being proposed in different sections of the Horizon 2020 programme. For instance, the cross-cutting activities on unconventional and novel design technologies (e.g. several calls under the focus area Factories of the Future (FOF) may lead to making new multi-material products or technologies from non-critical raw materials. The upcoming calls, e.g. SC5-15-2016-2017 (Raw materials policy support actions) and NMBP-03-2016 (Innovative and sustainable materials solutions for the substitution of critical raw materials in the electric power system) will also contribute to further strengthening the EU's expert network on critical materials and delivering innovative, sustainable and cost-effective materials solutions.

Table 2: Overview of principal EU-funded research projects related to the substitution of critical raw materials [CORDIS, 2016]

Project title	CRM	Main objective	Timeline	Project details
Replacement and Original Magnet Engineering Options (ROMEO)	Rare earths in permanent magnets	Research and development of novel microstructural engineering methods that dramatically improve the properties of magnets and develop a totally rare-earth-free magnet	From 01/12/2012 to 30/11/2015	Call: FP7-NMP-2012-SMALL-6 Total cost: EUR 5 477 788 EU contribution: EUR 3 978 306
Nanocrystalline permanent magnets based on hybrid metal-ferrites (NANOPYME)	Rare earths in permanent magnets	Design and development of permanent magnets without rare earths based on hybrid nanostructured metals and metal ferrite oxides	From 01/12/2012 to 30/11/2015	Call: FP7-NMP-2012-SMALL-6 Total cost: EUR 4 506 353 EU contribution: EUR 3 479 493
Rare earth free permanent magnets (REFREEPERMAG)	Rare earths and platinum in magnets	Develop a new high energy density magnets without rare earths or platinum by exploitation of shape anisotropy of high magnetic moment and using high-throughput thin-film synthesis methods	From 01/05/2012 to 30/04/2015	Call: FP7-NMP-2011-SMALL-5 Total cost: EUR 5 186 669 EU contribution: EUR 3 841 400
New permanent magnets for electric-vehicle drive applications (MAG-DRIVE)	Rare earths in permanent magnets	Research and development of novel microstructural engineering methods for improving the properties of magnets based on light rare-earth elements, for electric vehicle applications	From 01/10/2013 to 30/09/2016	Call: FP7-SST-2013-RTD-1 Total cost: EUR 3 576 526 EU contribution: EUR 2 549 000
Advanced Reluctance Motors for Electric Vehicle Applications (ARMEVA)	Rare earths in permanent magnets	Develop a new rare earth-free generation of advanced reluctance motors in electric vehicles by multi-physics simulation models, comparative assessments and integrated electric drive systems	From 01/11/2013 to 31/10/2016	Call: FP7-SST-2013-RTD-1 Total cost: EUR 3 566 110 EU contribution: EUR 2 200 000
Switched/synchronous reluctance magnet-free motors for electric vehicles (VENUS)	Rare earths in permanent magnets	Develop high-efficiency motors using a limited number of permanent magnets or completely new magnet-free motor designs for electric vehicles	From 01/11/2013 to 31/10/2016	Call: FP7-SST-2013-RTD-1 Total cost: EUR 2 939 897 EU contribution: EUR 1 999 491
Synchronous reluctance next generation efficient motors for electric vehicles (SyrNemo)	Rare earths in permanent magnets	Development and application of an innovative synchronous reluctance machine with higher power density driving cycle efficiency in a next-generation electric motor for fully electric vehicles	From 01/10/2013 to 30/09/2016	Call: FP7-SST-2013-RTD-1 Total cost: EUR 3 757 303 EU contribution: EUR 2 739 190
Drastically Reduced use of Rare Earths in Applications of Magnetocalorics (DRREAM)	Rare earths in permanent magnets	Reduce the volume of rare earth permanent magnets and eliminate wastage of rare earths during the scalable manufacture of magnetocaloric materials used in magnetic phase change technologies	From 01/01/2013 to 31/12/2015	Call: FP7-NMP-2012-SMALL-6 Total cost: EUR: 5 158 863 EU contribution: EUR 3 707 143
Development of next generation cost efficient automotive catalysts (NEXT-GEN-CAT)	PGMs in automotive catalysts	Develop novel eco-friendly nanostructured automotive catalysts utilising transition metal nanoparticles (PGM-free) by an effective dispersion and controllable size of metal nanoparticles	From 01/02/2012 to 31/01/2016	Call: FP7-NMP-2011-SMALL-5 Total cost: EUR 5 615 292 EU contribution: EUR 3 938 298

Doped carbon nanostructures as metal-free catalysts (FREECATS)	Rare earths and PGMs in catalysts	Develop new PGM-free catalysts in the form of bulk nanomaterials or hierarchically organised structures used in catalytic transformations	From 01/04/2012 to 31/03/2015	Call: FP7-NMP-2011-SMALL-5 Total cost: EUR 5 071 614 EU contribution: EUR 3 955 619
Novel cheap and abundant materials for catalytic biomass conversion (NOVACAM)	Rare earths and PGMs in catalysts	Develop catalysts using non-critical elements for the conversion of biomass to chemicals and fuels by applying a “catalysis by design” approach	From 01/09/2013 to 28/02/2017	Call: FP7-NMP-2013-EU-Japan Total cost: EUR 2 415 573 EU contribution: EUR 1 786 842
Indium replacement by single-walled carbon nanotube thin films (IRENA)	Indium and gallium in electronic devices	Develop high-performance materials such as metallic and semiconducting single-walled carbon nanotube (SWCNT) thin films to eliminate the use of critical metals in electronic devices	From 01/09/2013 to 28/02/2017	Call: FP7-NMP-2013-EU-Japan Total cost: EUR 2 349 301 EU contribution: EUR 1 799 648
Towards indium free TCOs (INREP)	Indium in electronic devices	Deploy robust alternatives such as transparent conducting oxides (TCOs) to indium-based transparent conductive electrode materials	From 01/02/2015 to 31/01/2018	Call: H2020-SC5-2014-1 stage Total cost: EUR 6 197 149 EU contribution: EUR 4 999 433
Indium-free transparent conductive oxides for glass and plastic substrates (INFINITY)	Indium in electronic devices	Develop an inorganic alternative to indium-tin-oxide (ITO) as a transparent conductive coating (TCC) for display electrodes on glass and plastic substrates via nanostructured coatings and printing methods	From 01/12/2014 to 31/01/2018	Call: H2020-SC5-2014-1 stage Total cost: EUR 4 003 243 EU contribution: EUR 4 003 243
Cycling resources embedded in systems containing Light Emitting Diodes (cycLED)	Rare earths, gallium and indium in LED	Optimise the flows of critical materials over all life-cycle phases (e.g. production and manufacturing, assembling, use and material recycling) to achieve an efficient management of the material resources	From 01/01/2012 to 30/06/2015	Call: FP7-ENV-2011-ECO-INNOVATION-2 stage Total cost: EUR 5 405 295 EU contribution: EUR 4 046 195
Heusler alloy replacement for iridium (HARFIR)	Iridium (a PGM element) in alloys	Develop antiferromagnetic (AF) Heusler alloy (HA) films as a substitute for iridium-based alloy in spin electronic technologies, employing *ab initio* calculations and HA film growth techniques	From 01/09/2013 to 31/03/2017	Call: FP7-NMP-2013-EU-Japan Total cost: EUR 2 312 580 EU contribution: EUR 1 781 910
Next generation of superhard non-CRM materials and solutions in tooling (Flintstone2020)	Tungsten and cobalt in hard materials	Provide a perspective for the replacement of W and Co in cemented carbides/WC-Co, and PCD/diamond-Co by developing innovative alternative solutions for tooling operating under extreme conditions	From 01/02/2016 to 31/01/2020	Call: H2020-SC5-2015-1 stage Total cost: EUR 4 996 180 EU contribution: EUR 4 996 180
A novel process for manufacturing complex shaped Fe-Al intermetallic parts resistant to extreme environments (EQUINOX)	Chromium, nickel, molybdenum, and vanadium in steels and superalloys	Develop a novel near-net-shape technology for the production of a new class of highly advanced ductile Fe-Al-based intermetallics that will substitute Cr/Ni-based (stainless) steel parts used in high volume end consumer products in the lock industry, electronics, process industry and automotive industry	From 01/02/2016 to 31/01/2019	Call: H2020-SC5-2015-1 stage Total cost: EUR 4 678 345 EU contribution: EUR 4 678 345

2.2 Substitution (or substitutability) in assessing criticality of raw materials

Concerns about supply security, the consequences of supply restrictions and the environmental impact of raw materials have led to numerous studies to evaluate the criticality of materials. Various methods and methodologies are used to assess criticality, which are developed for monitoring the materials flow and helping decision-makers to prevent or mitigate the effect in case of supply shortages. Until now, there has not been a single approach to quantify criticality because of the different objectives criticality studies try to accommodate or studies which are specifically designed to meet the purpose of a company, country or region, for a specific application or regional economic sector. Therefore, the results of these studies are highly influenced by the adopted methodology and selection of indicators. Several factors/parameters are more commonly taken into account when assessing the criticality of raw materials [DESIRE, 2014]:

- Supply factors (geological/economic availability, recycling);
- Geopolitical factors (policy and regulation, geopolitical risk, supply concentration);
- Demand factors (future demand projections, substitutability);
- Vulnerability to supply restriction;
- Other factors (environmental performance, cost impact, economic importance, etc.).

Substitution or substitutability at material level is often used as a sub-indicator for assessing criticality. At present, there are no comprehensive quantitative data on the substitutability of raw materials because too many parameters can influence the degree to which a critical material is substituted. Similarly, there is no consensus in the attribution of substitution and substitutability in criticality assessments. Some studies assign substitutability to the supply-risk dimension, others to vulnerability to one or even both dimensions.

A criticality assessment of raw materials conducted in 2013 by the European Commission at the EU level combines two components: economic importance and supply risk due to poor governance [EC, 2014a]. Within this methodology it is considered that the supply risk derived from primary production can be reduced by the existence of options for full substitution and by increasing recycling rates from end-of-life products (Fig. 5). The degree of substitution expressed in terms of a 'substitutability index' was estimated for each application of a material and then scored and weighted with values ranging from 0 to 1 (1 corresponds to the least substitutable).

Since substitution could influence the consequences to the European economy in the case of a supply shortage, the revised criticality assessment by the European Commission, and with the support of the JRC, includes substitution in the economic importance component, too. Given the fact that, to some extent, the availability of substitutes could mitigate the risk of supply disruptions by reducing demand for a given raw material, substitution is also used to evaluate the risk to supply. However, different aspects of substitution are considered in the two dimensions of criticality. The substitute's performance and cost are incorporated into the economic importance component, and other parameters, i.e. substitute production, substitute criticality and substitute co-production, are taken into account in the risk to the supply (Fig. 5). The results of the new criticality analysis will be available in 2017. The revised EU methodology focuses on the current situation (snapshot in time). As a result, only those substitutes (substitution) available today and not potential future replacements (substitutability) are taken into consideration in the new assessment.

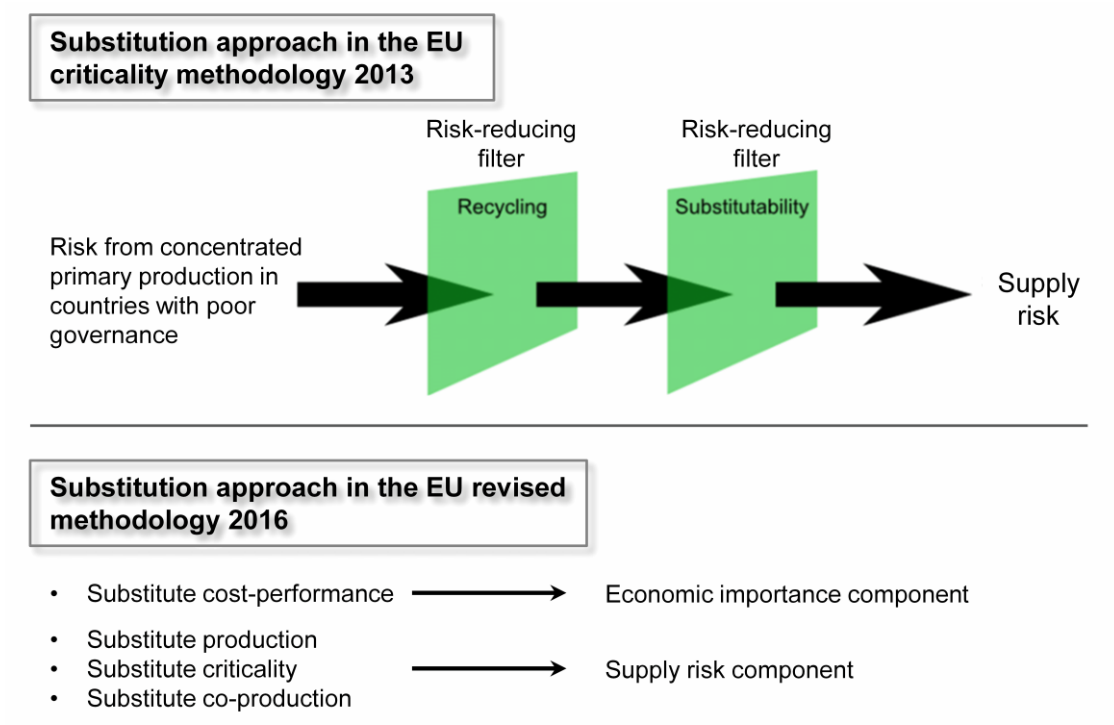


Figure 5: Visualisation of substitution approaches in the EU's 2013 criticality assessment and in its 2016 revised methodology

In general terms, substitution remains a complex factor as it could be influenced by many parameters and because of constant fluctuation in material use in response to technological innovation, market forces, economic development, etc. To be considered feasible, in general, substitution should meet at least three main conditions: (i) it should align with performance requirements; (ii) it should make sense economically (the cost of the substitute material and of the manufacturing process should remain competitive); and (iii) it should be effectively scalable. Moreover, the substitution should not lead to another pitfall, e.g. the solution is not to replace a critical raw material with another critical one, thereby raising supply constraints for other applications. To a certain extent, these factors are also taken into account in this study for evaluating the substitution possibilities of critical raw materials in low-carbon technologies.

The substitution potential of critical raw materials can be seen from many perspectives. In most cases, the direct replacement of a critical raw material by other more readily available and less critical ones, while maintaining the product's original performance, would appear to be either inadequate or inexistent [Graedel, 2015]. Moreover, a recent study carried out by the European Parliament concluded that "the majority of substitutes are currently in the research and development stage and market-ready solutions are rarely available" [EP, 2012]. Therefore, the scope of the substitution concept needs to be broadened to also include other aspects such as product design, changes to process, higher material efficiency, and product replacement by new technology. Nonetheless, explorations into primary substitution, e.g. direct material substitution, are already ongoing and fundamental research must be further encouraged.

Since the substitution prospects are associated with the properties and specifications of each element, the next section gives a brief description of the characteristic and technological aspects of critical raw materials in phosphors and LEDs as well as in permanent magnets.

2.3 Overview of critical materials used in lighting, wind turbines and electric vehicles

This chapter provides a summary of relevant information about critical raw materials used in phosphors and LEDs, and in permanent magnets. Comprehensive information on general market aspects (e.g. current and expected demand, global market, production chain, main applications) is given in the critical raw materials profiles published by the European Commission as an appendix to the report on critical raw materials for the EU [EC, 2014b]. An overview of the CRM and components used in lighting, wind turbines and electric vehicles, highlighting the principal substitutes, is presented in Table 3.

Table 3: Critical raw materials in the lighting, wind energy and electric vehicle sectors and main substitution paths currently available or under development

Sector	Technology/ component	Critical raw materials	Substitution path	Substitute material
Lighting and displays	Fluorescent lamps and light-emitting diodes (LEDs)	Europium, terbium, yttrium, indium, gallium and germanium	LED for fluorescent technology (high materials efficiency) and organic-LED	Zinc, magnesium, metal-organic compounds
Wind energy	Permanent magnets synchronous generators (PMSG) in wind turbines	Neodymium, praseodymium, dysprosium and terbium	Traditional turbines with gears based on induction generators	Copper
Electric vehicles	Permanent magnets synchronous motors (PSM) in electric powertrain	Neodymium, praseodymium, dysprosium and terbium	Alternative motor types with less or without REE	Copper, ferrite

To understand why these critical materials are so indispensable for the three sectors mentioned and what challenges are related to secure supply and price volatility, it is important to look at each element individually. Introduction of export quotas for rare earths by the monopoly-supplier China contributed to a significant increase in REE prices in 2011/2012, as illustrated in Figure 6. After 2012, prices of rare earths fell continuously, mainly for three reasons: the bursting of the speculative bubble, the global economic downturn, and company efforts to increase material efficiency and adopt substitution. In January 2015, China eliminated export quotas after a WTO ruling legal actions against export restrictions. Nevertheless, rare earths supplied by China still require an export licence.

Historically, prices of indium, germanium and gallium have been volatile due to frequent changes in the supply and demand of key technologies (Figure 6). For instance, the indium price peak in 2015 coincided with the adoption of liquid crystal display (LCD) flat-panel TVs on the market. In 2012, indium prices fell as result of a fall in Japanese consumption by almost 70 %. In the case of germanium, it is assumed that the recent stockpiling by the USA and China has contributed to its global price increase. In 2011/2012, the price of gallium rose due to the growing demand for gallium nitride in mobile displays and electronic applications. The increase in gallium production has led to a significant lowering of its price.

In spite of the current low prices and relatively stable supply of REEs and other CRM, concerns about reliable and undistorted access remain high among industry and policy-makers. The European industry is still highly dependent on imports of several raw materials and a supply crisis, such as that experienced for REEs, remains a distinct possibility [ERECON, 2015].

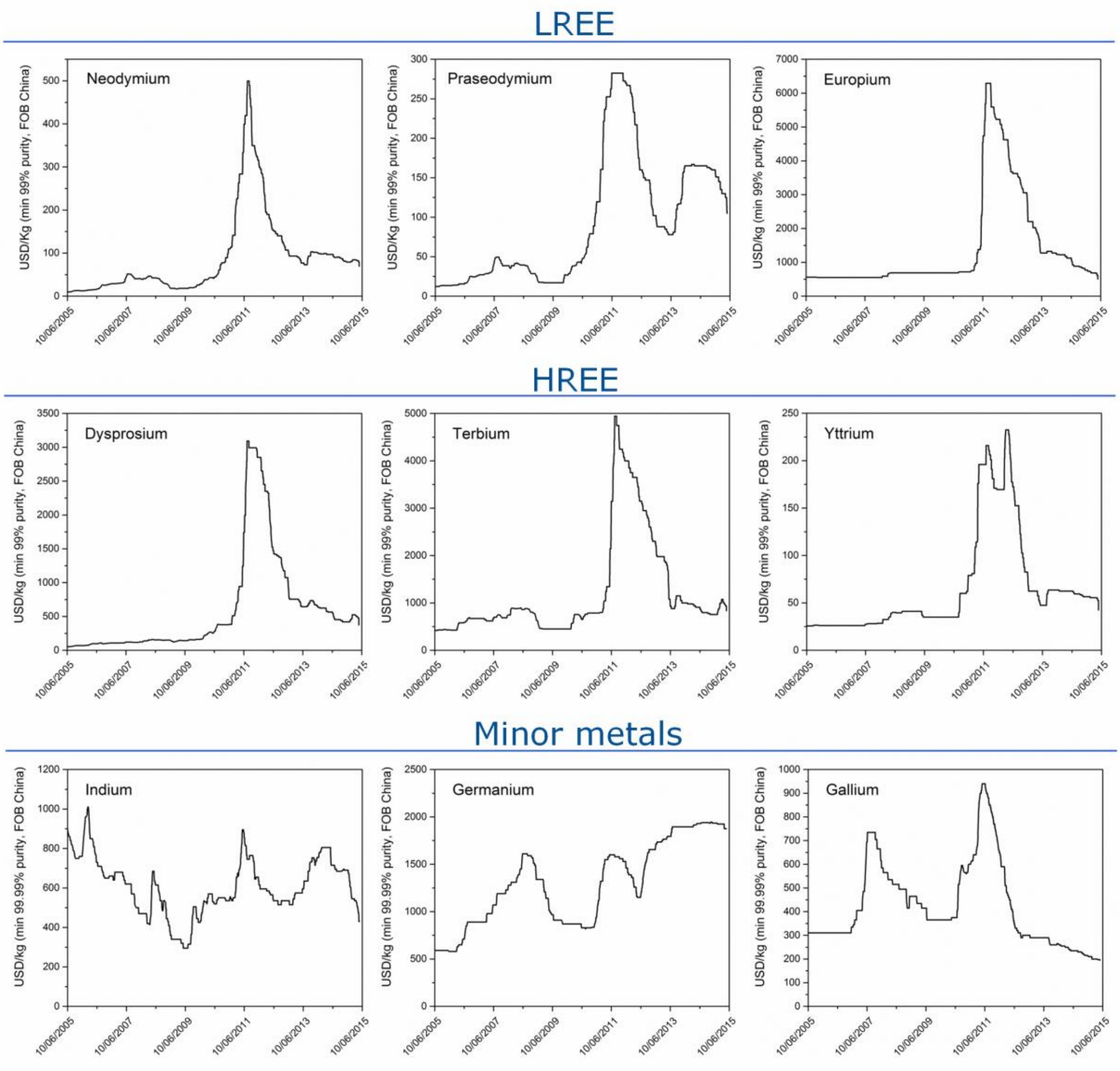


Figure 6: Price variations for Nd, Pr, Eu, Dy, Tb, Y, In, Ge and Ga from 2005 to 2015; values refer to metal form and are related to Free On Board (FOB) China; LREE – light rare earth elements; HREE – heavy rare earth elements [Asian Metal, 2016]

A summary of the principal characteristics in terms of production, applications and substitution opportunities of the nine CRM is given in the following sections. Most of the information is extracted from the reference [EC, 2014b] and updated based on recent developments.

2.3.1 Light rare earth elements – LREE

Light rare earth elements, including neodymium, praseodymium and europium, are mined together with other rare earths. China dominates mining production, but newly reopened mines in Mount Weld (Australia) operated by Lynas Corporation Ltd, and the Mountain Pass (USA) operated by Molycorp Inc. have also contributed to the LREE market since 2011.

Currently, there is no mining production of LREE in the EU and non-Chinese suppliers are facing difficulties due in large part to a recent collapse in rare earth prices. As result, in 2015 Molycorp was forced to apply for bankruptcy protection. Despite the current lack of incentive for opening new mining operations for LREE production, a new cycle of higher prices might alter the situation. Eventually this would lead to the consistent development of exploration projects outside China, some of which are already at an advanced stage. From the supply side, following the WTO dispute settlement, in 2015 China put an end to export quotas for rare-earth minerals.

2.3.1.1 Neodymium

Neodymium is a light rare earth element that is mostly used in magnet applications for NdFeB production. NdFeB is a permanent magnet with the highest energy density currently available, enabling compact and highly efficient applications. It plays a key role in wind turbines and electric motors as well as in other high-tech applications. Recent applications of NdFeB include high-efficiency pumps, washing machines and magneto-caloric refrigeration.

With relatively low prices – compared to the price peaks in 2011 – and due to growing numbers of applications in emerging high-tech and energy technologies, the demand for neodymium is expected to increase in the short term. A reduction in the amount of neodymium in NdFeB magnets is proving to be possible.

2.3.1.2 Praseodymium

Praseodymium is another light rare earth element with similar chemistry to neodymium. Most praseodymium is used together with neodymium in magnet applications (they are found in a Nd:Pr ratio of 4:1) for NdFeB production (see section 4.1.2). Around a quarter of total praseodymium consumption is used for phosphors, ceramics and polishing. Over the next five years, the demand for praseodymium is expected to grow steadily at around 6 % per year.

2.3.1.3 Europium

Almost all europium production is used in phosphors. It was evaluated by the EU as a critical raw material due to concerns about supply security and increasing demand for phosphor applications. Recent developments in the lighting sector, e.g. the ongoing adoption of the more energy-efficient LED technology, may attenuate and possibly even decrease future demand for europium. Secondary production has also reached maturity. Since 2012, Solvay Rhodia (France) has been recycling europium from end-of-life phosphor lamps.

2.3.2 Heavy rare earth elements – HREE

Heavy rare earth elements, including dysprosium, terbium and yttrium, are mined almost solely in China. The rare earth mines in Australia and the USA do not produce relevant amounts of HREE. Several promising advanced-stage projects are currently being developed outside China. As for LREE, a major change in HREE supply has been in place since China lifted the export restrictions.

Since 2012, secondary production of terbium and yttrium has been done by Solvay Rhodia (France) from recycled phosphors powder.

2.3.2.1 Dysprosium

Dysprosium is mainly used as an additive in magnets for wind turbine and electric vehicle applications. It was perceived as one of the most critical raw material due to past supply shortages and the strongly growing demand for permanent magnets. However, recent developments have led to a new evaluation of the future supply/demand balance. The steep demand curve for dysprosium has flattened out due to progress in the production of resource-efficient magnets, with important savings in dysprosium. Furthermore, high dysprosium prices have led to targeted-oriented use. For instance, dysprosium is currently no longer used in applications that do not require high-temperature stability.

2.3.2.2 Terbium

Terbium is mainly used in phosphors and less in magnets for wind turbines and electric vehicles. In magnets, it is applied as an additive to increase the stability of NdFeB at high temperatures, similarly to dysprosium. The EU regards it as critical metal due to serious concerns about future supply shortages and the strongly growing demand for phosphors. Following recent developments in the lighting sector, a re-evaluation of the future supply/demand balance is necessary. It is expected that the rapid penetration of LED technology will moderate and even decrease future terbium demand for phosphors.

2.3.2.3 Yttrium

Yttrium is mainly consumed as a high-purity compound for phosphors and ceramics. Until recently, demand was increasing to around 8 % per year, leading to an ongoing supply deficit. Recent success in LED market penetration will probably flatten this demand projection. The main reason for this adaptation is the extremely high material efficiency of LEDs technology as it requires much less yttrium than fluorescent lighting.

2.3.3 Indium

Indium is a post-transition metal that is only obtained as a by-product in the smelting of polymetallic ores containing zinc, copper and tin. Currently, China extracts over half of the global indium supply as a by-product of refining. The EU refinery capacity (located in France, Belgium and Germany) supplies about 9 % of global indium production. In the rest of the world, an increase in primary production also has great potential. Indeed, only 17 % of non-Chinese zinc refineries produced indium in 2011. Consequently, it can be assumed that indium supply will meet the expected growing demand as expanding the supply capacity seems possible. In addition, the secondary production of indium plays a major role. Around 50-60 % of the total indium production comes from recycling facilities.

More than half of primary indium production is used in the form of indium-tin oxide (ITO) in thin conductive layers for liquid-crystal displays. Other applications are soldering, LEDs, semiconductors and photovoltaics. According to the Indium Corporation, indium demand will continue to increase until 2020. LED and solar PV technologies are expected to contribute to indium demand.

2.3.4 Germanium

Germanium is a metalloid (semi-metal) with the electric properties of a semiconductor. It is obtained as a by-product of zinc production or recovered from coal fly ash. In addition, about 30 % of the germanium consumed globally is produced from recycled materials. China is the main supplier of germanium. In the EU, germanium is only produced in Finland, which accounted in 2014 for about 14 % of the production worldwide [WMD, 2016]. An increase in germanium production will depend on the willingness of zinc refiners and coal-fired power plants to engage in the germanium market. As production is expensive, the installation of new production facilities in zinc refineries are expected to occur gradually in order to avoid surplus capacity. The main barriers to increasing primary production include the low germanium content in ores and fly residue and the high investment necessary for installations.

Today, most of the germanium produced is used for fibre optics, military and civil infra-red optic applications, and polymerisation catalysts. Further minor application segments are electronics and space-based solar electric applications, semiconductors, metallurgy and chemotherapy.

Since germanium is an expensive and rare metal, substituting technologies have been developed in many applications. In the lighting sector, germanium is used as a semiconductor material in LEDs, requiring less than 5 % of its total apparent consumption. Effective substitutes with better light quality and higher efficiency, such as gallium nitride (GaN) and indium-gallium-nitride (InGaN), have been developed and have begun to replace germanium in this application.

2.3.5 Gallium

Gallium is a soft metal that is primarily obtained as a by-product of alumina production during the processing of bauxite ore and, to a lesser extent, from the smelting and refining of zinc. China is the main supplier of gallium while around 10 % of global production comes from Europe. In addition, larger amounts of secondary material from production waste are recovered. It is estimated that only 10 % of the bauxite refineries extract gallium. Consequently, an increase in supply could be possible with the appropriate investments.

About half the gallium primary production is used for integrated circuits. Further application segments are LEDs, solar, and alloys, batteries and magnets. Experts assume a continuous increase in gallium demand until 2020, with steady growth for semiconductors including integrated circuits. The highest growth rates will come from LEDs and solar applications.

Gallium has unique properties which makes it difficult to substitute in certain applications without losing product performance.

A summary of the major characteristics of the nine CRM is presented in Table 4.

Table 4: Main characteristics of the nine critical raw materials used in the three low-carbon energy technologies

Critical raw material	Major applications[2]	Low-carbon technology	Specific properties	Global primary production in 2014[3]	Substitution outline for low-carbon applications
Neodymium and praseodymium	NdFeB magnets (Nd – 89 % Pr – 73 %)	Wind turbines and hybrid and electric vehicles	Ability to induce high energy density in magnets	Nd: 21 000 tonnes Pr: 6300 tonnes (both almost entirely from China)	• Nd and Pr are partially interchangeable • no other similar strong magnets are available • possible reduction of amount of Nd/Pr • possible component substitution
Dysprosium	NdFeB magnets (98%)	Wind turbines and hybrid and electric vehicles	Dopant to stabilise the magnet at high temperatures, over 120 °C	1400 tonnes (almost entirely from China)	• Dy is interchangeable with Tb • no other material substitution available • reduction of the amount of Dy possible, through better material efficiency
Terbium	Phosphors (71 %) Magnets (24 %)	Fluorescent lighting	Emitter of green colour in Tb^{3+} form	340 tonnes (almost entirely from China)	• no substitutes in phosphors for mass production but Tb-free LEDs are available
Europium and yttrium	Phosphors (Eu – 96 % Y – 79 %)	Fluorescent lighting	Eu: red (Eu^{3+}) or blue (Eu^{2+}) emitter Y: as host for Eu or in Ce-doped yttrium aluminium garnet	Eu: 350 tonnes Y: 7000 tonnes[4] (both almost entirely from China)	• overall, the substitutes are less effective, more expensive or still at the research stage • reduction in the amount of Eu and Y through adoption of LED technology (OLED does not need Eu and Y in lighting)
Indium	ITO (56 %), LEDs and semiconductors (4 %)	Efficient liquid-crystal displays and LED lighting	Physicochemical properties leading to transparent and conductive coatings	844 tonnes[5] (refinery production) (about half in China, and 9 % in the EU)	• many candidates to replace indium in ITO, but not yet commercially available
Germanium	Fibre and infrared optics, catalysts, electronics	LED lighting	Electric properties of those of a semiconductor	163 tonnes[6] (refinery production) (majority in China – 72 %)	• in general, there are effective substitutes for germanium with the exception of fibre optics • in LEDs, Ge can be replaced by Ga and In
Gallium	Integrated circuits (41 %), LED (25 %), solar PV (17 %)	LED lighting	Good thermal and electric conductor (good anisotropy in electrical resistivity)	435 tonnes[7] (China, Germany, Japan and Ukraine are leading producers)	• no effective substitutes exist for gallium nitride (GaN) and indium-gallium-nitride (InGaN) in LEDs application

[2] Data from reference [EC, 2014b], unless otherwise stated
[3] Idem 2
[4] Data from USGS: United States Geological Survey. Rare Earths statistics and information, 2016. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2016-yttri.pdf
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[7] USGS. Gallium statistics and information, 2016. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/gallium/mcs-2016-galli.pdf

3. Substitution of critical raw materials – Eu, Tb, Y, Ga, Ge and In – in lighting applications

3.1 Technology background

3.1.1 The need to deploy innovative and energy-efficient lighting technologies

Lighting represents one of the largest electrical end-uses, accounting for about 19 % of global electricity consumption, and consuming more than 2650 TWh of energy annually to power approximatively 33 billion lamps worldwide [Almeida, 2014]. In the EU, about 14 % of the electricity is used for lighting. Worldwide, it is estimated that lighting is responsible for 6 to 8 % of global GHG, equivalent to 1900 million tonnes of CO_2/year. The energy demand for lighting, and consequently the correlated GHG emissions, could be drastically reduced by replacing the products in stock with more efficient technologies. Transition from inefficient incandescent bulbs to energy-efficient fluorescent lighting and more recently to the most innovative solid-state lighting (SSL) has already started worldwide. Concrete actions in this field are being taken by many countries and regions in line with two priorities: (i) banning the inefficient incandescent lamps; and (ii) adopting more stringent legislations on energy-efficiency requirements, for instance, in buildings and infrastructure.

The EU is committed to improving energy efficiency by 20 % by 2020 and to 27 % or more by 2030. Through the Energy Efficiency Directive [EE Directive, 2012] EU Member States are required to use energy more efficiently at all stages from its production to final consumption. Moreover, in March 2008, the Commission adopted a Regulation on non-directional household lamps through which inefficient incandescent bulbs had to be replaced by more efficient alternatives (such as improved incandescent bulbs with halogen technology and compact fluorescent lamps). Although the initial date for phasing-out inefficient lamps in the EU was September 2016, by analysing the lighting market and technological developments the Commission concluded that 2018 would be a more appropriate date for the phase-out.

Today, the adoption of energy-efficient lighting, such as fluorescent lamps is evident: about 64 % of global lighting is generated by fluorescent lamps, consuming 45 % of the energy needed for electric lighting. Currently, fluorescent lamps account for about half of global lamp sales and will continue to have a significant share of the lighting market [McKinsey, 2012]. The energy-efficient and environmentally friendly SSL technology is becoming more competitive and is expected to penetrate the general lighting market rapidly. SSL is based on light-emitting semiconducting materials that convert electricity into light and comprises light-emitting diodes (LED) and organic light-emitting diodes (OLED) technologies.

A comparison of the major characteristics of the incandescent and energy-efficient types of lighting is shown in Table 5.

The recent adoption of energy-efficient lighting technologies, i.e. fluorescent and LED, has increased the demand for several critical raw materials, such as the rare earths – europium, terbium and yttrium – as well as for gallium, germanium and indium.

Table 5: Performance characteristics of incandescent, fluorescent and LED lighting [Roskill, 2015]

Lighting technology	Lifespan (thousand hours)	Power use (W)	Relative cost		CRI	Efficiency (lumens/W)	Total mercury * (mg)
			purchase	operating			
Incandescent	0.7-1.2	60-100	1	8.5	100	7-24	4.6***
Fluorescent	8-10 (CFL) 10-50 (LFL)	13-25	2-3	2	80-98	44-80 (CFL) 33-100 (LFL)	5.0**** (CFL)
White LED	100	6-8	10-30	1	+85**	200	0.6***

* after over 6000 hours of use
** white LED lights with CRI up to 98 have been produced, but not commercially
*** from power plant emissions; 0 mg contained in the bulb
**** refers to 1.3 mg from power plant emissions, 3.7 mg contained in the bulb
CFL – compact fluorescent lamp; LFL – linear fluorescent lamp
CRI – colour rendition index

3.1.2 Specifications of major energy-efficient lighting technologies

Three lighting technologies are currently the most relevant when addressing the use of critical raw materials [JRC, 2016a]:

- Fluorescent lighting technology
- Light-emitting diode (LED) technology
- Organic light-emitting diode technology (OLED)

An overview of the current status, outlook and advantages/disadvantages of each lighting technology is presented in Table 6. Apart from the general lighting applications, all three technologies can also be used in displays. For instance, fluorescent technology has been used to backlight the first generation of flat-panel displays. Today, most flat-panel displays are based on LEDs. Three main technologies are currently used in large display applications (e.g. televisions and computer monitors) or smaller devices such as digital displays, tablet PCs, smartphones and e-book readers, as presented in Table 7.

Tables 6 and 7 indicate that LED technology is likely to take over the general lighting market in the coming years because it has several advantages, such as high efficiency and a long lifetime. Moreover, it is expected that LCD displays with LED backlights will dominate the market for large-screen displays such as televisions. OLED displays are expected to play an increasingly important role in small and special applications, such as smartphones or automotive displays, their main advantage being their physical flexibility.

The impact of these technological trends on the short-term demand for critical raw materials is analysed in the last chapter. To understand the role of materials in lighting and display technologies, the working principle of these technologies is further explained.

Table 6: Overview of major lighting technologies

Lighting technology	Critical raw material	Current status	Major advantage	Major disadvantage	Outlook
Fluorescent lighting	Eu, Tb, Y in phosphors	Widely used in tertiary and domestic lighting	Low purchasing cost Low life-cycle cost	High demand for rare earths in phosphors (Eu, Tb, Y) Contains mercury	Fluorescent lamps are losing significance in all lighting technologies
LED lighting	In, Ga, (Ge) Eu and Y (in very small amounts)	Present on the market in all applications ('LED revolution')	High lifetimes and efficiency Rapid market development expected Very low demand for Eu, Y	High purchase prices (expected to rapidly drop even further) Need for indium and gallium (InGaN systems)	LED lighting will mostly dominate the market in the next 5-10 years
OLED technology	In as part of ITO	First product versions on the market	Flexible surface High efficiency	Short product lifetime	Unlikely to make a significant entrance in the lighting market in the next 5-10 years

Table 7: Overview of major display technologies

Lighting technology	Critical raw material	Current status	Major advantage	Major disadvantage	Outlook
Liquid crystal display (LCD) with fluorescent backlighting	In (in ITO) Eu, Tb, Y (in phosphors)	Used in televisions, computer monitors	Low prices	High demand for rare earths in phosphors (Eu, Tb, Y) Contains mercury	Will be further replaced by LED backlighting
Liquid crystal display (LCD) with LED backlighting	In (in ITO and LED) Minor amount of Eu, Y (in phosphors)	Widely used in notebooks (almost 100 % market share)	High lifetimes and efficiency Very low demand for rare earths in LED (Eu,Y)	Demand for ITO as transparent conductive layer	LED backlighting will dominate the market in all LCDs
OLED display	In (if ITO applied)	Used in smartphones, small displays Frontrunners in high-end TVs	Flexible displays Could possibly substitute ITO in future	Short lifetimes	Widely used in special display applications (e.g. flexible displays); competing with LED displays

NB: Plasma display is not included in this list since the main industrial manufacturers stopped the production of this technology in 2014.

3.1.2.1 Basic operating principles of fluorescent technology

Fluorescent lamps are gas-discharge lamps, which means that a glass tube is filled with a mixture of mercury vapour and an inert gas such as argon. In the lamp, an electrode emits electrons. A very high voltage is needed to ionise the gas in the glass tube so that the electrons can flow in the lamps. This causes an excitation of the mercury atoms that emit UV radiation. In order to transmit visible light, the glass tube in a fluorescent lamp is coated with phosphors (Fig. 7). Conversion of UV radiation to visible light takes place based on the fluorescence properties of phosphor materials, which could be transition metals or rare earth elements such as europium, terbium and yttrium.

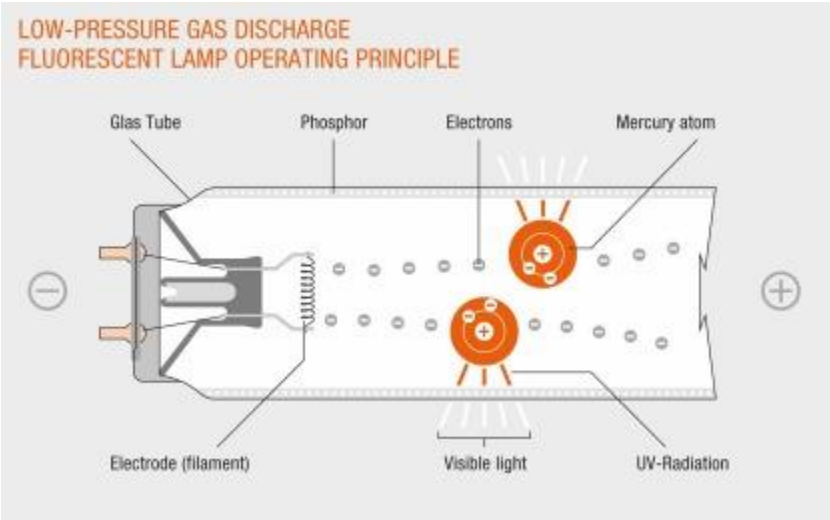

Figure 7: Operating principle of a fluorescent lamp [source: OSRAM AG]

Different types and compositions of phosphor can be used to provide specific colours. The quantities of rare earth differ for each phosphor combination and manufacturer. Fluorescent lamps are produced as compact, linear and circular fluorescent types, their main applications being in the residential and tertiary sectors.

3.1.2.2 Basic operating principles of electroluminescence technology (light-emitting diode)

Whereas gas discharge lamps make use of fluorescent lighting, LED technology is based on the electroluminescence effect. Basically, LEDs follow the structure of any semiconductor diode, which is an electronic component that only permits an electric current in one direction. Within the diode chip, two layers of differently doped semiconductors are directly put together, i.e. n-doped and p-doped semiconductors (Fig. 8). While the n-doped semiconductor allows load-carrying electrons, the p-doped one has a large concentration of holes (so-called "p-holes"). As soon as an electric current flows through the diode in the permitted direction, electrons flow from the n-doped side to the p-doped side. This transition leads to a release of energy. Although in common semiconductors the energy is emitted in the form of heat, in LEDs the transition results in light emissions. In common and light-emitting semiconductors the crystal material structures are different. The frequency (or colour) of the light emissions depends on the band gap of the semiconductor material used. In addition, this colour can be modified by coating the semiconductor material with phosphors. There are several methods of producing white light through LED systems. The first white LEDs, which still predominate, consist of a blue chip coated with a yellow phosphor comprising cerium-doped yttrium aluminium garnet (YAG). The chip is commonly made of gallium nitride (GaN)-based diodes with an indium gallium nitride (InGaN) active layer.

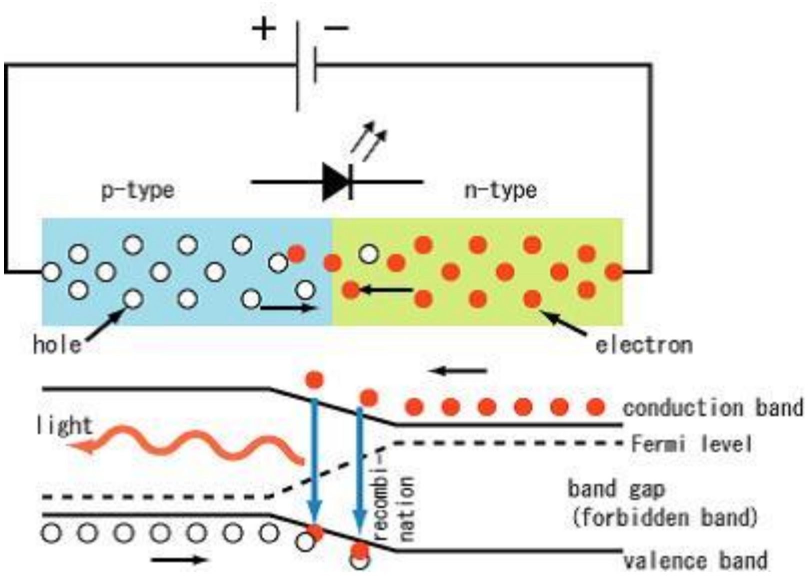

Figure 8: Operating principle of a light-emitting semiconductor diode [Buchert, 2012]

The yellow phosphor absorbs blue light from the chip and emits green to red light with most of the output in the yellow range. This yellow colour can be tuned to white light by adding a small amount of rare earths such as terbium or europium.

Alternative methods for generating white light include coating a near-UV chip with red, blue and green (RBG) phosphors in a similar way to fluorescents, or by combining red, green and blue diodes.

The operating principle of OLED technology is similar to that of semiconductor LEDs as the emission of light is based on the electroluminescence effect. However, the materials used for OLED are mostly organic rather than metallic. Several organic-based layers are evaporated on a supporting substrate (e.g. glass), which is pre-coated with conductive indium-tin-oxide (ITO). A metal cathode contact layer (e.g. aluminium) is placed on top of these organic layers. The colour of OLED depends on the structure and properties of the light-emitting organic molecules. For instance, white-light emission is achieved by mixing different colour-emitting molecules. Hence, the typical rare earth-based phosphors are no longer necessary.

3.1.2.3 Basic operating principles of display technologies

Three main display technologies are generally used for televisions, computer monitors and smaller devices (Table 7). The most relevant is based on liquid crystal displays (LCD), which use liquid crystals to change the direction of light polarisation, depending on the electric voltage. LCDs need backlighting. Displays are made of different segments that can change the transparency independently. In general, six different layers can be differentiated:

- Polarising filter with a vertical axis;
- Transparent substrate with indium tin oxide (ITO) electrodes;
- Liquid crystals;
- Transparent substrate with common indium tin oxide (ITO) film;
- Polarising filter with a horizontal axis;
- Light source for backlighting (either fluorescent or LED technology).

LCD displays are widely applied in flat-panel televisions, computer monitors, smartphones, tablets and other applications such as automotive displays.

3.2 Specification of critical raw materials used in lighting and display applications

The estimated demand in 2014 for the critical raw materials Eu, Tb, Y, Ga, Ge and In in phosphors, LED and displays is shown in Figure 9.

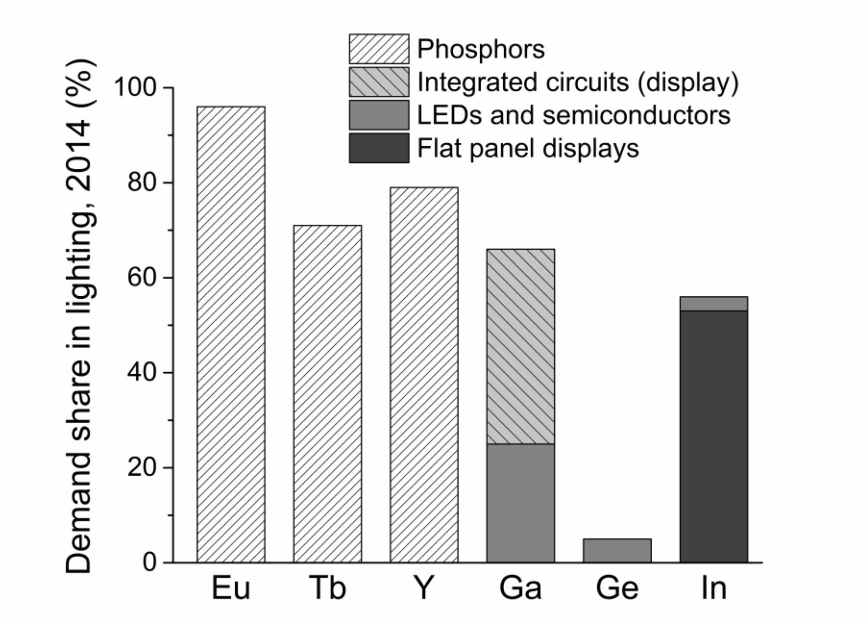

Figure 9: Estimated demand share of CRM in phosphors, LEDs and display applications in 2014 [JRC, 2016a]

Europium, terbium and yttrium are mainly used in the lighting sector (e.g. lighting represents over 70 % of the demand for these materials). They are used in both linear fluorescent lamps (LFL) and compact fluorescent lamps (CFL) as well as in fluorescent backlighting (e.g. cold cathode fluorescent lamp – CCFL) in flat-panel displays. Rare earths are also found in LED lighting and LED backlighting in displays. In all these applications the rare earths are key constituents of tri-band phosphors because of their unique optical properties which arise from the localisation of electrons in f-orbitals.

The amount of rare earths in a fluorescent lamp depends on the efficiency level and size/type of lamp. Where there is high material content, it is estimated that the loading of rare earths is about 0.9 g in a CFL bulb and could vary from 1.5 to 7 g in LFL bulbs, depending on the length and diameter (an average loading of circa 2.4 mg rare earth/cm^2 is a fair assumption) [DOE, 2011a].

A large fraction of gallium is used in semiconductors in integrated circuits (about 40 %), which include applications in smartphones or wireless communication, and in LED systems (about 25 %) for lighting. Currently, germanium only has minor applications in semiconductors for LEDs. Its demand is mainly driven by fibre-optic and infra-red optic applications. Over 55 % of primary indium production is used in flat display panels and about 3 % in compound semiconductors and LEDs.

An overview of the properties and specifications of these six elements in phosphors and semiconductors for different lighting and display applications is given as follows:

- **Europium.** Based on its oxidation state, europium has different luminescent properties and therefore can be used as a red (Eu^{3+}) or blue (Eu^{2+}) emitter. The Eu^{3+} ion is the main red-emitting dopant for displays and lighting devices, its emissions varying from orange (585 nm) to deep red (627 nm). Today, yttrium-europium oxide (Y_2O_3:Eu^{3+}) is the most common compound because of its high-quality emission and red colour purity at 611 nm [Lucas, 2015]. The typical composition of the Eu^{2+}-blue phosphor is (Ba,Sr,Eu)(MgMn)$Al_{10}O_{17}$:Eu^{2+}. It emits blue colour at the wavelength of 450 nm. The high colour quality in the emission spectrum and high activation efficiency achieved by europium ions has led to over 95 % consumption of europium in phosphor applications. According to experts, these exceptional properties cannot be matched by other alternative elements.

- **Terbium.** This represents the most important emitter of green colour in fluorescent lighting in its trivalent form (Tb^{3+}). It enables the emission of yellowish-green light with the main peak around 542 nm. Over 70 % of the demand for Tb is for phosphors in compounds such as $(La,Ce)PO_4:Tb^{3+}$ and $CeMgAl_{11}O^{19}:Tb^{3+}$. It is noteworthy that, to a lesser degree, Tb^{3+} phosphors can be substituted by compounds such as $(Ce,Gd)MgB_5O_{12}$, but these potential alternatives are still at the research stage.
- **Yttrium.** Up to 80 % of its consumption is used in fluorescent lighting and LEDs, mainly as host materials in phosphor production. The most relevant phosphor using yttrium is in combination with cerium ions in compounds like $Y_3Al_5O_{12}:Ce^{3+}$ (YAG). As regards any potential alternatives to yttrium in phosphors, currently there are no economically sustainable substitutes for YAG-phosphors in white LEDs lighting. According to expert opinion, it is possible to substitute yttrium-based phosphors with lanthanum (La) and gadolinium (Ga), but these materials remain too expensive.
- **Gallium.** In LEDs, gallium is relevant in compounds with nitrogen such as gallium nitride (GaN) or indium-gallium-nitride (InGaN). The colour of LED depends on the composition of the semiconductor chip and type of phosphors used as the dopant in the semiconductor material. Commonly, the white light in LED lamps results from gallium-based semiconductors coated with specific phosphors.
- **Germanium.** This is used as semiconductor material in LEDs for general lighting purposes as well as in displays for cameras and smartphones. The germanium-based LEDs are already widely substituted by gallium-based semiconductors. Today, the proportion of germanium used for this application is estimated at less than 5 % of its total apparent consumption, and according to experts it will continue to fall in the near future. The best performance in term of light quality, efficiency and price of the gallium compounds will probably result in germanium losing its relevance in LED technologies over the next 10 years.
- **Indium.** The major use of indium is as indium-tin-oxide (ITO) in thin conductive layers in a variety of flat-panel devices, e.g. liquid crystal display (LCD) televisions, monitors, notebooks, mobile phones, automotive displays, etc. The advantage of ITO is that it is transparent, conductive and heat resistant. The average content of indium in displays varies from 39 mg for a notebook to 79 mg for a computer monitor (flat-panel) and 254 mg for a television (on average, LCD displays have an estimated indium content of 700 mg/m^2) [Buchert, 2012]. As a result of the potential supply risk for indium and its price fluctuations, considerable research is being focused on finding alternatives for ITO. No other compounds are able to perform at the same level of ITO in commercial flat-panel display applications. A further use of indium in the lighting sector, e.g. in LED modules, is in compounds like InGaN with semiconductor properties.

3.3 Opportunities for the substitution of critical raw materials in lighting

3.3.1 Material substitution in phosphors

As already evidenced by other studies [CRM_Innonet, 2015], there are currently no proven substitutes for Eu, Tb and Y in phosphors that can be used in commercial fluorescent lighting applications for both technical and economic reasons. The unique properties of Eu, Tb and Y prevent them from being substituted in fluorescent and LED technology phosphors. However, better material efficiency and improvements in luminous efficacy or a longer lifetime can contribute to reducing the amount of critical raw materials required by the lighting sector.

As the result of the high prices of REEs in 2011/2012 and overall concerns about supply shortages, major lamp manufacturers increased their research efforts to reduce rare earth consumption in phosphors. Research into nanoparticulate processing, new phosphor compositions (e.g. as cerium-based phosphors) and redesigning phosphors, in particular green phosphors, has helped to reduce the amount of rare earths (by up to 20-25 % per lumen) without sacrificing lamp performance. In line with this, the identification of a green phosphor with 90 % less Tb and a new rare earth-free red phosphor was recently announced [LLNL, 2015]. Although these new phosphors appear to meet the stringent performance requirements in the laboratory, the feasibility for commercial fluorescent lighting has yet to be assessed. Moreover, a possible substitution method for rare earths could be to use manganese (Mn) in its various oxidation states (e.g. $ZnO/Zn_2SiO_4:Mn^{2+}$) [Ramakrishna, 2014]. Such alternatives are still in the early stages of development and to date stability and performance have been reported as major issues.

Although LED technology still requires minor amounts of phosphors to produce white light, it can be considered as an effective component substitute for fluorescent technology.

3.3.2 Substitution of fluorescent technology with LED in lighting applications

For general lighting purposes (e.g. domestic, tertiary and street lighting), markets have started to shift from conventional technologies, such as fluorescent discharge, compact fluorescent and linear fluorescent lamps, towards LED technology, including LED lamps and LED luminaires. It is worth pointing out that this shift has not been driven by concerns about security of supply or the price volatility of rare earths, but as a result of the research and innovation trend in the lighting industry. A similar trend can be observed in display technologies. LEDs demonstrate better energy efficiency and a longer lifespan than fluorescent lamps and require much smaller quantities of rare earth phosphors. A further reduction or even complete elimination of rare earths and other critical raw materials in LED lighting is possible by making an additional leap from semiconductor LEDs towards OLED. Whilst used mainly in display applications today, OLED may represent the next-generation energy-efficient lighting. The technological development status of the component substitution in lighting applications, as well as its implications for the demand in critical raw materials is presented in Figure 10.

A broad adoption of LED technology and the expected increase in demand for critical raw materials gallium and indium will probably motivate the industry to search for substitutes. Market implementation of gallium-based semiconductor material can be regarded as a successful substitution for germanium in lighting. However, until now, possible substitutions for gallium in LEDs have been very limited. Ongoing research activities are focusing on replacing gallium with zinc oxide (ZnO) or magnesium sulphide (MgS), but issues with chemical stability are also preventing these materials from successfully substituting gallium in LEDs [CRM_Innonet, 2015]. In addition, yttrium-based phosphor could, in theory, be substituted by phosphors containing lanthanum and gadolinium. However, these alternatives are not competitive in performance or price.

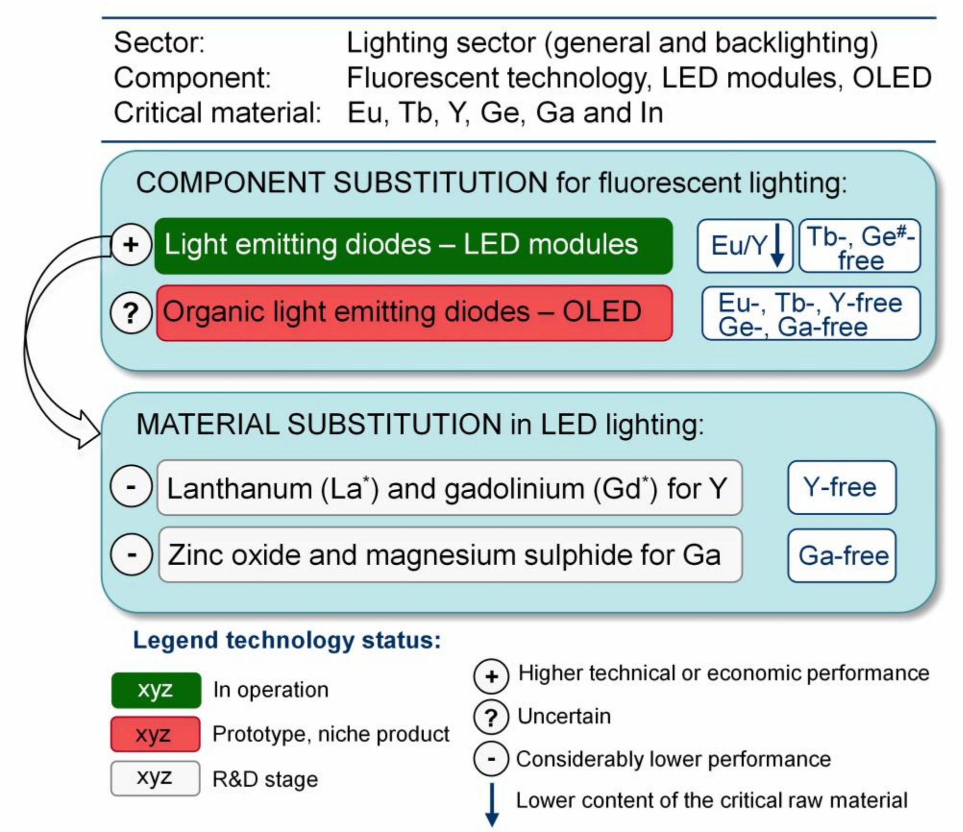

Figure 10: Substitution paths and technological development status in lighting. NB: (#) Ge is no longer relevant as a semiconductor element for LED backlighting since gallium-based substitutes give a better performance. (*) La and Gd are rare earths and therefore may be considered as non-effective substitutes

From a technological perspective, the transition towards LED technology is accompanied by a change in the type and amount of phosphors. Examples of phosphors used in fluorescent and LED lighting are presented in Table 8.

Table 8: Typical composition of phosphor in fluorescent and LED technologies. [Own compilation based on information from Lucas, 2015]

Phosphors in fluorescent lighting	Phosphors in white LED lighting
$Y_2O_3:Eu^{3+}$ (red emitter)	$(Y,Eu)_2O_3$ (YOX phosphor)
$Y(V,P)O_4:Eu^{3+}$ (partly used to improve CRI)	$Sr_2Si_5N_8:Eu^{2+}$ (red phosphor)
$BaMgAl_{10}O_{17}:Eu^{2+}$ (most relevant to obtain blue colours in fluorescent lighting)	$CaAlSiN_3:Eu^{2+}$ (red phosphor)
$Sr_5(PO_4)Cl:Eu^{2+}$ (alternative use as phosphor for blue light)	Alpha-SiAlON:Eu^{2+} (red phosphor)
$CeMgAl_{11}O_{19}:Tb^{3+}$ (CAT) (green phosphor)	$Ba_2SiO_4:Eu^{2+}$ (orange/red phosphor)
$(La,Ce)PO_4:Tb^{3+}$ (LAP) (green phosphor)	$Sr_2Si_2O_2N_2:Eu^{2+}$ (green phosphor)
	$Y_3Al_5O_{12}:Ce^{3+}$ (YAG) (yellow phosphor, highly relevant for white LEDs)

Following the comparisons illustrated in Table 8 and based on the information received from various experts, several conclusions can be drawn relating to the implications for CRMs:

- LED substitution for fluorescent technology in the lighting sector does not lead to the complete abandonment of rare earth use;
- LED lighting applications still require Y (mostly in YAG with trivalent cerium ions as the activator) and Eu (as the activating ion or dopant for specialty refractory ceramics, e.g. SiAlON) phosphors. Tb is not required as a phosphor in LED;
- Future demand for Y and Eu phosphors is likely to fall due to the transition from fluorescent to LED lighting;
- 'Rare earths efficacy' in term of lumens (lm) produced per gram of REE is about 18 times higher for LED technology in comparison to fluorescent lamps. This translates into a reduction in the need for rare earths by 15 to 20 times in LEDs for the equivalent lumen output [DERA, 2014];
- According to expert interviews, the substitution of Y and Eu in LED phosphors has been studied for years. At one time, the most promising substitute was manganese (Mn^{4+}). However, this was not competitive with Eu and Y phosphors either in terms of technical or economic performance;
- Rare earth phosphors are mainly produced in China. It is estimated that the Chinese capacity for fluorescent lamp phosphors is roughly three times higher than current production. In Europe, lamp phosphors are produced by Osram and Philips Lumileds.

Besides the advantages in terms of a lower demand for rare earths, there are other drivers promoting the rapid substitution of fluorescent technologies as well as other conventional lighting technologies, such as halogen and/or filament technology, with LED technology on the lighting market:

- LED technologies have considerable longer lifetimes compared to fluorescent technologies. Whereas the best available technology (BAT) for compact fluorescent lamps lasts around 15 000 hours, BAT LED lamps double that, with 30 000 hours or more [Oeko Institut, 2015];
- LED technologies have mainly surpassed energy efficiency requirements. Compared to the lumen output of around 60 lm/W for fluorescent lamps, LED lighting products have an average efficacy of 89 lm/W [VITO, 2015];
- As a consequence of longer lifetimes and higher energy efficiency, life-cycle costs of LEDs are considerably lower compared to fluorescent technology. In addition, market prices for LEDs have fallen considerably in recent years and will continue to do so until 2020 as a consequence of economies of scale.

All these factors stimulate the rapid substitution of fluorescent and conventional technologies with LED in the lighting market. Today, Japan has the highest level of LED penetration (it intends to ban all conventional lighting, including fluorescent technology by 2020), followed by the USA and Europe.

While the current stock of installed LED light sources is still relatively small in the EU, the penetration of LEDs in the light market is much faster than might have been expected in the past. In this context, Figures 11 and 12 show the estimated stock and sales volumes, respectively, of light sources in the EU for the period 1990-2030 [VITO, 2015].

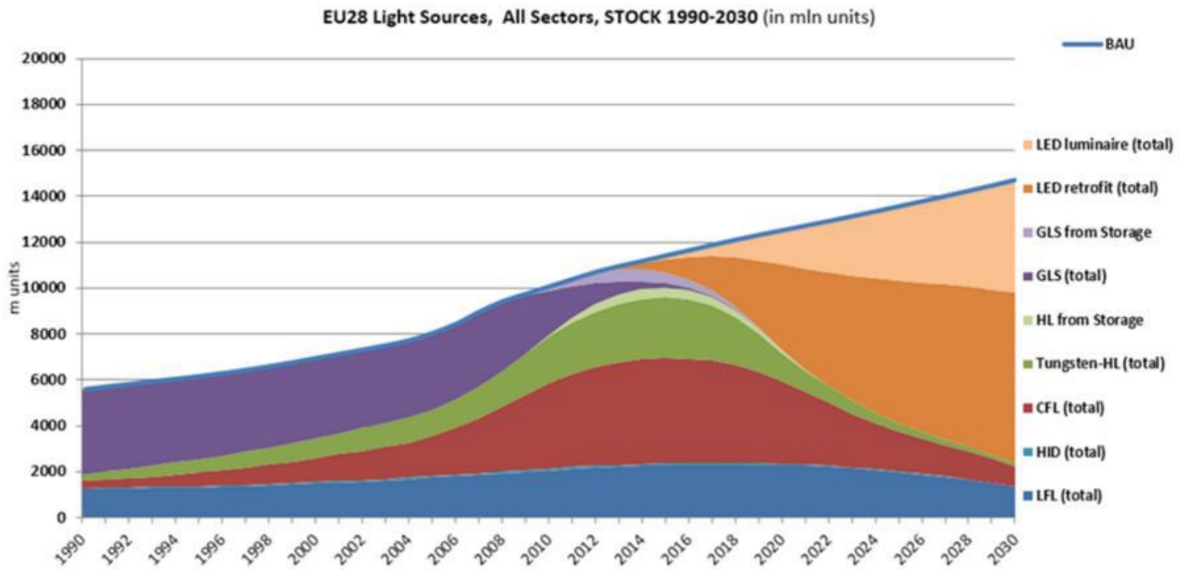

Figure 11: Installed stock of light sources[8] in the EU for the period 1990-2030 [VITO, 2015]

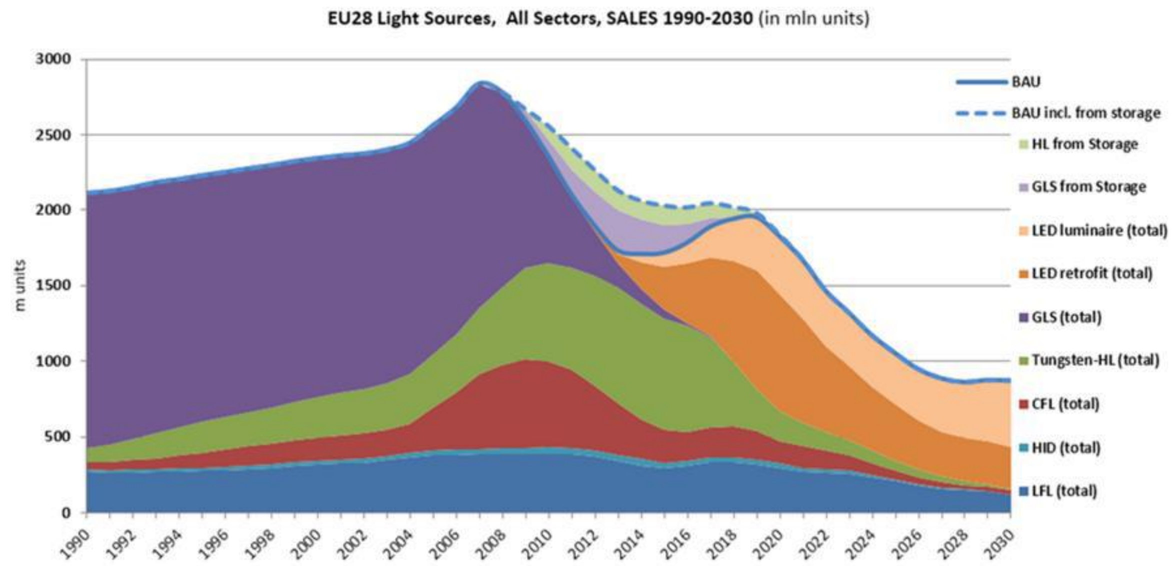

Figure 12: Sales volumes of light sources[8] in the EU for the period 1990-2030 [VITO, 2015]

The results of the MELISA[9] model for the business-as–usual scenario (Figs. 11 and 12) indicate that the total EU stock of light sources totalled 11.4 billion in 2015 (56 % of which was in the residential sector); this will rise to 12.5 billion in 2020 and 14.7 billion units in 2030. The share of LED-based products in stock will sharply increase from 7 % in 2015, to 42 % in 2020 and 84 % in 2030. In terms of the annual sales of light sources in the EU, the data show an increase from 1.7 billion units in 2015 (of which 22 % were LED) to 1.8 billion in 2020 (63 % LED), followed by a significant drop to 0.87 billion (82 % LED) in 2030. This fall is the result of the substitution of incandescent and fluorescent technologies with longer lifetime LED lamps.

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[8] BAU = business-as-usual scenario; LFL= linear fluorescent lamp; HID = high-intensity discharge lamp; CFL = compact fluorescent lamp; HL = halogen lamps; GSL = general lighting service (aka incandescent lamp); LED = light emitting diode.

[9] MELISA = Model for European Light Sources Analysis. It was developed for scenario analysis in the EU under the project 'Light Sources – Lot 8/9/19' assigned by the European Commission [VITO, 2015].

At a global level, McKinsey estimates LED's value share of the total lighting market at 41 % in 2016, rising to 64 % by 2020 [McKinsey, 2012]. This share is higher for the general lighting[10] market (45 % in 2016 and almost 70 % in 2020). It is also estimated that Europe will lead the global LED general lighting value-based market in 2020 with 73 %.

It is evident that the market and stock shares of LED lighting will rapidly increase within the next 5 to 10 years, precise values depending on each world market region. Asia is estimated to be at the forefront of lighting technological changes, followed by Europe and North America. The impact of lighting market evolution on the future demand for critical raw materials is analysed in chapter 7.1 of this report.

3.3.3 Substitution of fluorescent technology with OLED in lighting applications

OLED represents a possible substitute for fluorescent and LED technologies in the general lighting sector and for backlighting in displays. OLED technology does not contain the critical metals Eu, Y, Tb, Ga or Ge, as is found in LED and/or fluorescent technology.

Although OLED prototype luminaires have been launched by some manufacturers, OLED technology is not expected to broadly penetrate the general lighting market before 2025. Three major barriers still prevent the large deployment of this technology: (i) its competitiveness in terms of efficiency; (ii) high price; and (iii) lifetime consideration. According to experts, the current price per lumen output is at least 100 times higher for OLED compared to LED. Hence, it is expected that OLED technology will not be able to compete significantly with LED in general lighting applications in the short to medium term (5-10 years). From a technological perspective, the most important issue in OLED research and development (R&D) concerns its lifetime. One key player in OLED R&D is Osram AG (Germany). Other European industries and institutions involved in OLED research include Merck, University of Bayreuth, Philips Research, Fraunhofer IPMS, Ghent University, Holst Centre TNO and AIXTRON.

3.3.4 Substitution of critical raw materials in displays

3.3.4.1 Substitution of conventional fluorescent backlighting with LED, OLED and quantum-dot (QD) technologies

In parallel to general lighting, fluorescent technology is also applied in display backlighting, e.g. in televisions, computer screens and notebooks. Since from the technological point of view fluorescent technology used in display backlighting is comparable to that in general lighting, the component substitution paths of critical raw materials are very similar in these two sectors (Fig. 10). Moreover, displays rely on a distinct component: indium-tin-oxide (ITO). Hence the substitution paths for indium in ITO are examined separately.

Demand for phosphor materials, i.e. europium, yttrium and terbium in display panels has fallen considerably in recent years following the replacement of cathode ray tubes (CRTs) with flat-panel displays (FPDs). In traditional CRTs, rare earth phosphors are used to provide both colour and illumination. Today, the majority of FPDs are based on a liquid crystal layer (which contains no rare earths) to provide colour, but they need to be illuminated by backlight lamps such as cold cathode fluorescent lamps (CCFLs). LED and OLED technologies can successfully substitute the CCFLs in display backlighting. It is estimated that in 2015 the market share of LED in all display backlighting applications

[10] General lighting is the largest lighting market and includes several applications: residential, office, shop, hospitality, industrial, outdoor and architectural lighting. It excludes automotive lighting and backlighting.

was 70-75 % compared to 25-30 % of CCFL [Roskill, 2015]. LED backlighting share for large display applications, such as televisions and computer monitors, is currently smaller (around 40 % in 2015) than for notebook screens (over 95 % in 2015). LED technology will continue to expand in the backlighting sector. It is expected that the market share for LED backlighting displays will reach almost 100 % in the short term. However, the penetration of OLED technology is also expected to grow in mobile and flexible display applications. In terms of materials, this trend will contribute to reducing the demand for phosphor in display backlighting applications. However, the demand for indium and gallium used as indium-gallium-nitride in LED compounds is expected to increase.

OLED is an emerging technology using organic carbon-based materials and containing no phosphors such as terbium, yttrium and europium. Also, gallium and germanium are not needed technologically. OLED displays are self-illuminating which means they do not require a backlight and therefore are thinner and more energy-efficient than LCDs. Today, OLED is mainly applied in smaller FPDs such as smartphones, tablets and navigation appliances, but high-end screens (e.g. television) based on OLED are also available on the market. They offer a series of technological advantages in terms of energy efficiency, colour and contrast, viewing angle and thickness/weight. Despite these benefits, LED technology is expected to remain a very strong competitor for OLED in large-size televisions screens. The key players in OLED development for displays are mainly the same companies which are active in solid-state lighting.

In future, the market share for OLED technology is expected to increase, in particular for small devices and flexible display applications (major smartphone manufacturers maintain that OLED will soon be competitive in the mass market). Market adoption of OLED in various display applications will also contribute to reducing the consumption of phosphors. To date, however, there has been no breakthrough in mass production, mainly due to continuing high prices as well as poor lifetime performance. Although there is still a high level of uncertainty about any significant uptake, OLED is often considered to be the next-generation technology in both display applications and lighting. Penetration of OLED technology in the display and lighting sectors will eliminate the need for CRMs. The only exception to this is indium, which will still be required as conductive layers, unless suitable substitutes become available.

A breakthrough technology, i.e. quantum dots (QD) semiconductor nanocrystals, can also potentially be a substitute for the conventional CCFL and LED in displays. As for OLED, the lighting effect of QD is based on organic electroluminescence. The main advantages of QD displays include flexibility and their non-plane shape. OLED displays have the major disadvantage of degrading quickly, whereas QD systems are more stable. Hence, future flat-panel TVs, digital cameras and mobile phones might make use of QD technology. However, upscaled and marketed solutions have yet to be documented. As QD displays are entirely based on organic dyes, phosphors using rare earths, such as europium and yttrium currently in LEDs, would not be needed.

3.3.4.2. Material substitution of indium-tin-oxide (ITO) in displays

As most of the global demand for indium is used for ITO in ICT equipment with screens (e.g. notebooks, televisions, etc.) investigating possible substitutes in this field is very relevant. Thus, extensive efforts have been allocated in the past to find suitable substitutes in this field. Figure 13 provides an overview of the ongoing research activities identified for ITO substitution in displays, and assesses the development status of the potential substitutes.

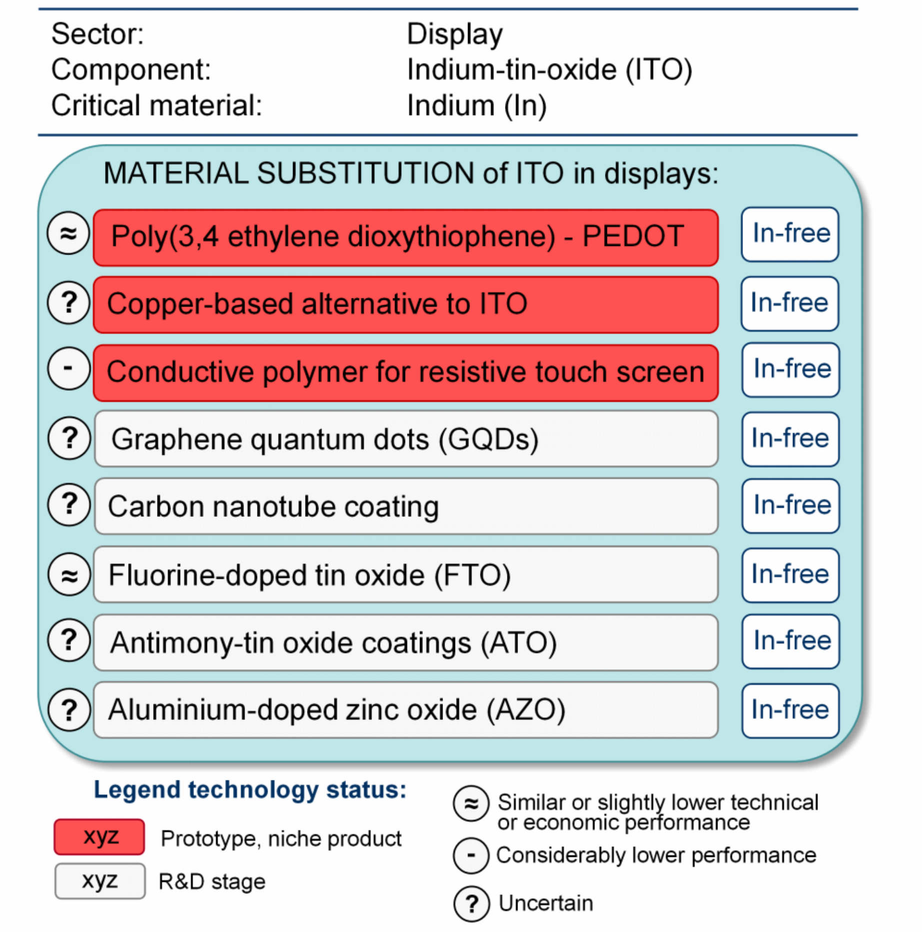

Figure 13: Substitution paths and technological development status of ITO substitutes

Despite considerable research activities aimed at substituting ITO, this compound is still used for providing transparent electronic conduction in display technologies. The potential substitutes are either prototypes (red boxes in Fig. 13) or at the research stage (illustrated by light grey boxes in Fig. 13). The main barrier to substitution is poor performance in terms of electronic conductivity and low stability [CRM_Innonet, 2015]. Brief overviews of possible substitutes in the future ITO are given below:

- **Poly 3,4-ethylene dioxythiophene (PEDOT)** is an optically transparent and electroconductive polymer which can be used in flexible displays, OLED or solar cells. PEDOT coatings (trade name: Clevios) have shown good stability over different charge and discharge cycles and are proposed for touch screens as alternatives to ITO [Heraeus, 2016].
- **Copper-based alternative to ITO**: innovative performance-engineered films based on copper metal plating have been developed as an alternative to traditional touch sensors. The manufacturing process is branded 'Copperhead' and, according to the producer, this technology can reduce the complexity, cost and risk of manufacturing touch panels. It employs a high-fidelity micro-contact printing process that can create complex structures required for touch sensors [UniPixel, 2016].
- **Conductive polymers for resistive touch screens** have been developed by Fujitsu Ltd [Fujitsu, 2008]. They consist of pliable and transparent organic conductive polymers instead of ITO for typical resistive touch panels. A series of advantages, such as better endurance, qualifies this substitute in particular for pen-touch-based devices. Their production is cheaper and more ecologically friendly than ITO-film touch panels. Applications include cell phones, PDAs, tablet PCs, and other pen-based devices where longer life and greater reliability are

required. However, the application refers only to touch-pen-based devices rather than touch-panel systems that can be controlled by hand.

- **Graphene quantum dots (GQDs)** is a new class of nanomaterials with exceptional luminescence properties comprising one up to tens of graphene layers less than 30 nm thick. Intensive research worldwide is leading to investigations into the potential applications of GQDs in optoelectronic, bio-imaging and energy devices [Li, 2015]. However, upscaled and marketed solutions have yet to be found.
- **Carbon nanotube coating** represents another potential substitute for ITO in flexible displays and touch screens and, like GQDs, is the subject of considerable research.
- **Fluorine-doped tin oxide (FTO)** aims to be used as transparent polymer foil in displays (flat-panel LCD, touch screen) as well as in OLED technologies. Although the mass content of tin (Sn) in FTO is similar to that of indium in ITO, the first element is not considered a critical material. The results from the subITO-Project [Althues, 2014] show that the current FTO foils comply with research project goals. The next steps are to upscale the process, facility design and construction. A last step will be to demonstrate and evaluate application of FTO in a touch panel, an electroluminescent foil and an organic solar cell.
- **Antimony-tin oxide (ATO)** is an alloy of tin oxide with antimony pentaoxide that has very high conductivity and is transparent to visible light. Various research activities explored the substitution potential of ATO [Babar, 2013]. However, a marketable breakthrough has not been reached yet.
- **Aluminium-doped zinc oxide (AZO)** is a transparent semiconductor which was proposed to substitute ITO because of high transmittance and good conductive properties. Despite its high transparency, which is comparable to commercially available ITO [Vunnam, 2014], issues of etching and degradation by moisture still need to be solved before commercialisation.

3.3.5 European research activities on CRM substitution in lighting applications and displays

In the framework of the call FP7-NMP-2013-EU-Japan [11], three projects engaged European and Japanese organisations in the development of new materials for the substitution of critical metals. Among them, IRENA[12] strives to develop high-performance materials to completely eliminate the use of critical metals in electronic devices, such as flat-screen TVs or touch-screen mobile devices. Metallic and semiconducting single-walled carbon nanotube (SWCNT) thin films are being investigated for the substitution of indium in transparent conducting films or indium and gallium in semiconductor materials. Project partners have produced uniform transparent conductors with very high conductivity as well as SWNT thin films, successfully used as electrodes in several types of novel solar cells.

In the framework of the H2020 call SC5-12a-2014[13], two projects are looking into materials for electronic devices:

- The project INREP[14] is aiming to develop transparent conducting oxides to replace indium in electrode materials. This research project targets numerous applications (e.g. LEDs, solar cells, touch screens, etc.) with tailored solutions for each of them.

[11] http://cordis.europa.eu/search/result_en?q=contenttype=%27project%27%20AND%20/project/relations/associations/relatedCall/call/identifier=%27FP7-NMP-2013-EU-Japan%27
[12] http://cordis.europa.eu/result/rcn/171839_en.html or http://irena.aalto.fi/
[13] http://cordis.europa.eu/programme/rcn/664587_en.html
[14] http://www.inrep.eu/ or http://cordis.europa.eu/project/rcn/193859_en.html

- INFINITY[15] is studying an inorganic alternative to ITO produced with low-cost sol-gel chemistry and using more widely available metallic elements. Printing procedures are also within the remit of this project, with the ambition of reducing the waste associated with current practices.

Under the prime objective of eco-innovation, the CYC-LED[16] project strived to decouple the growth of the market from the use of resources. A material flow analysis identified key challenges to be addressed, such as longevity improvements, reuse and recycling – aspects contributing to the resource efficiency of the LED-market. Following the assessment of technical solutions, an overall approach for reducing the consumption of targeted critical raw materials has been developed, complemented by business models for and barriers to eco-innovation.

[15] https://infinity-h2020.eu/ or http://cordis.europa.eu/project/rcn/193863_en.html
[16] http://www.cyc-led.eu/ or http://cordis.europa.eu/project/rcn/102056_en.html

4. Substitution of critical raw materials – Nd, Pr, Dy and Tb – in permanent magnets

4.1 Technology background

There are materials that manifest high magnetic polarisation once they are exposed to an external magnetic field. While some magnets become demagnetised in very low external fields (soft magnets), permanent (hard) magnets show a significant resistance (coercivity) to external demagnetisation, retaining their magnetic field even after removal of the original field. Because of their strong coercivity, only hard permanent magnets can be used in wind generators and electric traction motors.

4.1.1 Developments in permanent magnet sector

Over the last century, several types of permanent magnets have been discovered in the attempt to increase their magnetic strength (Fig. 14).

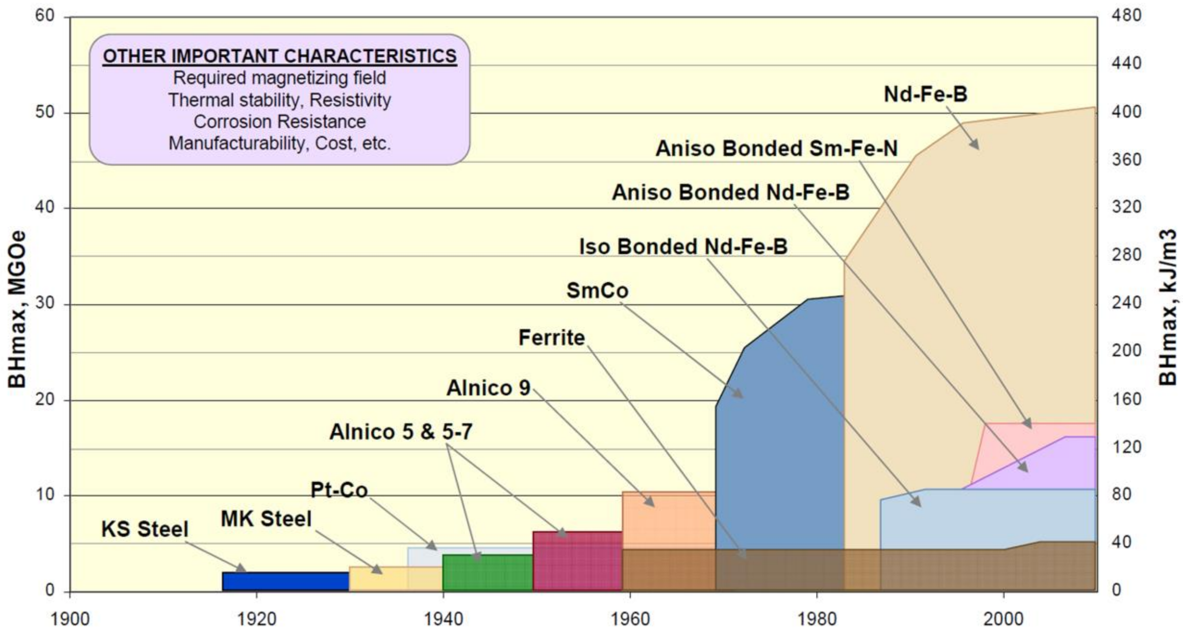

Figure 14: Development of permanent magnets, 1990-2010 [AMT, 2012]; maximum energy density is expressed in megagauss-oersted (MGOe, left vertical axis) and metric system (right axis)

Steel magnets were known about and in use before 1940s. Since then, various permanent magnets have been developed: aluminium-nickel-cobalt (AlNiCo) and platinum-cobalt (Pt-Co) in the 1950s, hard ferrite in the 1960s, samarium-cobalt (SmCo) in the 1970s and neodymium-iron-boron (NdFeB) in the 1980s. The NdFeB magnet was invented as a result of research efforts to find solutions to the cobalt supply issue and price spike in the 1980. With these developments, magnetic energy density has significantly increased from 40 $kJ{\cdot}m^{-3}$ for ferrites, 80 $kJ{\cdot}m^{-3}$ for AlNiCo, 250 $kJ{\cdot}m^{-3}$ for SmCo to over 400 $kJ{\cdot}m^{-3}$ for NdFeB.

In general, permanent magnets exhibit high magnetic energy for a given volume. This allows for a reduction in size, which then promotes their use in many high-tech sectors such as computers, telecommunications (e.g. mobile phones, cordless tools, etc.), audio-visual equipment (e.g. speakers, magnetic resonance imaging (MRI), etc.) and energy-related devices. Table 9 summarises the composition and other characteristics of the major types of permanent magnets.

Table 9: Main permanent magnet types and material implications [Gutfleisch, 2011]

Permanent magnet	Specification	Product example
Ferrite	Iron oxide combined with barium, strontium or cobalt oxide. Low magnetic moment up to 250 °C and low corrosion. Relatively cheap, widely used in low-performance applications.	Sr-ferrite ($SrFe_2O_3$, sintered)
Aluminium-nickel-cobalt (AlNiCo)	Iron alloy with aluminium, nickel and cobalt. Low magnetic field that can withstand high temperatures up to 500 °C.	AlNiCo (sintered)
Samarium-cobalt (SmCo)	Alloy mixed with 20-25 % iron and high cobalt content. High magnetic strength even at high temperatures (up to 400 °C). Good corrosion properties, but very expensive.	$SmCo_5$ (sintered) $Sm(Co,Fe,Cu,Zr)_7$ (sintered)
Neodymium-iron-boron (NdFeB)	High-strength magnet withstanding temperatures up to 120 °C; adding dysprosium allows higher temperatures of up to 200 °C. High reliance of critical rare earths.	$Nd_2Fe_{14}B$ (bonded, usual isotropic or sintered, anisotropic)

4.1.2 The NdFeB permanent magnet

The NdFeB magnet has the highest energy density compared to other permanent magnets, making it the material of choice in high-performance applications where the size and weight are key requirements. NdFeB also promotes high energy efficiencies as the magnet replaces copper windings that typically show energy losses. These qualities are needed by the wind power sector, especially for large turbines (> 5 MW), where a light turbine design is crucial to reduce the otherwise challenging mechanical constraints. In electric vehicles, a lower weight correlates with smaller batteries and longer driving distances.

The outstanding properties of the NdFeB magnet derive from the unique combination of high magnetic moments of 3d transition elements (e.g. iron or cobalt, nickel) with 4f electron configuration of rare earths. This coupling results in a high magneto-crystalline anisotropy which in certain circumstances enables a coercivity to be achieved comparable to the magnetisation. Based on these advantages, most of the production of Nd, Pr and Dy goes to the permanent magnets sector (Fig. 15).

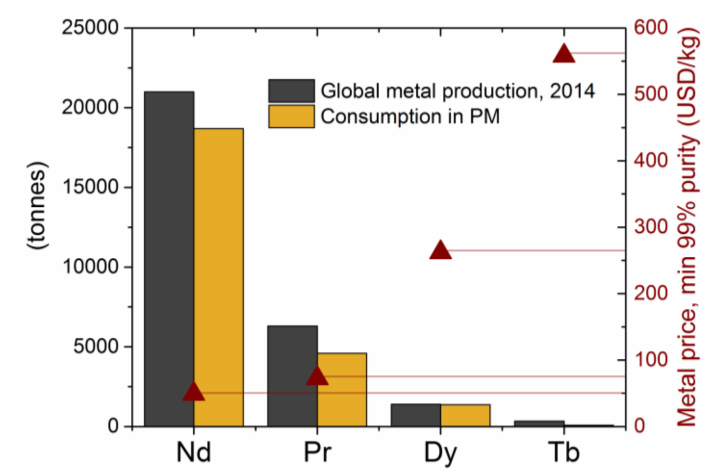

Figure 15: Estimated global production, consumption in permanent magnets and prices of Nd, Pr, Dy and Tb. Production/demand data refer to 2014 [EC, 2014b] and metal prices (FOB China) to September 2016 [Asian Metal, 2016]. NB: Tb is used less in permanent magnets because of its high price compared to Dy

Today, NdFeB material is the most powerful and commercially important magnet. No other materials with superior qualities have been discovered yet for large-scale applications. NdFeB accounts for the majority of rare earth permanent magnet sales. Based on its superior magnetic properties, NdFeB plays an important role in those applications where high performance, high efficiency and small size are indispensable. A breakdown of the projected industrial applications of NdFeB is shown in Fig. 16.

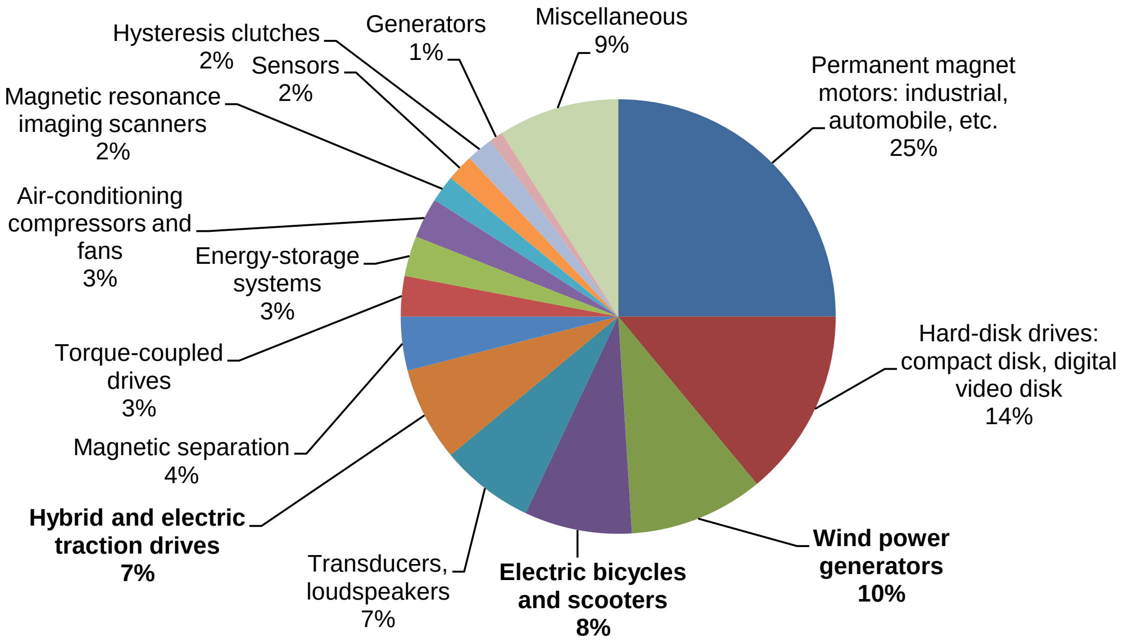

Figure 16: Estimated industrial end-use share of NdFeB magnets in 2015 [Davenport, 2015]

The largest market for the NdFeB magnet is the industrial and automotive industry for piezoelectric devices, followed by hard-disk drives in electronic components and computers. Currently, it is estimated that demand share of NdFeB magnets is below 10 % in the wind power sector, electric vehicles or e-bikes. Since the market of these 'green technologies' is becoming more significant, the growth rate for NdFeB is expected to increase in the near future.

The global annual production of NdFeB permanent magnets has steadily increased from 6000 tonnes in 1996 to about 63 000 tonnes in 2012 and up to 79 000 tonnes in 2015 [Gutfleisch, 2011; Benecki, 2013]. Today, more than 85 % of the total NdFeB production is located in China, around 10 % in Japan and less than 5 % in the USA, the EU and other regions [Roskill, 2015]. The European manufacturers that produce and sell NdFeB magnets are located in Germany (Vacuumschmelze and Magnetfabrik Schramberg), Czech Republic (PZK) and Finland (Neorem).

Over 90 % of the global production of NdFeB magnets is produced in sintered form. The remaining 10 % or less is made in bonded form. Other production methods can also be used, i.e. injection moulding and extrusion. The bonded NdFeB has a significantly lower magnetic strength than the sintered NdFeB magnets, due to use of a resin for bonding together the magnetic grains. But they are easier to produce in various shapes and sizes. In case of sintered NdFeB magnets, the fine powder of fused alloy is first compacted in a die and then sintered in a vacuum furnace, followed by annealing, shaving and polishing. A protective coating could be applied to seal the material surface. Finally, the material is magnetised to saturation [AMT, 2016]. The typical composition of an NdFeB magnet is presented in Table 10.

Table 10: Example of composition of sintered NdFeB magnets for applications at room temperature [E-Magnets, 2016]

Chemical elements	Percentage by weight
Neodymium (Nd) and/or praseodymium (Pr)	29-32
Iron (Fe)	64.2-68.5
Boron (B)	1.0-1.2
Aluminium (Al)	0.2-0.4
Dysprosium (Dy)* and/or terbium (Tb)	0.8-1.2

* The Dy content is increased up to 9 % to allow the magnet to operate at high temperatures, i.e. up to 200 °C.

The composition of an NdFeB magnet varies according to the properties required in the end-use application. For example, in applications with a shorter operating period (e.g. in speakers, mobile phones, computer devices, etc.) the NdFeB permanent magnet is ideal. However, for other applications like motors or wind turbines, which have longer operation times and generate significant amounts of heat, NdFeB is less suitable due to its reduced coercivity. In fact, at temperatures above 80-120 °C, the coercivity of NdFeB declines significantly to about 20-30 % of the theoretical maximum. Adding dysprosium or terbium can enhance the coercive force of NdFeB magnet making it more stable at higher temperatures. Currently, dysprosium is the most convenient dopant because of its low price in relation to terbium. The dysprosium loading in the NdFeB magnet for applications at high temperatures can reach up to 9 % and the resulting compound shows a lower temperature gradient and increase coercivity between 100-200 °C. For higher temperature applications, one alternative to the NdFeB magnet is the SmCo permanent magnet, which performs better above 20 °C.

Neodymium can be replaced by praseodymium in NdFeB compositions. For instance, in contrast to pure praseodymium magnets, pure neodymium magnets produce slightly higher magnetic energy. As both rare earths have very similar chemistry, the complete separation cost of these two metals is too high. Thus, the 'neodymium' supply usually contains praseodymium in a 4:1 ratio concentration.

4.2 Substitution of rare earths in permanent magnets

4.2.1 Increasing the material efficiency in NdFeB magnets

4.2.1.1. Increasing the material efficiency of neodymium and praseodymium

Current research indicates that the quantity of neodymium and praseodymium needed to produce NdFeB might decrease in the future. Based on the proposed specifications in innovation process technology, the efficiency and magnet strength of the NdFeB magnet could improve by 2030. As a result, the neodymium/praseodymium content in NdFeB magnets at equal magnetic density might fall from 31 % in 2010-2012 and about 29 % in 2015, to 25 % by 2020 and down to 20 % by 2030 [Lacal, 2015]. Although these specifications are highly ambitious, this would result in a rise of material efficiency for Nd and Pr of up to 29 % from 2015 to 2030 in an NdFeB magnet of equal magnetic strength. Such significant material efficiency could occur for instance by modifying and optimising the microstructural composition of the NdFeB magnet.

Although the research aims to reduce the content of Nd/Pr in the NdFeB magnet, a strong improvement in neodymium efficiency remains a challenging task. With the current technologies, it is unlikely that the proposed specifications will be reached by 2030. Although the research efforts are ongoing, it is sometimes difficult to keep track within commercial companies. There is often no detailed information available on industrial activities covering magnet production with reduced neodymium content.

Overall, various solutions in term of material efficiency are already being applied, as highlighted in green boxes in the technology development map (Fig. 17).

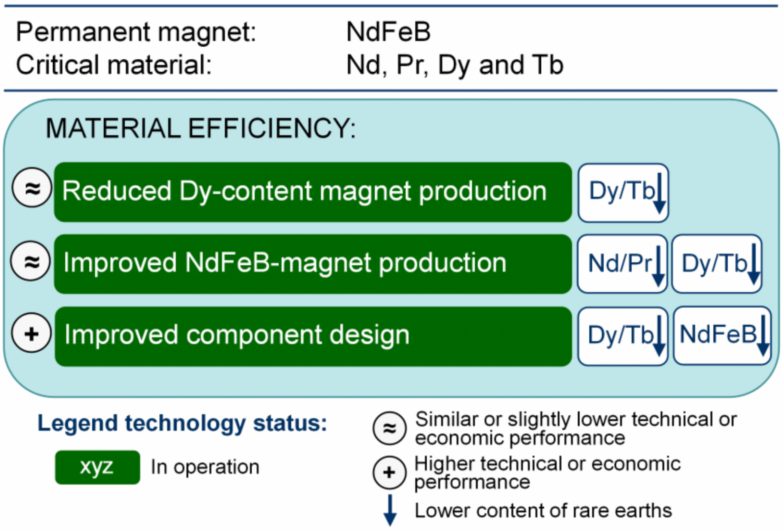

Figure 17: Material efficiency paths in reducing the content of rare earths in an NdFeB magnet

4.2.1.2. Increasing the material efficiency of dysprosium

The current permanent magnet applications in a high-temperature environment, such as for wind power or electric vehicles, use sintered NdFeB magnets with up to 9 % dysprosium (or terbium). The main approach to reduce the amount of dysprosium in the NdFeB magnet is to improve the grain boundary diffusion. For instance, instead of losing a lot of dysprosium in the primary phase, the dysprosium is allowed to diffuse along the grain boundaries and concentrate in the grain boundary phase [Loewe, 2015; PerEMot, 2013]. Using this grain boundary phase technique, experts estimate dysprosium savings of around 30 %. This enormous increase in material efficiency is expected to significantly reduce the forecasted dysprosium demand. By applying a lower-temperature annealing process, TDK has improved dysprosium diffusion in grain boundaries resulting in 50 % less compared to the old manufacturing technology [TDK, 2013]. In addition, TDK claims to produce a dysprosium-free NdFeB magnet with a higher intrinsic coercive force (NEOREC47HF) using an oxygen-free process.

Based on the above-mentioned research activities, the reduction of dysprosium content in NdFeB magnets appears to be feasible. High-temperature magnets formerly contained 3-7 % Dy in wind turbines and 9 % Dy in electric vehicles. By 2020, the JRC and Öko-Institut expect both the extended use of very low (≤1 %) or dysprosium-free magnets in wind turbines and the use of dysprosium-reduced magnets (~5 % Dy) in electric vehicles. In addition, some manufacturers will also shift to component substitution, which is analysed in chapters 5 and 6.

4.2.2 Substitution of rare earths with other materials in NdFeB magnets

To date, no promising results have been announced regarding the full substitution of rare earths in the commercial sintered NdFeB magnet.

Pathak et al. claimed to have developed a method to fully replace dysprosium and partly replace neodymium (by about 20 %) in NdFeB magnets using cobalt and cerium (a much cheaper and more available rare earth) [Pathak, 2015]. The cerium and cobalt co-doped alloys have shown excellent high-temperature magnetic properties, with intrinsic coercivity among the highest known for T ≥ 180 °C. However, laboratory tests were performed using melt-spun ribbons, which cannot fully represent sintered NdDyFeB permanent magnets. This approach is summarised in Figure 18.

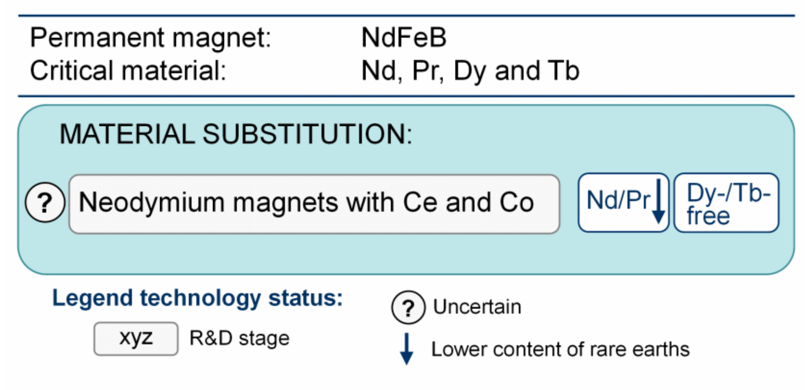

Figure 18: Substitution paths for rare earths in an NdFeB magnet

4.2.3 Substitution of NdFeB with other magnets

Even though much research has concentrated on reducing rare earth content and substitution with other less-critical materials, NdFeB still remains the predominant commercially available permanent magnet with the highest performance [CRM_Innonet, 2015]. Apart from the direct substitution of rare earths in the NdFeB magnet, which is currently considered not feasible, R&D efforts are also focusing on finding new magnet compositions with high magnetic strength. In this respect, two different approaches are more relevant. First, in the more fundamental approach, research projects are looking to find new materials that exhibit good magnetic characteristics comparable to those found in hard magnets made from rare earths. To achieve this, the researchers are applying theoretical modelling and simulation methods combined with experimental melt metallurgy techniques. An evaluation of a wide range of material combinations, while simultaneously analysing their magnetic properties, is being carried out through a systematic computational high-throughput screening technique. Similar strategies have already been successfully applied to find new materials for batteries.

A second approach consists of further developing the existing types of magnets. One example is replacing the bonded NdFeB magnets with ferrites modified with lanthanum and cerium [TDK, 2013] or anisotropic SmFeNi bonded magnets. Other researchers are looking at the optimisation of lower-performance magnets, e.g. AlNiCo, SmCo ($SmCo_5$,Sm_2Co_{17}) and their iron homologues (Sm_2Fe_{17}, carbides, nitrides), or combining well-known magnetic materials such as iron nitrides with hard ferrites at the nanoscale level [KomMa, 2014].

It appears that these approaches do not have the potential to achieve similar high magnetic energy densities to those of sintered NdFeB in the short term. Unless a major R&D breakthrough occurs, it is unlikely that NdFeB will be substituted in wind-turbine and electric-vehicle applications by 2020. Instead, these new magnets might close the gap between low-performance/price magnets and sintered NdFeB. This may lead to replacing NdFeB in some applications where size and efficiency are not key requirements, for the benefit of the emerging sectors such as wind energy and EVs.

4.2.4 European research activities on rare earth substitution in permanent magnets

Several EU-funded projects, as listed in Table 2, target the substitution of critical materials in permanent magnets and related systems. A short overview of the relevant projects is given below:

- **ROMEO** [17] aimed to develop magnets with reduced HREE content while maintaining magnetic properties above 100 °C. After three years and a budget of approximatively EUR 3.5 million, the 13 project partners were able to produce magnets in which the dysprosium content was reduced by a factor of 16. This invention has been patented and magnet prototypes for EV and wind turbines have been developed.
- **NANOPYME**[18] set out to develop permanent magnets based on nanocrystalline ferrites. Following the scope of developing a new generation of rare earth-free permanent magnets with high magnetic energy, the 12 partners demonstrated production ramp-up and magnet integration in two different types of motors.
- **REFREEPERMAG**[19] aims at developing magnets operating at high temperatures (T>200 °C) based on metallic Fe-Co nanoparticles with large magnetocrystalline anisotropy. Theoretical modelling using a combinatorial approach allowed for the down selection of promising nanostructures, which have been synthesised and characterised in the form of novel materials. Successful candidates were then selected for the manufacture of practical devices, tested by industrial experts in different application areas.
- Similarly, **MAG-DRIVE**[20] aims at developing REE-free permanent magnets for automotive application, although the methods applied differ. MAG-DRIVE strives to produce a magnetic material powder with reduced grain size and thus enhanced characteristics. These powders are then transformed into permanent magnets which are characterised and tested.
- **ARMEVA**[21], **VENUS**[22] and **SyrNemo**[23] projects are aiming to reduce the need for rare earths in automotive applications. This entails the development of alternative components/systems, namely electric motors based on reluctance technology, to substitute permanent magnets. While ARMEVA has selected the switched reluctance motor (SRM) technology, VENUS is also investigating PM-assisted synchronous reluctance motors (PMSynRM). SyrNemo is striving to deliver the design and prototype of an innovative synchronous reluctance machine (SYRM).
- **DRREAM** [24] strived to reduce the need for CRM in magnetic refrigeration technology. Through magnetisation, for instance with permanent magnets, some materials – mainly gadolinium-based alloys – heat up. After adiabatic cooling, demagnetisation causes further cooling of the materials. For three years, the eight partners investigated material efficiency both in the magnetocaloric (for cooling) and thermomagnetic material. Should these efforts prove successful, substitution could take place at the technology level.

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[17] http://www.romeo-fp7.eu/ or http://cordis.europa.eu/project/rcn/105901_en.html
[18] http://cordis.europa.eu/project/rcn/105595_en.html
[19] http://refreepermag-fp7.eu/project/what-is-refreepermag/ or http://cordis.europa.eu/project/rcn/103430_en.html
[20] http://mag-drive-fp7.eu/ or http://cordis.europa.eu/project/rcn/110008_en.html
[21] http://www.armeva-project.eu/ or http://cordis.europa.eu/project/rcn/110867_en.html or http://www.egvi.eu/projectslist/93/37/ARMEVA
[22] http://www.venusmotorproject.eu/index.php/project or http://cordis.europa.eu/project/rcn/110532_en.html
[23] http://www.syrnemo.eu/ or http://cordis.europa.eu/project/rcn/110530_en.html
[24] http://www.drream.eu/Mission.html or http://cordis.europa.eu/project/rcn/106437_en.html

5. Substitution of rare earth-based permanent magnets in wind turbines

5.1 Technology background and market evolution of wind power

5.1.1 Wind power outlook in energy generation

Wind power is one of the most advanced renewable energy technologies able to generate 8000 TWh or between 18 % and 21 % of the world electricity by 2050, compared with 4 % in 2015 [JRC, 2016b]. China, the EU and the USA are leaders in the installation of wind power, currently accounting together for more than 83 % of global installed capacity, with another 6 % located in India [JRC, 2016b]. According to the "new policies scenario"[25] of the IEA, renewable energy as well as wind power will continue to expand rapidly [IEA, 2015b]. In terms of global installed capacity (different to electricity generation, quoted previously), it is expected that wind power will increase from 433 GW in 2015 to 617 GW in 2020, further to 1046 GW in 2030 and up to 1376 GW in 2040 [IEA, 2015b] (Fig. 19).

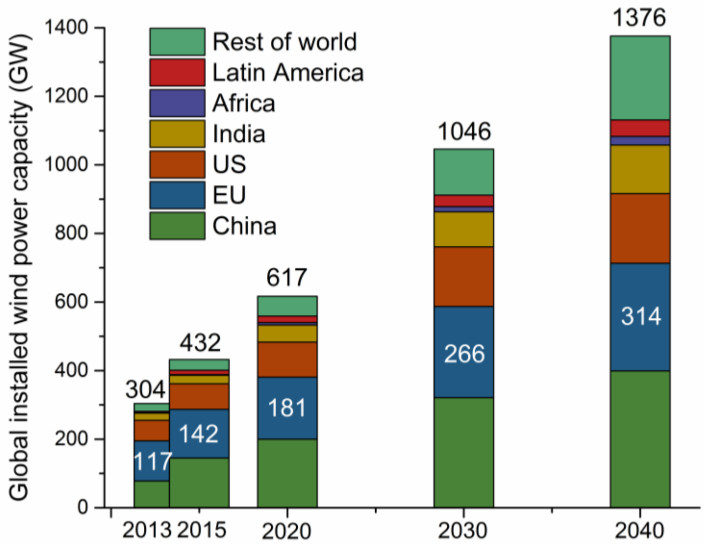

Figure 19: Evolution of global installed wind power capacity by region in IEA's "new policies scenarios" – World Energy Outlook 2015. [Sources: IEA, 2015b for 2013, 2020, 2030 and 2040, and GWEC, 2016 for 2015 data]

The EU led wind power deployment until 2015 when it was surpassed by China. Nevertheless, the deployment of wind power will continue in the EU as well in other regions/countries.

As a result of low installation cost, onshore currently dominates the global market (97 %); however, offshore wind power is starting to become more relevant in some regions and could play a significant role in the future.

The 2050 roadmap developed by IEA implies intermediate stages of annual installed wind power global capacity, i.e. from 25 GW in 2012 to 65 GW by 2020, to 90 GW by 2030 and to 104 GW by 2050 [IEA, 2013a]. Achieving these targets also requires undistorted access to material resources, including rare earth elements (REEs).

[25] The New Policies Scenario is the central scenario of World Energy Outlook which takes into account the policies and those implementing measures affecting energy markets that were adopted as of mid-2015 (as well as the energy-related components of climate pledges in the run-up to COP 21, submitted by 1 October), together with relevant declared policy intentions.

The EU has long been the frontrunner in wind power. In 2015, wind energy produced 299 TWh, representing about 10 % of final electricity consumption in the EU through the cumulative installed capacity of 142 GW (of which 11 GW was offshore) [JRC, 2016b]. The EU was the first region to adopt offshore wind at the commercial scale and today about 90 % of global offshore wind parks are located in Europe. Further expansion of the offshore wind power is a strategic objective for Europe. The European wind turbine manufactures want to keep the industrial lead in this sector. According to the European Wind Energy Association (EWEA)'s Central Scenario, up to 169 GW of onshore and 24 GW of offshore wind energy capacity will be installed in the EU by 2020, increasing to 254 GW of onshore and 67 GW of offshore by 2030 [EWEA, 2014 and EWEA, 2015] (Fig. 20). The main regions in Europe for offshore wind will be the North Sea, the Atlantic and the Baltic Sea.

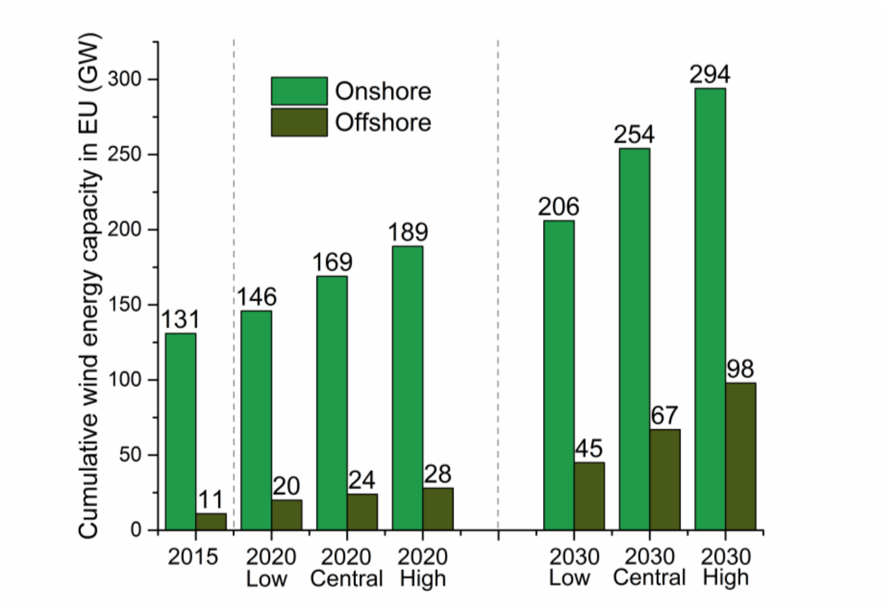

Figure 20: EU wind power installation according to EWEA scenarios (low, central and high). [Sources: EWEA, 2014 and EWEA, 2015 for 2020 and 2030, and GWEC, 2016 for 2015 data]

JRC analysis indicates a more optimistic scenario for growth in offshore wind energy in the EU by 2030. It has estimated a cumulative capacity of around 181 GW of onshore and 27 GW of offshore wind energy capacity by 2020, increasing to 241 GW of onshore and 112 GW of offshore by 2030 [JRC, 2015a].

Achieving the EU wind energy targets for 2020 and 2030 will depend on the regulatory framework, economic developments and the effectiveness of future energy policies, but could also be influenced to a certain extent by the supply issues surrounding raw materials, in particular REEs.

Reduction of electricity costs is one primary priority for manufacturers. One approach to mitigating the specific high cost comprises installations of wind farms with turbines providing greater efficiency and reliability.

5.1.2 Recent development of wind turbine generators

Recent developments in wind-power generation indicate that a mixture of wind turbine types is currently used to meet the various specific onshore and offshore site conditions. They are specifically designed to enhance the performance in terms of energy production, reliability, operation, maintenance, capital cost and transportation. Modern wind turbines integrate a series of highly optimised components to produce the lowest possible cost of energy.

Today, the onshore wind global market is dominated by the traditional doubly-fed induction generator (DFIG) with capacities ranging from 2 MW up to 6 MW. Permanent magnet synchronous generators (PMSGs) are also present on the wind market. These two technologies differ in principal by generator type, drive train system and interconnection to the grid. While the DFIG topology with gearbox allows variable-speed operation over a limited range of revolutions per minute (rpm), the direct drive PMSG configuration has full power conversion and a more significant variable-speed range for operation. Overall, both turbine types offer good performance levels.

Rare earth-free Siemens 3.6-MW wind turbine is currently the most used type in the offshore wind market. It operates with high-speed transmission and a squirrel-cage asynchronous generator with full converter. The main manufactures have started developing larger wind turbines of over 5 MW that can be used in strong winds, especially in offshore conditions. Such large turbines are expected to outperform smaller turbines in the wind market. Consequently, an intensive effort is under way aiming to develop new large-size turbines. High investment costs pose a major challenge in the offshore market. Table 11 summarises technology standards for some of the newly developed turbines and shows the wide variety of possible technologies that require different amounts of rare earths.

Table 11: Wind power technologies for large turbines and an indication of permanent magnet demand [Jensen, 2012]

Manufacturer	Technology	Generator type and capacity	Permanent magnet amount***
Siemens Wind Power	Low speed/direct drive	PMSG 6 MW	High
Vestas (MHI Vestas)	Mid speed/geared	PMSG 8 MW	Medium
Enercon*	Low speed/direct drive	EESG** 7.58 MW	None
Alstom	Low speed/direct drive	PMSG 6 MW	High
Senvion	High speed/geared	DFIG 6.2MW	None
Areva/Gamesa	Mid speed/geared	PMSG 5 MW	Medium

* Over time Enercon has upgraded the capacity of its generator
** EESG – electrically excited synchronous generator
*** Typical permanent magnet amount: High = 650 kg/MW; Medium = 160 kg/MW; Low = 80 kg/MW

Among different designs, the direct-drive wind turbine operates without a transmission and is predominantly equipped with a large permanent magnet generator. In the long term, wind generators may use high-temperature superconductors (HTS) technology which would allow for low weight in direct-drive mode. However, this concept is currently at the research stage.

Based on the configuration of the drive train that connects the blade hub with the generator and transforms the turbine blade speed to a certain level of generator drive speed, three major drive types are currently in use, namely: low-, mid- and high-speed drives (Fig. 21):

- **Low speed or direct drive (DD):** The wind turbine blades are directly connected to the generator which runs at a low speed (e.g. about 20 rpm). For technical reasons (high torque), the low speed in DD requires bigger generators. In order to reduce the generator weight and complexity, DDs are often equipped with the lighter PMSGs. However, rare earth-free electrically excited generators (EESG) are also used;
- **Mid speed:** To enhance the rotational speed of the generator to around 100-500 rpm, a compact gearbox is placed between the generator and turbine blades. The

generator contains smaller amounts of permanent magnets than required for low-speed configuration;

- **High speed:** A geared, full-sized transmission system transfers the low speed of wind turbine blades to a higher speed in the generator (above 900 rpm). In general, they are smaller than low-speed generators. Typical high-speed generators are DFIG, squirrel-cage or wound-rotor generators.

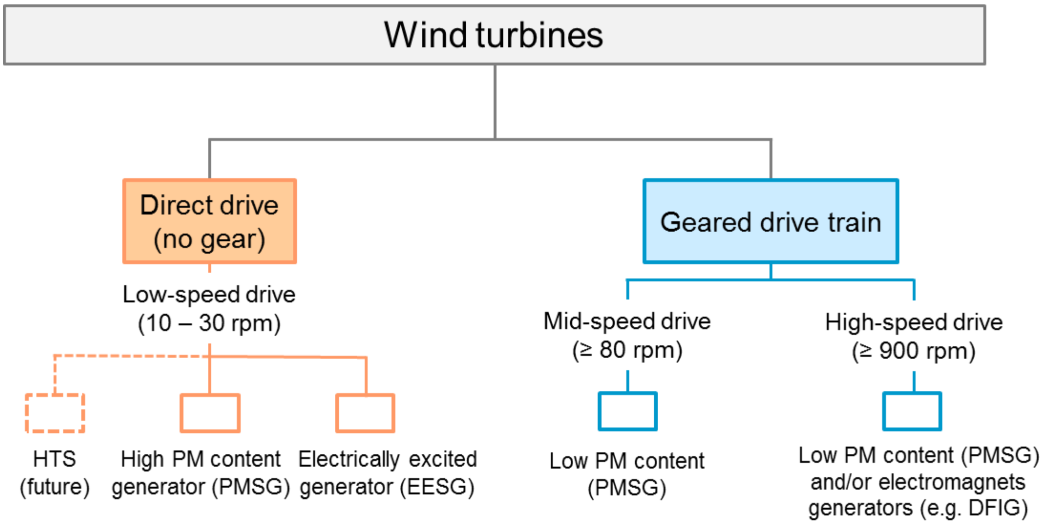

Figure 21: Principal wind turbines types according to drive train configuration

The PMSG type is used in all three designs. The permanent magnet content in mid- and high-speed turbines is lower than in direct-drive low-speed turbines. In general, the direct-drive low-speed turbines containing permanent magnet synchronous generators (DD-PMSG) offer certain advantages (Table 12).

Table 12: Characteristics of main wind power technologies in comparison to DD-PMSG

Characteristic	Low-speed direct drive (PMSG)	Low-speed direct drive (EESG)	Mid- or high-speed geared (PMSG)	High-speed, geared (DFIG)
Overall generator efficiency, including partial load	++	++	++	+
Maintenance offshore	++	n.a.	+	+
Generator and gearbox weight	++	+	++	++
Dependence on REE, price risk	- -	++	-	++
Available for offshore	++	n.a.	+	+
Cost	-	- -	+	++

'++' strong advantage; '+' advantage; '-' disadvantage; '- -' strong disadvantage

Although the DD-PMSG design is associated with the highest rare earth content, the market share of this turbine is expected to increase in the future due to its technical advantages. Alternative turbine designs have good efficiency levels, although there might be moderate performance losses in some aspects.

The EU wind-turbine industry is well represented by various manufacturers (e.g. Siemens Wind Power (DK), Vestas (DK), Enercon (DE), Alstom (FR)[26], Senvion (DE), Areva (FR/DE)[27], Gamesa (ES), Acciona (ES) and Nordex (DE)). Today, many of these players have started to develop new turbine designs that exhibit nominal capacity up to 6-8 MW, targeting in principal the offshore market. The DD-PMSG technology is of special interest as the manufacturers claim significantly lower turbine weight, among other benefits.

5.1.3 Role of NdFeB magnets in wind turbines

Manufacturers aim to reduce the weight and improve the efficiency of wind turbines to achieve good economic performance. PMSGs present a series of attributes such as:

- Allowing for a lighter and more compact turbine design, achieved by the very strong magnetic field of integrated NdFeB magnets;
- Offering higher efficiency at low blade-rotation speeds in low winds. For most of the operation time, wind turbines run at partial load and lower speeds, resulting in efficiency losses. Thus, the overall efficiency of PMSGs is potentially higher than that of other generator types.

Based on these features, the DD-PMSG contributes two important characteristics. First, DD-PMSG requires lower maintenance costs. In the past, frequent transmission failures led to higher maintenance costs and down-time periods. Secondly, low speed design employs larger and heavier generator sizes compared to mid- and high-speed designs. A weight reduction can be achieved by using lighter PMSG.

In 2015, it was estimated that the global market share of DD-PMSG was 19 % and 5 % for mid- or high-speed PMSG technologies (by installed capacity) [JRC, 2016b]. Taking into account various deployment scenarios for the wind turbine market, JRC estimates an increase in the DD-PMSG share in the wind market of up to 29 % in 2020 and 44 % in 2030 [JRC, 2013b]. For mid- or high-speed geared drives, the market share of PMSG is estimated at 12 % in 2020 and 28 % in 2030. Different amounts of permanent magnets are required in the PMSG configuration. About 2 tonnes of permanent magnets are used in 3 MW DD-PMSG turbine (low-speed design), or approximately 650 kg PM per MW of generator capacity [JRC, 2015a]. In contrast, a PMSG that is attached to a gear and rotates at mid speed may operate with a 160 kg magnet per MW. This amount decreases up to 80 kg per MW in high-speed PMSG configuration [JRC, 2012 and 2015].

The rare earth content accounts for about one-third of the magnet weight (Table 10) [Buchert, 2011a, Wuppertal, 2014]. In 2015, from a total production of about 79 000 tonnes of NdFeB, it is estimated that the wind power sector required about 10 % (Fig. 16). In 2015, this would translate into a global consumption of rare earths in the wind sector of approximately 2600 tonnes.

The price increase in rare earths during 2011/2012 adversely affected the production costs and profit margin of wind-turbine manufacturers. Partly as a result of issues concerning REEs supply, manufacturers have opted for other generator designs with lower or zero permanent magnets. Moreover, they started developing new technologies, for instance based on superconductive materials. Although rare earth prices have declined since 2013, concerns about disruptions in rare earth supplies still exist in the wind industry.

[26] Now taken over by GE (http://www.alstom.com/ge-alstom-transaction/)
[27] Focused on the offshore sector, in March 2015 AREVA created a 50/50 joint-venture with GAMESA called Adwen (http://www.areva.com/EN/operations-3591/areva-wind-energy-solutions.html)

5.2 Substitution opportunities for rare earths in wind turbines

5.2.1 Material substitution and increased material efficiency of rare earths in NdFeB magnets used in wind turbines

Today, PMSG wind turbines rely on NdFeB magnets containing neodymium, praseodymium and dysprosium. No other high-performance magnets are currently available for wind-turbine applications. Material substitution by totally replacing rare earths in NdFeB magnets with non-critical materials that give a similar high-energy output has yet to be achieved and will probably not be available in the near future, as described in chapter 4.2.

Nevertheless, current research indicates that the amount of rare earths necessary to produce NdFeB magnets at a similar strength might fall in the future. For neodymium and praseodymium, a significant rise in material efficiency of up to 29 % is the target for 2030.

Ongoing research projects also aim to reduce dysprosium or terbium content in permanent magnets for wind turbines. This can be achieved either by lowering the working temperature of the turbine, e.g. through the optimisation of PMSG design and better cooling arrangements, or by improving the magnet manufacturing technique. For new types of wind turbine generators, JRC estimates a dysprosium content in permanent magnets of approximately 2 % [Lacal, 2015].

The German Federal Institute for Geosciences and Natural Resources claimed that the measures applied by the wind industry had already led to less dysprosium in the new PMSG wind turbines [BGR, 2014]. Instead of using magnets with 3-6 % Dy, more recent PMSG models can use permanent magnets with only about 1 % Dy or even less. Some manufacturers are aiming to completely eliminate dysprosium from wind turbines. Siemens, a leading turbine manufacturer in the offshore segment, has announced that by 2017 their DD-PMSG turbine will not require any heavy rare earth elements (HREE) such as dysprosium or terbium [Pulkert, 2014]. This efficient HREE-free generator has been specifically developed for wind turbines by changing the magnet design. The magnet will be larger and will require more neodymium, thus compensating for the coercivity losses. It is unlikely that this concept will be suitable for other applications.

5.2.2 Component substitution for PMSG in wind turbines

A wide variety of alternative technologies to PMSG that require smaller amounts of rare earths or are rare earth free is available today in the wind market. Their adoption could contribute to reducing the pressure from rare earth supply on wind turbine applications.

For instance, there are mid-speed turbines that can operate with gears and a much smaller PMSG generator (with significantly lower rare earth content) as well as high-speed turbines that may include a conventional generator (e.g. DFIG or squirrel-cage) without permanent magnets. These different turbine designs are already available on the market and have also shown good performance. In this report, such alternatives are referred to as 'component substitution' for a permanent magnet generator (PMSG). These substitute turbines can be used in both onshore and offshore applications as they have their individual strengths and weaknesses. The technological development status of the main substitutes for PMSG is presented in Figure 22. More details about the principal rare-earth-free turbine types – DFIG, EESG, SCIG – as well as a possible next-generation turbine – HTS – are given in the following subsections.

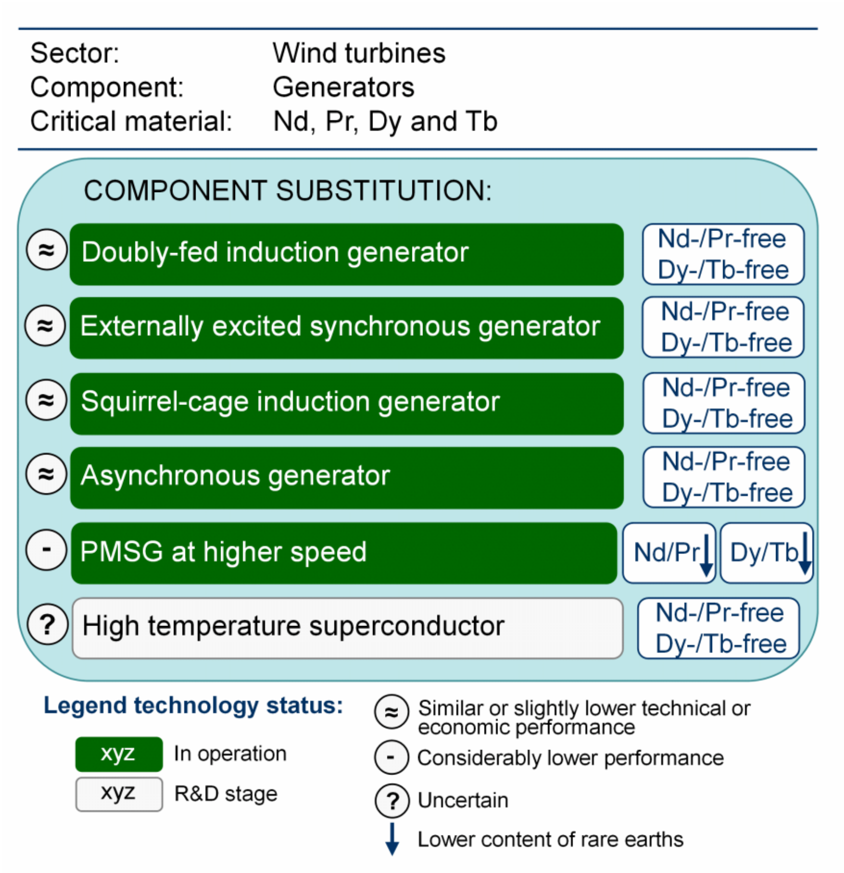

Figure 22: Component substitution for PMSG in wind turbines and their technological development status

5.2.2.1 PMSG substitution with a doubly-fed induction generator (DFIG)

The rare earth-free DFIG technology was developed before PMSG and is currently the most common generator type in the wind power sector. It is based on an electromagnet and is used in a traditional drive train with gears, running at high speed. DFIG is more advantageous for smaller-geared turbines (<5 MW) in onshore applications. The offshore wind farms points to greater reliability and therefore reduced maintenance costs, which favour PMSG. The experts consider that as long as the price of REEs remains low, DFIG technology will probably not achieve wide penetration of the large-generator market (over 5 MW). The advantages and disadvantages of the DFIG type are summarised in Table 13.

Table 13: Major characteristics of DFIG technology

DFIG advantages	DFIG disadvantages
• Capability to adjust to wind speed over a wide range • Low manufacturing costs • Easy connection to the grid • Similar efficiency to PMSG when operating at 100 % nominal power • Uses cheaper partial converter • No reliance on rare earths	• Lower efficiency than PMSG in partial load at low wind speeds • Cannot comply with the most demanding specifications in grid codes (e.g. black start) • Higher indirect maintenance costs related to the gearbox, especially down-time cost

5.2.2.2 PMSG substitution with an electrically excited synchronous generator (EESG) in direct-drive turbines

The EESG is connected to a direct-drive train offering high performance in partial and nominal loads. Due to the higher torques in direct-drive configuration, the EESG needs a larger, multi-pole design generator with a wider diameter compared to smaller traditional turbines. EESG technology is also much heavier than PMSG. The EESG was prominent in the 2000s for direct-drive turbines, offering high performance in partial and nominal loads. However, only a few manufacturers provided this technology in Europe, e.g. Enercon. Table 14 shows the main advantages and disadvantages of EESG technology.

Table 14: Major characteristics of EESG technology

EESG advantages	EESG disadvantages
• High performance in partial and nominal loads • More simplified drive train without gear, compared to DFIG • Overall higher efficiency than DFIG • High reliability by omitting the gearboxes • Simple generator design using available know-how • Very good grid connectivity due to the use of a full converter	• Heavier than PMSG • Requires many parts and windings, including slip rings and brushes for external excitation • Higher copper demand than for PMSG • Currently, no manufacturer interested in EESG offshore plants • Cannot comply with the most demanding specifications in grid codes (e.g. black start)

5.2.2.3 PMSG substitution with squirrel-cage induction generators linked to a full converter

Several manufacturers have developed turbine designs based on a gearbox and a simple, high-speed squirrel-cage induction generator (SCIG) connected to the grid through a full converter. The SCIG was the main type of electricity generator used in wind turbines in the 1990s [Iglesias, 2011]. However, at that time the generator was connected directly to the grid (through a transformer) and needed to maintain a very constant rotating speed, a difficult match with the variability of wind speed. New designs (e.g. Siemens NetConverter®) introduced a full converter between the electricity generator and transformer, which allows the SCIG to rotate freely at any speed (through a gearbox). Vestas manufacturer abandoned PMSG in their onshore machines (e.g. V90 Gridstreamer) in favour of a SCIG/FC configuration also with the intention of reducing its dependence on rare earths that are costly and hard to access.

5.2.2.4 Potential of PMSG substitution with high-temperature superconductors (HTS)

The US Department of Energy estimates that future wind turbines must be larger to reduce the impact of a turbine's own electricity costs [DoE, 2011b]. According to US' cost targets, next-generation turbines should have:

- Larger size, of 10MW or more;
- Lightweight construction;
- Advanced drive concepts;
- Light-weight generator, preferably a HTS generator.

Conventional wind turbines (geared or direct-drive PMSG) are difficult to scale up to these targeted sizes because the equipment and operating costs would also increase significantly [SUPRAPOWER, 2013; DOE, 2011b]. A potential new generation of wind turbines with capacities of more than 10 MW and employing high-temperature superconductors (HTS) might close this gap. HTS allows for electrical currents 100-times higher which therefore can generate magnetic fields 100-times stronger than copper windings for the same dimension. Consequently, this could even become superior to high-performance permanent magnets. Some design studies and investigations have been already initiated (Table 15).

Table 15: Projects on HTS-based wind turbines of more than 10 MW [Jensen, 2012]

Manufacturer	Transmission	Generator
American Superconductor	Direct-drive	10 MW
General Electric	Direct-drive	10-15 MW
Advanced Magnet Lab	Direct-drive	10 MW based on MgB_2 *
EU-FP7/SUPRAPOWER	Only superconductor generator	10 MW based on MgB_2

* MgB_2 is a superconducting material with one of the highest known transition temperatures (Tc).

In terms of rare earth demand for a HTS wind turbine, the first estimations indicate a very low content of about 2 kg REEs/MW. The main rare earth requested is yttrium in the range of 0.1-0.8 kg/MW [Wuppertal, 2014]. Yttrium in these applications could be substituted by lanthanum or cerium [Buchert, 2011a].

All superconductors work at very low temperatures (HTS requires from 30 to 50 Kelvin). The extremely high costs and technical challenges related to the cooling system largely offset the superconductor advantages and represent the main obstacles to commercial use in the wind-power sector. Although prototypes were supposed to be launched in 2014, none have been presented yet. Overall, HTS generators are still under investigation and it cannot be predicted when practical HTS applications will enter the market.

In conclusion, the full substitution of rare earths in the NdFeB magnet is not yet possible and no other materials with a similar magnetic strength as NdFeB have been discovered up to now. However, alternative rare earth-free turbines with good efficiency levels are available on the wind market, although there might be moderate performance losses in some aspects, in particular in offshore conditions. Moreover, significant progress has been achieved by wind turbine manufacturers towards improving material efficiency, especially for dysprosium.

The future European market for various wind turbine types, including DD-PMSG containing rare earths, will be highly influenced by the overall evolution of the wind power sector. It will be partially shaped by the advantages of using rare earth-based technology (i.e. PMSG) and the evolution of rare earth prices, alongside regulatory frameworks and the effectiveness of future energy policies. No matter what the future market brings, the global wind power sector is prepared for potential rare earth shortages in both the short and medium term, thanks to the progress made in material efficiency and the availability of substitution at the component level. However, European competitiveness, wind industry profits and the EU’s leadership in the offshore wind market will be affected more by potential supply disruption and price increases in rare earths than other regions. This is due to the strategic importance of offshore wind for Europe, a sector where PMSG has already proven several advantages, and the result of a lack of domestic REEs production. In the long term, new technologies such as HTS might lead to the production of very large wind turbines (10 MW or more) which will require a tiny amount of rare earths. Currently, this technology faces a lot of technological challenges and is therefore still under development.

6. Substitution of rare earth-based permanent magnets in electric vehicles

6.1 Technology background and outlook for electric vehicles

6.1.1 The shift towards low-emission mobility

Electrification of the global passenger-vehicle fleet coupled with low-carbon electricity production is essential for changing the emissions trajectory in the transport sector. It is estimated that today transport is responsible for almost one-quarter of the global energy GHG emissions [IEA, 2016a]. Several sustainable solutions have to be adopted, among them electric mobility and the rapid deployment of electric vehicles (EVs).

Transport represents more than 30 % of final energy consumption in the EU [EC, 2015]. In view of the global shift towards a low-carbon economy and limiting the global temperature rise, the European Commission has recently set up an integrated project called 'Low-emission mobility strategy' [EC, 2016a]. It encompasses three main elements: (i) increasing fuel efficiency; (ii) speeding up the deployment of low-emission alternative energy sources; and (ii) moving towards zero-emission vehicles. These elements will contribute to meeting the EU's ambitious 2050 goal of reducing the GHG emissions from the transport sector by at least 60 % compared to 1990 and to be firmly on the path towards zero emissions.

According to the EU reference scenario 2016[28] [EC, 2016b], the penetration of electric vehicles will occur in future as a result of EU and national policies (e.g. through incentive schemes, lower taxation, etc.) aiming to boost larger penetration of EVs and meeting ambitions sustainability and climate goals (Fig. 23).

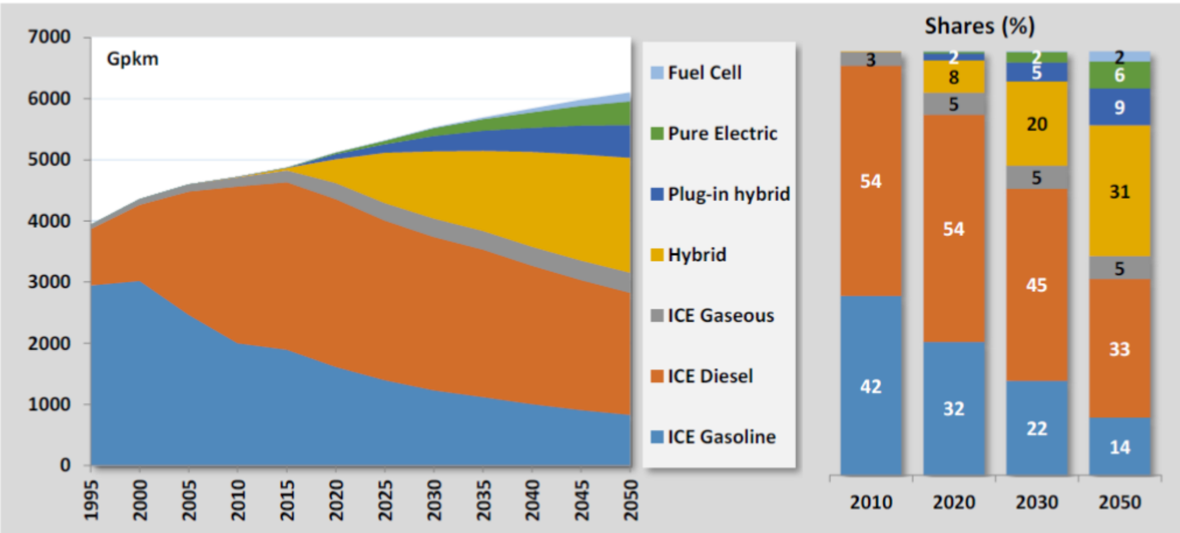

Figure 23: Evolution of activity in light-duty vehicles (passenger cars and vans) in the EU by 2050, according to the PRIMES model [EC, 2016b]. NB: Gpkm – giga passenger-kilometre

The share of EVs (i.e. fuel cell, pure electric (battery electric vehicles – BEVs) and plug-in hybrid (PHEV)) in the total activity of light-duty vehicles in the EU is expected to reach 17 % in 2050. PHEV may contribute to just over half of this share. Hybrid electric vehicles (HEVs), which are not part of the EV category, will remain the consumers'

[28] Modelling exercise (PRIMES) for transport takes into consideration the national plans already in place in EU countries to support the penetration of advanced vehicle options such as electric vehicles.

preference as this type do not impose any range limitation on travellers and does not depend on the charging infrastructure (31 % of total activity will derive from HEVs in 2050).

It can be considered that some European countries have already entered the implementation phase for electro-mobility. In 2015, six European countries, namely Norway, the Netherlands, Sweden, Denmark, France and the United Kingdom, registered a market share of electric vehicles above 1 % [IEA, 2016b]. For instance, in 2015, EVs' share reached 23 % in Norway and nearly 10 % in the Netherlands [IEA, 2016b]. In terms of total annual sales, in the same year the EU accounted for about 150 000 EVs (about 30 % of the global market), comprising mainly PHEVs (60 % of total EV sales) and BEVs (40 % of total EV sales) [EAFO, 2016]. In addition, about 192 000 HEVs were sold in the EU in 2015 [JATO, 2016].

In view of creating an integrated electro-mobility ecosystem and the national roadmaps needed to gather support from policy-makers, several countries have set ambitious sales and/or stock targets for vehicle electrification. Among various uptake scenarios, the International Energy Agency (IEA) and the Electric Vehicles Initiative (EVI), a multi-government policy forum, presented an aggregated global deployment target of 7.2 million in annual sales of EVs and 24 million in EVs stock by 2020 [IEA, 2013b]. This is an important milestone in meeting the global deployment target of a fleet of 100 million EVs by 2030, as announced at COP 21 in the Paris Declaration on Electro-Mobility and Climate Change and Call to Action [IEA, 2016b]. An even more ambitious target (a fleet of 140 million EVs globally by 2030) is presented by the IEA under the 2 °C scenario (2DS) [IEA, 2016b].

According to the European Roadmap: Electrification of Road Transport, over 5 million EVs will be on EU roads by 2020, rising to 15 million by 2025 [ERERS, 2012]. To accomplish the emissions reduction goals, McKinsey introduces more ambitious targets amounting to 8-9 million EVs on the road by 2020 [McKinsey, 2014]. However, specific targets and timelines are the subject of negotiation with EU Member States.

Despite the progress made on the electrification of the vehicle fleet, there are still many challenges that can hinder the achievement of future deployment targets for EVs. The most significant are the cost, range limitation, technological aspect and consumer acceptance, alongside the economic/political framework. Among these limitations, it is also important to consider the full access to certain raw materials. The JRC report on critical materials in low-carbon energy technologies demonstrated that a large and rapid adoption of electric vehicles could be at risk because of potential bottlenecks in the supply chains of certain rare earths [JRC, 2013a]. These rare earths, i.e. Nd, Pr, Dy and Tb, are key ingredients in the NdFeB permanent magnet, which is an essential material for producing light, compact and highly efficient electric traction motors.

6.1.2 Recent developments in electric propulsion systems

There is a large diversity of electric propulsion systems on the automotive market. In general, electric vehicles refer to those passenger cars that have an electric motor as the primary source of propulsion [JRC, 2015b; IEA, 2016b]. The battery electric vehicle (BEV), fuel cell electric vehicle (FCEV), range-extended electric vehicle (REEV) and plug-in electric vehicle (PHEV) usually belong in the EVs category (Fig. 24). The REEVs, also called serial hybrid, have an electric propulsion system and are also equipped with a smaller combustion engine for recharging the battery. FCEVs have electric propulsion similar to the BEV traction motor.

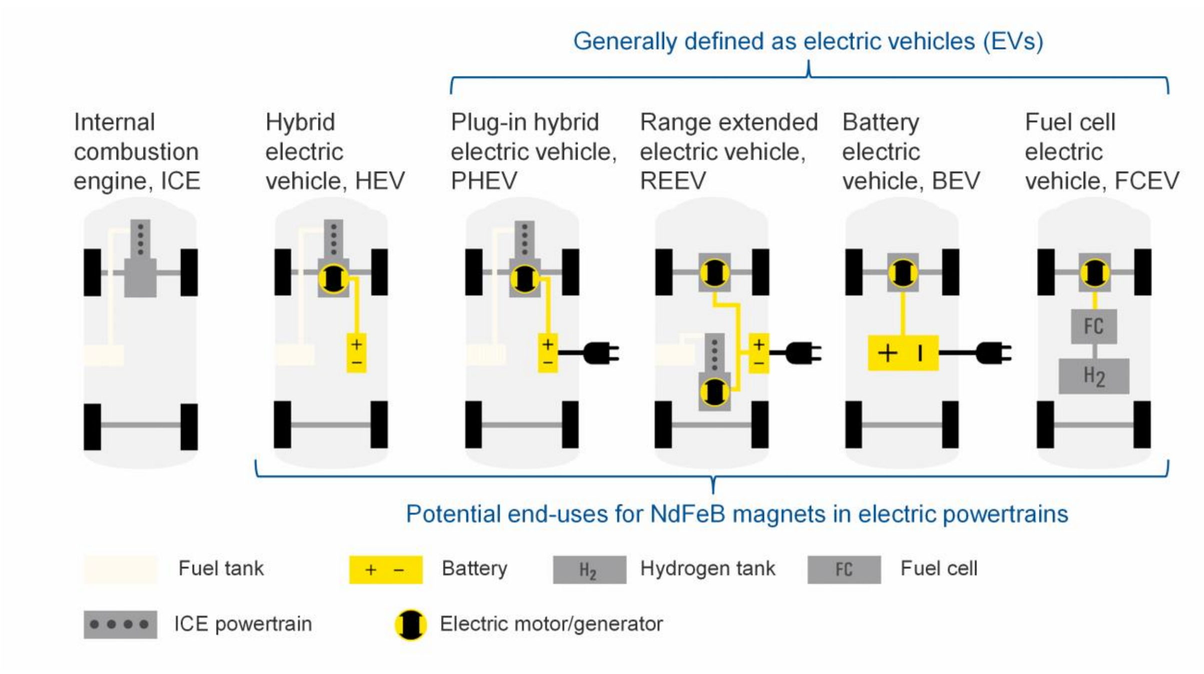

Figure 24: Electric powertrain concepts compared to conventional ICE propulsion system [representation adapted from Fraunhofer, 2011]

Today, the most common and dominant electric powertrain is the hybrid electric vehicle (HEV). It is not included in the EV category since its electric motor is a secondary source of propulsion in parallel configuration with the ICE (internal combustion engine) drive. Moreover, HEV does not use electric power from the grid.

In this report, we refer to electric passenger vehicle types BEV and PHEV as well as HEV as these three categories are the most common variants and all of them may make use of rare earth in the NdFeB permanent magnet:

- **BEV** runs exclusively with one or more electric motors. Most EVs are powered by a rechargeable battery, thus using energy stored on the grid;
- **PHEV** contains rechargeable batteries that can be plugged into an external electric power source for charging. It also has ICE to extend the vehicle's range;
- **HEV** combines an internal combustion engine (ICE) and one or more electric motors. Here, we consider the larger fully hybrid electric vehicles that allow the vehicle to be powered solely by an electric motor under certain operating conditions.

In recent years, traditional asynchronous motors have continued to be replaced by more efficient devices containing NdFeB permanent magnets, e.g. highly efficient PM synchronous-traction motor (PSM). Currently, most HEVs and EVs (referred to in this paper as H&EVs) use PSM technology. It is estimated that by 2025, between 90-100 % of H&EVs sales will be based on PSM [CRM_Innonet, 2015].

Alternative electric traction motors exist in the serial production of BEVs, for example the Tesla S incorporates an asynchronous motor (ASM) and the Renault Zoe has an electrically excited synchronous motor (EESM). While different electric motor types are used commercially in BEVs, the hybrid (HEVs and PHEVs) motor market is one-sided: almost all manufacturers currently produce their serial HEVs and PHEVs models with PSMs. The main reason for this is a PSM's high power density which can lead to compact sizes. This makes them favourable, especially for hybrid models which have to cope with serious space restrictions due to the integration of two drive trains in a car: the electric engine and the combustion engine.

Overall, there are several reasons for the common use of NdFeB-based PSM in H&EVs:

- The very strong magnetic field of integrated NdFeB magnets allows for a light and compact motor design;
- PSMs have a high efficiency since no external power system is needed to induce a magnetic field in the rotor. The magnetic field is provided by a permanent magnet whereas other motor concepts require electricity to generate this electric field;
- PSMs supply high torque and can be controlled more easily.

Despite the availability of other motor prototypes, which are analysed in detail in chapter 6.2, three main types of electric traction motors are currently in use for the serial production of BEVs: PSM, ASM and EESM. However, these motors are different in terms of design, materials, efficiency, production cost, etc. A summary of their principal characteristics is shown in Table 16.

Table 16: Principal characteristics of PSM, ASM and ESSM motor types

Characteristic	**PSM**	**ASM**	**EESM**
Materials for structural parts			
Rotor	Permanent magnets	Copper or aluminium bars	Windings
Stator	Windings	Windings	Windings
Average total efficiency according to CADC [Doppelbauer, 2015]*			
Urban	96.0	92.2	94.8
Road	93.6	95.4	96.3
Motor 130	84.6	95.7	96.2
Other advantages and disadvantages [Stoll, 2013]			
Construction space	++	+	+
Weight	++	+	+
Cooling	++	+	-
Production costs	+	++	+
Power density	++	+	+
Reliability	+	++	+
Noise	+	+	+

* CADC - Common Artemis Driving Cycle
** '++' strong advantage; '+' advantage; '-' disadvantage

Magnetic fields can principally arise from permanent magnets or from windings, which produce a magnetic field when an electric current passes through them. When permanent magnets are used, these materials can be affixed to the rotor's surface (surface magnets) or they can be located in pockets within the rotor (buried magnets). The stator carries windings connected to the power supply to produce a rotating magnetic field. The torque results from the interaction between these different magnetic fields. Externally excited EESMs only differ from PSMs in their rotor design. An electric current from the battery magnetises the copper windings in the EESM rotor to create an electromagnet.

Synchronous machines and ASM operate on different physical principles. For instance, in ASM, the torque is obtained by electromagnetic induction from the magnetic field of the stator winding. The ASM is also called an induction motor as it is based on the principal of induction.

A crucial point in developing electric vehicles is the improvement of the overall motor efficiency to enable larger operation ranges. This means that the efficiency of different power train designs and their embedded motors is one major issue for vehicle manufacturers. Therefore, the alternative motor types have to compete with PSMs' high efficiency. A sound comparison between different motor types has to take into account that the motor efficiencies are not constant during the operation range. Whereas EESM shows the highest efficiency at fast speeds, PSM is most efficient at lower and medium speeds. On average, the ASM is efficient in all operational ranges. However, the data presented in Table 16 indicate that there is no clear advantage for any of these motor types in all driving applications. Compared to the PSM, the ASM is less efficient in urban conditions but is much more efficient on motorways with high speeds. Good efficiency at the lower and medium speeds of PSM and EESM technologies encourage their applications in urban conditions. However, industry is aiming at higher EV driving ranges, which also require high efficiency at high speeds.

Despite the fact that the PSM technology shows several advantages in terms of power density, weight, space and cooling, it is associated with the need for critical rare earths. Although the ASM and EESM types demonstrate a series of advantages, they are unable to meet the requirements of hybrid electric vehicles (i.e. HEV and PHEV). Since none of these motor types can satisfy all conditions in terms of material reliance, technical and economic aspects, manufacturers have to find the best solution for each vehicle in terms of costs and technical specifications.

6.2 Substitution opportunities for rare earths in electric vehicles

6.2.1 Higher material efficiency of rare earths in NdFeB magnets used in electric vehicles

Research currently focuses mainly on reducing the rare earth content in electric traction motors using two main approaches: (i) increasing material efficiency in magnet production (e.g. grain boundary diffusion processes), thereby obtaining NdFeB magnets with less rare earth content but with similar performance; and (ii) optimising the motor design, enabling high technical performance while using fewer NdFeB magnets. Details about improving material efficiency and potential REEs substitution options have already been described in chapter 4.2. Overall, current research indicates a possible reduction in the amount of neodymium and praseodymium in permanent magnets by up to 29 % from 2015 to 2030.

As the result of research developments, Daimler estimates that the dysprosium content in magnets used in electric traction motors in hybrid or plug-in hybrid vehicles will be significantly reduced. The current dysprosium share in NdFeB magnets used in PSM is about 9 % and will decrease to approximately 5 % by 2020 and thereafter to 2.5 % [Ruland, 2015]. For BEVs, Daimler foresees manufacturing rare earth-free asynchronous electric motors. Terbium, another critical rare earth element, can completely replace dysprosium without losing any magnet performance. As previously mentioned, due to its higher price and a supply criticality issue, terbium is not considered to be a convenient substitute for dysprosium.

From the motor-design side, high torque densities can be obtained in the optimised PSM by designing new electrical machines while simultaneously using less NdFeB [Widmer, 2014]. The most successful approaches focus on hybrid-motor technologies that use fewer magnetic materials embedded into salient rotor structures. Since these motors provide both magnet and reluctance torques, they are also called 'permanent magnet assisted reluctance motors' or simply 'hybrid motors'. This hybrid motor resembles MotorBrain's PSM concept which uses ferrite magnets to create reluctance torque [MotorBrain, 2014]. BMW's i3 hybrid motor is a prominent example of increased material efficiency in an optimised PSM motor design. This model uses from 30-50 % less rare earths in its motor compared to standard PSM designs, or about 1 kg magnets to produce 125 kW power [Widmer, 2015]. This amount is significantly lower than 1-2 kg of rare earths containing magnets for a comparable EV [CRM_Innonet, 2015].

6.2.2 Component substitution for PSM in electric and hybrid vehicles

While the substitution of rare earths at the material level is currently very limited for electric traction motors in automotive applications, alternative rare earth-free motors exist in the serial production of some BEVs. Apart from the available ASM and EESM types, described above, there are several prototypes with a high potential for adoption in the future serial production of EVs and HEVs. The technological development status of the main substitutes for PSM is shown in Figure 25.

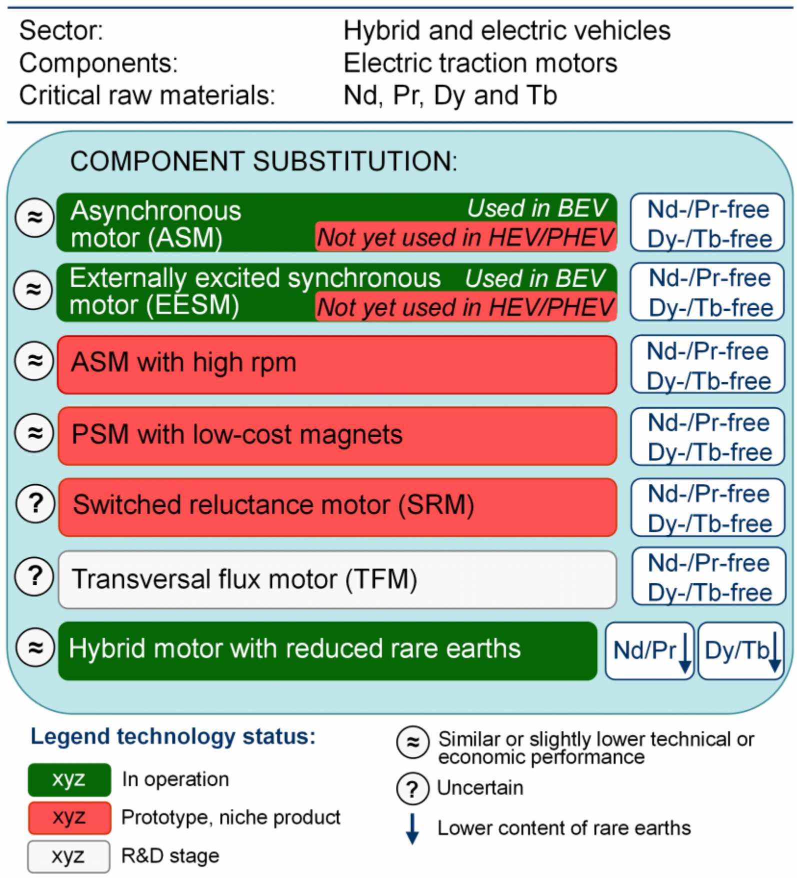

Figure 25: Component substitution for PSM and its technological development status

The ASM and EESM technologies are technically available and have good performance, but they are not applied in serial HEV and PHEV production. Other promising alternatives, such as ASM with high revolution per minute (rpm) and PSM with low-cost magnets (e.g. ferrite materials), have the potential to enter the market for EVs and HEVs. Another substitute for PSM might be the switched reluctance motor (SRM), if R&D can solve several technical issues. The current status and major advantages and disadvantages of the most promising electric motor concepts, along with the outlook for 2020, are given in Table 17.

Table 17: Overview of main component substitution for PSM in hybrid and electric vehicles, and comparison with current state-of-the art PSM

Motor type	Rare earth content	Current status	Major advantages	Major disadvantages	Outlook 2020	Reference
Permanent synchronous motor (PSM)	0.56 kg REEs per EV motor* (less in HEV**)	Used in all serial HEV and PHEV, and in most serial EV	• High efficiency at low and medium speeds • Compact size/ high power density • Wide dissemination	• Dependency on rare-earth supply and their price variation • Lower efficiency at high speed	Maintains a key role in EV and HEV as long as the price of rare earths does not increase significantly	[Widmer, 2015; Paulsen, 2015; Els, 2015]
Asynchronous motor (ASM)	Free of rare earths	Used in some serial BEV (e.g. Tesla S, Mercedes B class, Renault Twizy) and PHEV prototypes	• Low production costs • Robustness • High reliability • High efficiency at high speed	• Lower efficiency than PSM in urban conditions • Lower power density than PSM, requiring more package space and weight • Higher copper demand than PSM	Maintains serial application in some EV and in mild hybrids, partly as improved ASM with high rpm	[E-mobil, 2011; Hackmann, 2013]
Externally excited synchronous motor (EESM)	Free of rare earths	Used in a few serial BEV (e.g. Renault Zoe) and PHEV prototypes Also available for HEV	• High efficiency across all speed ranges	• Lower power density than PSM • More package space needed • Complex structure resulting in high manufacturing costs	Remains an efficient alternative to PSM, but application in HEV is unlikely	[Gutfleisch, 2011; Continental, 2015]
ASM with high rpm	Free of rare earths	Serial production announced	• Potential for high energy and material efficiency • Potential for low production costs	• No experience in serial production yet	Offers high potential for serial production in BEV, HEV and PHEV due to high efficiency and good cost effectiveness	[Widmer, 2015; Speed2E, 2015]
PSM with low-cost magnets	Free of rare earths	Prototypes using ferrite or AlNiCo magnets	• Potential for good overall performance	• No experience in serial production	Offers good potential for serial production due to high technical performance and reasonable cost effectiveness	[CCC, 2013; Kakihara, 2013; Lay, 2014; Yaskawa, 2013]

Switched reluctance motor (SRM)	Free of rare earths	First prototype	• Robust construction • Potential for cheap engine production	• High noise level • Requirement for a specific inverter, which is not compatible with production lines for power electronics for other engines	Needs further R&D to achieve highly efficient and silent engines suitable for serial production	[Kumar, 2014; CCC, 2015]
Transversal flux motor (TFM)	Free of rare earths	Early R&D stage	• Potential for high power density and efficiency	• Low technology readiness level	Might offer high power density and high efficiency, but needs more intense R&D	[Stoll, 2013; VENUS, 2015]
Hybrid motor (e.g. combine synchronous reluctance principle with permanent excitation)	0.37 kg*** REEs or less per motor	Used in the BEV BMW i3 and PHEV BMW i7	• Similar performance as PSM with less rare earths	• Remaining rare earth demand	Applied in serial BMW i3 and BMW 7 PHEV production with high potential for further vehicle types and models	[CCC, 2013; MotorBrain, 2014]

* The rare earths content in PSM takes into consideration the range of 1.5 kg permanent magnet per EV traction motor and the following chemical composition of NdFeB: 30 % Nd/Pr (Nd:Pr=4:1) and 7.5 % Dy.

** An HEV propulsion motor needs circa 42 % of the EV motor magnet weight. This is equivalent to about 0.63 kg magnet per HEV [Buchert, 2011b].

*** This value relates to 1 kg NdFeB magnet per traction motor with the same chemical composition as above.

This summary table shows that a wide range of motor designs is technically available. Since technical requirements vary with vehicle type and the area of application, a variety of electric motors with specific performance characteristics is needed for the development of efficient and competitive H&EVs. Indeed, the experts interviewed for this study believe that different electric motor concepts will contribute to the future H&EV market. Manufacturers will favour a motor type that best meets the specific needs of the vehicle and are also reasonably cost-effectively.

The development time required for a new electric motor for H&EV applications is highly dependent on economic conditions. Currently, low rare earth prices and a readily available rare earth supply will not stimulate the substitution of PSM with rare earth-free motors, unless they become more cost-effective. In this context, experts see a significant potential for low production costs for the newly developed ASM, which has high rpm and high material efficiency. Based on the MotorBrain project, which developed a new motor prototype in three years [MotorBrain, 2014], it has been estimated that moving from the conceptual stage until serial production will take about five years. This time could decrease significantly if electric motor design has merely to be adapted from other similar applications. Given the variety of motor prototypes available today, a commercially rare earth-free motor can probably be produced within a short time.

In general, the electric motor manufacturers are also leaders in R&D activities. Europe is well represented by several companies, e.g. Bosch, Continental, Siemens, ZF, Brose/SEW Eurodrive, etc. There are also vehicle manufacturers with their own electric motor production lines, such as VW, BMW and, in the near future, Renault. Many universities and research institutes support the large manufacturers through contracted research projects or they work on smaller company-independent projects. It can be assumed that many other companies work on technologies related to the development of different PSM substitutes, but for confidentiality reasons no information about their research activities is readily available. Table 18 shows selected leaders in R&D with published research activities.

Table 18: Key players in developing component substitutes for PSM

Motor type	European R&D leaders	Non-European leaders
Asynchronous motor (ASM)	Continental, Renault	Tesla
Externally excited synchronous motor (EESM)	Continental	n.a.
EESM with ferrite magnets	ZF, Siemens, Volkswagen, Fiat	n.a.
ASM with high rpm	ZF	n.a.
Switched reluctance motor (SRM)	Jaguar Land Rover Punch Powertrain	n.a.
Hybrid motor	BMW	n.a.

As of today, the PSM remains the technology of choice for automotive manufacturers, especially for hybrid vehicle (HEV and PHEV) models. The peak in rare earth prices in 2011/2012 revealed the risk of high material costs for PSM using rare earths. Better material efficiency and a wider adoption of motors free of rare earths, such as ASM, EESM or others, have the potential to overcome the supply pressure from rare earths.

Rare earth substitution in the EV sector relates to the vehicle's general performance. This includes multiple parameters, such as efficiency, dynamics, noise level, range, etc. Another challenge for substitution in electric traction motors is linked to the overall cost of electric vehicles. If such costs do not decline significantly, EVs will not penetrate the market significantly and will remain niche vehicles. The electric traction motor is just one component, along with the battery, gear drive, power electronics, etc. Successful integration of different components in an effort to improve overall performance is on the agenda of current R&D activities.

6.3 Rare earths in e-bikes

Electric bicycles (e-bikes) represent an additional end-use for NdFeB-based PSMs as they offer low weight and compact size, thus competing for the same rare earths with EVs and other high-tech applications. E-bikes integrate a small electric motor and rechargeable batteries to assist the rider in pedalling. In general, they are classified as bicycles, given their ability to be pedalled, distinguishing them from electric scooters and motorcycles. Most e-bikes use PSMs with an NdFeB magnet, either as hub motors (integrated in the front or rear wheel) or as mid-drive motors (near the bottom bracket). The amount of NdFeB material used per e-bike is estimated to be about one-fifth of that in an EV motor (around 0.3 kg to 0.35[29] kg NdFeB per e-bike [Roskill, 2015]). Since the NdFeB magnet may have to cope with temperatures up to 100 °C, the magnet is also likely to contain a low share of Dy. The e-bike market could impact the rare earth market since global e-bike sales are much higher compared to the current sales of electric vehicles. Figures show that around 40 million e-bikes were sold globally in 2013, with China being the biggest market, followed by Europe, Japan and the USA (Table 19) [INSG, 2014].

Table 19: Global e-bikes sales in 2013 [INSG, 2014]

Country	E-bikes sold
China	32 million
Europe	1.8 million
Japan	440 000
USA	185 000
Other	5.6 million
TOTAL	40.02 million

Although sales of e-bikes have slowed recently, the global e-bikes market is expected to grow at a CAGR (compound annual growth rate) of over 4 % from 2014 to 2019 [PRNewswire, 2015]. Experts believe that the European market potential is much higher, at around 3 million sales per year.

There are no effective alternatives to PSM available for e-bikes on a large production scale. Today’s low rare earth prices give no incentive to e-bike manufacturers to look for alternative solutions, which might result in efficiency losses or higher e-bike weight. This assumption is confirmed by industry experts. Several European manufacturers, e.g. Bosch, Brose Antriebstechnik, Derby Cycle and Accell Group, supply high-quality e-bikes to customers who demand high energy efficiency and light powertrains. Consequently, the competitiveness of these manufacturers is highly reliant on the production of premium products. Future shortages or high prices of rare earths might be tackled by the rapid development of alternative motor systems. The development time span for motors is estimated to be around two to five years, although motor designs derived from other application fields can be developed more quickly. This is evident in e-bike motors that have been derived mainly from automotive applications like electric power steering or windshield wiper motors.

[29] This range of magnet weights for e-bikes probably does not reflect recent developments in PSM design. Thus, the current magnet content might be lower. Precise data are not available due to confidentiality issues.

7. Potential impact of substitution on short-term demand for critical raw materials

Variations in global demand in the short term (2020) for all nine critical raw materials are estimated in this chapter, based on forecasted market scenarios of the three low-carbon technologies. The impact of substitution on this demand is analysed under certain penetration scenarios of available substitutes and material efficiency developments.

7.1 Transitions in lighting towards LED technology and implications for critical raw material demand

The global transition towards energy-efficient LED lighting for general lighting purposes as well as backlighting in displays will reduce the demand for terbium in lighting applications (this element is not needed for LED). In parallel, LED technology needs significantly lower amounts of europium and yttrium compared to fluorescent technologies [JRC, 2016a].

Unlike fluorescent lighting, LED relies on high-performing semiconductor materials, such as GaN or InGaN, to create the electroluminescent lighting effect. Until now there have been no effective substitutes for gallium and indium in semiconductors because other components do not meet the high performance of the actual systems. Germanium is no longer relevant for lighting applications as its substitution with gallium and indium in state-of-the-art LED is already far advanced.

In the display sector it is expected that fluorescent technology will be phased out by 2020 and LED-backlighting LCD technology will become the dominant technology in all applications (e.g. notebooks, computer monitors and televisions). Indium in ITO layers remains the most competitive and technically advanced transparent conductor used in LCD displays. It will continue to play a crucial role in display applications as no effective substitute has been discovered yet.

In this context and based on several assumptions[30], a possible variation in demand for critical raw materials in lighting and display applications has been estimated (Figure 26):

- **Rare earths.** As a result of substituting fluorescent technology with LED, the annual global demand for rare earths in lighting and displays is expected to decrease by 2020 as follows: from 30 % to 50 % less europium and yttrium, and from 50 % to 80 % less terbium (65 % on average);
- **Gallium.** The strong market penetration of LED will lead to a growing demand for gallium in 2020 by up to 150-340 % (245 % on average) compared to 2014. There are currently no available substitutes for gallium that might lower its demand in these applications;
- **Germanium.** This element is no longer required in lighting and display applications;
- **Indium.** The demand for indium in both display (as ITO) and LED technology (as InGaN semiconductor) applications is expected to increase from 30 % to 50 % by 2020. The rapid development of suitable substitutes, which might lower the demand for indium, is not expected over the next five years.

[30] A growth rate of 13 % for general lighting, backlighting and the displays sector was assumed between 2014 and 2020. The LED share of 70 % in general lighting and 100 % for backlighting in all display applications was considered for 2020. Data on the current demand for each critical raw material in lighting-related sectors was extracted from the annex of the European Commission's report on critical raw materials, referred to as 'Critical raw materials profiles' [EC, 2014b].

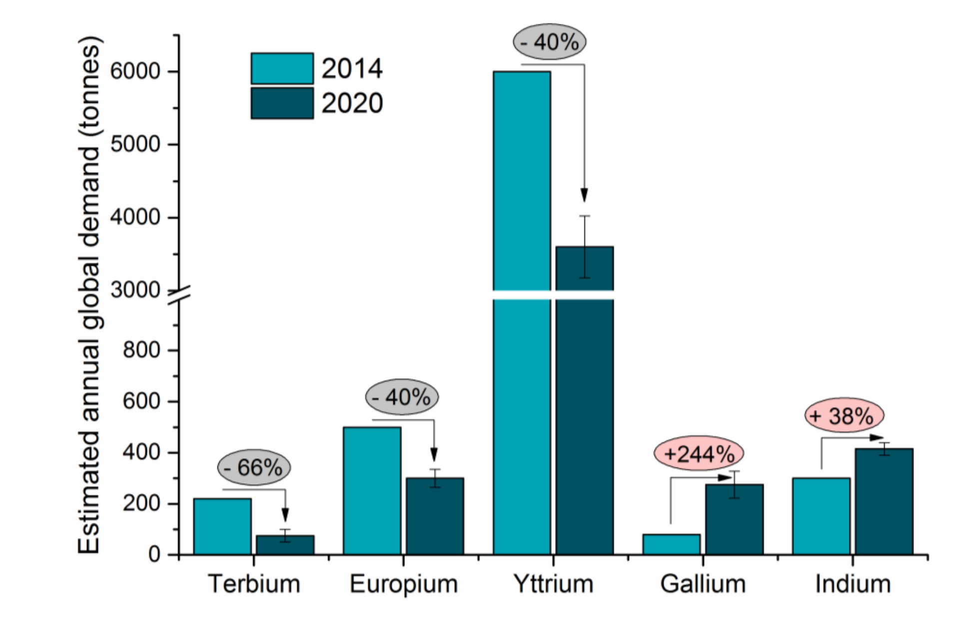

Figure 26: Estimation of annual global demand and average percentage change for critical raw materials in lighting and display applications from 2014 to 2020. Error bars represent the standard error calculated from the variation in minimum and maximum demand. As germanium is no longer relevant for lighting applications, it was omitted from this figure

The purpose of these estimations is to show the impact of lighting trends and implications for material demand in order to highlight the need for actions to ensure a secure access for CRM (in particular for gallium and indium) and prevent potential bottlenecks in their supply chain. Future demand for critical materials cannot be forecasted precisely due to the relatively high uncertainty of a large number of parameters, such as the success of different countries in adopting efficient lighting policies, the evolution of technology, economic conditions, the development of substitution, etc.

OLED represents the next-generation technology that would prevent the need for critical raw materials in lighting and display applications. The only exception here is indium in ITO, which might be substituted at some point as research activity is already ongoing in this field.

OLED technology is present on the market in high-end applications and small display devices. For general lighting, OLED is being proposed as flexible lighting panels by several companies (e.g. Phillips, Osram, LG, etc.). However, OLED technology is not expected to be able to compete in the short term with LED in the general lighting sector. A review of the technological trends in the lighting sector and the CRM involved is given in Figure 27.

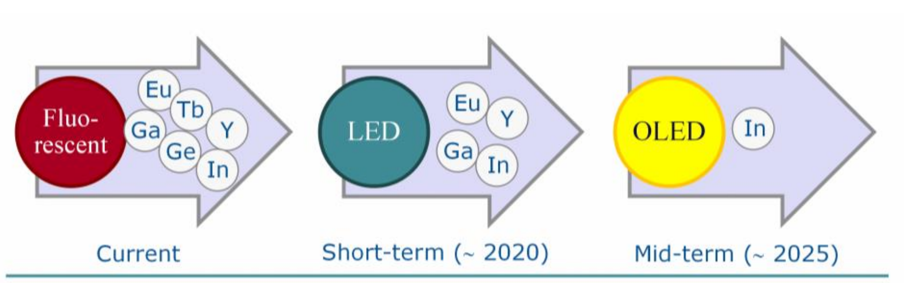

Figure 27: Possible megatrends in lighting applications and the CRM involved [JRC, 2016a]

7.2 Potential impact of substitution on the demand for rare earths in wind turbines

According to the Global Wind Energy Council, the new global annual installed wind capacity in 2015 was 63 GW, of which 12.8 GW was in the EU [GWEC, 2016]. The global wind power market is expected to grow, i.e. up to 65 GW in 2020 [IEA, 2015b].

The demand for NdFeB magnet for wind turbines largely depends on the market share of different turbine types. JRC estimated a global demand for permanent magnets (PM) of 3400-4000 tonnes for wind turbines in 2011 [JRC, 2013b]. In 2015, the annual installed capacity was 55 % higher than in 2011. Moreover, the market share of direct drive PMSG turbines also increased. In 2015, the estimated global market share was 19 % for DD-PMSG turbines by capacity and 4 % for mid- or high-speed technology [JRC, 2016b]. This brings the global demand in 2015 for NdFeB magnets in wind turbines to about 8000 tonnes. Based on the magnet composition[31], this amount corresponds to about 2000 tonnes of neodymium, 500 tonnes of praseodymium and 570 tonnes of dysprosium (the demand for terbium in wind turbines is estimated to be almost zero as it is interchangeable in magnets with the cheaper dysprosium). When compared to the primary production in 2014, it appears that about 9 % Nd, 8 % Pr and 40 % Dy of global production would have been requested for the global wind power sector.

Taking into account the global annual installed wind capacity forecast for 2020 (i.e. 65 GW) and the projected market share of 29 % DD-PMSG turbines and 12 % for mid- or high-speed technologies, the demand for NdFeB magnet for wind turbines will increase to about 13 200 tonnes. If magnet composition remains invariable, about 3180 tonnes neodymium, 800 tonnes praseodymium and 930 tonnes dysprosium would be requested by the global wind power sector in 2020. This is equivalent to 15 % Nd, 13 % Pr and up to 66 % Dy of their production in 2014. The production of REEs and downstream products (e.g. NdFeB magnets) will probably increase in the future.

A wide range of substitutes for PMSG-based turbines is already available, including methods to reduce the content of rare earths in permanent magnets (see chapter 5.2). It is difficult to predict precisely how much of these substitution options will be adopted in the future. Based on possible technological trends documented in this study and input from experts, two substitution scenarios have been developed along two parameters: material efficiency and component substitution (Table 20).

Table 20: Proposed substitution scenarios for rare earths in wind turbines by 2020

Substitution scenarios for rare earths in wind turbines	Year	Material efficiency*		Component substitution (%)
		Nd/Pr loading** in PM (%)	Dy loading in PM (%)	
Base line	2015	30	7	0
Reference case (no substitution)	2020	30	7	0
Substitution case A (high material efficiency + low component substitution)	2020	25	1	10
Substitution case B (low material efficiency + high component substitution)	2020	27	3	50

* based on inputs from experts and documented throughout this report
** Nd and Pr are found in the ratio 4:1

[31] The average rare earths loading in NdFeB is 30 % Nd/Pr (in the ratio 4:1) and 7 % Dy. Dysprosium share in the latest wind turbine designs might be lower following research efforts to improve material efficiency.

A strong improvement in material efficiency in NdFeB magnets by 2020 will incentivise the manufacturers to use PMSG technology in their turbine design. Conversely, if a large amount of rare earths is still needed in magnet composition, the adoption rate of rare earth-free generators might be higher. Therefore, *substitution case A* takes into account a high material efficiency but a low component substitution rate, and *substitution case B* considers a low degree of material efficiency but a high adoption rate of component substitution. The results indicate that the future demand for rare earths in the global wind power sector can be highly influenced by the type of substitution and its degree of adoption (Fig. 28).

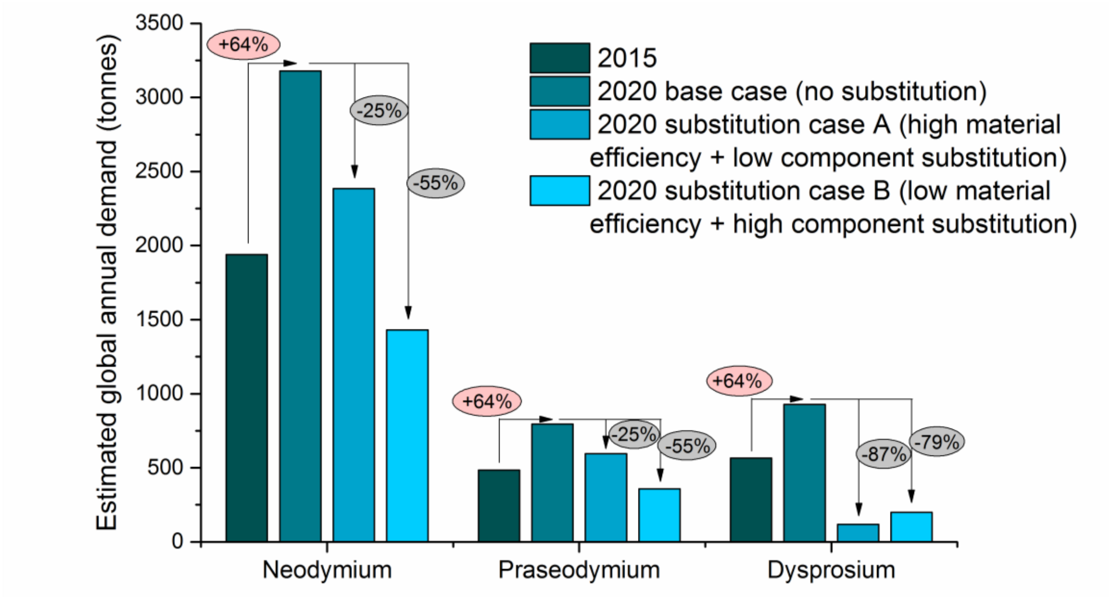

Figure 28: Estimation of global annual demand and average percentage change from 2015 to 2020 for Nd, Pr and Dy in wind turbines, based on several assumptions[32]. Terbium is not expected to be used in wind turbines

A significant improvement in the material efficiency in NdFeB magnets, such as reducing Nd/Pr content from 30 % down to 25 % and of Dy from 7 % down to 1 %, sustained by a modest component substitution (10 %), will be very beneficial for dysprosium. In this case (substitution case A), up to 90 % of dysprosium demand could be cut off by 2020 in comparison to a reference without substitution. If Dy-free PMSG is developed by wind manufacturers by 2020, the reduction in dysprosium demand will be even more significant, down to almost zero. A high rate of component substitution in DD-PMSG turbines, although with lower material efficiency (substitution case B), would be effective to reduce the demand for neodymium and praseodymium, bringing it to the 2015 level.

For the wind-power sector, a combination of the two substitution paths, material efficiency and component substitution, could represent an effective strategy towards mitigating another potential crisis in the supply of rare earths. While alternative turbine designs with either a limited amount of rare earths or none at all are already present on the wind market, additional efforts must be taken to achieve material efficiency targets and production of NdFeB with low rare earth content and at the large scale.

[32] The new global annual installed capacity in 2015 was 63 GW. This was considered as a market share of 19 % for DD-PMSG turbines (with 650 kg PM/MW) and 4 % for mid- or high-speed technology (with an average of 120 kg PM/MW). In 2020, it is estimated that the new global annual installed capacity will be 65 GW [IEA, 2015a]. This assumes a market share of 29 % DD-PMSG turbines and 12 % for mid- or high-speed technologies. The content of magnets per megawatt (MW) in both cases was kept identical, as for 2015.

7.3 Impact of substitution on short-term demand for rare earths in electric vehicles

Today, the estimated global demand (2015) for NdFeB magnets and the constituent rare earths – neodymium, praseodymium and dysprosium (or terbium) – in electric vehicle applications is moderate compared to total supply. If all the 550 000 EVs (BEV and PHEV) sold worldwide in 2015 had been produced with NdFeB magnets, up to 825 tonnes[33] of NdFeB would have been required. This amount represents just 1 % of global NdFeB production in 2015, which was estimated at about 79 000 tonnes. The highest demand comes from PHEV types as they constitute the majority and exclusively use NdFeB magnets in their electric traction motor. In terms of demand for rare earths, about 200 tonnes of neodymium, 50 tonnes of praseodymium and 60 tonnes of dysprosium would have been required[34] to satisfy the EV market in 2015. This is the equivalent of 1 % of Nd and Pr production in 2014, and about 4 % of Dy production in the same year. As is the case for wind turbines, the demand for terbium is considered negligible in EV applications. Currently, a much larger amount of rare earths is requested for traction motors in other electric road applications, such as hybrid electric vehicles (HEVs) and e-bikes [JRC, 2016c]. These sectors are expected to see also significant growth levels in the short term, thus competing with electric vehicle for the same materials.

To meet the global deployment target of 7.2 million EV sales in 2020, set by the International Energy Agency [IEA, 2013b], the annual demand for NdFeB magnets in the EV sector will have to increase by up to 14 times from 2015 to 2020 (on the assumption that all 7.2 million EVs will use rare earth-based PSM motors). This translates into a significant and rapid increase in the demand for rare earths. It is estimated that on average up to 2600 tonnes of neodymium, 715 tonnes of praseodymium and 900 tonnes of dysprosium would be requested by the EV market in 2020 in order to meet the deployment targets. In 2020, in terms of demand/production share, the EV sector will account for about 13 % Nd, 10 % Pr and up to 60 % Dy on the assumption that production is constant. It is evident that the highest pressure in terms of supply is expected from dysprosium.

Although there are currently no substitute magnets with similar properties to those of NdFeB, improving the material efficiency and development/adoption of alternative technologies may contribute to mitigating the challenge associated with the supply of rare earths. Developments in the material efficiency and technological status of rare earth-free motor designs were discussed in chapter 6.2. It remains unclear to what extent such substitution solutions could penetrate the EV market in the short term, as there are too many parameters and significant uncertainty which can influence this evolution. Two substitution scenarios are proposed in this report with scope to highlight the potential impact of substitution on reducing future demand for rare earths in the EV sector by 2020. These scenarios were developed based on the technological developments analysed in the previous sections, as well as input received from experts. Details about the parameters taken into considerations, i.e. material efficiency and component substitution, are presented in Table 21. *Substitution case A* takes into account increasing material efficiency by 2020, as pointed out by industry experts. In *substitution case B*, in addition to the material efficiency it is assumed that 30 % of PSM technology is substituted by rare earth-free products.

[33] The current demand for NdFeB for EVs was calculated assuming the average value of 1.5 kg NdFeB for all EV types. The quantity of NdFeB magnets may vary in the range of 1-2 kg PM, depending on an EV's motor power, car size, model, etc. A very precise estimation of the amount of NdFeB is difficult to obtain due to a very large pool of car models and power as well as limited data access.

[34] These amounts of rare earths take into account the following weight fractions in magnet composition: 30 % Nd/Pr (Nd:Pr ratio = 4:1) and 7.5 % Dy.

Table 21: Proposed substitution scenarios for rare earths in electric vehicles by 2020

Substitution scenarios for rare earths in electric vehicles	Year	Material efficiency*		Component substitution (%)
		Nd/Pr loading** in PM (%)	Dy loading in PM (%)	
Base line	2015	30	7.5	0
Reference case (no substitution)	2020	30	7.5	0
Substitution case A (better material efficiency)	2020	26.5	5	0
Substitution case B (better material efficiency + high component substitution)	2020	26.5	5	30

* based on inputs from experts and documented throughout this report
** Nd and Pr are found in the ratio 4:1

The results show that substitution could greatly impact future REE demand in EV applications (Figure 29).

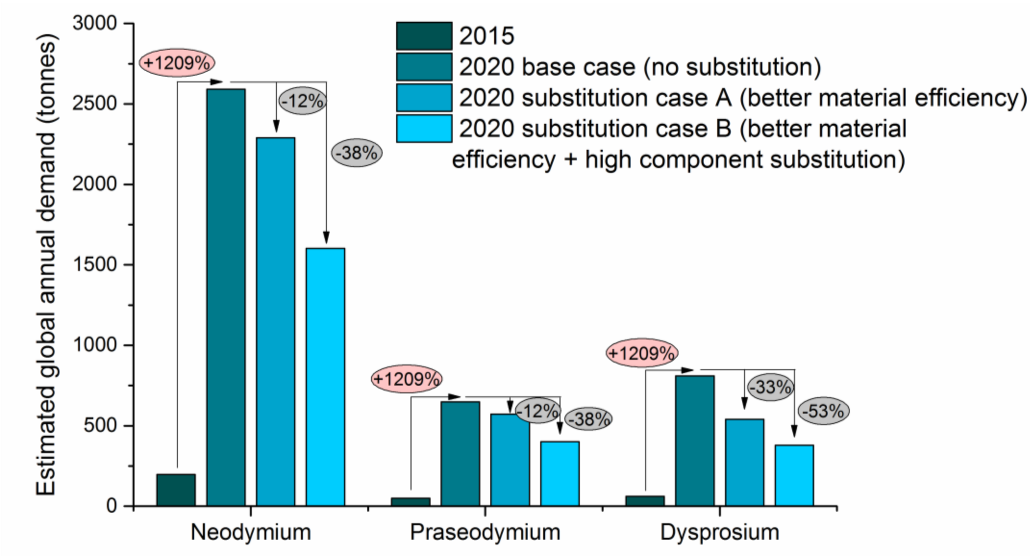

Figure 29: Estimation of global annual demand and average percentage change from 2015 to 2020 for Nd, Pr and Dy in electric vehicles. The demand for REEs in 2020 is calculated on the global deployment targets of 7.2 million EV sales [IEA, 2013b]

Compared to the 2020 reference case, a 12 % reduction in demand for Nd and Pr, and up to 33 % for Dy can be achieved by improving material efficiency, e.g. reducing rare earth loading from 30 % to 26.5 % for Nd/Pr and from 7.5 % to 5% for Dy. This reduction can be more significant if 30 % of the PSM is also replaced by REE-free alternatives. In this case (substitution case B), the demand can be 38 % less for Nd/Pr and about half for Dy, as regards the 2020 reference case without substitution. But even if the most ambitious substitution scenario B is achieved successfully, the demand for rare earth in the EV sector is expected to grow by eight times over the five-year period (2015-2020) in order to meet the global deployment targets set for 2020 by the IEA.

Such a significant growth in the demand for rare earths indicates a need for action to ensure a secure supply and/or the development of cost-effective and high-performance rare earth-free traction motors. This will enable the EU and other countries, which lack a domestic production of rare earths, to respond to concerns about disruption in the supply of REE as a potential barrier to the widespread adoption of electric vehicles.

8. Conclusions

In the view of the decarbonisation of the European energy system and the challenges associated with the future supply of critical raw materials, this study assesses the options for substituting CRM in lighting, wind turbines and electric vehicles. From the report it is evident that substitution is a relevant mitigating option which can alleviate the pressure on the supply of CRM in the short term (2020) by easing future demand. This is particularly valid when substitution is seen from the perspective of reducing the amount of CRM required either by better material efficiency or replacing the entire component.

Substitution of fluorescent lighting with more advanced LED technology will significantly reduce future demand for rare earths, although demand for other CRM (e.g. gallium and indium) will increase. Alternative rare earth-free turbines are available on the wind market, and ready to be adopted should prices of REE rise. The EV sector is at greater risk to potential disruptions in the supply of rare earths because of the lack of suitable substitutes, in particular for hybrid models.

Overall, the recommendation is that R&D projects focusing on developing high-performance materials and technologies that use limited amounts of CRM should be promoted. This approach might be more effective in reducing future demand for CRM than material substitution per se.

Several conclusions can be drawn regarding the feasibility of substitution and its implications for the demand for CRM in the three low-carbon energy technologies:

Lighting and display technologies

- For general lighting purposes, markets have started shifting from conventional technologies, including fluorescent lighting, towards LED technology. This transition is leading to a rapid decline in the demand for terbium (terbium is not needed as a phosphor in LED applications) and also drastically reducing the need for europium and yttrium compared to fluorescent technologies;
- LED technology makes use of gallium and indium, i.e. in InGaN semiconductors, to create the most efficient electroluminescent lighting. There are not yet available competitive substitutes for these elements;
- Germanium is no longer relevant for LED applications since gallium-based systems substitute it in LED technologies;
- OLED represents a possible substitute for LED technology, but more research is needed to improve the product efficiency and lifetime. It is expected that OLED will be widely used in general lighting applications after 2025;
- In OLED, the critical raw materials are completely substituted by organic compounds, with exception of indium in indium-tin oxide (ITO).
- In the display sector, LED-backlighted LCD technology will dominate the market for small and large-screen displays in the short term. Despite intense R&D activities, today ITO is still required as a transparent conductor in LED-backlighted displays because no substitution is available.

Wind turbines

- In recent years, the wind turbine market has been dominated by the traditional rare earth-free high-speed doubly-fed induction (DFIG) and squirrel-cage asynchronous generators, which have capacities between 2 and 5 MW. The future trend in wind power is towards large turbines of more than 5 MW. It is likely that the direct drive permanent magnet synchronous generator (DD-PMSG) will become the leading technology for large turbines, especially for offshore applications. DD-PMSG offers advantages in terms of efficiency and maintenance;
- Alternative technologies to large DD-PMSG have been developed by several manufacturers because of their concerns about the supply of rare earths. These alternatives either contain lower amounts of rare earths (e.g. low- and mid-speed PMSG technology) or are rare earth-free (e.g. DFIG and electrically excited synchronous generator - EESG). Overall, they provide good performance levels;

- For the long-term, new technologies such as high-temperature semiconductors (HTS) might lead to production of very large turbines (10 MW or more);
- Until now there has been no alternative to the NdFeB magnet in wind turbine applications. R&D efforts have resulted in reducing the content of dysprosium by up to 1 % in the recent PMSG turbines. Future turbine designs might not require any dysprosium or other HREE. For neodymium and praseodymium, there is an indication of rising material efficiency of up to 29 % by 2030, based on 2015 figures, but more research is needed to reach this target;
- Substitution has a high potential to reduce the future demand for rare earths in the wind power sector even in the short term. Although the global annual demand for rare earths in wind turbines is expected to increase more than two-fold in 2020, a strong substitution effort (e.g. adoption of high component substitution and better material efficiency) could bring it to the same level as that in 2015;
- Overall, it can be considered that no matter what the future market brings, the global wind industry is well prepared for potential disruptions in the supply of rare earths, thanks to the availability of substitutions at component level and improvements in material efficiency. However, the competitiveness of the European wind power sector might be more affected by potential REE shortages as the EU is leader in offshore wind, a sector where PMSG turbines containing rare earths have demonstrated several advantages.

Electric vehicles

- Currently, most electric vehicles use PM synchronous traction machines because of their ability to deliver light, compact and highly efficient motor designs;
- Rare earth-free alternative motors, such as the asynchronous machine (ASM) and the electrically excited synchronous machine (EESM) exist in the serial operation of a few battery electric vehicle (BEVs) models, for example in Tesla S and Daimler B-class models, and Renault Zoe, respectively. Since the plug-in electric vehicles (PHEV) have stricter requirements in terms of compact size and temperature stability, no rare earth-free motors are used in their serial production. In between of these approaches is an electric hybrid motor with a reduced rare earth content of 30 % to 50 %, e.g. used in the BMW i3 and BMW 7 series PHEV models;
- There are no alternative motor types for other related electric road applications, such as hybrid electric vehicles (HEVs) and e-bikes. These applications compete with EVs for the same PSM type;
- The most promising solutions in terms of component substitution are: ASM with high rpm, PSMs with low-cost magnets (e.g. ferrite or AlNiCo material) and switched reluctance motors (SRM). The timing for further developments and adoption to serial production depends to a very large extent on economic conditions (it is estimated that it takes about five years from the conceptual stage to serial production). Currently, because of the low prices and a readily available supply of rare earths there are no incentives to switch to rare earth-free motors;
- As in the case of wind turbines, fully substitution of rare earths in NdFeB magnets with non-critical elements providing a similar high-energy output is still not possible. It could be that such a solution will not be available in the near future either. However, material efficiency could improve as the result of intensive research. For example, the dysprosium loading in a permanent magnet for hybrid electric vehicles could be significantly reduced from 9 % to around 5 % by 2020 and later to 2.5 %. The quantity of neodymium and dysprosium needed to produce NdFeB magnet should also decrease in the near to mid-term;
- In view of a widespread adoption of EVs, the demand for rare earths will increase significantly in the future. The lack of component substitution for hybrid vehicles (PHEV and HEV) is a major challenge because these will continue to dominate the EV market. Substitution would only be able to partially mitigate a potential shortage in the supply of rare earths in EV applications. Therefore, the indication is that a policy for the integrated security of supply for REEs should also consider substitution alongside secure access and recycling as potential solutions.

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List of abbreviations and definitions

ASM	Asynchronous motor
BEV	Battery electric vehicle
CADC	Common Artemis Driving Cycle
CCFL	Cold cathode fluorescent lamp
CFL	Compact fluorescent lamp
CRI	Colour rendition index
CRM	Critical raw material
CRT	Cathode ray tube
DD	Direct drive
DFIG	Doubly-fed induction generator
EESG	Electrically excited synchronous generator
EESM	Electrically excited synchronous motor
EIP	European Innovation Partnership
EIT	European Institute of Innovation and Technology
ERECON	European Rare Earth Competency Network
EV	Electric vehicles
EWEA	European Wind Energy Association
FCEV	Fuel cell electric vehicle
FP7	Seventh Framework Programme for Research and Innovation
FPD	Flat panel display
GHG	Greenhouse gas
GW	Gigawatt
HEV	Hybrid electric vehicle
HREE	Heavy rare earth element
HTS	High temperature semiconductor
ICE	Internal combustion engine
IEA	International Energy Agency
ITO	Indium-tin-oxide
JRC	Joint Research Centre, a Directorate-General of the European Commission
KIC	Knowledge and Innovation Community
LCD	Liquid crystal display
LED	Light-emitting diode
LFL	Linear fluorescent lamp
LREE	Light rare earth element
MW	Megawatt
OLED	Organic light-emitting diode
PHEV	Plug-in electric vehicle
PM	Permanent magnet
PMSG	Permanent magnet synchronous generator
PSM	Permanent magnet synchronous motor
QD	Quantum dots
REE	Rare earth element
REEV	Range-extended electric vehicle
RMC	Raw Materials Commitments
RMI	Raw Materials Initiative
SIP-RM	Strategic Implementation Plan on Raw Materials
SRM	Synchronous reluctance motor
SSL	Solid state lighting
TWh	Terawatt hour
WEO	World Energy Outlook

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