CRM_InnoNet

Substitution of Critical Raw Materials

Roadmap for the Substitution of Critical Raw Materials in Electric Motors and Drives

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THE CRM_ROADMAP TEAM ALSO WISHES TO THANK THE LARGE NUMBER OF EXPERTS, WHO HAVE CONTRIBUTED TO DEVELOPING THIS ROADMAP DURING THE DIFFERENT PHASES OF THE WORK.

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Deliverable description

This document presents the roadmap for the substitution of critical raw materials in electric motors and drives.

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Abbreviations

AC	Alternating Current
AEV	All-Electric Vehicle
BLDC	Brushless Direct Current
CN	China
CRM	Critical Raw Material
DC	Direct Current
DD	Direct Drive
EHS	Environment, Health and Safety
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
FOB	Free On Board
HDD	Hard Disk Drive
HEV	Hybrid Electric Vehicle
H&EV	Hybrid and Electric vehicles (includes HEV, PHEV and AEV)
HPMSR	Hybrid Permanent Magnet excited and Synchronous Reluctance Machines
HPMSSR	Hybrid Permanent Magnet excited and Switched Synchronous Reluctance Machines
HREE	Heavy Rare Earth Elements
HTS	High Throughput Screening
IE	International Efficiency
IMPM	Inner Mounted Permanent Magnet excited
GHG	GreenHouse Gas
LED	Light Emitting Diode
LREE	Light Rare Earth Elements
MQ2	Hot-pressed isotropic NdFeB magnet
OLED	Organic Light Emitting Diode
PHEV	Plug-in Hybrid Electric Vehicle
PM	Permanent Magnet
PMDC	Permanent Magnet exited Direct Current
PMG	Permanent Magnet Generator
R&D	Research & Development
REE	Rare Earth Element
SCIM	Squirrel Cage Induction Motor
SMEs	Small and medium-sized enterprises
SMPM	Surface Mounted Permanent Magnet excited
SSD	Solid State Drive
SR	Synchronous Reluctance
SSR	Switched Synchronous Reluctance
TM	Transition Metal
USD	US Dollar
VR	Variable Reluctance
WRIM	Wound Rotor Induction Motor

Elements and compounds

AlNiCo	Aluminium-Nickel-Cobalt
Ce	Cerium
Co	Cobalt
Dy	Dysprosium
FeCo	Iron-Cobalt
FeN	Iron-Nitride
FeNi	Irin-Nickel
La	Lanthanum
LaCo	Lanthanum-Cobalt
MgB_2	Magnesium-Boron
MnBi	Manganese-Bismut
Nb	Niobium
NbTi	Niobium-Titanium
Nd	Neodymium
NdFeB	Neodymium-Iron-Boron
NdFeN	Neodymium-Iron-Nitride
PGM	Platinum group metals
Pr	Praseodymium
Sm	Samarium
SmCo	Samarium-Cobalt
SmFeN	Samarium-Iron-Nitride
Tb	Terbium
Y	Yttrium
YBCO	Yttrium-Barium-Copper-Oxide

INTRODUCTION

Material innovation has been one of the main drivers of human development since the origins, to the point that evolutionary phases are defined by the type of material that characterized them, i.e. the “bronze age” or “the iron age”. Fabrication and arts advanced when new materials became available, substituting the traditional ones or giving rise to hitherto unknown work processes and products. Apparently, the world is undergoing another one of these far-reaching transition processes, triggered by an increasing strain on energy and minerals resources.

Material substitution takes place naturally as part of industrial innovation processes, as seen, for example, by the substitution of metals and natural fibres by plastics during the petroleum age. Advances in material sciences and a much improved understanding of processes taking part on micro- and nanoscale have made it possible to develop completely new types of nano- and biomaterials in the laboratory, frequently mimicking efficient processes observed in nature.

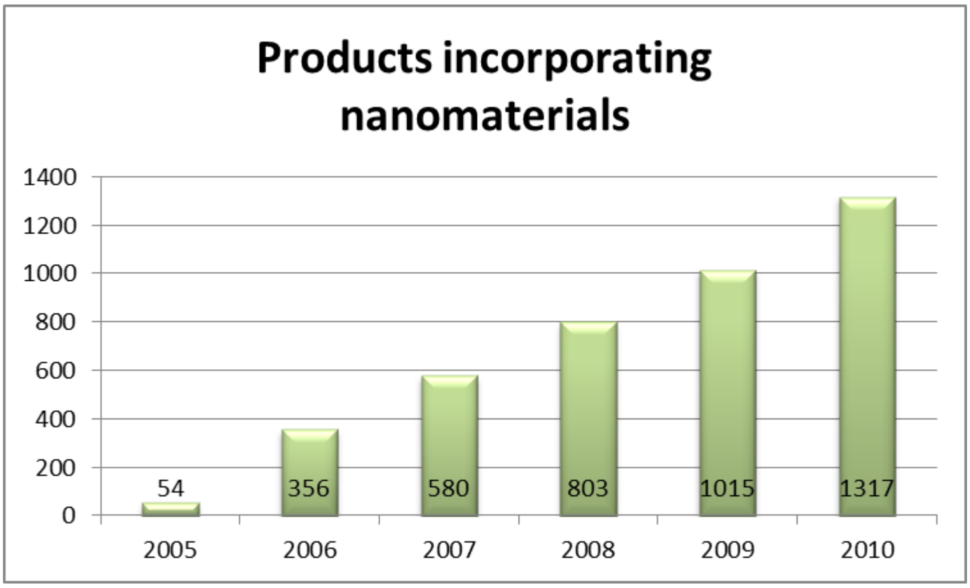

Figure 1 – Increase in products incorporating nanoparticles 2005 - 2010

Source: Own elaboration, based on Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars (2013)

However, innovation in the material fields has been driven during the last decades by the quest for new material functionalities (e.g. for improving energy efficiency) which often use “exotic” compounds, without considering changing material availabilities (e.g. supply risks due to mining oligopoly or speculation). Now, pressure increases to govern and steer these innovation processes towards substitution solutions in order to respond to severe social, economic and environmental concerns and to do so quickly and effectively. This transition process to a new materials age is complex, not always linear and its far-going implications for society and economy are difficult to grasp as changes are still under way.

Raw materials are fundamental to Europe’s economy, and they are essential for maintaining and improving our quality of life. The EU defines critical raw materials (CRMs) as those that combine high economic importance to the EU with a high risk associated with their supply. Twenty CRMs were identified as critical from an initial list of fifty-four candidate materials:

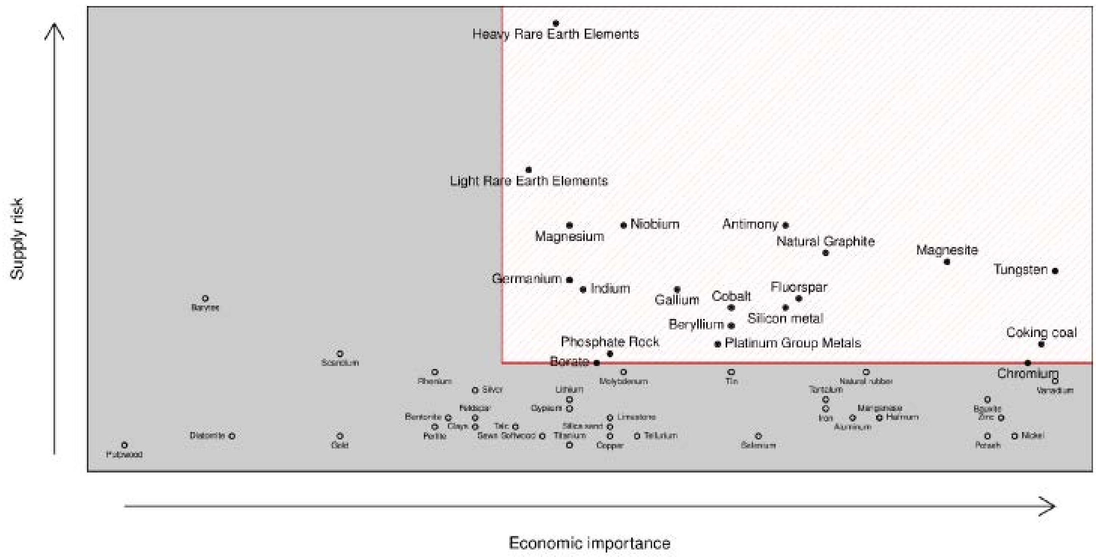

Figure 2 - EU List of Critical Materials

Source and note: EU Ad-hoc Working Group 2014; this list is an update of the list published in 2010 (see Annex A). It should be noted, however, that work in CRM_InnoNet, which started out in 2012, has focussed on the 14 materials originally identified, so that borates, chromium, coking coal, magnesite, phosphate rock and silicon metal have not been considered in the roadmapping work.

The EU does not have an economy-wide substitution strategy in place. It is the purpose of the CRM_InnoNet roadmaps to shed light on possible pathways to material substitution in products and technologies essential for providing energy, transport and communication services

In the context of the CRM_InnoNet project, five roadmaps for the substitution of CRMs have been elaborated in work package 5. They focus on applications, which have been considered to be of strategic importance for the European industry, as a result of the work carried out in work packages 3 and 4 of the project, as well as the prioritization exercise (work package 2). The roadmaps explain possible substitution strategies for CRMs in:

- Printed Circuit Boards and electronic components
- Permanent-magnet based applications such as electric drives and motors
- Batteries and accumulators
- High value alloys
- Photonics (also referred to as “high-end optics” in other CRM deliverables)

The CRM_InnoNet roadmaps consider four substitution strategies, which make it possible to reduce Europe’s demand for critical materials.

- “Substance for substance” is considered material substitution, for example nanodots replacing rare earths-based phosphors in lasers
- “Process for process” means a major change to the way a product is fabricated, for example metallurgical synthesis processes to replace CRM in alloys
- “Service for product” refers to business models, which help to extend the useful life of a product and the intensity of use, for example through leasing or sharing arrangements, and which can also help to increase recycling rates
- “New technologies for substance” refers to innovative technologies, for example OLED, which could gradually substitute others, which require a higher CRM content (LED).

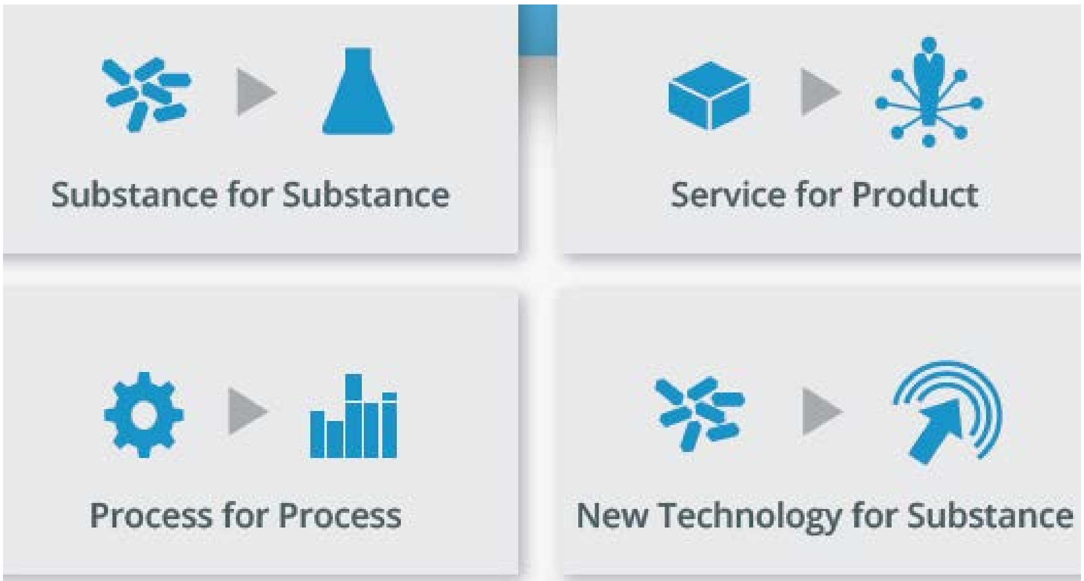

Figure 3 – Substitution strategies

1. METHODOLOGY

Roadmaps are appropriate tools for long-term planning, as they describe multi-level changes over time. This section describes, first, the theoretical framework for the research and innovation roadmaps, second, time frames for substitution strategies and, third, the work process applied to all five roadmaps.

The roadmapping exercise started out from the following premises:

1. Substitution of scarce materials may not only be driven by developments in a given industry sector, but also by growing demand in other economic sectors.

2. The substitution roadmaps must be aligned with the industry's own technology roadmaps in terms of time frames and material needs, supporting "natural" innovation processes. These innovation processes may respond to other drivers than material cost or scarcity, but still affect the material composition of a product (example: light-weight materials in the automotive sector leading to lower fuel consumption). Furthermore, we need to understand the implications of material substitution in the fabrication processes and evaluate the effects from a life-cycle perspective.

3. The roadmaps must also be in line with the foreseeable evolution of relevant research on potential substitute materials or other innovative solutions reducing overall demand for critical raw materials.

The main drivers that had to be considered in each roadmap are summarized in figure 4.

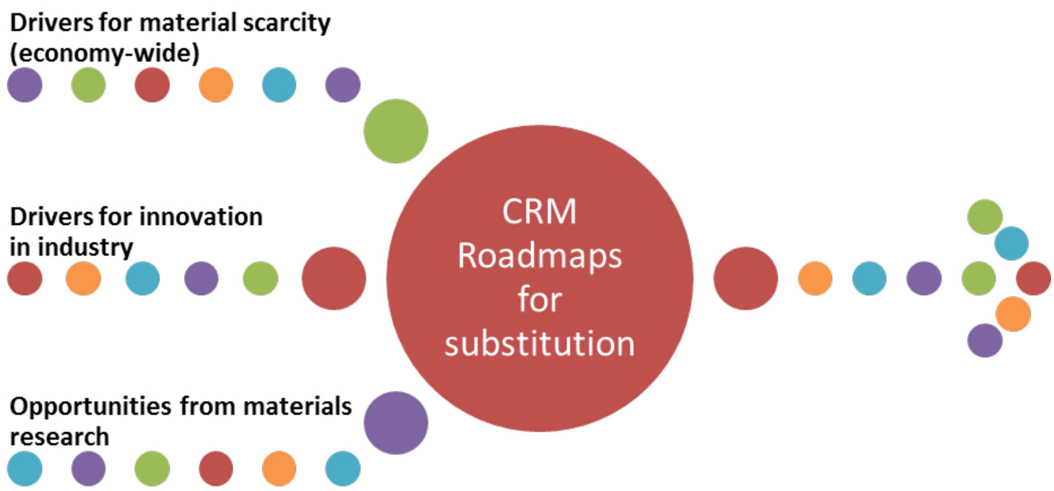

Figure 4 – Drivers for substitution

1.1 Theoretical framework for research and innovation roadmaps

The roadmapping methodology used by CRM_InnoNet is based on the theoretical framework of “Transition Theory” (Geels 2002 and 2004). Transition theory distinguishes between the “socio-technical regime”, which aligns the activities of major social groups to a predominant mainstream, the “niches” at the micro-level where radical novelties emerge, and the “landscape”, referring to the exogenous developments beyond direct impact of regime and niche actors. Figure 5 shows illustrative examples for the three levels of transition theory from the perspective of the incumbent, CRM-dependent regime.

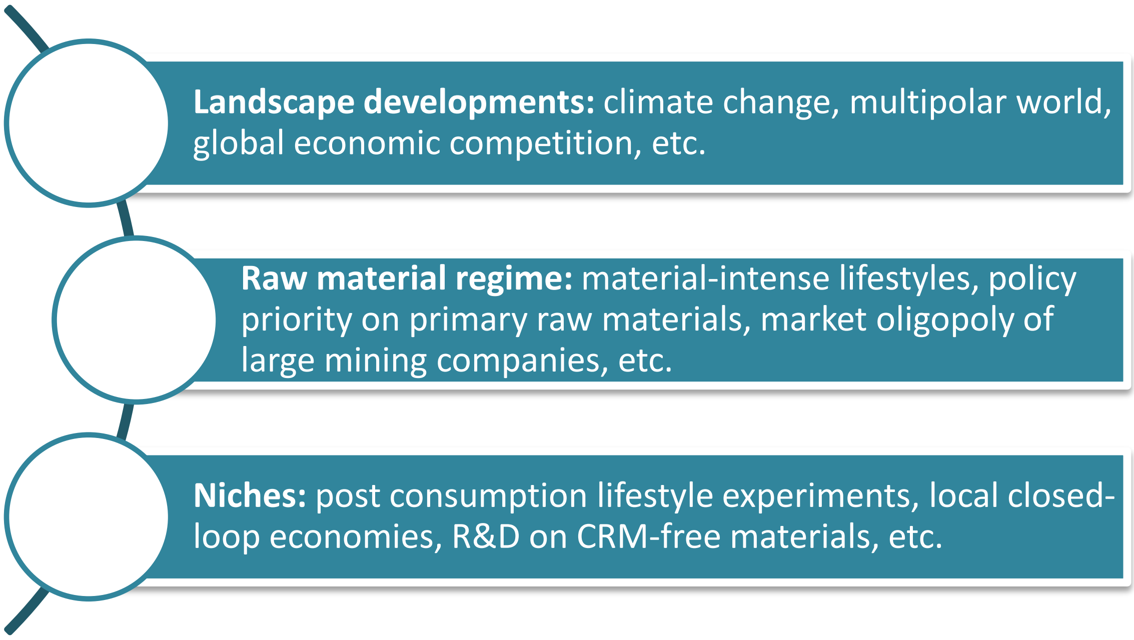

Figure 5 - The three levels of transition theory illustrated for the CRM-dependent socio-technical regime

The regime level is interpreted as the incumbent, CRM-dependent regime in Europe. It includes for example material-intensive lifestyles in Europe. The landscape is comprised by overarching context factors, such as the long-term trend towards a multipolar world, which cannot be directly influenced by developments on regime level in Europe. The niche level, in particular, includes R&D on CRM-free materials. Radical CRM-free concepts may provide the seed for systemic change of the CRM-dependent regime as landscape pressure increases.

Transition theory is one of the few theoretical approaches available to describe radical changes on system level, and has therefore been chosen as mental framework for the five Research and Innovation Roadmaps. For a more detailed discussion, please see

1.2 Time frames for substitution strategies

The horizon for the roadmap exercise was established at the outset of the project at 2030, since in this period presently emerging technologies can be taken to commercial maturity. Historical materials development timelines in the different markets, as shown in table 1, are taken into account to assess future material development timelines. Yet, new opportunities for accelerating material innovation are arising, thanks to new design and modelling techniques, and may speed up innovation processes.

Table 1 - Historical material development timelines in the aeronautics sector (according the General Electric)

Case	Activity	Time
Case I	Modification of an existing material for a critical structural component*	2-3 yr
Case II	Modification of an existing material for a critical structural component*	Up to 4 yr
Case III	New material within an existing alloy system • Includes time to define the chemistry and the processing details • Supply chain already exists	Up to 10 yr
Case IV	New material class with no prior application experience • Includes the time to develop design practices that fully exploit the performance of the new material class • Establish supply chain	20+ yr

Source and note: Schafrik/Walston 2008; the two similar case studies I and II gave different results in terms of timeframes.

Accelerating innovation in the materials field and shortening the time to market for new materials is a key element for substitution, according to industry sources and experts from academy participating in the CRM_InnoNet roadmapping exercise, as explained further in chapter 1.3.

1.3 Roadmapping process

Figure 5 shows the roadmapping process applied to all five roadmaps.

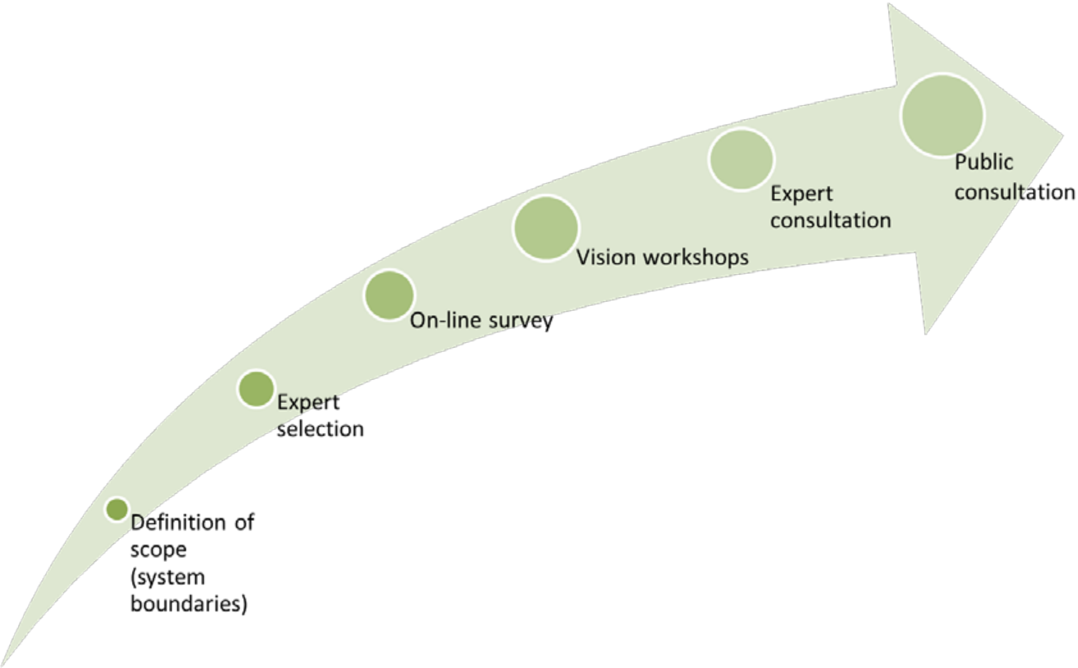

Figure 6 - CRM_InnoNet Process for Roadmap Elaboration

At first, the system boundaries are defined before entering the process of elaborating the roadmap (see Annex A). In a second step, specific expertise is drawn into the process to discuss the potential future courses of technologies and innovation strategies aiming to substitute critical raw materials. For this purpose, CRM_InnoNet drew on a long list of experts, using the extensive network created by the project, as well as the partner institutes' own contact lists to set up five groups of approximately fifteen experts for the first round of "Vision Workshops" (see Annex D for the expert group on substitution of CRM in electric motors and drives). The experts were invited to participate in a short on-line survey with Delphi-type questions on expected future developments for each of the priority applications (see Annex B) to prepare the discussions in the first round of Vision Workshops (see Annex C).

After collecting the expert opinions on substitution strategies during the Vision Workshops, a smaller group of project partners then drew up the actual roadmaps, adding time-lines and attributing responsibilities for the actions composing the research agenda for each priority application. The interim findings were then validated by a series of expert interviews and by public consultation.

By establishing the cause-effect relation and a logical sequence of actions, a strategic vision arises which can guide policy-making in the field of material substitution. The roadmaps also contributed to identifying priorities for policy and research action during the final phase of the project.

2 ROADMAP FOR SUBSTITUTING CRMS IN ELECTRIC MOTORS AND DRIVES

This section first describes the scope of the roadmap. In the second part it presents the roadmap, both as a table and explanatory text. The third part indicates potential game changers according to the transition theory framework.

2.1 Scope

The roadmap covers the levels of permanent magnet (PM) material, electric motors and drives (machines) and applications.

Permanent magnet materials

Permanent magnets have been developed to achieve higher energy densities and coercivity (Allcock 2014, Hart 2010). When exceeding a certain temperature, hardmagnetic materials lose a significant share of their magnetism irreversibly. Coercivity is the temperature-dependent ability of a magnetic material to resist demagnetization. Remanence is the magnetization left after an external magnetic field is removed. Progress in PM material performance is often illustrated by the development of their energy densities over time:

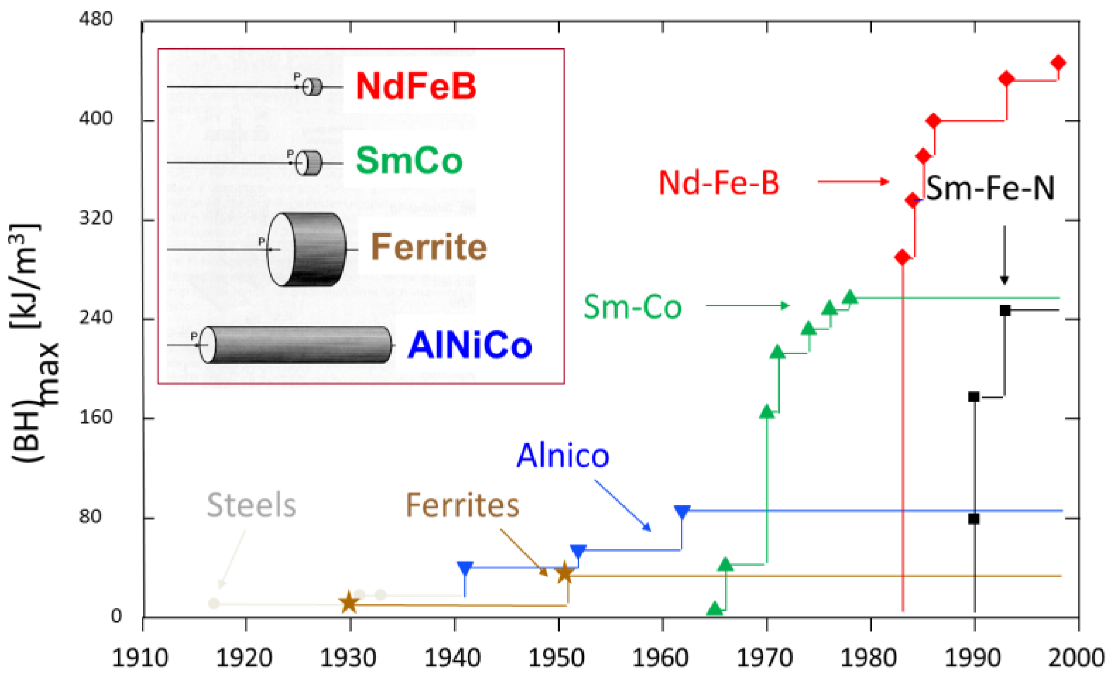

Figure 7 - Development of energy density in permanent magnets (TU Darmstadt 2015). Note: (BH)max – energy density of permanent magnets

Until 1970 energy density of permanent magnets has been very limited. Ferrites and Aluminium-Nickel-Cobalt (AlNiCo) PM achieved energy densities, measured by $(BH)_{max}$, far below 100 kJ/m^3. With the development of Samarium-Cobalt (SmCo) PM energy density increased to 250 kJ/m^3 in the 1970s. At the beginning of the 1980s

Neodymium-Iron-Boron (NdFeB) PM were developed which soon outperformed SmCo PM by reaching energy densities in excess of 400 kJ/m^3. Recently developed Samarium-Iron-Nitride (SmFeN) already achieve energy densities up to 240 kJ/m^3.

Ferrites are the least expensive but also among the weakest permanent magnets commercially available. They have good thermal stability between -40°C and 250°C. AlNiCo is available at low costs but has a very low coercivity. SmCo magnets have smaller energy densities than NdFeB magnets but better high-temperature stability (up to ~300°C). However, they are very costly. Today, NdFeB is the benchmark material for most commercial permanent magnet applications. New magnet materials using new alloys or processing techniques are explored to reach comparable properties to NdFeB PM-material at lower costs.

NdFeB PM-material uses mainly four critical raw materials (CRMs), all of which are Rare Earth Elements (REE):[1]

Table 2 – Critical raw materials used in permanent magnets

CRM	Characteristics
Neodymium	Key ingredient in $Nd_2Fe_{14}B$ magnet material (ca. 30 w.-%). $Nd_2Fe_{14}B$ has the highest energy density of all commercially available magnet materials (exceeding 400 kJ/m^3, theoretical limit 485 kJ/m^3)
Praseodymium	Neodymium can be substituted by Praseodymium up to a maximum of 25 % to increase the magnet's resistance to corrosion (at the cost of not too severe impacts on properties)
Dysprosium	Dopant in $Nd_2Fe_{14}B$ magnet material. Dysprosium-doping of $Nd_2Fe_{14}B$ increases the coercivity of $Nd_2Fe_{14}B$ magnet material (at the cost of a reduced remanence). In addition, Dysprosium increases the temperature stability of $Nd_2Fe_{14}B$ magnet material. Typical Dy-content in • HDD, CD, DVD, transducers, loudspeakers: 0 % • Magnetic refrigeration, MRI, sensors: 1,4 % • Gauges, hysteresis clutch, magnetic separation: 2,8 % • E-Bikes, energy storage, magnetic breaking, magnetically levitated transportation, motors/industrial/general auto, relays & switches, reprographics, torque-coupled drives, wind power generators: 4,2 % • Commercial and industrial generators, wave guides: 6,5 % • High-temperature motors & generators, hybrid & electric traction drives: 8,5-11 %
Terbium	Dopant in $Nd_2Fe_{14}B$ magnet material. Compared to Dysprosium-doping, Terbium-doping has a stronger influence on coercivity with a lesser impact on remanence.

[1] In addition, SmCo is used when temperature stability is vital, such as military satellite systems and small motors, sensors, automotive applications and actuators. The amounts of both critical Sm and critical Co (demand) are negligible in relation to total production figures (supply). Besides, superconducting NbTi alloy magnets require small amounts of critical Nb, and small quantities of critical Yttrium used in YBCO high temperature superconducting material. The Boron quantities in NdFeB are negligible in contrast to other uses of critical borates.

Sources and notes: Arnold Magnetic Technologies 2012, Constatinides et al. 2012, Kara et al. 2010, Komuro et al. 2010, Vakuumschmelze 2009; HDD – Hard Disk Drive, MRI – Magnetic Resonance Imaging

Neodymium and Praseodymium belong to the more abundant group of Light Rare Earth Elements (LREE), Dysprosium and Terbium to the less abundant and more expensive group of Heavy Rare Earth Elements (HREE). Neodymium and Praseodymium, and Dysprosium and Terbium can be used interchangeably to some degree. Currently, Praseodymium is more expensive per kg than Neodymium, and Terbium is more expensive per kg than Dysprosium. Consequently Dysprosium-doped $Nd_2Fe_{14}B$ PM material is the base case for substitution.[2] However, future price relation may change, so that for example Neodymium could be substituted by Praseodymium up to 25 %.

Electric machines

Electric machines include generators that turn mechanical energy into electrical energy and motors that turn electrical energy into mechanical energy. An electric machine consists of a rotor spinning in a magnetic field. The magnetic field may be provided by permanent magnets or by electric current flowing through coils (excitation).

Electromechanical drives are divided into constant-speed drives, servo drives and variable-speed drives. In a servo system actual information is continuously monitored and fed back to the motor control. In a variable speed drive the speed is changed over a wide range by initial parameter settings (Gieras 2006).

Figure 8 shows the use of PM in electric machines.[3]

[2] Other reasons for moving away from PM technologies might be bottlenecks further up in the supply chain and adverse environmental and health impacts of REE mining.
[3] The classification of electric machines has been modified in this roadmap with regard to the one originally used in the scoping document (see Annex A).

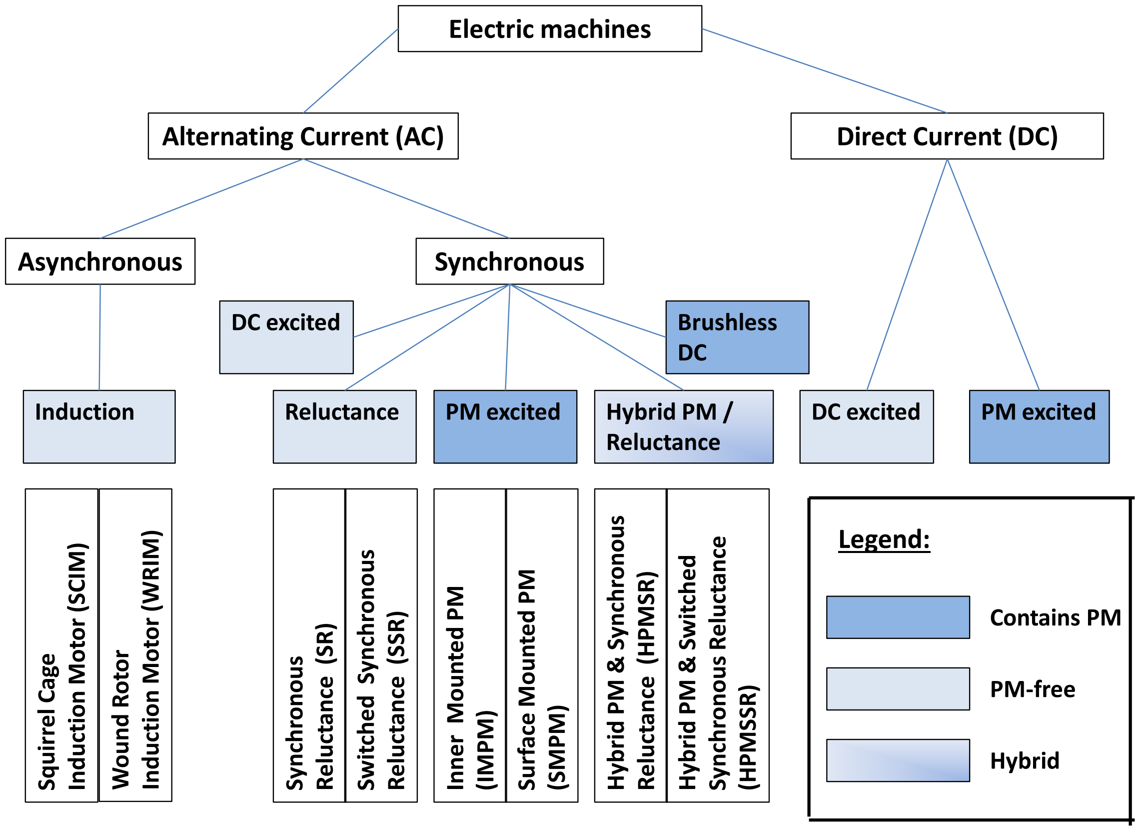

Figure 8 - Classification of electric machines and permanent magnet (PM) use (own compilation)

Electric machines are divided into alternating current (AC) and direct current (DC) machines. DC machines include self-excited DC machines and PM machines (PMDC). Modern generators with field coils are often self-excited, in which some of the power output from the rotor is used to power the field coils. PMDC machines are a relatively new technology.

AC machines fall into synchronous and asynchronous machines. An induction motor is an asynchronous AC motor, in which where power is transferred to the rotor by electromagnetic induction. The Squirrel Cage Induction Motors (SCIMs) have solid metal bars for induction, Wound Rotor Induction Motors (WRIM) many turns of insulated wire.

In a synchronous AC machine the rotation of the shaft is synchronized with the frequency of the supply current. Synchronous AC machines include DC-excited and PM-excited machines. Permanent magnets can be mounted to the rotor either surface mounted (SMPM) or interior mounted (IMPM). Brushless DC (BLDC) motors, also known as electronically commutated motors, are synchronous motors powered by a DC electric source, which produces an AC electric signal to drive the motor.[4] Reluctance electric motors induce non-permanent magnetic poles on the ferromagnetic

[4] In BLDC the armature current has a square waveform, while other synchronous motors are fed with sinusoidal waveforms.

rotor. While synchronous reluctance (SR) motors typically have 4-6 poles, a switched synchronous reluctance motor (SSR) has fewer poles. Both types of reluctance machines can also be combined with PM to hybrid machines (HPMSR and HPMSSR).

PMs are used for the provision of magnet fields in DC (PM excited) and in some synchronous AC machines (PM exited, BLDC and – to a reduced extent – in HPMSR and HPMSSR). Induction, reluctance as well as DC-excited DC and synchronous AC machines are PM free and can thus be considered substitution options for PM machines.

Permanent magnet motors are typically more efficient than other electric motors because they do not require current to be induced in rotor windings. The elimination of brushes for commutation also contributes to increased efficiency, reliability, and longevity. They can be used in applications with varied loads because they tend to have a more constant efficiency over a range of speeds instead of a high peak efficiency at a single speed (US Department of Energy 2013).

Applications

The roadmap covers three applications fields of PM using electric machines, all sharing a number of overarching drivers but each one also driven by specific developments:

1. Permanent Magnets for generators of wind turbines
2. Permanent Magnets for electric and hybrid vehicle traction motors
3. Permanent Magnets for general purpose motors

These three fields were chosen for several reasons. Wind turbines and hybrid & electric vehicle (H&EV) traction motors are emerging market segments for REE-based PMs that could drastically increase critical raw material dependency of the regime. The majority of offshore wind power manufacturers have chosen permanent magnet generators (PMGs) recently (JRC 2013) and car manufacturers frequently use PM-excited synchronous electric machines and BLDC (Chau and Li 2014).

Table 3 – Projections of future Dysprosium and Neodymium demand induced by direct drive wind turbines and hybrid & electric vehicles

	Material content			**Diffusion 2030**		**Material demand 2030**	
	Permanent Magnet	Nd content	Dy content	Total	PM-relevant share	Nd demand	Dy demand
Hybrid & electric vehicles	2,375 kg/vehicle	29,4 %	3,55 %	125 Mio. vehicles/a (conservative scenario)	13 % (H&EV)	11.300 t/a	1.370 t/a
DD Wind turbines	642 kg/MW	30,2 %	4,5 %	84.698 MW wind power/a (moderate scenario)	27,5 % (DD)	4.520 t/a	673 t/a

Sources and notes: Hoenderdaal et al. 2013, Greenpeace/GWEC 2014, TAB 2012; own projections based on average material contents and conservative/moderate scenarios; DD – Direct Drive; HEV - Hybrid and electric vehicle[5]

Rare Earth Element demand induced by H&EV and DD wind turbines is projected to contribute substantially to total REE demand. Dysprosium demand for both applications could surpass 2.000 t in 2030 compared to a total production of 1.600 t in 2010. Neodymium demand of some 16.000 t in 2030 would be a substantial additional contribution related to today's annual production of approximately 18.000 tons of Nd_2O_3 (Roskill Information Services 2012).

General purpose motors were chosen because it is the largest segment of permanent magnet use today, it has experienced strong growth over the past few years and short-term growth is expected to be substantial. This segment accounted for 25,5 % of REE-PM use in 2010 (Constantinides 2012). In summing up numerous PM uses, this field of general purpose motors may have significant future impacts on the total critical raw material dependency of the regime.

There are a number of application-specific requirements that justify the use of PM based solutions and that are thus prerequisites for substitution strategies:

1. Direct-drive (DD) synchronous generators in wind turbines do not require gear boxes, due to their ability to produce current at much lower rotation speeds. DD wind turbines need less maintenance than gearbox wind turbines which is particularly relevant in the case of offshore wind power generation. PM-based designs are preferred for such synchronous generators, because exciters and winding of the electromagnet is not required. This results in simpler rotor design and significant weight gains (about 25 % over induction systems). Still, such systems require higher investments than induction-based systems, which are expected to be amortised through performance and maintenance gains,

[5] The Wuppertal Institut (2014) calculates 201,5 kg Nd/MW and 1,5 kg Dy/MW for DD turbines. Middle-speed and high-speed gear drives have lower specific Nd and Dy contents.

especially under offshore conditions. Dysprosium is added to NdFeB PM material to reduce the demand for cooling and is a cost factor. Coating protects the PM material against corrosion.

2. Key requirements to electric machines in H&EV include high torque density and power density, high efficiency over wide torque and speed ranges, high reliability and robustness for vehicular environment, low acoustic noise, and reasonable cost. PM-based electric machines in hybrid and electric vehicles have certain advantages over induction and DC electric machines: lower weight, smaller size, along with greater reliability.[6] PM material and motor costs are relevant factors for drive train design, but other factors such as gasoline prices, government policies and battery technologies (costs and performance) are considered far more important factors for H&EV market uptake.
3. PM-less general purpose motors are often available for applications whenever mass and volume are not critical.[7] High-efficiency requirements to electric motors (IE4 standard) drive the uptake of PM-based general purpose motors. Small motors cover a power range from 120 W to 750 W, medium motors from 0,75 kW to 375 kW and large motors from 375 kW to 1000 kW (de Almeida 2014). Small motors are typically custom-made in large series to be integrated into specific machines or appliances (induction, shaded-pole, or DC/Universal motor types). Often they are required to be inexpensive. Medium motors are dominated by induction motors (around 85% market share) but other technologies are used, such as DC motors (declining market), PM motors and SR motors (increasing market). Large motors have customized design for very specific industrial applications and are often produced according to specific requirements of the purchaser.

The CRM Roadmaps consider four types of strategies for substituting critical materials, here illustrated for REE in PMs used for electric motors and drives:

A. “Substance for substance” is considered pure material substitution, e.g. substituting NdFeB by FeN PM material.
B. “Process for process” means a major change to the way a product is fabricated, e.g. grain-boundary engineering of PM material
C. “Service for product” refers to business models, which help to extend the useful life of a product or intensify product use, e.g. car-sharing of HEV
D. “New technologies for substance” refers to product-level innovation, e.g. PM-based synchronous electric motors substituted by reluctance motors.

The Electric Motors and Drives Roadmap focuses on three of these possible strategies, i.e. “Substance for substance”, “Process for process” and “New technologies for substance”. The “Service for product” strategy is considered to have rather small and indirect impact potentials on critical raw material demand induced by the major

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[6] In the car industry, electric motors are also widely used in seating, steering and the air condition system. The use of NdFeB magnets is limited to some 25+ motors.

[7] The PM material choice for a brushless motor (e.g. for air-conditioning compressor in a car) depends on space requirements in order to achieve a defined functionality: e.g. the performance of a 5 cm long NdFeB magnet is approximately equivalent to a 6 cm long SmCo magnet and to a 10 cm long ferrite-magnet.

application fields studied (wind turbines, electric & hybrid traction motors, general purpose motors).

2.2 The Roadmap

The roadmap is presented in three forms, first as a comprehensive text, second as a large table and third as a graph that extracts major R&D activities. For a quick overview directly refer to figure 9 on page 41.

The roadmap has a time line that covers the status quo in 2015, and projections for 2020, 2025 and 2030.

The roadmap displays developments for this timeline within five segments building upon the three transition-theory levels:

1. The landscape refers to the exogenous developments that may increase or relieve pressure on the REE-dependent raw material regime. It frames the conditions for all regime and niche actors.
2. Wind power: The regime level is approximated by the categories wind power market and policy & regulation in the wind power sector, while R&D on alternatives to REE-using PM material substitution in generators for wind turbines is classified as “niche innovation”.
3. Hybrid and Electric vehicles: The regime level is approximated by the categories H&EV market and policy & regulation in the H&EV sector, while R&D on alternatives to REE-using PM material in electric machines for H&EV is classified as “niche innovation”.
4. General purpose and other purpose motors and drives: No regime is singled out, as the diversity of applications is considered too high to allow for generalizations. However, the overarching landscape developments also apply to this segment. R&D on alternatives to REE-using PM material in general purpose motors is classified as “niche innovation”.
5. Cross-cutting material research: No regime is singled out, as the established material research regime is not included within the scope. However, the overarching landscape developments also apply to this segment. R&D on REE substitution in magnet material is classified as “niche innovation”.

Each roadmap segment contains several roadmap elements that develop over time. Roadmap elements interact with one or more other roadmap elements to different degrees. Some roadmap elements bear a game-changing potential, in particular those that are highly interconnected (see section 2.3).

Note: There is future uncertainty with regard to all developments. The roadmap fields for R&D indicate the earliest possible date of market introduction. Some developments are uncertain as such, i.e. it is unclear whether they will be introduced into the market at all. See figure 9 and the explanations in the caption.

2.2.1 Landscape developments

The landscape pressure on the REE-dependent regime in Europe is mainly shaped by developments in three realms: global REE markets (supply, demand, prices), global energy framework conditions and global patterns of value creation.

The situation in 2015

A global multipolar world is emerging that is characterised by stiff competition for value creation. The markets for electric motors and drives, converting electrical into mechanical energy or vice versa, are driven by energy markets and regulation. On a global scale, there are large differences in regional energy prices and different speeds of adoption to IE standards, the EU currently prescribing IE 2 standard conformity. The drive for greater energy efficiency has led to the strong market uptake of PM technology in a wide range of sectors, so that permanent magnets presently represent 20% of the demand of REEs by end-use (Brumme 2011).

In 2015 more than 90 % of REE raw material supply originates from China, while several new projects outside of China are being developed. REE mining and processing countries are striving to relocate value chains closer to their REE raw material sources. In Europe, only Vaccuumschmelze, Magnetfabrik Bonn, Magnetfabrik Schramburg and Magneti Ljubljana produce NdFeB magnets (Allcock 2014). UK-based Less Common Metals (LCM), a 100 % subsidiary of Great Western Minerals Group, also produce NdFeB magnet material. Supposedly, LCM will be the only European firm in the near future that is able to reduce REO to REE metals. The demand for REE-containing PM in electric motors and drives is mainly driven by the industrial, automotive (general), HDD/CD/DVD-drives and e-bike sectors. Prices for Nd and Pr were 83-87 USD/kg and 150-155 USD/kg, for Dy and Tb they were 470-630 USD/kg and 870-920 USD/kg respectively[8].

All in all, substitution pressure in 2015 is moderate. It stimulates a variety of R&D substitution strategies.

Near-term developments 2020

The Rare Earth Oxide production is expected to grow from 110 kt in 2014 to 200 kt in 2020 (USGS 2015, Lazenby 2014). The EU pursues the target to reduce its dependence on REE in permanent magnets imported from China to 70%. By 2020 new REE mining projects outside China will have matured and run at full performance (Lynas, Molycorp). It is expected that demand for REE-containing PM in wind turbines and H&EV will increase and add significantly to the demand for the established sectors.[9] All in all, REE prices are expected to remain stable due to large stockpile resources in Mongolia and new REE mining projects that compensate for moderate demand increase.

[8] All prices according to Metalpages (2015) for metal, 99% min, FOB (CN), July – December 2014.

[9] industry increasing, automotive stable, HDD decrease by substitution through solid state drives SSD, e-bikes increasing, residential air conditioning (fans, compressors) with robust growth, unclear classification of elevators (megacity markets)

Other current trends are likely to continue, such as electricity price increases providing incentives for energy efficiency, the adoption of IE3 efficiency standards in the EU, the electrification of the transportation sector (cars, naval, public transport fleets, etc.), the expansion of renewable energies (wind power, solar energy, biofuels, etc.) and the intensifying global competition between regions to locate manufacturing industries.

Mid-term developments 2025

Mid-term developments of REE markets are assumed to be more uncertain, as a variety of more thoroughly changing, counter- and interacting trends will shape the picture.

The outcomes of the global competition race for key industries such as automotive and wind energy is very uncertain.[10] New players might emerge.

There will be increasing pressure to transform energy supply and demand systems fundamentally. Technical requirements to PM material used in key sectors are likely to increase due to (efficiency) legislation and market demands. These requirements may boost REE demand for PMs or system innovation may provide REE-independent alternatives. On the supply-side, the HREE-dependency on China is likely to continue, while the LRRE-dependency is likely to be reduced by new projects. While REE separation methods with less impact on water and soil are developed, subsidy structures and enforcement of EHS standards are uncertain. Price trends for REE in 2025 are very uncertain due to unknown future supply-demand constellations.

All in all, pressure to substitute HREE will have increased by 2025 thus stimulating in particular R&D on direct HREE substitution and indirectly on full REE substitution. The trade-off between energy efficiency and REE raw material scarcity might intensify if system innovation does not provide REE-independent alternatives by then.

Long-term developments 2030

The road to 2030 might lead to the commercial development of new REE resources such as subsea resources (Japan) and Bauxite red muds (Jamaica). The EU could build upon own REE resources e.g. from Kvanefjeld (Greenland). These sources will only be developed if REE demand soars and REE prices remain at a high level.

Lower energy intensity in the economy is aimed at implying shifting mobility patterns, shifting energy supply and demand structures and management. The increasing pressure to develop system solutions could foster REE-substitution at system level.

Key uncertainties of 2025 such as REE price trends and the outcome of the global competition race for key industries persist.

All in all, system innovation is a bifurcation point for REE demand. REE may play a major role in these new system solutions or not. Both developments could have drastic impacts on REE supply and demand.

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[10] Standardization of HEV motors might stimulate industry relocalisation and concentration (e.g. to China) and raise trade levels.

2.2.2 Wind power

The situation in 2015

Wind turbines with gearbox technology (without permanent magnets) are available and make up the majority of globally produced wind turbines in 2015. The latest generation of offshore wind power technologies is highly dependent on permanent magnets. DD generators with 5-8 MW (each contains 3 and more tons of PM) are more compact, lighter and easier to maintain, which is a key factor for design in the case of offshore wind power. Hybrid gearbox/direct drive systems are available at the market, too. In addition, wind turbines employ some general purpose motors.[11]

The global market share of DD wind turbines is estimated to some 28 %, roughly 18 % of total wind turbines are DD using PMs (Navigant 2014). Gear drive wind turbines may also contain PM, although with lower content (Wuppertal Institut 2014). The EU pursues its deployment target of 11,4 GW/a onshore and 3,1 GW/a offshore.

Advanced design tools and standards for offshore turbines are available in 2015. The fraction of total wind turbine cost associated with PM is relevant, but marginal in Life Cycle Costing considerations. Substitution strategies target PM material as a whole or Dysprosium in NdFeB. The Dysprosium amount used in DD generators is typically limited to some 2-4 %. Boulder Wind Power's patented wind turbine technology should have allowed for the use of permanent magnets that do not require dysprosium,[12] but the project has been stopped.

Research for the substitution of PM by superconducting technology for 10 MW generators is at an early stage. GE studies NbTi, AMSC investigates YBCO. With these High Temperature Superconductors critical raw material demand could be reduced from 6 tons to 10 kilograms. Another approach is pursued by Advanced Magnet Lab European Consortia, including Tecnalia. AML tests field coils made with MgB_2 tapes at cryogenic temperatures instead of a High Temperature Superconductor (Superconducting, reliable, lightweight, and more powerful offshore wind turbine).

Near-term developments 2020

On a global scale, wind energy markets are expected to increase. The relative market share of offshore grows at the expense of onshore wind power. The EU has an increased deployment target of 17,8 GW/a onshore and 6,9 GW/a offshore. Offshore wind power will be provided mostly by 6-8 MW direct drive turbines (each containing 200-600 kg PM/MW). Others (e.g. Wuppertal Institut 2014) expect technology mixes both onshore and offshore.

R&D is carried out to optimise REE content in PM for electric generators and performance of wind power generators as a whole.

[11] Cf. The project „Windenergieanlagen ohne SEE - PitchER“ aims at the development of a magnetless drive for a pitcher (used to direct the rotor). The amounts of magnet material used for pitcher drives are low compared to DD PM used in the generator.

[12] Boulder Wind Power Dy-free PM for wind turbines (2011): http://www.molycorp.com/molycorp-invests-in-groundbreaking-wind-energy-technology-company/

By 2020 demonstrators for superconducting technology in very large offshore turbines (10 MW) might be available.

Mid-term developments 2025

Growth of global wind energy markets is expected to continue. Estimated market shares of REE-containing wind turbines vary considerably from 15-75 % for onshore and 25-75 % for offshore (US Department of Energy 2011) to 25-30 % for direct drives (Hoenderdaal et al. 2013). The EU target for deployment of wind energy is almost equal for onshore (13,1 GW/a) and offshore (10,5 GW/a).

Wind power industry is likely to be able to deliver superconducting technology for very large offshore turbines (10 MW). Direct drive wind turbines using superconducting material are expected to perform better than the PM using ones.

Long-term developments 2030

Globally, growth of annual onshore wind energy installations is likely to lose its pace as suitable sites are already sufficiently equipped. However, offshore wind energy installations are taking off and expected to yield 20 % of total installations by 2035 (IEA 2014). The EU's deployment target for offshore wind energy amounting to 13,7 GW/a outnumbers the onshore target of 10 GW/a.

Wind power industry produces superconducting technology for very large offshore turbines (10MW). Superconducting wind turbines are likely to achieve performance characteristics suitable for offshore wind parks between 2025 and 2030 (Public Consultation 1). In scaling up production, manufacturing processes will be optimised.

At the end of this period, wind producers are supposed to deploy a new generation of large offshore wind turbines (10 MW and beyond), for which high-temperature superconducting (HTS) materials are available. These HTS may also contain REE, although in drastically reduced amounts (Wuppertal Institut 2014). In the case of deployment target realisation REE-demand from this segment may collapse in the case of superconducting machines. REE-content minimization strategies will be very relevant if the deployment of superconducting large off-shore turbines takes longer than expected, due to technical problems or unfavourable trends in the energy market.

2.2.3 Hybrid and electric vehicles

The situation in 2015

Today, the market for H&EV is a comparatively small demand sector for REE-containing PM material. The market share of H&EV in all vehicles sales is negligible. Early adopters of HEV belong to the LOHAS segment (Lifestyle on Health and Sustainability), appreciate the high-torque drive of H&EV, represent an organisation's CSR strategy or can be due to a procurement strategy. In California and other regions, Urban Air Quality standards are a driver for H&EV.

The automotive industry is sensitive to weight and space restrictions with regard to traction motors and general purpose motors.[13] DC machines have been widely used in electric vehicles for traction, PMDCs having a higher power density and higher efficiency than separately excited DC machines. DC machines suffer from commutators causing torque ripples and limiting motor speed, from brushes causing friction and radio-frequency interference and maintenance requirements. Induction machines are a mature technology at comparatively low-costs, it is robust and maintenance free, but they are considered less efficient than PM synchronous or PM brushless machines. Switches reluctance machines have potential for H&EV because their construction is simple, manufacturing costs are low and torque-speed characteristics are outstanding, however their power density and problems to control non-linearity and acoustic noise have limited their application in H&EV. PM synchronous machines and PM brushless machines are attractive for use in H&EV due to high power density (compact and lighter design), high efficiency, easy heat dissipation and increased rotor acceleration. Drawbacks are high PM costs and uncontrollable PM fluxes.

Table 4 – Electric machines used in H&EV

Machine Type	**Car model**
Direct Current (DC)	Citroen Berlingo Electrique, Fiat Panda Elettra, Reva G-Wiz DC
Switched reluctance (AC)	Chloride Lucas, Holden ECOmmodore
Induction (AC)	BMW Mini E, Fiat Seicento Electra, Ford E-KA, GM Chevy Volt, GM EV1, Imperia GP, Reva G-Wiz I, Tesla Roader, ZF Friedrichshafen
PM synchronous (AC)	BYD e6, Citroen C-Zero, Ford Escape Hybrid, Ford Fusion Hybrid, Honda Accord Plug-in, Mitsubishi i-MiEV, Nissan Leaf, Peugeot iOn, Toyota Prius
PM Brushless DC (AC)	Honda Civic Hybrid, Smart Fortwo
DC excited synchronous (AC)	Renault Fluence Z.E., Renault Kangoo Z.E.
HPMSR (AC)	BMW i3

Sources and note: own compilation based on company information by BMW, Fiat, Ford, Honda and Renault, VDI Nachrichten 2013, Chau and Li 2014; AC – alternating current, DC – direct current, PM – permanent magnet, HPMSR - Hybrid Permanent Magnet excited and Synchronous Reluctance Machines

PM synchronous and PM brushless are often first choice electric machines for middle class cars. The first generation of hybrid vehicles were split path vehicles. The Toyota Prius consists of several electric machines, in particular an electric motor and an electric generator and an Electric Variable Transmission system. Permanent magnets in its electric machines are interior mounted (IMPM). Small cars often use DC and induction motors. The Renault Fluence Z.E. has a wound rotor synchronous motor

[13] NIDEC SR Drives develops electrical motors of ancillary units for mobile machines (tractors, construction machines) funded by the German Federal Ministry of Education and Research under the program "Kommune Innovativ".

without PM (DC excited), which is advertised of being 10 % more efficient than the PM containing alternative (Renault 2014). ZF Friedrichshafen has developed an electric drive for small vehicles (up to 1.250 kg weight), that is based on an asynchronous, REE-free motor with high rotational speeds (21.000 rotations per minute) (VDI Nachrichten 2013). In the BMW i3 a hybrid synchronous/reluctance motor with reduced REE content moves the vehicle. A large company claims that PM-free electric motors already achieve performance characteristics suitable for the automotive mass market (Public Consultation 2). However, not all automotive market segments are reached.

The automotive industry is researching a great variety of solutions, which do not require rare earths or work with lower quantities of Nd and Dy. R&D activities of the large vehicle manufacturers are closed to the public with the exception of several publicly funded projects. Alternative technologies are also being developed by smaller innovative companies. Chau and Li (2014) count Stator-PM machines, with PMs located in the stator, and Variable Reluctance (VR) PM machines, for low-speed high-torque direct drive applications, among the advanced PM machines for H&EV. Maturity levels range from low (Vernier PM as a particular VR PM machine) to high (Doubly Salient PM as a particular Stator-PM machine.

Current R&D activities of the industry include in-wheel electric drive systems for cars with REE-content reduced by 30 % (Protean Electric, USA, i.V.m. FAW-Volkswagen Automotive Company and Michelin Active Wheel), advanced reluctance motors – REE-Free SRM Switched Reluctance Motors, Variable Reluctance Synchronous and DC-Excited Flux-switching motors – (ARMEVA, PunchPowertrain, HEVT) and brushless PM machine enabling low coercivity PM (AlNiCo, FeCoW) with performance characteristics of NdFeB PMs (UQM Technologies with ORNL, patent granted in January 2015).

At the PM-level there is material research specifically for the use in electric traction motors for Ce-TM (transition metal) magnet (AMES Laboratory and General Electric, ARPA project) and hardmagnetic ferrites (Motorbrain project). Such new material research in the context of electric traction motors is related to the design of new motor topologies. In particular, there is R&D on the new design of motor topology for synchronous machines to reduce temperature stress of PM. This allows for a reduction of Dysprosium in PM material.

Some manufacturers reconsider motor topologies fundamentally and openly explore new configurations (GE Global Research and General Motors, some magnet-free, some REE-free).

The technical readiness levels of these activities vary. The in-wheel electric drive is available for light-duty vehicles but still needs to be developed for passenger cars, advanced reluctance-motors and brushless PM machines enabling low coercivity PM are under development, the Ce-TM and hardmagnetic ferrite based motors still involve basic material research. Technical readiness levels of motor topology explorations can hardly be assessed as the concrete development directions are usually not made public. According to a large car manufacturer, substitution barriers often come from the supplier of the technologies (Public Consultation 2).

Near-term developments 2020

Aggregate national deployment goals suggest 5,9 million H&EV in stock by 2020. This would require a substantial acceleration of annual H&EV sales (200,000 H&EV sold in 2012). There will be an increasing market uptake of HEV, PHEV and AEV in the total vehicle market, also driven by the increasing pressure to enforce air quality standards in megacities and emerging air pollution hot spots, and fuel efficiency standards (e.g. the EU prescribing . 90 g/CO_2 per km by 2020). The pure battery electric vehicle (AEV) is likely to remain unpopular unless there is a breakthrough in battery technology (specific energy, cycle life, costs). Hence, HEV and PHEV will make up for the largest share of this market. There is no market forecast available for the different traction motor concepts. PM-based traction motors require 1-2 kg PM material per vehicle.

The various R&D lines mentioned above are likely to continue by 2020. In-wheel drive solutions might be developed also for passenger cars, research concepts may reach the demonstrator case (e.g. Punch Power Test vehicle, Brushless PM machine with low coercivity PM material). Whether these R&D lines will be ceased or succeed as innovations is highly uncertain. Vehicle manufacturers may reorient their strategies in the light of moderate substitution pressure. More likely is a successful redimensioning of the required Dy-content by systemic optimisation of parameters (temperature profile, rotation, space, price, useful life, etc.) and subsequent market introduction. This strategy clearly responds to the high prices of HREE and potential future bottlenecks without requiring time-consuming, completely new concepts.

Mid-term to long-term developments 2025 / 2030

Hybrid and electric mobility could become the dominant technology for vehicles from 2025 on only if much stricter emission standards are enforced in key vehicle markets such as China, North America and Europe. According to the International Energy Agency, electric drives are expected to dominate the world market by 2030.

The US fuel efficiency standard 70 g/CO_2 per km in 2025 can only be achieved by hybrids from today's perspective. This will stimulate the market uptake of H&EV significantly. The H&EV market is likely to be dominated by hybrid and plug-in hybrid electric vehicles.[14] By 2025 it is estimated that 90-100 % of annual sales of H&EV will use PM-based traction motors.

Market introduction of the motor-level R&D activities dating back to 2015 could be envisaged for 2025 (in-wheel motors, advanced reluctance motors, brushless PM machine enabling low coercivity PM) – provided that manufacturers keep their R&D track and that substitution pressure for REE remains high and is not solved at the material level.

[14] HEV: 4,2-19,1 Mio., PHEV: 0,0022-13,22 Mio., AEV: 0,0022-4,56 Mio.

2.2.4 General purpose motors

The situation in 2015

There are many industrial applications for general purpose motors using PM material (elevators, servo motors, conventional vehicles, pumps, fans, etc.) whose consumption in the coming years will remain very relevant. PM-less motors are often available for applications whenever mass and volume are not critical.

In the medium motor range, the DC motor market is expected to decline further. Induction motors fed by Variable Speed Drives can have a dynamic performance, cost less and require less maintenance. Permanent Magnet DC Motors are often customized (de Almeida 2014).

Market leaders such as ABB and Hitachi reacted quickly to the REE price developments and now offer a magnet-free synchronous reluctance motor and a REE-free PM synchronous motor, respectively, with high efficiency levels for a wide range of applications (IE4 performance). Also smaller motor producers and users are attracted by the idea of a PM-free alternative to reduce dependence on permanent magnets, but face greater difficulties in implementing these solutions.

Future developments 2020-2030

In the case of industrial motors, for which the quest for high-efficiency (IE4 standard) is decisive, the demand for PM will remain high, since this solution combines high efficiency with compactness. In addition, PMs allow reducing the amount of other materials such as copper, aluminium and steel. This trend, combined with additional uses of PMs in other applications, such as consumer electronics or magnetic cooling, are likely to keep demand growing.

General purpose motor manufacturers are continuously pursuing incremental innovations, which permit to reduce PM content. Among the key measures are improved motor management, modifications of the winding layout and mechanical improvements such as reductions of the air gap to minimise PM demand. Permanent Magnet DC Motors are expected to become widely available commercially in standard mechanical dimensions over the next years (de Almeida 2014).

Hybrid SR / SSR with less PM content are under development. Market introduction is expected by 2020-2025. Axial flux machines (transversal, homopolar) with increased power density and reduced material demand may replace radial machines in some niches by 2020-2025. Experts argue that presently available and foreseeable motor designs are close to the maximum efficiency level achievable, so that completely new motor designs need to be implemented by 2030.

2.2.5 Cross-cutting material research

The situation in 2015

Currently, NdFeB is the predominant commercially available PM material with highest performance characteristics. Dysprosium or Terbium are added in small amounts to increase coercivity and temperature stability.

High-Throughput-Screening (HTS) is used to identify promising PM candidate materials and their magnetic properties (Coey 2012).

A large R&D realm focuses on nanoscale solutions. New nanocomposite hardmagnetic materials (REE or HREE-free) are searched for to fill the performance gap between ferrites and NdFeB. Nanocrystalline Dy-free, Nd-reduced PM material has been demonstrated (Molycorp). Nanostructures of highly anisotropic materials, probably restricted to magnets with limited coercivity, are investigated.

Advanced production technologies aim at the reduction of REE/HREE, such as Netshape magnet production (Nd, Dy), Dysprosium-Layer-Technology (Dy), Grainsize-Tuning-Technology (Dy) and Grain Boundary Engineering (Dy).

Shaped field magnets allow for a reduced REE-content. However, there is no universal shaped field solution. Shaped field magnets have to be developed individually for each application, thus requiring high production numbers for the return of investment.

Near-term developments 2020

In the near term progress is expected in the development of bulk magnets with finely tuned structures using iron-based mixtures that contain 80% less rare earth materials than traditional magnets.

These finely tuned structures might be achieved by novel microstructuring engineering strategies such texturing of nanocomposite material or hot packing of meta-stabile thin-film $NdFe_{12}N_x$. Hot pressing of nanocrystalline NdFeB magnet (MQ2) eliminates the need for dysprosium in PMDC Motors (less efficient than conventional PM material).

The high anisotropy field layer production process reduces REE-demand by 20-50 % (TDK). The need for Dysprosium can be curtailed by grain size reduction and grain boundary diffusion (Yan 2013).

Mid-term to long-term developments 2025 / 2030

By 2025 and beyond, new phases of intermetallic RE-TM compounds (YCo_5 and $(Y,X)(Co,Z)_5$; REE_1-TM; REE_1TM_5, REE_2TM_{17}; $RE_2TM_{14}B$; LaCo-Ferrite) are likely to be commercially available. Nanoscale powders of FeCo-, FeNi-, FeN-, MnBi-based PM material might be synthesized commercially provided that texturing at full density is possible.

In the long term there is CRM substitution potential by novel production of high-aspect-ratio (length-to-width ratio: >5) nanostructures such as nanowires, nanoparticles, nanorods and nanoflakes by exploiting the magnetic shape anisotropy of the constituents.

All in all, as a prerequisite for long-term solutions more funding is required in the near-term for both basic material research and close-to-market projects. In particular SMEs need broader access to expensive state-of-the art modelling techniques for new material combinations. Long patenting procedures are a barrier to CRM substitution.

2015	2020	2025	2030	References
Landscape Developments: Overarching developments influencing long-term REE supply and demand				
REE raw material supply: more than 90 % from China, several new projects outside of China developing	Market growth from 110 kt to 200 kt; EU target to reduce its dependence on REE in permanent magnets imported from China to 70%, new REE mining projects outside China maturing and running at full performance (Lynas, Molycorp)	HREE dependency on China likely to continue, LRRE dependency likely to be reduced by new projects; REE separation methods with less impact on water and earth developed; subsidy structures and enforcement of EHS standards uncertain	New REE resources commercially developed: Subsea resources (Japan), Bauxite red muds (Jamaica), Kvanefjeld (Greenland)	Lazenby 2014, USGS 2015, Greenland Minerals and Energy Ltd 2015
REE raw material demand: driven by multiple and cross-sectoral uses, key market segments: industrial, automotive (general), HDD/CD/DVD-drives, e-bikes	Strong increase in wind turbines and electric vehicles ; industry increasing, automotive stable, HDD decrease by substitution through solid state drives SDD, e-bikes increasing, residential air conditioning (fans, compressors) with robust growth, unclear classification of elevators (megacity markets)	Increasing PM material requirements by key segments due to (efficiency) legislation and market demands	Increasing pressure to develop system solutions could foster REE-substitution at system level	Allcock 2014, Binnemanns et al. 2013

2015	2020	2025	2030	References
REE prices (July-Dec. 2014): Nd Metal 99 % min FOB (CN) - ca. 83-87 USD/kg, Pr Metal 99 % min FOB (CN) 150-155 USD/kg, Dy Metal 99 % min FOB (CN) - ca. 470-630 USD/kg, Tb Metal 99 % min FOB (CN) - ca. 870-920 USD/kg	REE prices likely to remain stable due to large stockpile reserves in Mongolia and new REE mining projects that compensate for moderate demand increase	Uncertain price trends due to unknown supply-demand constellations	Uncertain price trends due to unknown supply-demand constellations	Lazenby 2014, Metal-pages 2015
Energy markets: Large differences in regional energy prices	Electricity price increase providing incentives for energy efficiency	Increasing pressure to transform energy supply and demand systems fundamentally	Lower energy intensity in the economy, shifting mobility patterns, shifting energy supply and demand structures and management	Richards 2013, Greenpeace/GWEC 2014
Energy efficiency standards for electric motors and drives: IE2 standard in EU	By 2017, only motors with IE3 efficiency standards admitted in the EU	Spread of IE3 high efficiency motors; Standardization of EV motors might stimulate industry relocalisation and concentration (e.g. to China) and raise trade levels	IE4 standard widely accepted (no timeframe decided yet)	Summary regulation: Lenze 2013; relocation: Richards 2013
Global patterns of value creation: attempts to relocate value chains closer to REE raw material sources	Intensifying global competition between regions to locate manufacturing industries	Uncertain outcomes of global competition race for key industries such as automotive and wind energy, emerging new players	Uncertain outcomes of global competition race for key industries such as automotive and wind energy, new players may succeed	UK Government (2010), US Government (2008)

2015	2020	2025	2030	References
Generators for wind turbines				
Wind turbines - market				
Wind turbines with gearbox technology (without permanent magnets) available and make up the majority of globally produced wind turbines. Megawatt generators with direct drives (each contains 2-3 tons of PM). Advantages of wind turbines with direct drive: compact, lighter and better maintainability. Hybrid gearbox/direct drive systems available				Expert consultations No. 1 and 4, Schüler et al. 2011, JRC 2013, EWEA 2015
Market share of DD wind turbines using REE magnets (low/high penetration): overall 10-18 %	Increasing offshore market share, mostly 6-8 MW DD wind turbines with PM content of 200-600kg/MW	DD wind turbines with PM market shares - Onshore: 15-75 % / offshore: 25- 75 %		US Department of Energy 2011, Navigant 2014
Wind turbines - policy and regulation				

2015	2020	2025	2030	References
Wind energy EU targets: onshore/offshore 11,4 bzw. 3,1 GW/a (installation per year)	Onshore: 17,8 GW/a, offshore: 6,9 GW/a	Onshore: 13,1 GW/a, offshore: 10,5 GW/a	Onshore: 10 GW/a, offshore: 13,7 GW/a	EWEA 2011; similar to aggregate national renewable energy action plans: Athanasia et al. 2012
Wind turbines - R&D				
Design tools and standards for offshore turbines (available 2015)	Further optimisation of REE content and performance			US Department of Energy (2014a)
Substitution of PM by superconducting (partially/full) technology for 10 MW generators: a) GE: NbTi (HTS) b) AMSC: YBCO (HTS) c) Advanced Magnet Lab European Consortia/ AML: MgB2 (at cryogenic temperatures) d) Other non-public initiatives (e.g., Siemens, Sinovel) Reduction of REE-content from 6 tons (PM) to 10 kg (HTS) (research)	Substitution of PM by superconducting technology for very large offshore turbines (10 MW), demonstrator	Market introduction of superconducting technology for very large offshore turbines (10 MW)	Optimisation of production of superconducting machine	Magnusson at al. 2013, General Electric (Meyer 2014), AMSC Sea Titan (power-technology.com 2014), EU Innwind 2014, EU SUPRAPOWER 2014, AML Superconductivity and Magnetics (US Department of Energy 2014b), Tecnalia 2015, public consultation No. 1

2015	2020	2025	2030	References
Electric motors for transport				
Electric motors for transport - market				
PM Synchronous motor /BLDC allowing a more compact and lighter design (available 2015: e.g. Toyota Prius)	Uncertain market uptakes			JRC 2013, Toyota 2014
Induction motor without PM smaller performance to weight ratio (available 2015: Fiat Seicento Electra, Ford E-KA, Tesla, GM)	Uncertain market uptakes			JRC 2013
Wound rotor synchronous motor without PM smaller performance to weight ratio (available 2015: Renault Fluence Z.E.)	Uncertain market uptakes			JRC 2013, public consultation No. 2
Hybrid Synchronous/ Reluctance Motors with reduced REE content (available 2015, BMW i3)	Uncertain market uptakes			Green Car Congress 2013
Global market penetration by vehicle type (low/high penetration)	Increasing market share of HEV, PHEV and AEV in total vehicle market, with PM-content 1-2 kg/vehicle	Hybrid, hybrid plug-in and all electric vehicles assumed to use REE magnets: 90-100 %, annual sales HEV: 4,2-19,1 Mio., PHEV: 0,0022-13,22 Mio., AEV: 0,0022-4,56 Mio.		US Department of Energy 2011

2015	2020	2025	2030	References
Electric motors for transport - policy and regulation				
Fuel efficiency standards	EU fuel efficiency standard 90 g/CO_2 per km	US fuel efficiency standard 2025 of 70 g/CO_2 per km can only be achieved by hybrids (with presently available technologies)		Nelsen 2012
Urban Air Quality standards (diverse measures locally in place)	Increasing pressure to enforce air quality standards in megacities and emerging hot spots			Gujar 2014
Governmental E-mobility deployment goals	5.900.000 EV vehicles deployed in 2020 globally (sales in 2012: 200.000)			International Energy Agency 2013
Electric Motors for Transport - R&D				
In-wheel electric drive system for hybrid, plug-in hybrid and battery electric light-duty vehicles with REE content reduced by 30 % (Protean Electric, USA, i.V.m. FAW-Volkswagen Automotive Company and Michelin Active Wheel: near to market)	Development of in-wheel drive solutions for passenger cars	Market introduction of in-wheel drive system technology for hybrid, plug-in hybrid and electric passenger cars (uncertain)		Protean Electric (IEEE 2012, IEEE 2014, Krapfl 2013), Michelin (Adcock 2012), Transport electrification roadmap: ERTRAC et al. (2012)

2015	2020	2025	2030	References
Advanced reluctance motors including REE-Free SRM Switched Reluctance Motors, Variable Reluctance Synchronous and DC-Excited Flux-switching motors for EV and hybrid vehicles (ARMEVA, PunchPowertrain, HEVT: under development)	Punch Power Test vehicle (EV and hybrid), demonstrator	Market introduction of advanced reluctance motors (uncertain)		EU ARMEVA 2014, punchpowertrain 2014, Schelmetic 2012 (HEVT), ERTRAC et al. (2012)
Brushless PM machine construction enabling low coercivity PM (AlNiCo, FeCoW) with performance characteristics of NdFeB-PM (UQM Technologies with ORNL, under development, patent granted in January 2015)	55kW EV motor (scalable to 120kW) with AlNiCo magnets, demonstrator	Market introduction of high-performance AlNiCo-based traction motors (uncertain)		Ley/ Lutz 2012, Green Car Congress 2015, Continental patent for Brushless PM EP 1746707 A1
Ce-TM (transition metal) magnet for use in electric traction motors (AMES Laboratory and General Electric, ARPA project; material research)	Ce-TM PM material development	Market introduction of Ce-TM-based PM traction motors (uncertain)		McCallum 2012, McKittrick 2012
New design of motor topology based on hardmagnetic ferrites (Motorbrain project)	Traction drive based on ferrites, soft magnetic composites, Klauenpol-Rotor, demonstrator	Market introduction ferrite-based PM traction motors (uncertain)		EU MotorBrain 2014

2015	2020	2025	2030	References
Exploration of motor topologies (GE Global Research and General Motors, some magnet-free, some REE-free)	REE-free, high-performance traction motors for hybrid vehicles, demonstrator			El Rafaie and Johnson 2012
New design of motor topology for permanently excited synchronous machines to reduce temperature stress of PM	Redimensioning the required Dy-content by systemic optimisation of parameters (temperature profile, rotation, space, price, useful life, etc.), market introduction			Fraunhofer 2014
General applications				
R&D on electric motors and drives for general and other purposes				
PM-less motors and drives often available for applications whenever mass and volume are not critical, new motor designs: e.g. Brushless motor (e.g for air-conditioning compressor in a car): NdFeB magnets – 5 cm long, SmCo magnets – 6 cm long, ferrite-magnets 10 cm long. Material choice depending on space requirements			Completely new designs necessary to meet advanced energy efficiency requirements	Expert consultations No. 3 and C

2015	2020	2025	2030	References
Permanent magnet synchronous motor w/o rare earths (Hitachi 11 kW axial-gap permanent magnet synchronous motor w/o rare earths, IE4 performance, presented in 2012)				Green Car Congress 2012, Mikami 2012
Magnet-free synchronous reluctance motor (ABB magnet-free, low voltage IE4 synchronous reluctance motor for pump and fan applications, available 2015)				ABB 2013
Hybrid SR / SSR with less PM content. Squirrel-cage induction or synchronous reluctance design, enhanced with permanent-magnet technology (under development)	Market introduction of Hybrid SR / SSR with less PM content			Rick et al. 2013
Radial machines	Market introduction of axial flux machines (transversal, homopolar) in some niches replacing radial machines			Tecnalia 2015
PMDC, customized solutions available	Market introduction of standardized PMDCs			

2015	2020	2025	2030	References
R&D on REE-free magnetic materials				
$(Nd,Pr)_2Fe_{14}B$ PM material with highest performance, 2-10 % Dy / Tb increase coercivity and temperature stability (SmCo replaced due to limited availability of Sm, high costs and lower performance)				Expert consultations No. 2 and C
High-Throughput-Screening (HTS) to identify promising candidate materials and their magnetic properties (available 2015)				ReD-PuMa 2014, EU REfreepermag 2014, EU Romeo 2014
Nanocomposite: New REE-free hardmagnetic materials to fill the performance gap between ferrites and NdFeB (research)	Progress in texturing of nanocomposite material	Nanoscale powders of FeCo- or FeNi-based PM material; FeN powder, MnBi potentially available (provided that texturing is possible at full density), at demonstration stage		RESPONSE 2014 (FeCo, FeNi), Cui et al. 2014 (MnBi), Tomioka and Monozukuri 2011 (FeN), expert consultation No. C
Nanocomposite: New HREE-free hardmagnetic materials to fill the performance gap between ferrites and NdFeB (research)	Progress in hot packing of metastabile thin-film $NdFe_{12}N_x$ (Japan). Bulk magnets with finely tuned structures using iron-based mixtures that contain 80% less rare earth materials than traditional magnets (USA)	New phases of intermetallic RE-TM compounds: YCo_5 and $(Y,X)(Co,Z)_5$; REE_1-TM; REE_1TM_5, REE_2TM_{17}; $REE_2TM_{14}B$; LaCo-Ferrite, at demonstration stage		EU ROMEO 2014, REd-PuMa 2014, Hadjipanayish 2013, Johnson 2013, Hirayama et al. 2015 ($NdFe_{12}N_x$), expert consultation No. C

2015	2020	2025	2030	References
Nanostructures of highly anisotropic materials, probably restricted to magnets with limited coercivity (research)	Synthesis of novel hybrid nanostructures based on metals and ferrites, nanocomposite ferrites (demonstrators)	Novel production of high-aspect-ratio (>5) nanostructrures (nanowires, nanoparticles, nanorods, nanoflakes) by exploiting the magnetic shape anisotropy of the constituents		EU NANOPYME 2014, expert consultation No. C
Nanocrystalline Dy-free, Nd-reduced PM material (Molycorp, demonstrators available 2015)	Hot pressed Nanocrystalline NdFeB magnet (MQ2): market entry eliminating the need for dysprosium in PMDC Motors (less efficient than conventional PM material)			Sketh 2013, expert consultation No. C
Grain Boundary Engineering to drastically reduce HREE (under development)	Novel microstructuring-engineering strategies	Potential market introduction		EU ROMEO 2014, RESPONSE 2014, expert consultation No. C
Reduction of REE/HREE by advanced production technologies (Netshape magnet production (Nd,Dy), Dysprosium-Layer-Technology (Dy), Grainsize-Tuning-Technology (Dy) (under development)	High anisotropy field layer production process (-20-50 % REE by TDK), further reduction of grainsize			Expert consultation No. C, Fraunhofer 2014, Allcock 2014

2015	2020	2025	2030	References
Shaped field magnets with reduced REE-content (Arnold Magnetics, available 2015)	further market spread (to be developed individually for each application, thus requiring high production numbers for return of investment)			Allcock 2014, expert consultation No. C

2.3 Transition pathways

The findings of this roadmap should be interpreted with care. Many developments are beyond control of regime actors, so that there is no clear road to a preferred state of the future. Substitution activities gathered and assessed in the CRM_InnoNet project reflect the public domain to a large extent, while for example car manufacturers are supposed to keep many of their activities secretly. However, recalling the mechanisms of transition theory and relating the different roadmap elements to one another a few indications of possible transition pathways can be made. For a more detailed discussion of transition mechanisms, please see CRM_InnoNet deliverable 5.3. “CRM_INNONET ROADMAPS FOR THE SUBSTITUTION OF CRITICAL MATERIALS”.

The landscape developments described in the roadmap suggest that there will be rather moderate landscape pressure. These dynamics may lead to transformation (1) or reconfiguration (4) of the regime in redirecting innovation pathways smoothly. This may be what we actually observe in the realm of CRM policy.

REE prices have declined over the past few years indicating even less or no pressure. In the latter case the raw material dependent regime would enter the reproduction path (0), i.e. no significant regime change would be necessary. This view might be shared by organizations that have managed to ensure a steady long-term supply of REEs.

Even though the bottlenecks along the supply chain of permanent magnets might become less severe over the next years, companies watch developments closely, as they are aware of the potential strong drivers for increased demand related to wind turbine deployment and hybrid & electric mobility, which could again provoke strong price oscillations and undermine the cost competitiveness of permanent magnet based motors and drives. The technological developments in the field of electric motors and drives are strongly guided by the need for achieving more demanding efficiency standards.

REE prices might soar again for a variety of potential reasons such as demand increases triggered by wind turbines and H&EV. In this case, the regime would perceive moderate landscape pressure. However, landscape developments may – slowly but thoroughly – bring about disruptive change. In this case a transition sequence (5) could unfold: transformation (1) and reconfiguration (4) would be followed by de-alignment and re-alignment (2) or substitution (3).

Landscape pressure could also happen suddenly, largely and diverging. If REE-free solutions are mature by then, a fast substitution of the existing CRM-dependent regime by novel proto-solutions could take place (3). If REE-free solutions are not fully developed by then, the existing CRM-dependent regime would erode and niche would compete for supremacy to establish a realigned regime (2). These mechanisms underpin the necessity to establish a strategic niche management for CRM-free/CRM-reduced PM.

Some R&D activities bear the potential for radical niche innovation. Magnet material research might reduce REE-efficiency by an order of magnitude (e.g. nanoscale magnet R&D). If there is a “Substance for Substance” breakthrough, this might change the entire substitution game, i.e. “Process for Process” or “Technology for Substance” might become obsolete substitution strategies.

At the level of electric machines, system optimization of H&EV could drastically reduce HREE dependency and thus weaken substitution pressure on REE significantly. Also PM-free concepts such as switched reluctance motors in the realms of H&EV and of general purpose motors could significantly change the game (“Technology for Substance”).

On the other hand, the mass electrification of all means of transport and other new killer applications could change the game again and put heavy pressure on future REE markets.

The “Process for Process” substitution strategy is to bring about incremental impacts. However, progress in grain size reduction and grain boundary diffusion (grain boundary engineering) may broadly affect REE demand in a variety of PM applications.

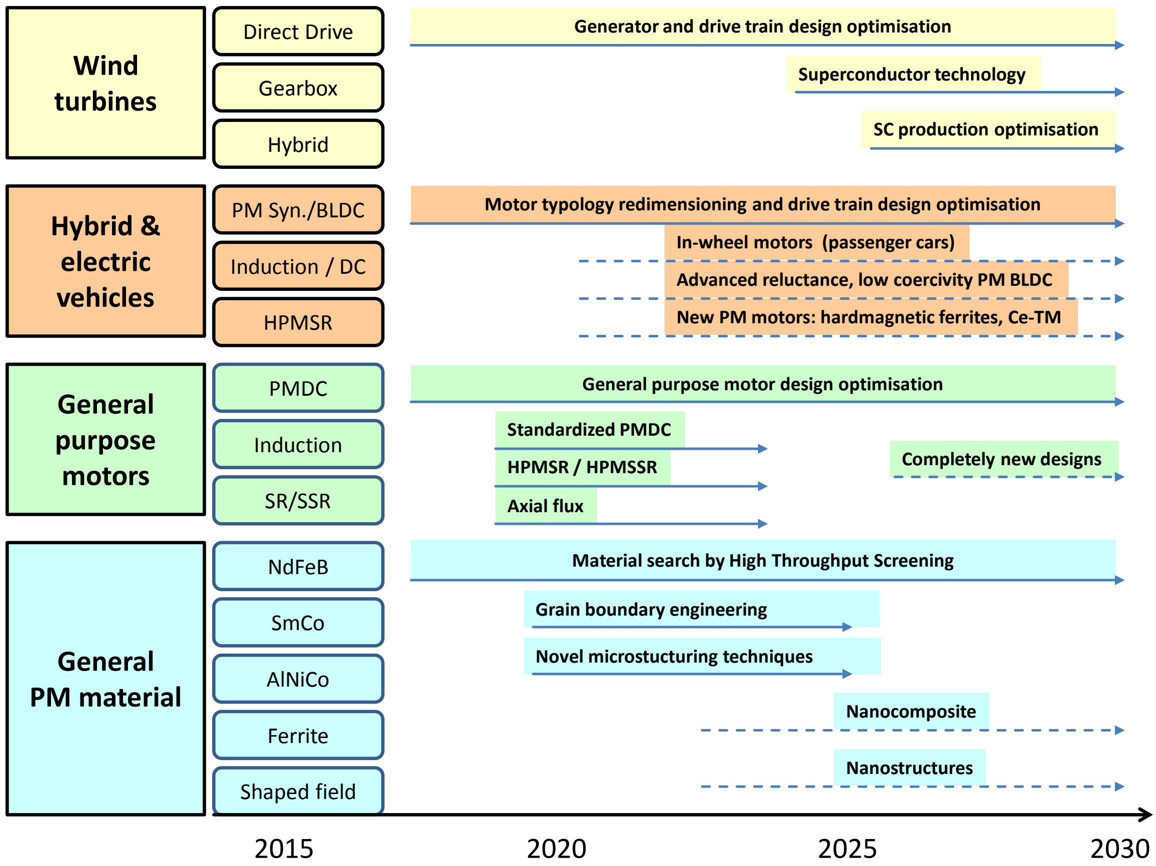

Figure 9 - R&D Roadmap for Substitution of REE in PM for electric machines (own compilation)

Note: technologies already in the market: in front of the vertical 2015 line; ongoing processes: from today (started before) until 2030; earliest possible future market introduction: ring; full arrow: market introduction likely within this time interval; dashed arrow: market introduction unknown, in case of actual market introduction likely within this time interval.

At the regime level, in particular manufacturing industry and consumers drive the demand-side of the REE market. Prevailing R&D paradigms used to reflect REE availability in product design to a limited extent, and policies are focusing and will focus on market growth backed by measures to expand primary REE supply. In principle, European industry could drive REE-substitution in electric motors and drives, in particular with public support (Public Consultation 2). However, many key players that could drive REE substitution in PM are outside the EU asking for smart coalitions to drive the substitution agenda further.

The levers of change at the regime-level mainly include the development of own large REE sources in Europe, energy efficiency and EHS regulation as well as deployment policies for wind energy and H&EV. Such activities have to be reflected in the light of the global race for relocating value creation for one's own benefit. The regime might withdraw from its H&EV and wind energy deployment targets for economic reasons thus further relieving the pressure to substitute REE in PM.

As a prerequisite for long-term solutions more funding is required in the near-term for both basic material research and close-to-market projects. In particular SMEs need broader access to expensive state-of-the art modelling techniques for new material combinations. Long patenting procedures are a barrier to CRM substitution.

All three applications fields of PM-based electric machines studied bear high innovation dynamics. These innovation dynamics originate from motivations beyond the substitution of CRMs. Hence, it is recommended to encourage radical system innovation in these fields and to mainstream CRM supply & demand as an issue across all system innovation projects.

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ANNEXES

A. Scoping document for Vision Workshop "Permanent Magnets based applications such as electric drives and motors"

Introduction

The European Commission has identified the following 14 critical raw materials due to their high relative economic importance and to high relative supply risk.

List of critical raw materials at EU level (in alphabetical order):

Antimony	Indium
Beryllium	Magnesium
Cobalt	Niobium
Fluorspar	PGMs (Platinum Group Metals)[1]
Gallium	Rare earths[2]
Germanium	Tantalum
Graphite	Tungsten

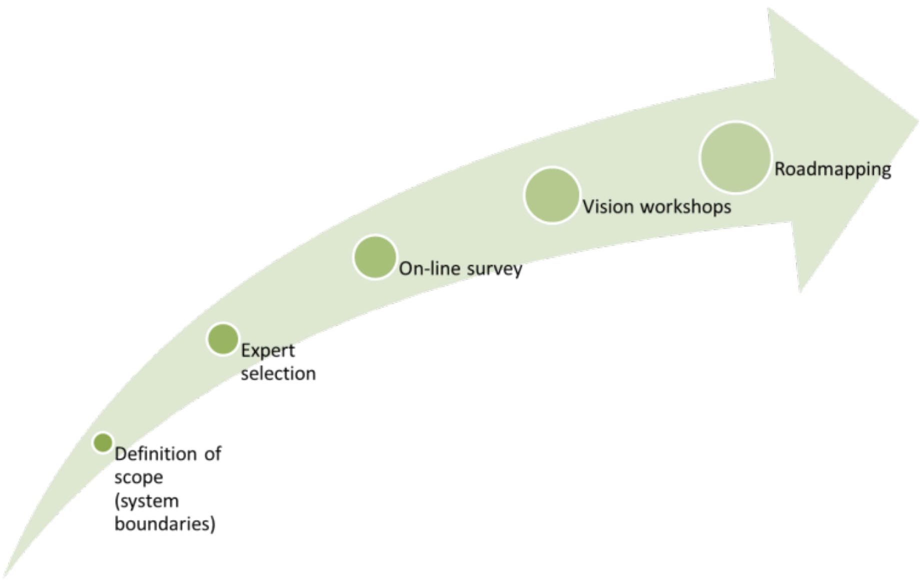
[1] The Platinum Group Metals (PGMs) regroups platinum, palladium, iridium, rhodium, ruthenium and osmium.
[2] Rare earths include yttrium, scandium, and the so-called lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium)

The list is now under revision and will most probably be enlarged, but the newest version has not yet been released. If further information is made available on the new list of critical materials, it will be presented at the workshop.

The Vision Workshops are part of a process, which will lead to the elaboration of five roadmaps for the substitution of critical raw materials

Substitution strategies for critical raw materials – material by material substitution, product by product substitution and redesign of products or applications - will be systematically discussed during the Vision Workshop, analyzing trends and possible trend breaks on three levels:

1. Landscape: worldwide developments affecting the predominant infrastructure and rules, which are likely to increase or decrease demand for permanent magnets in motors and drives
2. Regime: trends affecting the economic (market) and regulatory context in Europe, including company strategies and relevant research initiatives
3. Niche: emerging ideas, technologies or societal trends, which may provide new solutions in the medium-long term



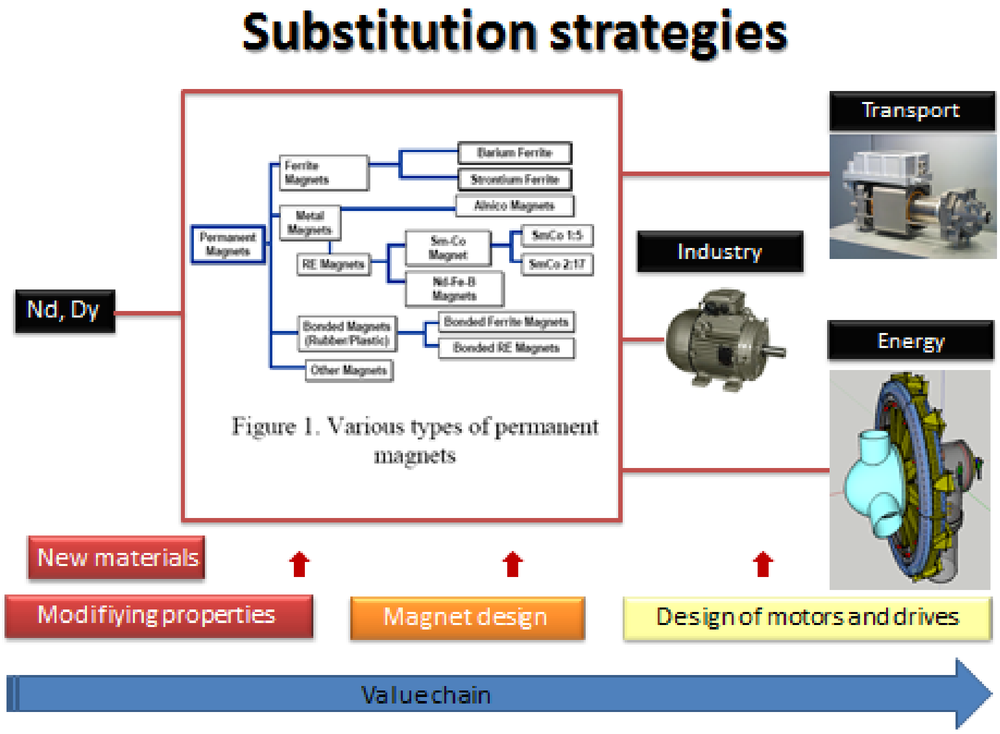


Figure 10 – Possible substitution strategies for permanent magnets in motors and drives

Scope of the Vision Workshop on Permanent Magnet based applications

Permanent magnets motors and drives have been selected as a priority application for substitution strategies, as they play a key role in emerging technologies, especially in the energy and transport field. Their main applications are in generators (wind turbines) and motors of electric and hybrid vehicles, in addition to the established markets in magnetic resonance imaging (MRIs) technology, hard disc drives, speakers, as well as a large range of high-efficiency industrial motors. A schematic presentation of the different PM motor types is shown in figure 11:

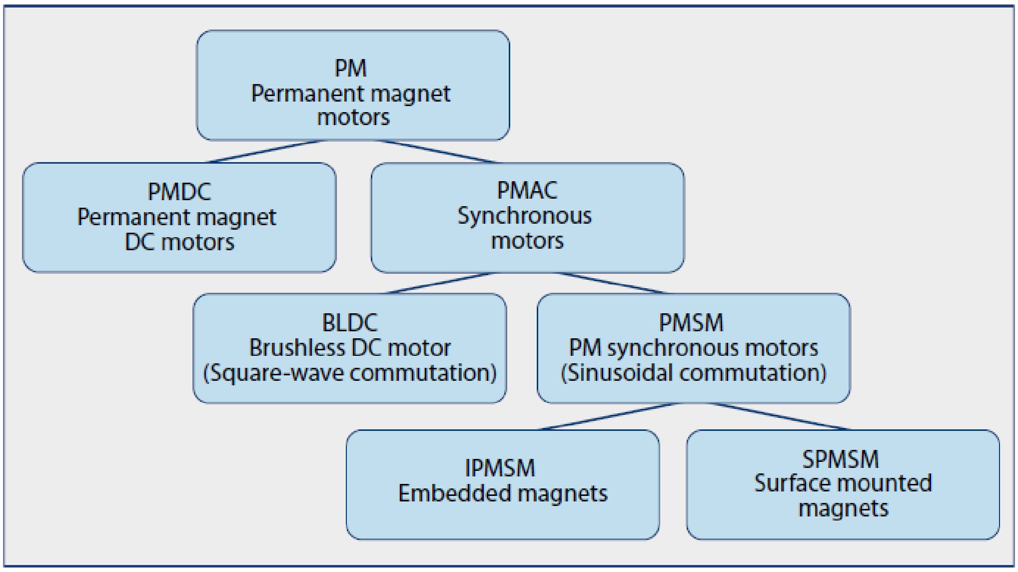


Figure 11 – Classification of permanent magnet (PM) motors

Source: Danfoss 2011

The drive for greater energy efficiency has led to the strong market uptake of PM technology in a wide range of sectors, so that permanent magnets presently represent 20% of the demand of REEs by end-use (Brumme 2011). Table **4** shows the main critical materials used in permanent magnets and their uses and, when available, consumption trends.

Table 4 – Critical materials used in permanent magnets

CRM	Characteristics
Samarium - Cobalt (Co)	Used in PMDC Motors in which temperature stability is vital, such as military satellite systems and small motors, sensors, automotive applications and actuators
Neodymium (Nd)	Used in PMSM high-efficiency motors (class IE3 and IE4), PMDC motors & automotive starters, servo motors. Also used in new PMAC motors, BLCD, IPMSM and SPMSM motors. Industry estimates predicts an increase in Nd content in permanent magnets of 54% between 2010 and 2015.
Dysprosium (Dy) and Terbium (Tr)	Added to NdFeB magnets in order to confer the ability to remain magnetized when confronted with other magnetic fields or high temperatures (at the cost of a reduced magnetisation). Industry estimates predicts an increase in dysprosium content in permanent magnets of 80% between 2010 and 2015.
Niobium (Nb), yttrium (Y)	Used in superconducting Niobium –Titanium NbTi alloy magnets and in high temperature superconducting materials (Yttrium barium copper oxide YBCO)

Source: Arnold Magnetics and others

For the purpose of CRM InnoNet workshop on permanent magnet based applications the focus will be placed on: **direct drive turbines** used in **wind power generation** and PM **motors** used in **industrial applications**, as well **electric and hybrid vehicles.**

Direct drive turbines

The latest generation of off-shore wind power technologies is highly dependent on permanent magnets (PMG), as shown in table 2.

Table 5 – Wind manufacturers' technology choices

Manufacturer	Model	Size: MW/m	Technology	Status	S.P. W/m^2
Enercon	E126-7.5	7.58/127	LS-EMG	Commercially available (2010)	***598***
Senvion	6.2M126	6.15/126	HS-DFIG	Commercially available (2009)	***493***
XEMC-Darwind	XD115	5.0/115	LS-PMG	Prototype installed (2011)	***481***
Areva	M5000/116	5.0/116	MS-PMG	Commercially available (2009)	***473***
Sinovel	SL6000	6.0/128	HS-SCIG	Commercially available (2011)	***466***
BARD	BARD 6.5	6.5/122	2 MS-PMG	Prototype installed (2011)	***454***
Ming Yang	6.5MW SCD	6.5/140	MS-PMSG	Prototype was expected for late 2013	***422***
Guodian UP	UP6000	6.0/136	HS-DFIG	Prototype installed (2012)	***413***
Gamesa	G128/5.0	5.0/128	MS-PMG	Prototype installed (2013)	***389***
Vestas	V164-8.0	8.0/164	MS-PMG	Prototype installed (2014)	***379***
Areva	M5000/135	5.0/135	MS-PMG	Prototype installed (2013)	***349***
Alstom	Haliade 150	6.0/150	LS-PMG	Prototype installed (2012)	***340***
Goldwind	GW6000	6.0/150	LS-PMG	Prototype installed (2014)	***340***
Senvion	6.2M152	6.15/152	HS-DFIG	Presented at EWEA Offshore 2013	***339***
Siemens	SWT-6.0-154	6.0/154	LS-PMG	Prototype installed (2012)	***322***
Mitsubishi	SeaAngel	7.0/167	Hydraulic transmission	Prototype expected (early 2014)	***320***
Samsung	S7.0	7.0/171	PMG	Prototype installed (2013)	***305***
Haizhuang CSIC	HZ-5MW	5.0/154	HS-PMSG	Prototype installed (2012)	***268***

Table 3: A sample of large wind turbines in the market or being introduced sorted according to specific power. Acronyms used: PMG = permanent magnet generator; EMG = electromagnet generator; DFIG = doubly-fed induction generator, a type of EMG. LS/MS/HS=low/medium/high speed; LS is necessarily a direct-drive machine, HS involves a 3-stage, conventional gearbox and MS involves 1- or 2-stage gearbox. Size included rated capacity in MW and rotor diameter in metres

Source: 2013 JRC Wind Status Report

Direct-drive low speed synchronous generators do not require gear boxes, due to their ability to produce current at much lower rotation speeds. Permanent-magnets-based designs are preferred for such synchronous generators, due to significant weight gains (about 25%) over induction systems. Still, such systems require higher investments than induction-based systems, which are expected to be amortized through performance and maintenance gains, especially under off-shore conditions. According to EWEA (2013), the average size of offshore wind turbines is 4 MW, but larger turbines are already commercially available. A typical FeNdB magnet used in wind turbines contains about 29% of neodymium and 4% of dysprosium, which adds up to 218kg/MW of neodymium and 30kg/M of dysprosium in an average direct drive turbine. Depending on the assumed speed of deployment of offshore wind parks and not accounting for technology innovation, wind mill producers could consume up to 8,500 tons of rare earth per year by 2020 – 2025, according to different forecasts.

Industrial applications of permanent magnet electric motors

A strong trend towards the use of brushless DC motors has been observed during recent years**.**

Permanent magnet electric motors in vehicles

The PGM technology is also expected to be widely used in electric and hybrid vehicles over the coming decades, so that demand for CRM is closely related to the market up-take of these vehicles.

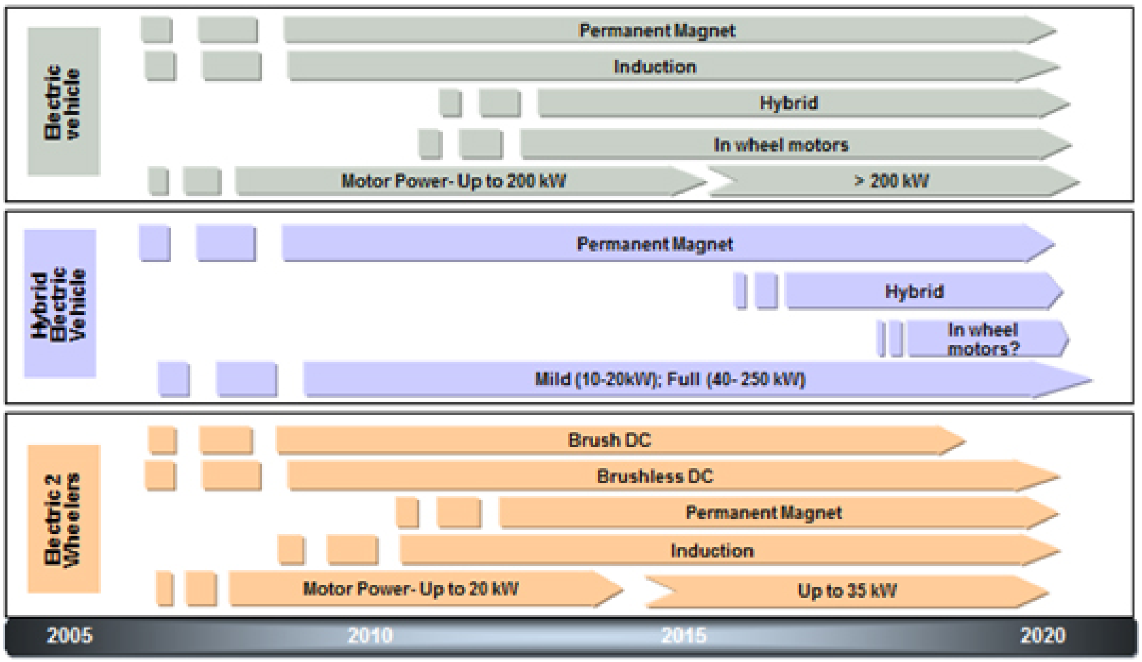


Figure 12 – Technology Roadmap for Electric Traction Motors (World), 2005-2020

Source: Frost & Sullivan 2011

Electric and hybrid PM motors have certain advantages over traditional synchronous and induction electric machines, which are extremely relevant for the car's efficiency: lower weight, smaller size, along with greater reliability. In the car industry, electric motors are also widely used in seating, steering and the air condition system, but the use of neodymium magnets is limited to some 25+ motors, plus the hybrid electric motor in the case of the Toyota Prius. However, many of the in-vehicle motors used by car manufacturers also have important applications in other industries, as shown in table

Table 6 – Permanent magnet based applications, CRMs and potential substitutes

Application	Sector / Market	CRM	Function	Substitute	Comments
Permanent magnet based direct drive wind turbines					
Direct-drive low speed synchronous generators mainly for large off-shore turbines	Wind power generation	Neodymium, dysprosium, terbium	The advantage of PMs compared to traditional consists in that winding of the electromagnets is not required (mass reduction) and Joule losses disappear. There are other losses but smaller. Exciters are not required and rotor design of machines is simpler. Reduced maintenance costs are also expected. Dysprosium and terbium are added for temperature tolerance and resistance to the demagnetizing effects of other mechanical equipment.	Superconducting materials Manganese composite magnets- MnBi/Al (ARPA projects, University of Delaware. Professor Hadjipanayis) Research on the use of nanostructured REE magnets with 30% lower Nd content Nanocrystalline permanent magnets Iron nitride (Fe16N2) magnet on hybrid metal-ferrites (NANOPYME project)	GE and Siemens working on substitute materials, including superconductors One possible change to the material composition of permanent magnets is the usage of didymium. Didymium is a mischmetal mixture of neodymium, praseodymium, dysprosium, and terbium (Nd-Pr-Dy-Tb). Praseodymium is substituted for neodymium so that 22.5% of the magnet's weight is neodymium and 7.5% is praseodymium - the amounts of terbium and dysprosium remain unchanged. (Hart 2013). Another option is that of reducing the air gaps of large diameter machines. The mass of magnets is proportional to the air gap dimension.
Medium speed hybrid drive turbine-incorporating PM in	Wind power generation	Neodymium, dysprosium	As above	Hybrid generator technologies decrease the quantity of PM used through design so this	One main approach is the minimization of rare earth use in permanent magnets, for example by exploiting grain boundary

Application	Sector / Market	CRM	Function	Substitute	Comments
geared turbine		, terbium		technology could be considered as a substitution option per se	diffusion processes. Vestas: hybrid-drive 7MW offshore generator, Gamesa going in the same direction. There other approaches such as Boulder Durham University looking to very large diameters. The very large diameter machines shift the solution towards mechanical approach.The requirement of magnets is small, possible to implement aLNICOs
Small low-speed synchronous PM generator	Wind power generation	Neodymium, dysprosium, terbium	As above		Goldwind has opted for fabricating a family of windmills without permanent magnet (rare earth) technology for lower-cost markets.
Permanent magnet electric motors (transport and industrial uses)					
Permanent Magnet Synchronous (PMSM) Motors	Industry	Neodymium, dysprosium, terbium	High magnetic capacity per weight, high energy efficiency, low noise	Hybrid permanent magnets without rare-earths or lower REE content Synchronous reluctance motors Synchronous reluctance helped by Permanent	BALDOR / ABB: lower-grade neodymium iron boron (NdFeB) and SmCo (samarium cobalt) magnet alternatives, as well as Cu (copper) rotor technology ABB and Nidec Corp.: synchronous reluctance motors without magnets. Hitachi Metals Ltd: IE4 machine that

Application	Sector / Market	CRM	Function	Substitute	Comments
				Magnets	uses traditional ferrite and amorphous metal technology NovaTorque Inc.: proprietary design that includes standard, off-the-shelf ferrite magnets, achieving IE4-efficiency levels
BLDC Motors	Industry (pumps, fans), Energy & buildings (HVAC), automotive	Neodymium, dysprosium, terbium	High magnetic capacity per weight, high energy efficiency, low noise		Brushless Motors are experiencing high growth rates, especially in automotive
PMDC Motors	Industry (Lifts, pumps), automotive	Neodymium, dysprosium, terbium	High magnetic capacity per weight, high energy efficiency, low noise	Hot pressed nanocrystalline NdFeB magnets (MQ2) do not require dysprosium nor terbium (Sheth, Molycorp, 2013)	
IPSMS Motors of **hybrid vehicle**	Transport	Neodymium, dysprosium, terbium	Weight reduction, mileage	High-performance “switched reluctance motor” presented in 2012 by start-up HEVT REMY HVH electric motor technology (induction motor).	HEVT was acquired by SOFTWARE MOTOR CORPORATION (SMC) in March 2014 REMY: Loss of performance said to be overcome by system changes

Application	Sector / Market	CRM	Function	Substitute	Comments
IPSMS Motors for **electric vehicles**	Transport	Neodymium, dysprosium, terbium	Weight reduction, mileage	Manganese composite magnets (ARPA project)	Renault has developed a rare-earth free electric motor. High-efficiency induction motors are suggested

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B. Results of the on-line survey Permanent-magnet based applications such as electric drives and motors

Purpose of the survey

The purpose of the on-line survey, which was launched prior to the Vision Workshops, consisted in focussing the debate of part I of the workshop, during which the long-term trends and possible trend breaks influencing demand for critical raw materials in a given application were analysed.

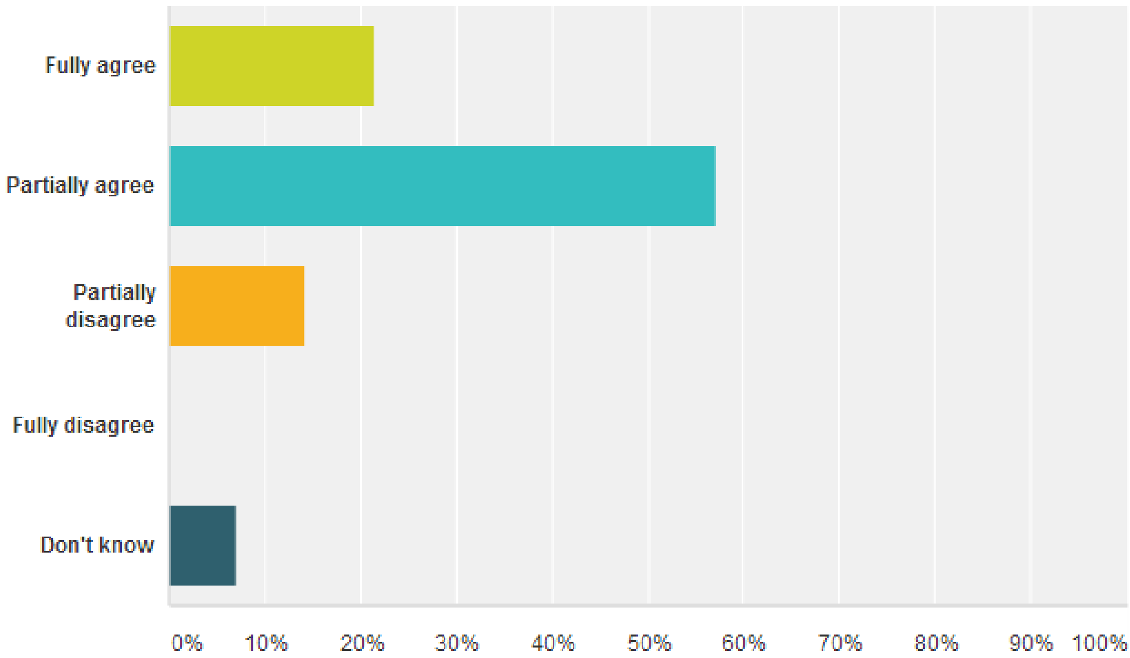
It was not the purpose of this survey to obtain representative results, but to use this first contact with the experts to get them into the right mind-set to discuss future trends, which are always associated with a high level of uncertainty.

The answers collected – both quantitative and qualitative - were displayed on screen during the initial part of the workshop and helped the moderators to guide the discussion.

The survey followed the Delphi methodology, in which questions must be clear and can only contain one statement, with which the expert can either agree or disagree – and explain his or her answer in written, if desired. In order to obtain a high response rate, the number of questions was limited to five for each workshop.

PARTICIPANTS: 14

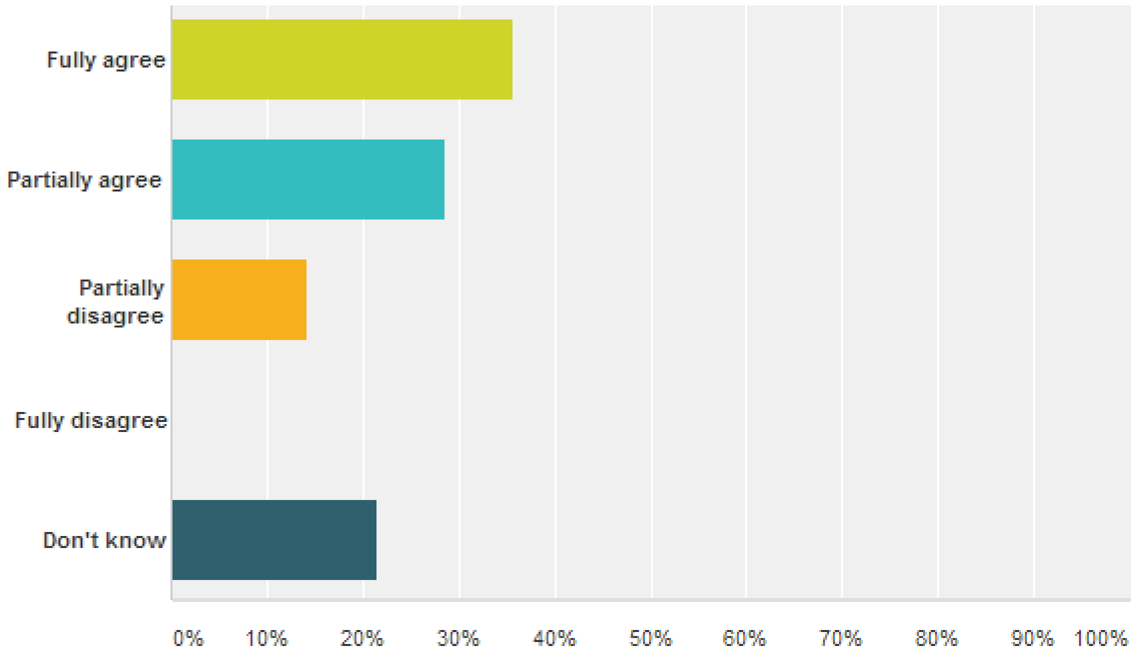
1. **Increasing costs of dysprosium and NdFeB magnets will seriously affect the competitiveness of European wind turbine producers during the next decade.**



Fully agree	21,43%	3
Partially agree	57,14%	8
Partially disagree	14,29%	2
Fully disagree	0,00%	0
Don't know	7,14%	1
Total		14

Several experts considered that alternative, CRM-free solutions will be available for the new generation of wind turbines. The main problem in terms of cost is dysprosium, since this material represents 6% of mass in permanent magnets, but 68% of material cost. A decisive factor will be the fraction of total wind turbine cost associated with magnets and technological progress reducing the need for Dy use.

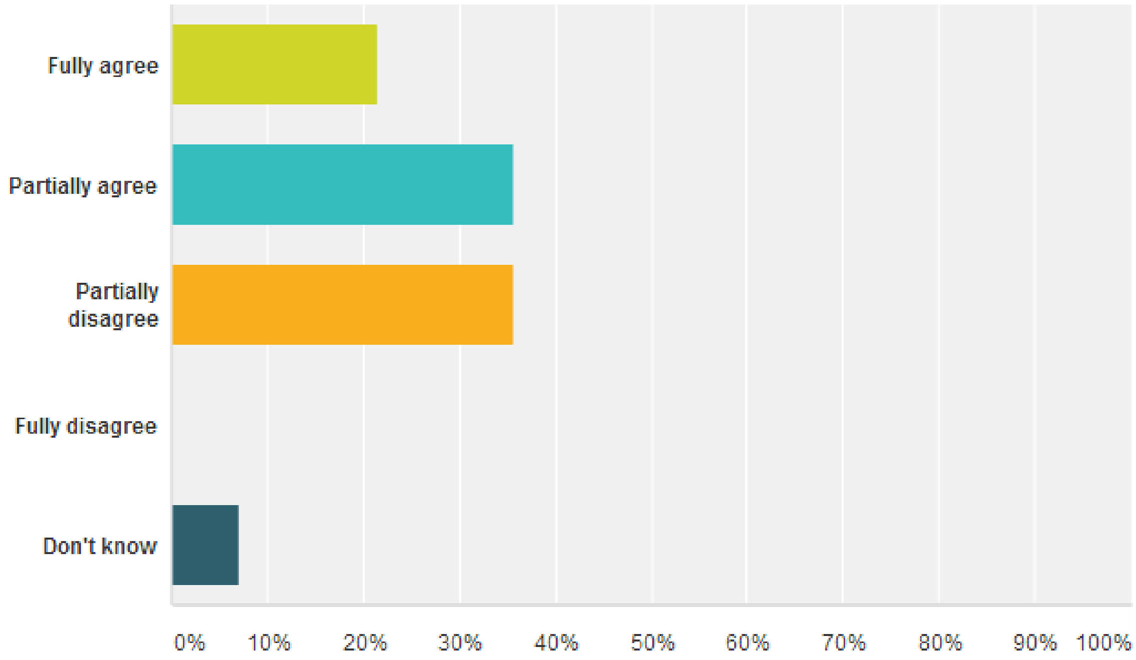
2. **The quest for high-efficiency motors (IE4 standard) will continue to increase the use of permanent magnet technologies in industrial motors**



Fully agree	35,71%	5
Partially agree	28,57%	4
Partially disagree	14,29%	2
Fully disagree	0,00%	0
Don't know	21,43%	3
Total		14

The experts argue that the statement holds true for technologies presently in the market, but synchronous reluctance machines can reach the same level of efficiency and a new generation of permanent magnet motors with lower REE - content it is also under development. It has to be considered that the permanent magnet technology brings along material savings for copper, aluminium and steel.

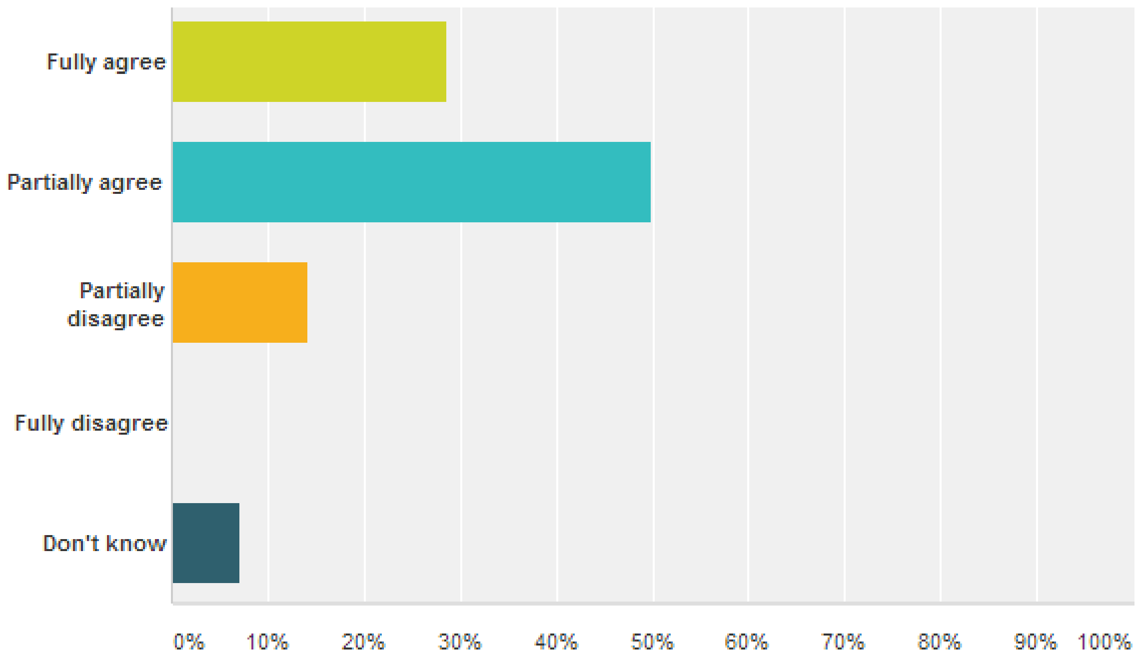
3. **The increasing demand for neodymium magnets will be a strong barrier to the wider market uptake of hybrid vehicles**



Fully agree	21,43%	3
Partially agree	35,71%	5
Partially disagree	35,71%	5
Fully disagree	0,00%	0
Don't know	7,14%	1
Total		14

Although motors for hybrid or electrical vehicles use up to 12% Dy and Tb and 2 kg of permanent magnet for a life-span of 15 years per car, magnet and motor cost, while not trivial, may not be the driver for consumer adoption. Other factors, including the price of oil and gasoline, regulation/government incentives, and battery technologies may be as relevant or more so in driving market demand. Alternatives motor technologies are under development, for example at Tesla, so that the impact of rising demand for Dy will only be a factor for companies that do not take mitigating action.

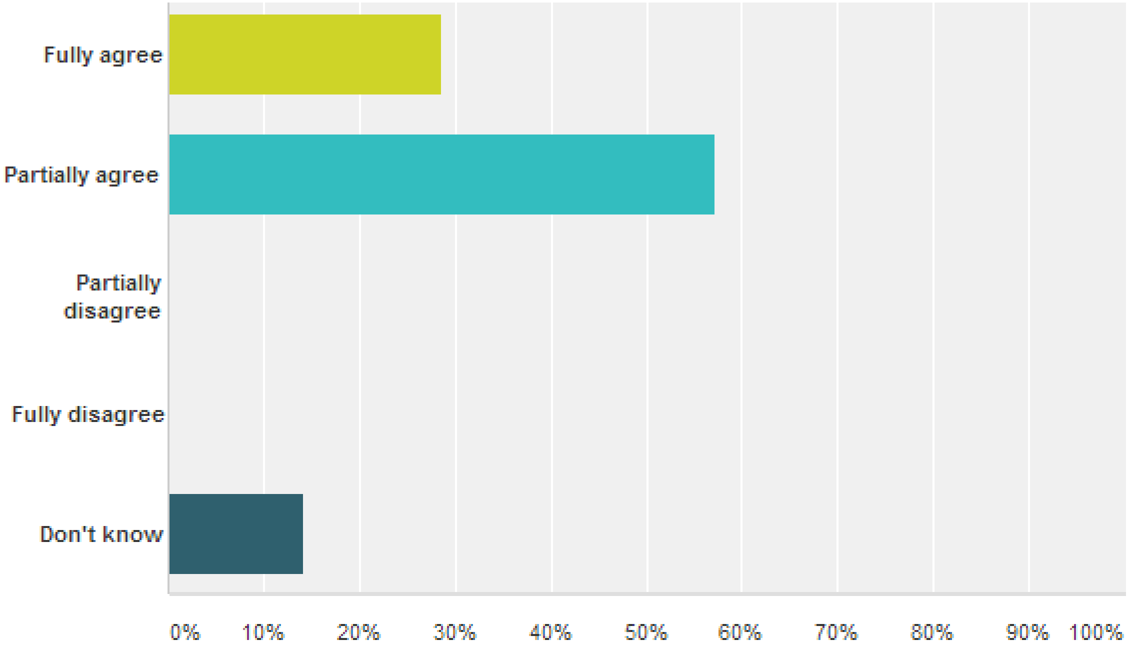
4. **Increased electrification of other transport sectors will put additional pressure on the markets of scarce materials**



Fully agree	28,57%	4
Partially agree	50,00%	7
Partially disagree	14,29%	2
Fully disagree	0,00%	0
Don't know	7,14%	1
Total		14

The experts point to complex and multiple challenges related to electric mobility. The trend to use permanent magnet-based machines has been growing in naval applications, public transport fleets, vehicles produced in smaller volumes than cars, and even other uses such as magnetic refrigeration. This has increased demand, but has also enhanced the use of alternative approaches (e.g. copper rotor motors being used again in some applications), which in turn may adversely affect prices of copper and aluminium. Experts point to batteries, and especially battery electrodes, as one of the major challenges for future mobility in terms of material demand.

5. **The growing shares of renewable energy in Europe will expand the market for recycling of permanent magnets**



Fully agree	28,57%	4
Partially agree	57,14%	8
Partially disagree	0,00%	0
Fully disagree	0,00%	0
Don't know	14,29%	2
Total		14

Although the expansion of renewable energy is not the only driver, most experts consider increased recycling of permanent magnets as a desirable, although partial solution to meet growing demand for Dy and Nd. However, recycling technologies need to become more efficient, both in terms of cost and performance (purity specifications/re-processing constraints), and collection schemes have to be set up on European level.

C. Summary of workshop results

Introduction and General Remarks

This summary of the Vision Workshop highlights the main points discussed during the event. The full content will be included in the final roadmap, which will be made available in October 2014. Comments on the need for recycling have been omitted from this summary, as the complex relationship between the different strategies for avoiding material scarcity, including mining, recycling, minimization and substitution, will be discussed in the generic part of the roadmaps.

Comments on the scope of the workshop

For a proper preparation of the Vision Workshop, the participants received a “scoping document” and were asked to give their opinion on some Delphi-type statement in a short on-line survey prior to the event. The experts considered that the use of permanent magnets in consumer electronics (white goods), cell phones and tablets should also be considered, but that wind turbines and industrial motors are by far the most important field of application, along with the increasing use of permanent magnet technologies in other transport modes (trams, bicycles) or elevators and machinery.

Landscape Developments

Trends and possible trend breaks, barriers, etc. influencing the demand for CRMs, which are beyond the control of single actors were presented by the workshop moderator as a starting point for the expert debate.

There was agreement among the participating experts that the competitiveness of the European wind turbine producers during the next decade will continue to be seriously affected by the increasing costs of dysprosium used in NdFeB magnets as additive to improve its performance in high temperature environments and so will Europe’s dependence on imports[15], but, in the longer term and for larger wind turbines (10 MW), permanent-magnet (PM) based technologies will not be the optimum solution – direct drive machines using superconducting materials are expected to perform better. Anticipated growth rates for wind power may, nevertheless be too optimistic, since solar technologies may become a strong competitor. Yet, for industrial motors, for which the quest for high-efficiency (IE4 standard) is decisive, the demand for PM will remain high, since this solution combines high efficiency with

[15] Even though China’s production monopoly in rare earth minerals has been lowered from 98% in 2010 to 92% nowadays, Europe’s dependence on Chinese exports is still extremely high

compactness, as well as lower demand for other materials, such as copper, aluminum and steel. This trend, combined with additional uses of PMs in other applications, such as trams, tires consumer electronics or magnetic cooling, will keep demand growing.

Trends in the EV and hybrid vehicle markets are less clear, since growth rates have been overestimated historically. Also, alternative traction technologies, such as induction or synchronous reluctance machines, are being developed or already introduced in the market. Furthermore, the deployment of EV and hybrids faces additional barriers, for instance, battery costs and performance, and there is also the possibility that alternative technologies such as second generation of biofuels may compete with electric transport, so that the pressure on the prime materials demand will not become apparent in the short term. Most experts agreed, however, that substitution or minimization of CRM use is necessary to reduce the pressure on prime material costs. Further reasons for moving away from PM technologies are bottlenecks further up in the supply chain (there is hardly any permanent magnet production left in Europe, except for Vakuumschmelze in Germany) and that, taking into account the entire life-cycle of PM technologies, these cannot be considered “green”, due to the strong environmental and health impacts of REE mining.

Regime level

Relevant policy and regulatory initiatives or industrial substitution strategies (R&D) for the priority applications were discussed in smaller working groups, with the following results:

Policy and regulatory initiatives

After the strong price hikes in 2008 – 2010, the EU, national governments, as well as large corporate players have started research and networking activities for rare earth substitution (Romeo, Mag-Drive, Erecon, CRM InnoNet, the KIC Raw Materials to be started in 2015, and more), but some experts expressed the wish that more funding should be made available both for basic material research and close-to-market projects. The need for faster patenting procedures was also identified.

Market initiatives

Industry has been reacting to price increasing by looking first of all to minimization options, trying to reduce especially de Dy-content, as these solutions are easier to implement than complete substitution or the redesign of motors or machines. Incremental innovations, which permit to reduce CRM content are, among others:

- ✓ Axial Flux: increasing power density, decreasing material

- ✓ Soft magnets
- ✓ Mechanical improvements reduction of magnet volume in motors by reducing airgap or increasing the volume of other raw materials such as copper or iron
- ✓ Improved motor management

Research initiatives

Developing complete CRM-free alternatives to PM motors will take longer and will require greater levels of cooperation between designers, material scientists and engineers, as shown in the figure on the next page. Broad access for companies to presently very expensive state-of-the art modelling techniques for new material combinations is considered critical in this context.

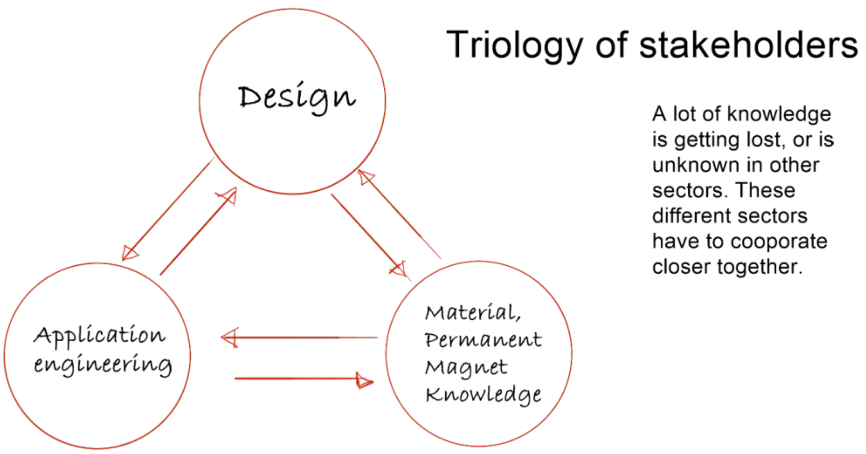


Figure 12 – Triology of stakeholders

The participating experts suggested looking into new motor designs to substitute PM technology, including concentrated winding and advanced reluctance motors, as well as non-radial flux machines for electric vehicles.

Niches (emerging technologies, innovative ideas, social trends influencing markets and policies)

Some experts had been invited before the workshop to present some innovative ideas about possible, but still very uncertain developments, which could potentially have an impact on the demand for critical materials in the selected priority applications, as well as on substitution strategies. The following potential developments should be considered in the case of electric motors and drives:

a. New magnetic materials, for example significant improvement in magnetic performance of Hc and Br (Higher |BH|max) or the development of low grade PM’s made with traditional alloys such ALNICO, Ferrites for use in general purpose motors.

b. Synchronous reluctance avoiding totally the PM’s in general purpose motors, in which size is not the main determining element for competitiveness

c. New electric machines (non radial)

On a more general level, potential new drivers of demand need to be considered, for example new transport modes and mobility behavior or the phasing-out of renewable support and competition between renewable sources (solar vs wind)

D. List of participants vision workshop "Electric Motors and Drives"

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