CRM_InnoNet

Substitution of Critical Raw Materials

Deliverable report

D5.3 Final Roadmap Report

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Inspiring Business

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Deliverable description

This report describes the five roadmaps for the substitution of critical raw materials in products and technologies, which are essential for technological, economic and social progress, due to their application in a large number of European industries, i.e. Printed Circuit Boards, permanent magnets, batteries, high-value alloys and photonics.

The report summarizes the insights gained on substitution options, as well as the barriers and gaps encountered, but it does not contain the initial scoping work, which was already described in Deliverable 5.2. All roadmap reports are also available as stand-alone documents.

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Abbreviations

3D	Three-dimensional
AC	Alternating Current
AEV	All-Electric Vehicle
AQDS	Aqueous flow batteries
BES	Battery Energy Storage
BLDC	Brushless Direct Current
CHEMSEC	International Chemical Secretariat
CN	China
CMC	Ceramic-Matrix Composite
CRM	Critical Raw Material
CSR	Corporate Social Responsibility
DC	Direct Current
DD	Direct Drive
EHS	Environment, Health and Safety
ESFRI	European Strategy Forum on Research Infrastructures
EU	European Union
EV	Electric Vehicle
FC	Fuel cell
FCV	Fuel Cell Vehicle
FOB	Free On Board
GHG	Greenhouse gas
H&EV	Hybrid and Electric vehicles (includes HEV, PHEV and AEV)
HDD	Hard Disk Drive
HEV	Hybrid Electric Vehicle
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
IARC	International Agency for Research on Cancer
IE	International Efficiency
IMPM	Inner Mounted Permanent Magnet excited
LED	Light Emitting Diode
LFP	Lithium Iron Phosphate (battery technology)
LiS	Lithium Sulphur (battery technology)
LREE	Light Rare Earth Elements
MLCC	Multilayer Ceramic Capacitors
MQ2	Hot-pressed isotropic NdFeB magnet
NaS	Sodium Sulphur (battery technology)
NCA	Nickel Cobalt Aluminium (battery technology)
NGO	Non-Governmental Organisation
NiCd	Nickel Cadmium
NiMH	Nickel Metal Hydride (battery technology)
NiZn	Nickel Zinc (battery technology)
NMC	Nickel Manganese Cobalt (battery technology)
OEM	Original Equipment Manufacturer
OER	Oxygen Evolution Reaction
OLED	Organic Light Emitting Diode
ORR	Oxygen Reduction Reaction
PCB	Printed Circuit Board

PCBA	Assembled Printed Circuit Board/Printed Circuit Board Assembly
PEM	Proton Exchange Membrane
PEMFC	PEM Fuel Cell
PGM	Platinum Group Metal
PHEV	Plug-in Hybrid Electric Vehicle
PMDC	Permanent Magnet exited Direct Current
PMG	Permanent Magnet Generator
R&D	Research & development
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
REE	Rare earth element
RES	Renewable Energy Source
RF	Radio Frequency
RoHS	Restriction of Hazardous Substances Directive
SCIM	Squirrel Cage Induction Motor
SMEs	Small and medium-sized enterprises
SMPM	Surface Mounted Permanent Magnet excited
SOC	System on Chip
SR	Synchronous Reluctance
SSD	Solid State Drive
SSR	Switched Synchronous Reluctance
TM	Transition Metal
USD	US Dollar
VR	Variable Reluctance
WBG	Wide Band Gap
WRIM	Wound Rotor Induction Motor

Elements and compounds

Ag	Silver
Al	Aluminium
B	Boron
Be	Beryllium
Cd	Cadmium
Ce	Cerium
Co	Cobalt
Dy	Dysprosium
Er	Erbium
Eu	Europium
Fe	Iron
Ga	Gallium
Gd	Gadolinium
Ge	Germanium
Ho	Holmium
In	Indium
Ir	Iridium
La	Lanthanum
Li	Lithium
Lu	Lutetium
Mg	Magnesium
Mn	Manganese
Na	Sodium
Nb	Niobium
Nd	Neodymium
Ni	Nickel
Pd	Palladium
Pr	Praseodymium
Pt	Platinum
Re	Rhenium
Rh	Rhodium
Ru	Ruthenium
S	Sulphur
Sb	Antimony
Sc	Scandium
Si	Silicon
Sm	Samarium
Ta	Tantalum
Tb	Terbium
Tm	Thulium
W	Tungsten
Y	Yttrium
Yb	Ytterbium
Zn	Zinc

1. 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 completely new work processes and products.

Material substitution, along with new ways of using energy, therefore forms the basis of natural innovation processes, as seen, for example, by the substitution of metals and natural fibres by plastics during the petroleum age. Presently, the world is undergoing another one of this far-reaching transition processes, triggered by an increasing strain on energy and minerals resources. 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.

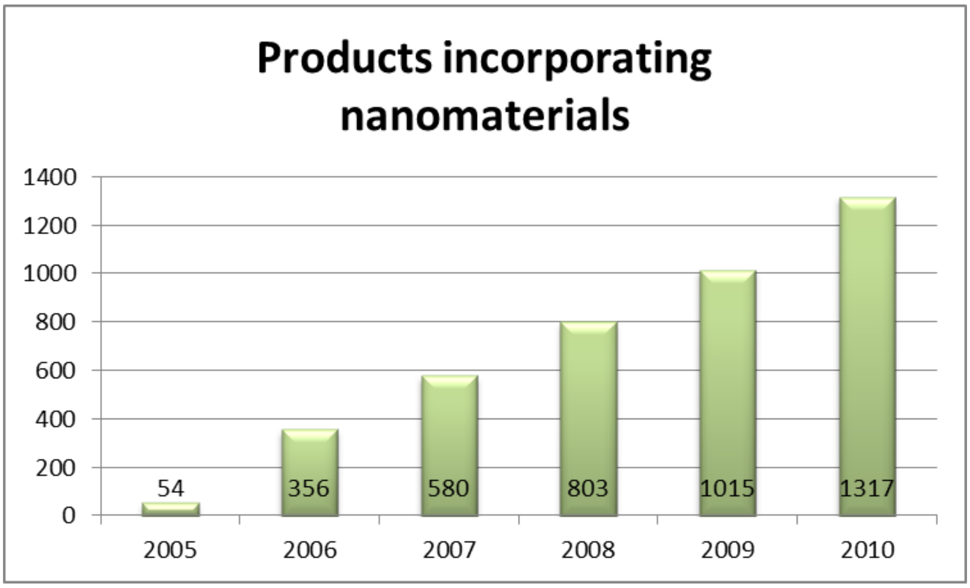

Figure 1 – Increase in products incorporating nanoparticles 2005 – 2010. Source: Own elaboration, based on Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars (2013)

This transition process to a new materials age is complex, not always linear and its far-reaching implications for society and economy are difficult to grasp as changes are still under way. At the same time, pressure increases to govern and steer these innovation processes in order to respond to severe social, economic and environmental concerns and to do so quickly and effectively. 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.

The roadmaps elaborated in the context of this project focus on five 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 in work package 2.

The roadmaps therefore explain possible substitution strategies for critical raw materials (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, including high-end optics

The CRM_InnoNet roadmaps consider four substitution strategies, which make it possible to reduce Europe's demand for scarce materials or to use these materials more efficiently during a product's lifetime. Extending the useful life of products also needs to be considered as an option for bringing down overall material demand in Europe.

- "Substance for substance" can be considered "pure" 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, which is one of the most attractive options in metal processing (example: advanced metallurgical synthesis processes to replace CRM containing 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 products, for example OLED, which could gradually substitute others, which require a higher CRM content (LED).

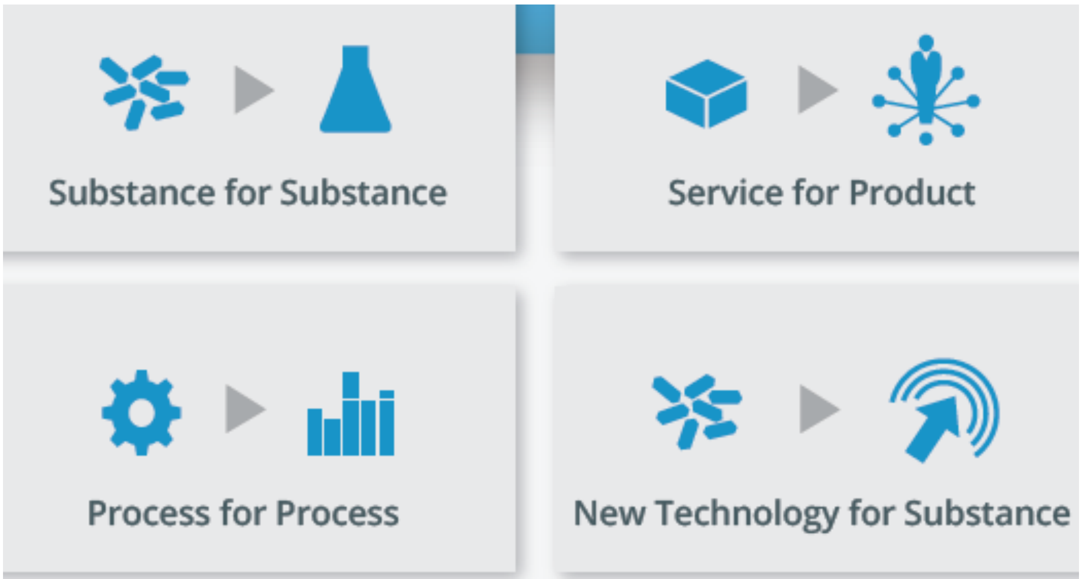

Figure 2 – Substitution strategies

2. CONTENTS OF THIS REPORT

This final report on the roadmaps for the substitution of critical materials in the five priority applications describes promising pathways for reducing or eliminating CRMs over the next 10 to 15 years (in select cases up to 2050).

The report consists of

- A description of the process applied for the elaboration of the five roadmaps
- An explanation of the methodological considerations behind the roadmapping work and material substitution, based on a transition theory approach
- A comparative interpretation of the drivers for material substitution for each priority sector, as well as the most promising substitution pathways
- A detailed description of the five roadmaps
- A summary of the substitution potential in each field.

The reader should note that extensive work was done with the help of experts to define the substitution priorities and future trends affecting material demand in the field of PCBs, permanent magnet applications, batteries, high-value alloys and photonics (five surveys and vision workshops). These initial deliberations and the findings are documented in Deliverable 5.2., which can be made available on request. Other relevant project reports, which have helped to shape the contents of the substitution roadmaps, are available on the project website[1].

3. METHODOLOGY FOR DEVELOPING THE CRM_INNONET ROADMAPS FOR THE SUBSTITUTION OF CRITICAL MATERIALS

3.1. Pressures for substituting critical materials

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 3 shows illustrative examples for the three levels of transition theory from the perspective of the incumbent, CRM-dependent regime.

[1] www.criticalrawmaterials.eu/documents

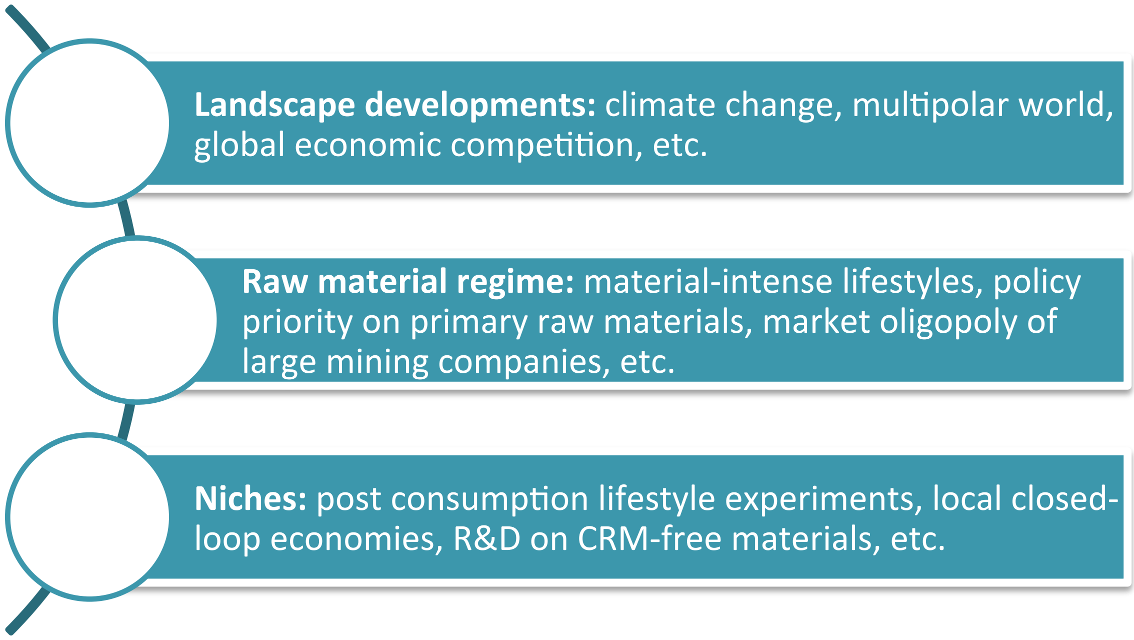

Figure 3 - The three levels of transition theory illustrated for the CRM-dependent socio-technical regime

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.

This mental framework has proven very useful for understanding present trends and developments affecting substitution of critical materials in the EU.

In analysing the interaction mechanisms among the three levels Geels and Schot (2007) identify different modes of systemic change:

0 Reproduction process: If there is no landscape pressure on the regime, then the regime will remain stable and reproduce itself. Applied to the field of raw materials, this describes a state, in which the supply side can keep up with growing demand by making additional resources available, which can be primary or secondary (recycling).

1 Transformation path: If landscape pressure is moderate at a moment when niche innovations are not fully developed, then the regime will modify the direction of innovation activities. Examples for this are R&D programs for materials, which gradually change material stocks and flows over a long time, such as the increased use of nanomaterials in commercial products.

2 De-alignment & re-alignment: If landscape pressure is divergent, large and sudden at a moment when niche innovations are not fully developed, then the regime will de-align and erode. Immature niche innovations co-exist and compete for attention and resources. Eventually one niche innovation becomes dominant building the core for re-alignment of a new regime. Such a situation of potentially competing solutions, which are under development at the same time, is found in the CRM_InnoNet roadmap on electric motors and drives, as companies working with these applications have been seriously affected by the steep and relatively sudden price increase for the rare earth elements neodymium and dysprosium in recent years.

3 Technological substitution: If there is much landscape pressure at a moment when niche innovations are fully developed, then the latter will break through and replace the existing regime. This is not yet the situation in most of the priority applications reviewed, but in the case of one of the sectors most affected by price hikes of critical materials – wind power – we do see a coexistence of CRM-containing and CRM-free technologies. It has also been confirmed that one of the main challenges with regard to the substitution of critical materials is that of the right timing for market entrance of alternative, CRM-free solutions (see also chapter 3.2. of this report).

4 Reconfiguration pathway: Symbiotic innovations are developed in niches and initially adopted by the regime locally. This triggers adjustments of the basic architecture of the regime. Applied to the CRM_InnoNet Roadmaps, this describes a hypothetical situation, in which changes to mobility behaviour produce a modal shift in transport, favouring lower cost options, which require no (or a lower amount) of critical materials (and fossil fuels).

5 Sequences of transition pathways: If landscape pressure is disruptive (i.e. slow, but fundamental), then regime actors will initially perceive it as moderate. As landscape pressure builds into a certain direction, a sequence of mechanisms is likely, beginning with transformation, leading to reconfiguration and followed by de-alignment & re-alignment or by substitution. Industry contributions to the roadmapping work in CRM_InnoNet have repeatedly pointed out that, although a certain supply risk is perceived, it is still considered moderate, especially if the critical materials are used in small quantities and therefore do not represent a major cost factor for the producer of final goods. Normally, the immediate reaction of industry is to try to minimize the amounts of critical materials used, rather than turning directly to more radical substitution options.

3.2. 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, have also been taken into account to assess future material development timelines. The example from the aeronautics sector, which is subject to severe security constraints, shows that, until now, developing an entirely new material and introducing it into the market takes 20 years or more, but minor modifications are possible in shorter time frames.

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

Case	Activity	Time
Case I	Modification of an existing material for a critical structural component*	2-3 years
Case II	Modification of an existing material for a critical structural component*	Up to 4 years
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 years
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+ years

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

Yet, new opportunities for accelerating material innovation are arising, thanks to new design and modelling techniques, and may speed up innovation processes. This 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 4.

3.3. Roadmapping process

Figure 4 shows the roadmapping process applied to all five roadmaps.

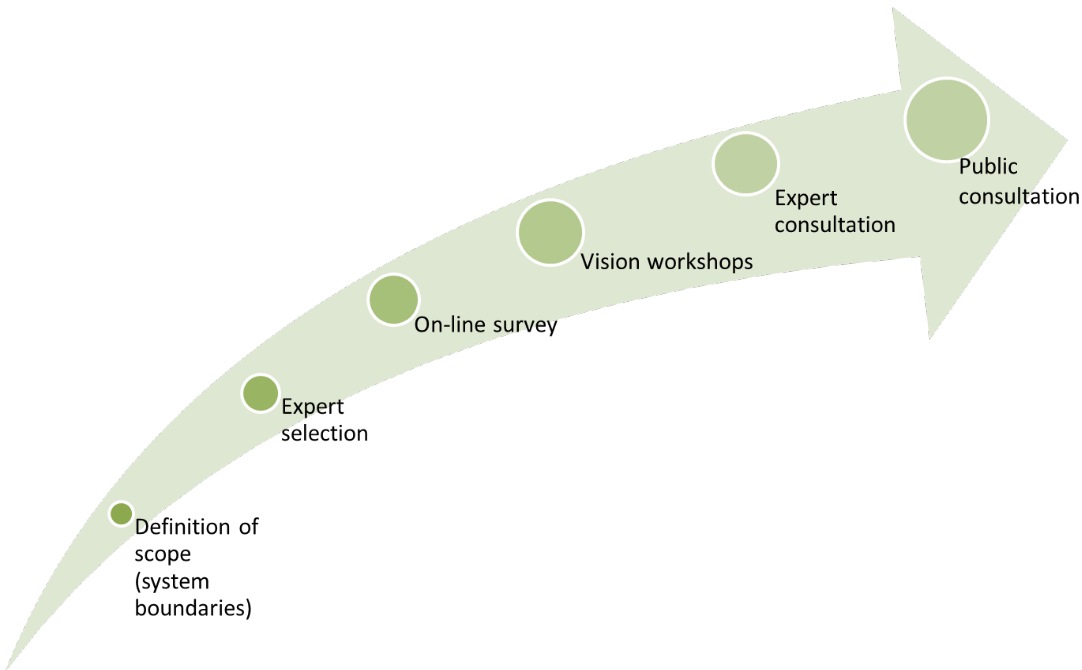

Figure 4 - CRM_InnoNet process for roadmap elaboration

At first, the system boundaries were defined before entering the process of elaborating the roadmap. The concrete CRM content was identified for all applications, along with their function and known substitute materials. In a second step, specific expertise was 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 five parallel "Vision Workshops". 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 to prepare the discussions in the workshops.

After collecting the expert opinions, 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.

4. MAIN CONCLUSIONS

4.1. Drivers for substituting critical materials (cross-analysis of the five roadmaps)

The five priority applications were selected because their future development is highly dependent on the availability of critical materials. Addressing supply and price risks, however, requires a profound change in the companies' innovation strategies, which, in recent years, have tended towards an ever-increasing use of "exotic" materials to achieve improved performance. Performance, expressed as flexibility, miniaturisation, temperature resistance and – important - short lifecycles of products, is especially relevant in the electronics industry, which, for this reason, is even anticipating a greater use of the CRM gallium in future applications. This implies that a substitution strategy aiming at reducing CRM use is contrary to the "natural" innovation trends in these industries and will only be implemented if landscape pressure increases and access to these prime materials is no longer guaranteed.

The situation is similar in photonics, with the slight difference that many of the applications in this field have entered the market quite recently and have not yet reached the maximum production level. The same situation has been observed in the battery market and, in both cases, leads to a situation, in which concerns about CRMs do not rank high on the companies' list of priorities. However, in the most advanced segments of these two markets (LEDs and batteries for transport purposes), the possible need for substituting CRMs is recognized and reflected in the research agendas. Cross-fertilization, i.e. the potential transfer of a substitute solution from one application to another, could become an important element for composing the "reconfiguration pathways" referred to in chapter 3.

Drivers for substitution are much more evident in the case of electric motors and high-value alloys, due to high importance of material cost for these industries and recent experiences with volatile prime material markets. In these industries, the main challenge consists in speeding up innovation processes so that companies can respond in a more flexible way to pressures on the landscape level. The most promising substitution strategies identified in the roadmaps for these sectors are embedded in entirely new designs (motors, batteries for transport) or material combination and compositions (CMCs).

4.2. General recommendations (cross-analysis of the five roadmaps)

There are four key issues related to strategies for the substitution of critical materials, which are a common concern for all applications covered in the five roadmaps and therefore need to be addressed at a general level. The cross-sectoral challenges identified in the expert discussions are:

1. Material substitution is presently addressed on the level of individual companies. The EU does not have an economy-wide substitution strategy in place. In relevant reference documents, such as the Roadmap to a Resource Efficient Europe[2], substitution is mentioned alongside mining, reuse, recycling and other strategic actions, but fact is that there is not yet an established industry network pursuing material substitution in response to price increases or supply risks of scarce materials, whereas companies active in the mining and the recycling sector do make their voice heard in related EU initiatives. At first glance, there appear to be conflicts between these multiple strategies, since the recycling business might become less profitable if certain high-value fractions of the waste are eliminated or used in lesser quantities (minimisation of CRM content). Mining companies or suppliers of CRM-based products with a strong market position can also show opposition to research on material substitution as substitution would reduce demand for CRM supply. However, from the policy perspective, these strategies are complementary, because, as shown in the roadmaps, substitution aims at the transformation of markets and products over a period of time, which is long enough for other actors to adapt to changes in the material composition of products.
2. It has been observed that companies first react to pressures on material costs by trying to minimise the content of expensive materials and only consider full substitution and a redesign of a product when minimisation is not feasible or does not solve the problem. A second short-term option available to companies is that of trying to increase the useful life of a product, which is also beneficial from the EU perspective, as it helps to decrease the overall material demand of the economy, expressed as “material intensity”. This solution, however, only fits with companies, whose business model is at least partially service-oriented or which consider durability to be one of the competitive advantages of their product. As discussed in the roadmaps, this is the case in some sectors, for example battery production for transport, but is not deemed equally relevant in quickly evolving sectors, such as electronics.
3. In the annex of the EU Resource Efficiency Roadmap it is remarked that better foresight is needed to anticipate price hikes for critical materials, which can endanger the profitability of certain sectors of industry. This is an extremely relevant question, since developing new materials and new processes is expensive and companies shy away from investing in R&D when rates of return are highly uncertain. The problem is exacerbated because prices of raw materials are greatly influenced by speculation, which, in turn, is facilitated by monopolies on the supply side and bottlenecks along the value chain, so that price forecasts are characterized by a high level of uncertainty. It is, however, possible to anticipate which materials could become a preferred playing field for speculation by analysing the mentioned bottlenecks, for example the lack of producers of rare earth magnets in the Western countries, along with the elasticity – or lack of elasticity – on the supply side and the overall trend in demand. Part of this analysis has been done by the EU expert group and has been confirmed in earlier work in CRM_InnoNet (WP 3), but was mostly limited to the present situation. Much work is still needed to obtain a clear overview how worldwide developments in all economic sectors combined will shape the future demand for materials, since the roadmaps only cover a limited number of applications, although of high strategic relevance.

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[2] COM(2011) 571, http://ec.europa.eu/environment/resource_efficiency/about/roadmap/index_en.htm

4. The expert consultations made clear that a specific, new research field “design for substitution” has to be defined to face the challenge of declining mineral resources. A higher level of cooperation between designers, material scientists and companies – or their associations – is required to deliver innovations in the material field quicker and to accelerate the market uptake of solutions that can help to reduce Europe’s dependence on imported materials and semi-finished products. New testing facilities may be necessary to guarantee that especially SMEs have access to new materials and characterization tools and such facilities should be considered in the work of ESFRI on large research infrastructure.
5. Finally, one question has been raised during the roadmapping work that cannot be answered by a single project on material scarcity. In many industries, European companies operate at the end of the value chain and import most of their semi-finished products from outside Europe. This implies that some direct substitution measures are beyond the influence of the European producers, unless Europe is able to rebuild its industrial base and to create entirely new material supply chains. Medium and large companies have the option of solving this problem by transferring part of their production in countries with abundant supply of materials, which are also often closer to growing markets. This trend has considerably weakened Europe’s industrial base and increased its dependence on imports. As one expert put it “It's a problem for Europe as a continent, companies can relocate, and Europe cannot”. But this means that it is of utmost importance to identify those actors, who could be the driving force for large-scale structural change in the European economy. Synthesizing new materials in the lab to reduce dependence on mining in developing countries may well become a cornerstone of Europe’s reindustrialization.

5. SUBSTITUTION ROADMAP – PRINTED CIRCUIT BOARDS AND ELECTRONIC COMPONENTS

5.1. CRMs used in PCBs and substitutive options

CRMs used in PCBs

Antimony (Sb): Antimony is used as a dopant in n-type silicon semiconductors, amounts used are very small (EPOW 2011). Also used as a flame retardant in PCBs.

Beryllium (Be): High performance electrical connectors use beryllium copper alloys as contacts (EPOW 2011). Beryllium is used as an alloy with copper for contacts because it is six times stronger than copper alone (Ylilammi 2013). Alloys contain around 2%, and an average PC contains approximately 2.1 grams of Be. Beryllium oxide is most commonly used as an electronic substrate. High power devices and high-density electronic circuits for high-speed computers use beryllium oxide (EPOW 2011). Beryllium oxide ceramic has an exceptionally high thermal conductivity and therefore it is used as an insulator plate between the silicon chip and the metallic package in high-power devices. Previously, BeO powder slurry in oil was used to fill power transistor packages for the same reason. Nowadays this is rare because of the high toxicity of Be. Beryllium is also a p-type dopant in III-V compounds like GaAs, AlGaAs, InGaAs and InAlAs. (Ylilammi 2013)

Gallium (Ga): Ga containing III-V semiconductors GaAs, AlGaAs, InGaAs etc. are used in high-frequency transistors, light emitting diodes and solar panels (Ylilammi 2013). Gallium arsenide (GaAs) is used in the circuitry of wireless and Wi-Fi products (EPOW 2011). The majority of gallium consumed is used in integrated circuits (Salazar & McNutt 2013). In 2010, 106 tons of gallium were used in PCBs (Peiró *et al.* 2013).

Germanium (Ge): Ge was extensively used in making the first generation transistors but nowadays this use is very small, although not completely phased out. An alloy of silicon and germanium (SiGe) is used in high-frequency diodes and transistors and also in power semiconductor devices. Ge is also used as a substrate material for III-V semiconductors for solar cells and light emitting diodes. (Ylilammi 2013) It can be used as an alternative to GaAs semiconductors (EPOW 2011). Approximately 9 tons of Ge was used in PCBs in 2010. (Peiró *et al.* 2013)

Indium (In): According to Ylilammi (2013) indium can be used as p-type dopant in silicon but is seldom used because B, Al, Ga can be used instead. Indium antimonide (InSb), indium phosphide (InP) and indium nitride (InN) are semiconductors used in infrared light detection, magnetic field sensors, fast transistors, light-emitting diodes and solar cells. Indium is used in III-V semiconductors such as InGaAs etc. for fast transistors and light emitting devices. Indium is used in several solder formulations, for example In90Ag10 can solder silver, fired glass, and ceramics. Indium is also used as a thermal interface material in the form of pre-shaped foil sheets fitted between the heat-transfer surface of a microprocessor and its heat sink (Ylilammi 2013). Around 6 tons of In were used in minor alloys in 2010. (Peiró *et al.* 2013)

Niobium (Nb): Niobium is used in ceramic capacitors.

Palladium (Pd): Palladium or palladium alloys are used as an electrode metal in multilayer ceramic capacitors (Ylilammi 2013), conductive tracks in hybrid integrated circuits and plating connectors and lead frames (CRM_InnoNet 2013b). It is a key material of multi-layer ceramic capacitors, a passive component used in consumer electronics devices such as computers. Annual demand for palladium producing these capacitors is over 15.5 tons (EPOW 2011). Pd is also used as a plating material in electronic components to improve adhesion of solders and to prevent oxidation in connectors (Ylilammi 2013).

Ruthenium (Ru): Ru is used in thick film chip resistors. The amount used is around 12.2 tons annually representing around 61% of the total supply of Ru (EPOW 2011). Ruthenium alloys are used in electrical contacts because of their good wear resistance. Metallically conducting ruthenium oxide can be used to replace platinum metal electrode in certain microelectronic devices. (Ylilammi 2013)

Tantalum (Ta): Tantalum is used as an anode metal in tantalum electrolyte capacitors where the electrolyte forms a thin layer of insulating tantalum pentoxide, which gives a very high capacitance density (Ylilammi 2013). More than 60% of tantalum is used in capacitors (Salazar & McNutt 2013), however, only 3-5% of all capacitors use Ta. It is also used in semiconductors (EPOW 2011) and resistors. Mixtures containing tantalum oxide are used in gate dielectrics of very small MOS (metaloxide-semiconductor) transistors and as dielectrics of other capacitors in integrated circuits. Tantalum nitride (TaN) is used as a diffusion barrier beneath copper metal (Ylilammi 2013).

Available substitutes

There are several substitution options for critical raw materials used in printed circuit boards. More specific descriptions of many of these methods are seen in CRM_InnoNet (2013b) report “Raw Material Profiles”.

Antimony (Sb): Antimony is used as a dopant in n-type silicon semiconductors. Other, more often used type dopants in silicon are phosphorus (P) and arsenic (As). Antimony has lower solubility in silicon than P or As do. Otherwise Sb can be readily substituted by P or As. Flame retardants are sometimes used in the polymeric constituent (e.g. epoxy) of the printed circuit boards (PCB) because the US Safety Standard UL 796 defines test procedure for flammability. Antimony in this use can be replaced by halogen or phosphorus compounds. The same applies to the plastic packaging materials of electronic components (Ylilammi 2013). In general, antimony trioxide used in flame retardants can be substituted with selected organic compounds, hydrated aluminium oxide (Salazar & McNutt 2013) or mixtures of zinc and boric oxide (Borax Firebrake ZB 2013).

Beryllium (Be): Be is a p-type dopant in III-V compounds like GaAs, AlGaAs, InGaAs and InAlAs. It can be replaced by magnesium (Mg) but the amount of dopant materials is very small (Ylilammi 2013). The use of nickel and silicon, tin, titanium, or other alloying elements or phosphor bronze alloys can substitute beryllium containing copper alloys; however, performance losses are possible. Beryllium oxide can be substituted with aluminium nitride or boron nitride (Salazar & McNutt 2013).

Gallium (Ga): Ga containing III-V semiconductors GaAs, AlGaAs, InGaAs etc. are used in high-frequency transistors, LEDs and solar panels. To some extent Ga can be replaced by aluminium (Al) or indium (In) but the resulting device properties are not identical. (Ylilammi 2013.) Ge is used as an alternative to GaAs semiconductors. Germanium materials used in the electronics industry can be produced at a fraction of the cost compared to GaAs semiconductors (EPOW 2011). The substitution of gallium in integrated circuits is currently possible for a limited number of applications, however, the substitution is limited to another CRM containing material SiGe (CRM_InnoNet 2013b).

Germanium (Ge): Silicon can substitute germanium in some electronic applications (Salazar & McNutt 2013), although this may lead to performance losses (CRM_InnoNet 2013b). Some metallic compounds can be used for high-frequency electronics (Salazar & McNutt 2013).

Indium (In): Indium can be used as p-type dopant in silicon but is seldom used because B, Al, Ga can be used instead (Ylilammi 2013). Tin-based alloys can substitute indium alloys in the least thermally sensitive applications. It is also possible to use tin-alloys for bonding on gold instead of indium alloys (CRM_InnoNet 2013b).

Palladium (Pd): Palladium or palladium alloys are used as electrode metals in multilayer ceramic capacitors. Silver or nickel can partially or totally replace palladium. Nickel is used particularly in low-voltage capacitors (Ylilammi 2013).

Ruthenium (Ru): Oxide compounds of ruthenium are used as resistive material in integrated resistors. Oxides of other metals (Ti, Ta, Ni etc.) can be used to replace Ru but the properties are not identical. Ruthenium alloys are used in electrical contacts because of their good wear resistance. Another alternative is rhodium but it is more expensive. Metallically conducting ruthenium oxide can be used to replace platinum metal electrode in certain microelectronic devices (Ylilammi 2013).

Tantalum (Ta): Before Ta capacitors aluminium was used for the same purpose and is still used at higher voltages (Ylilammi 2013). Tantalum can also be substituted with ceramic capacitors and niobium (CRM_InnoNet 2013b).

5.2. Detailed Presentation of Roadmap

The roadmap for substitution of critical raw materials in printed circuit boards and electronic components can be found in Table 3.

5.2.1. Landscape developments

Supply risks or criticality of raw materials have not been among the main concerns of the electronic components sector. The key drivers are the performance requirements as defined by the applications, including flexibility, miniaturisation, temperature resistance, short lifecycles of the products and, to an extent, price. The sector is dependent on the requirements of the end producers and to most of them substitution is not a priority topic. However, regulations, policies, sustainable image and pressure from NGOs are seen as potential drivers of substitution. So far the main focus of legislation has not been on CRMs, but on the phasing out of toxic compounds, such as lead solders. Some of the CRM or their compounds used in electronic components are potential candidates for restrictions in the future. For example Beryllium (Be) is classified as human carcinogen by IARC, and Be is on the "controlled substances" list of some consumer electronics providers. Prohibition of toxic As in GaAs components has been discussed, but there are currently no high performance substitutes for GaAs in electronic components. The forward-looking companies of the sector have also started discussions on taking into account the impact of extraction and on conflict-free material sourcing, which could enhance substitution.

Because the developments of the sector are mainly driven by the performance requirements, it is important to identify the key technology trends, evaluate their impacts to consumption of CRMs and identify the opportunities to integrate CRM substitution to these developments. The major research and development areas are new solutions to build and integrate the components as well as material and manufacturing technologies, enabling new kinds of electronics solutions and completely novel devices.

On the application side the most significant drivers of PCB and electronics market include (GBI research 2012, Ylilammi 2016):

- portable electronics (wireless devices capable of storing, processing or transmitting information)
- cloud computing leading to increasing adoption of data centres. Fast and stable connectivity is critical to cloud computing
- automotive sector, the rapid growth of the fabrication of electric vehicles (HEV and EV) as well as increase of the number of components related to safety, customization, entertainment and communication
- power electronics and smart grid utilisation
- ubiquitous electronics/Internet of Things creating new applications and markets of electronics
- defence, technological solutions and approaches developed for military sector transfer later to civil applications (e.g. millimetre wave radar systems, unmanned vehicles).

5.2.2. Market developments

The European electronic components industry has a significant impact on the EU economy both in production values and in jobs even though the biggest global actors are situated outside Europe. Europe is particularly strong in high performance electronics used in innovative industrial and professional end applications. The application sectors include transport, power, health, security and other industrial uses. Europe is also well positioned in the R&D of new manufacturing solutions and materials: printed and organic electronics, additive manufacturing/3D printing, nano electronics and system integration.

A few examples can be mentioned where the global developments have led to different types of substitution of CRM in electronic components:

- Replacement of PdAg multilayer ceramic capacitors (MLCCs) by Nickel based MLCCs in most of the applications has reduced the use of Pd. PdAg is still used in the high performance applications, especially in aeronautic and military sectors. The main driver for substitution has been the rising palladium (Pd) price. Wider substitution has been enabled by the development of ceramic materials. Also the consumption of PdAg in conductive tracks of hybrid integrated circuits has been decreased due to the miniaturisation of the circuits.
- Replacement of tantalum (Ta) capacitors by multilayer ceramic capacitors has decreased the consumption of Ta in electronics.
- Tablet and mobile phone substitution of PCs has reduced the consumption of ruthenium (Ru) in electronics. Ru is mainly used in hard discs, which are not required in mobile devices.

Currently, one of the main concerns is the use of Gallium (Ga) in PCBAs and electronic components. Due to its unique properties (higher electron mobility, breakdown voltages and saturation velocity compared to silicon-based devices) about 70 % of Ga is consumed in integrated circuits and transistors in mobile devices and networking solutions. In addition, the efficiency requirements of the power electronics applications have led to the substitution of silicon (Si) switches with wide band gab (WBG) semiconductor GaN (Gallium Nitride) or SiC (Silicon Carbide) switches, which enable high temperature operation. The use of SiC and GaN is still at the beginning because advanced switches require rethinking of power electronics design and application. Innovative packaging, topologies, new gate drive controls, and components need to be developed in order to gain vehicle benefits (USDRIVE 2013). However, it is expected that the consumption of GaN will grow significantly and be about tenfold by the year 2025 (LuxResearch 2014).

Silicon carbide (SiC) and Indium Phosphide (InP) have been studied as potential substitutes for GaAs, but both Si and In are CRMs. It has been found that InP transistors are of superior RF device performance compared with GaAs (Ylilammi 2013). First InP transistors are already commercially available (Northrop 2013). Another commercially available, CRM containing alternative for GaAs is SiGe (Gielen).

In future, large global investments in graphene and carbon nanotubes for nanoscale applications have the potential to fundamentally change electronics applications. There has been some research on graphene as a substitute for Si and potentially for Ga, but the applications are still in the early development stage. Probably graphene is not suitable for current type of circuits, which means that more fundamental changes in electronics are needed, and no short-term solutions can be expected.

A great deal of attention has also been paid to printable semiconductors. Various small molecule and polymeric organics, amorphous silicon and metal oxides (ZnO, Zn-Sn-O) etc. inorganics other than GaAs have been studied and demonstrated (Rogers, J. 2007). Until now the main focus has been to find printable materials with good performance characteristics, not substitution, but in future the development may lead to solutions that replace GaAs.

Future developments, such as the expansion of data centres and growing demand of high performance electronics may turn the consumption of Pt and Pd back to limited growth. Beryllium (Be) is a potential concern because of its criticality and toxicity. About 20 % of Be is used in electronics, mostly as BeCu alloy. Potential substitutes include alloys of Cu, Ni, Si, Sn, Cr and Ti. One example of phasing out of beryllium connectors in phones has been presented by Nokia (currently Microsoft). BeCu is still mostly used because of its performance characteristics, but there are possibilities for more extensive substitution in the future.

Substance by substance substitution strategies have in many cases turned out to be poorly suitable for electronic components, because in many cases the only substitutes with decent performance characteristics have been critical raw materials with similar properties as the original material. Therefore the most probable options for reducing the consumption of critical raw materials will take advantage of the expected future development of electronics manufacturing and material technologies, such as development of printed electronics, additive manufacturing technologies (3D printing) and nano electronics. Instead of trying to find substitutes with similar performance characteristics as the materials in the current electronic components, the new substitute solutions should offer new functionalities required by the future applications.

It is estimated that over the next ten years the advanced manufacturing methods, new material solutions and innovative concepts such as three-dimensional integration of circuits, the "System-on-Chip"[3] (SOC) concept and the infrastructure for small, locally connected intelligent systems (Internet of Things) will develop significantly. In 5-10 years they will be adopted by market leaders of selected sectors and applications. This stage is an opportunity for the countries investing in the technology development to be market leaders.

The changes in technologies and concepts offer opportunities for reduction of CRM consumption for example by further development of conductive polymers with electric properties, by development of organic inks and nanoscale solutions and by development of integrated SOC concepts and new kinds of electronics devices. The new developments do not automatically lead to reduced CRM use. For example, printed and flexible electronics may be dependent on the same critical materials as current solutions and further developments of printing technology are needed to reduce the consumption of CRMs in these cases. However, there are also development projects aiming to introduce new printed electronics materials instead of CRMs.

In twenty years, many of the early trends and techniques that begin to emerge at 10 years are expected to be more fully adopted (IDA 2012). In order to be sustainable the semiconductor industry has to radically change its manufacturing methods. One opportunity for reduction of CRM consumption may be the introduction of molecular scale electronics. Single molecule electronics is an emerging field, and entire electronic circuits consisting exclusively of molecular sized compounds are still very far from being realized (Livshits, G. et al. 2014).

[3] In the System-on-Chip concepts memory, computation, sensing, and transmission functions are integrated directly in the chip

Table 3 - Roadmap for substitution of the CRMs in PCBs and electronic components

2015	2020	2025	2030	References
LANDSCAPE: DRIVERS FOR SUBSTITUTION IN PCBAs AND ELECTRONIC COMPONENTS				
Demand for GaAs increasing , due to the growing “thirst for new gadgets” and strong trends towards higher consumption in the Asian Market. Other main drivers: smart grid utilisation, HEV, increasing adoption of data centres and energy harvesting (GBI research). The consumption of GaN (replacing Si) in power electronics (transistors, etc.) will also grow.	Market growth drivers: portable electronics, smart grid utilisation, HEV, increasing adoption of data centres and energy harvesting (GBI research).	Consumption of GaN in power electronics will be about tenfold compared to 2012 in 2024 (LuxResearch).		Vision Workshop; LuxResearch (2014): "Lux Populi Newsletter - December 7, 2014"; GBI research: "Power management integrated circuits market to 2016"; Diginova (2014) "Roadmap for digital fabrication".
Demand of Ta in capacitors has decreased due to the increased use of multilayer ceramic capacitors (MLCCs). Base metal (Ni, Cu) capacitors have substituted PdAg in lower voltage capacitors. New ultra low firing ceramic has enabled electronics manufacturers to further reduce the amount of palladium used in higher performance MLCCs (Bulliondesk 2014). Ru market has been in decrease and Pt market stabilised due to the increased use of tablets or mobile phones instead of PCs.	Trends towards hybrid mobility, growth of medical products (implantable, portable) and increased use of high-performance PCBs could lead to greater use of CRMs, e.g. Pt demand may start growing again by increasing adoption of data centres (Diginova 2014). Ni has replaced Pd in capacitors, except some high-performance applications. Some growth in the demand of Pd possible due to the growing need of high-performance applications.			Johnson Matthey (2014)PGM outlook webinar. Christoffer Scheffer (2015) Platinum Group Metals connect electronics applications. http://acceleratingscience.com/metals/platinum-group-metals-connect-electronics-applications/ Larkin, N. (2013) Ruthenium drops to 8-year low as iPad demand hurts hard disc use, http://www.bloomberg.com/news/articles/2013-09-11/ruthenium-slides-to-eight-year-low-as-hard-disk-demand-declines http://www.bulliondesk.com/gold-news/focus-escalating-palladium-costs-sees-drop-use-electronics-production-78835/#sthash.PFiTYuna.dpuf

2015	2020	2025	2030	References
LANDSCAPE: DRIVERS FOR SUBSTITUTION IN PCBAs AND ELECTRONIC COMPONENTS				
"Internet of Things": mobile internet, ubiquitous electronics, fast connectivity and cloud computing shape technology development and data storage requirement. Technologies whose future is linked with mobile internet include nano-miniaturization of electronics and optoelectronics, plastic electronics, wireless techniques and sophisticated encryption technologies, battery technology, advanced and low energy displays and new user interface designs. [Ylilammi 2014]	Ubiquitous electronics for wearable, implantable, portable, randomly shaped appliances is leading to the substitution of standard epoxy board materials by flexible, deformable, recyclable materials (flexible electronics)	Two complementary technology directions: 1) The "System-on-Chip" concept, which will integrate memory, computation, sensing, and transmission functions directly in the chip, and 2) the development of an infrastructure for small, locally connected intelligent systems. The networked sensor systems enable real-time data processing on wireless computing devices, creating intelligent and adaptive cyber environments for emerging applications such as autonomous transportation systems, and ubiquitous computing [IDA 2012].		Vision Workshop;Ylilammi (2014)-Future trends in electronic components[IDA 2012] Emerging Global Trends in Advanced Manufacturing, Institute for Defense Analyses, IDA Paper P-4603 (2012).

2015	2020	2025	2030	References
LANDSCAPE: DRIVERS FOR SUBSTITUTION IN PCBAs AND ELECTRONIC COMPONENTS				
The development of new manufacturing processes (advanced; additive; integration)		Advanced manufacturing will become increasingly globally linked as automation and digital supply-chain management become the norm across enterprise systems. This trend will be enabled by adaptive sensor networks that allow intelligent feedback to inform rapid analyses and decision-making [IDA 2012]	New advanced manufacturing processes that enable flexibility, such as biologically inspired nanoscale-fabrication processes and faster additive manufacturing techniques capable of assembling products by area or by volume rather than by layering materials [IDA 2012]. The current methods of semiconductor manufacturing will not be sustainable without cost lowering. The energy consumption and cost of the manufacturing will likely make the CMOS technology unsustainable by then. This can accelerate the development of new methods, where device materials are self-assembled utilising nanoscale phenomena [IDA 2012].	[IDA 2012] Emerging Global Trends in Advanced Manufacturing, Institute for Defense Analyses, IDA Paper P-4603 (2012).
Further reduction of size without affecting performance and efficiency (GBI research)				Vision workshop; GBI research: "Power management integrated circuits market to 2016".

2015	2020	2025	2030	References
REGIME: PCBAs AND ELECTRONIC COMPONENTS - MARKETS				
Substitution of graphite: Ultra high thermal conductivity materials for high-performance PCBs – alternatives to graphite for some types of PCBs patented (Thermasil and Electrasil)				American Standard Circuits, Inc. http://www.microwavejournal.com/ext/resources/whitepapers/2012/Thermal-Management-of-RF-and-Digital-Electronic-Devices-Feb-22-2012-Rev5.pdf?1378753220; http://www.microwavejournal.com/ext/resources/whitepapers/2012/Thermal-Management-of-RF-and-Digital-Electronic-Devices-Feb-22-2012-Rev5.pdf?1378753220; Thermally and Electrically Conductive Interface (United States Patent 7,527,873: Issued May 5, 2009); Thermally and Electrically Conductive Interface (United States Patent 7,867,353B2: Issued June 18, 2008)
Substitution of GaAs and GaN in circuitry, The electronic properties of GaAs and GaN circuitry enable use in portable devices for the power amplifiers and radio-frequency switches as well as in several high performance power electronics applications. No effective substitutes for GaAs in circuitry available	Research on i.a. SiC and InP to replace some GaAs components (Ylilammi 2014), CRM containing SiGe already on market. However Ge and In are on the EU CRM list. Research on graphene as replacement of Si and potentially GaAs, first prototypes (Hruska 2012). Potential plastics based substitutes of graphene identified (33rd Square)	Printed semiconductors relying on organic or inorganic non-CRM materials	Graphene as an alternative to Si and GaAs - first market scale applications	[EECA 2007] Arsenic and gallium arsenide are fundamental to semiconductor manufacturing. European Semiconductor Industry Association, http://hse-rohs.oeko.info/fileadmin/user_upload/Subst_Arsenic/Arsenic_Gallium_Arsenide_in_Semiconductors_ESIA.pdf, (2007). Ylilammi (2014) Joel Hruska (2012) Hype-kill: Graphene is awesome, but a very long way from replacing silicon, http://www.extremetech.com/extreme/133697-hype-kill-graphene-is-awesome-but-a-very-long-way-from-replacing-silicon Researches create graphene substitutes from plastics (33rd Square July 9 2014, http://www.33rdsquare.com/2014/07/researchers-create-graphene-substitute.html

2015	2020	2025	2030	References
REGIME: PCBAs AND ELECTRONIC COMPONENTS - MARKETS				
Substitution of Be in electronic components, Be has been substituted e.g. in some mobile phones	Phosphor bronze, alloys of Cu, Ni, Si, Sn, Cr and Ti. No substitute for high-performance applications		Substitutes with good performance characteristics on the market	
Flexible, organic and printed electronics. Current market: OLED displays (organic, not printed), first PV applications. Printed memories for simple applications.	Breakthrough of printed PV cells. RFID and memories for logistics and smart cards. Applications toys, sensors, logistics, smart packaging. Applications in health-, sport- and security sectors	Printed logic chips in portable consumer electronics. Integrated batteries and components. Memories for multimedia.	Stabile overlaying inks enable printing of whole electronic or electrical product. Directly printed active and passive devices, batteries etc. to smart objects (Oe-a). Market introduction of organic transistors and other organic electronic components (Frost & Sullivan).	JISSO Electronics Technology Roadmap Through 2020 – contacts at JEITA: http://www.jeita.or.jp/english/about/2014/profile_en_2014.pdf oe-a (2011). A roadmap for organic and printed electronics. Frost & Sullivan 2010. World printed electronics market.
Development of 3D printing of electronics (an additive manufacturing process, which automatically eliminates the need for any etching, stripping, metalizing and copper plating). Most common Sn-Cu solders contain small amount of Ge (< 100 ppm)	Conductive tracks can be printed and components mounted on a 3D substrate. Certain components can be printed - first applications batteries, antennas, sensors. New companies have come to market.	Consumption of silver (nano silver inks) in electronics production will grow when market share of the printed electronic components will grow. Cu consumption reduced. Printing of chips and memories.	Development of organic inks will enable reduction of metal use in printed electronics. 3D printing will enable printing inside the housing replacing printed circuit board. The 3D printing processes of electronics are have been industrialised.	Nano Technology Conductive Silver and Ceramic Dielectric, Caledon Controls http://www.printedelectronicsworld.com/articles/integrating-printed-electronics-and-pcb-technologies-00001553.as; Applications: http://www.caledoncontrols.com/uploads/3/0/7/8/3078706/ccd_120a.pdf; discussion: http://www.pcbdesign007.com/pages/columns.cgi?clmid=9&artid=50174&_pf_=1

2015	2020	2025	2030	References
REGIME: PCBAs AND ELECTRONIC COMPONENTS - MARKETS				
Paper-based substrates for PCBs (still in infant stage for electronics, but market entrance in health care sector).	Further developments in smart packaging, interactive magazines, etc.			Liu, J, et al (2014), "Future Paper based Printed Circuit Boards for Green Electronics: Fabrication and Life Cycle Assessment", Energy & Environmental Science, Issue 11, 2014 Rolland, J.P et al (2013), "Paper As A Novel Material Platform For Devices", MRS Bulletin — VOLUME 38 NUMBER 4, 2013, http://onlinedigeditions.com/display_article.php?id=1371716
System integration and continued miniaturisation of components and development of nanoelectronics reduce the consumption of CRMs: Integration of microelectronics, Roll-to-Roll manufacturing, and graphic printing shows promise to spawn an entirely new method of electronics manufacture for several product markets, including renewable energy, lighting, healthcare, and communications (iNEMI 2013).	Since product price is dependent on materials and manufacturing costs, graphic arts printing platforms and innovative engineering expertise promise to greatly reduce the cost of products, such as displays, sensors, and simple wireless products (iNEMI 2013). Use of self-assembly in chip fabrication is explored in the patterning process, but intense, long term research is needed [IDA 2012]. Embedded optics in PCB.		Integrated electronics, e.g. integration of electronics, sensors and batteries; offering of solutions instead of components. Self-assembly of device materials utilising nanoscale phenomena [IDA 2012].	iNEMI 2013 Research Priorities. Diginova 2014 Roadmap for digital fabrication.

2015	2020	2025	2030	References
REGIME: PCBAs AND ELECTRONIC COMPONENTS – POLICY & REGULATION				
The Commission's Materials Roadmap Enabling Low Carbon Energy Technologies Materials indicates "The development of ab-initio methods for the modelling of materials with catalytic, electrochemical, electronic or photonic functions requires a collaborative research effort". However, the roadmap mainly refers to power electronics.				
Producer responsibility: Moving from end-product responsibility to individual-product responsibility, where every individual producer in the supply chain is responsible for its products, could also enhance substitution (Source: Vision Workshop).	First generation models for assessment of the impact of extraction (Inemi Roadmap)	Exponentially expanding list of restricted materials. Effective models to make informed decisions taking into account the impact of extraction (iNEMI Roadmap 2013). Consideration in material selection and development in foregoing companies.	Impact studies using scientifically validated models are required globally and used for decision making (iNEMI roadmap)	
Conflict-material-free sourcing				Regulation conflict minerals and voluntary commitment by industry http://www.sec.gov/rules/final/2012/34-67716.pdf; OECD guideline and EU regulation: http://www.theguardian.com/sustainable-business/blog/eu-regulations-conflict-minerals-trade

2015	2020	2025	2030	References
REGIME: PCBAs AND ELECTRONIC COMPONENTS – R&D				
In Horizon 2020 research calls on CRM substitution in electronics. First projects focused on In substitution in displays.	H2020 projects on GaAs substitution on-going.		Most potential non-CRM GaAs substitutes in production	Innovative Electronics Manufacturing Research Centre (IeMRC) http://discovery.ucl.ac.uk/18106/1/18106.pdf Holden in PCB magazine 2013: http://www.magazines007.com/pdf/PCB-Jan2013.pdf
Hybrid / Integrated Optical and Electronic Interconnect PCB Manufacturing (OPCB)	Hybrid integration of electronics with other components on flexible substrates one of the R&D focus areas	Optical interconnects displace copper connects in modules and chips (Holden 2013).		
New composite materials: paper-based circuit substrate in combination with printed thermoplastic electrically conductive adhesives (ECA)				Wu, J, (2014), "Towards Practical Application of Paper based Printed Circuits: Capillarity Effectively Enhances Conductivity of the Thermoplastic Electrically Conductive Adhesives", Nature Scientific Reports http://www.nature.com/srep/2014/140903/srep06275/full/srep06275.html
Energy storage is a limiting factor in many technologies including consumer electronics, mobile computing, vehicles, remote mechanical systems and alternative energy production. If new ways to store energy at high density could be found, multiple new applications and potential for new manufactured products would be achievable [Foresight 2013].				[Foresight 2013] Foresight 2013, The Future of Manufacturing: A new era of opportunity and challenge for the UK, Project Report, The Government Office for Science, London (2013).

2015	2020	2025	2030	References
REGIME: PCBAs AND ELECTRONIC COMPONENTS – R&D				
Development of higher performance solution processable inks, such as semiconducting, OLED, PV active, etc. The increase in visibility for this field has seen the introduction of several new participants in the functional ink development field for both organic and inorganic inks that are addressing this need (iNEMI 2013).				iNEMI 2013 Research Priorities
A growing role of the NGOs is expected in boosting the development of European legislation or regulative measures in companies. An example is the SIN initiative “Substitute It Now”, an NGO driven project to speed up the transition to a world free of hazardous chemicals. The SIN List 2.1 consists of 626 chemicals that ChemSec has identified as Substances of Very High Concern based on the criteria established by the EU chemical regulation, REACH. These activities are creating awareness in industry for the need for and challenges of substitution strategies. Lead substitution in PCBs is already under way, halogen reduction sought.	Have scientifically evaluated alternatives for raw materials of concern (INEMI Roadmap).	All materials in electronics scientifically evaluated (INEMI Roadmap).		Vision workshop INEMI Roadmap 2013: new issues and Chemsec: http://www.chemsec.org/what-we-do/sin-list

5.3. Roadmap Summary and transition pathways

A short summary of the roadmap for substitution of critical raw materials in the PCBs and electronic components is presented in Figure 5 and the following paragraphs. The detailed roadmap can be found above in Table 3. Dependence on the performance requirements of a wide range of end products is characteristic to the PCB and electronics sector. Many of the applications are subject to rapid changes, which may significantly affect the consumption of CRMs in electronic components. This makes the development of a substitution roadmap for the sector challenging, which should be kept in mind when studying the roadmap.

Development of substitution solutions with new performance characteristics can be an opportunity to the European electronics industry, which is particularly strong in high performance electronics used in innovative industrial and professional end applications. In addition, Europe is well positioned in the R&D of new manufacturing solutions and materials.

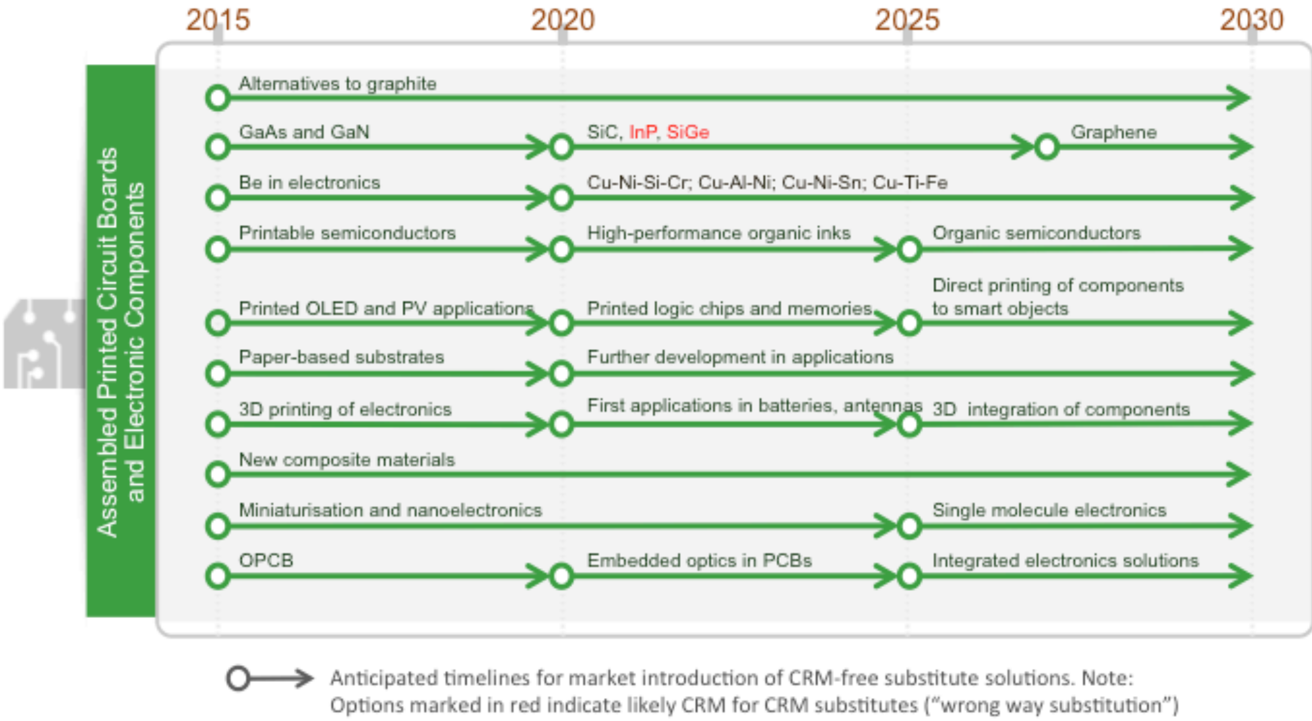

Figure 5 – Transition pathways for CRM substitution in PCBs and electronic components

It seems that current R&D projects related to PCBs are focused on component innovations and development of manufacturing methods, rather than the actual replacement of CRMs in printed circuit boards and electronic components. Nevertheless, there are examples where substitution has happened; in some cases due to price developments or legislative prohibition of materials, in some cases due to the market introduction of new kind of devices.

The on-going development of the manufacturing methods creates possibilities for reduction or substitution of CRMs in new solutions offering totally new functionalities, which are required by the future applications. Potential transition pathways include development of organic inks contributing to wider introduction of organic electronic components, 3D printing enabling direct printing of components inside the housing and thus replacing printed circuit board, and three-dimensional integration of components, such as electronics, sensors and batteries. Also continued miniaturisation of electronics will further reduce the consumption of CRMs.

Both graphene and printed electronics are potential candidates to enable substitution of Ga in electronics in the medium or long term. Several different alloys have been investigated for substitution of BeCu in electronics, see Chapter 8.4. Further development is needed, because the current substitutes lead to reduced performance of the components.

6. SUBSTITUTION ROADMAP – PERMANENT MAGNETS BASED APPLICATIONS

6.1. Detailed presentation of 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 6.

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 6 and the explanations in the caption.

6.2.1 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 IE2 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[4].

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.[5] 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.

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.[6] 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

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

[5] 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)

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

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.

6.2.2 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. Direct Drive (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 in the market, too. In addition, wind turbines employ some general purpose motors.[7]

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

[7] C.f. 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.

should have allowed for the use of permanent magnets that do not require dysprosium,[8] 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 (yttrium barium copper oxide). 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 (AML) 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.

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

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

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.

6.2.3 Hybrid and electric vehicles (H&EV)

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.[9] Direct Current (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 3 – 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: own compilation based on company information by BMW, Fiat, Ford, Honda and Renault, VDI Nachrichten 2013, Chau and Li 2014; HPMSR - Hybrid Permanent Magnet excited and Synchronous Reluctance Machines

[9] 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”.

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 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 cease 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 has the potential to become the dominant technology for vehicles from 2025 on as a result of much stricter emission standards. 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.[10] 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.

6.2.4 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 direct current (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.

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

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.

6.2.5 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 as 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.

Table 4 - Roadmap for substitution of CRMs in electric motors and drives

2015	2020	2025	2030	References
LANDSCAPE: 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-sectorial 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
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

2015	2020	2025	2030	References
LANDSCAPE: OVERARCHING DEVELOPMENTS INFLUENCING LONG-TERM REE SUPPLY AND DEMAND				
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: 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
GENERATORS FOR WIND TURBINES: POLICY & REGULATION				
Wind energy EU targets: onshore/offshore 11.4 /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
GENERATORS FOR 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: 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 & 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)
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)

2015	2020	2025	2030	References
ELECTRIC MOTORS FOR TRANSPORT: R&D				
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
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

2015	2020	2025	2030	References
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
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
GENERAL APPLICATIONS: 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
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

2015	2020	2025	2030	References
GENERAL APPLICATIONS: R&D ON REE-FREE MAGNETIC MATERIALS				
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
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

6.2. Roadmap summary: 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.

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 PMs.

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”).

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.

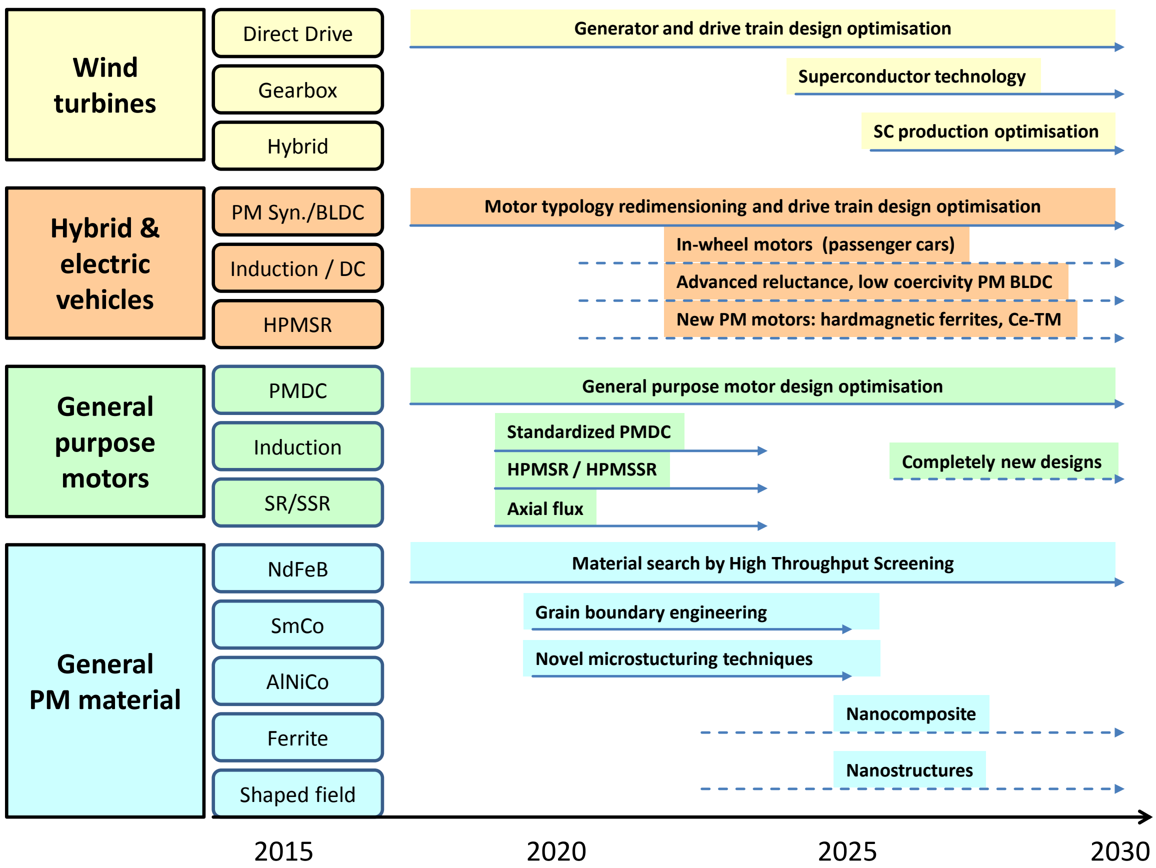

Figure 6 – Transition pathways for CRM substitution in Electric Motors and Drives Note: technologies already in the market: in front of the vertical 2015 line; ongoing processes: from today (started before) until 2030; earliest possible future market introduction: ring; full arrow: market introduction 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.

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.

7. SUBSTITUTION ROADMAP – BATTERIES AND ACCUMULATORS

7.1. Detailed presentation of roadmap – batteries and accumulators

7.1.1 Landscape developments

The priority field "batteries and accumulators" needs to be divided into three groups of products, which obey to different drivers and face a variety of challenges related to regulation, market and technology:

1. Batteries for hybrid and electric transport
2. Batteries for stationary electricity storage
3. Portable and wearable batteries and accumulators

Electrification of practically all types of transport modes is recognized by basically all experts as a strong driver for the development of new batteries with improved performance and durability. Although market uptake in the automotive sector has been slower than anticipated, the parallel developments in other transport modes (e-bikes, forklifts…) promise a likely strong uptake in the future and, with this, a potential increase in demand for CRM-based batteries. Li-ion batteries are expected to dominate the market in the coming couple of decades, whereas NiMH batteries are likely to lose market shares, as the major carmakers, except for Toyota hybrid, have progressively switched to Li-ion batteries. Longer electric range will also push the shift to Li-ion. At the 2030 horizon, hydrogen & fuel cells vehicles may become an important trend, partially shifting the CRM focus away from batteries to PGM-content in Fuel-Cells (FC), if platinum-content of FC has not been drastically reduced or substituted by then. Momentum of the market, together with possible FC/Battery hybrids, will, however, maintain attention focused on the CRM-content in battery technologies.

Transport applications currently strongly drive battery developments, due to the perspective of future and continuous market growth. The primary focus is on cost reduction and security, while maintaining good performances (power density – in particular for public transportation, and energy density – driving range).

In the case of **stationary electricity storage,** there is a high level of uncertainty with respect to future demand. Grid-integrated batteries are still facing strong hurdles in the market, but there is a growing demand on industrial sites, from telecom and the medical sector. A strong shift in market trends is feasible before 2030, or around the 2030 horizon, that may create strong demand around the end of the considered timescale (2030).

Due to a somewhat uncertain timescale and short-term demand volumes, specific R&D efforts on stationary storage are very limited and not driving battery research. Except for very specific technologies (ex. redox-flow batteries, high-temperature batteries), stationary storage is perceived as a "follower", benefitting from the advances in other applications (e.g. transport). Primary characteristics for stationary storage are cost, durability and security (but in a less demanding environment than that in which other applications operate).

The **portable and wearable batteries and accumulators markets** appear to be much more dynamic, both in terms of market demand (portability of devices) and in terms of technology push. While customer portable electronics (tablets, smartphones, etc.) will continue to provide a strong market base and show steady growth, other, more specialized applications, will develop, e.g. the “wearable/shapeable” field, taking advantages of new manufacturing processes, or specific technologies for e.g. active energy harvesting, although these technologies still have to improve their efficiency and attract investments.

Portable electronics will remain a mainstream and high-value application for batteries (on a per-unit basis), driven by the customers’ interest in increasing functionalities – and thus energy needs – of the portable devices, while seeking improved autonomy. In this area, cost is perceived less sensitive than in other applications (transport, stationary), but there is a strong focus on performance from the energy content stand-point (density & volumetric). In relation with the development of new manufacturing processes, increased *usability* is also sought in the ability to better shape and ultimately possibly wearable batteries.

Specific applications like energy harvesting are also investigated, the driving factors behind these developments being regulatory pressures and policies promoting a low-carbon society, but also new production techniques such as 3D-printing.

There is a possibility that some of these technology advances then spread to other uses, for example in the transport sector. The focus of innovation in this market appears however more on the process side – new manufacturing processes enabling improved performances and overall usability of batteries – although material research for improved autonomy is also pursued.

7.1.2 Main performance drivers in the different markets

Drivers for technology developments of a battery system can take several forms, for example:

- Cost
- Safety
- Energy density / power density
- Life-cycle
- Maintenance
- Ease of use (e.g. for electric cars)
- Reliability (e.g. for emergency generators)
- Packaging
- Sustainability (environmental friendly, using available raw materials)
- Macro-economic and regulatory conditions, customer preferences…

Overall, *cost, performance* and *safety* are the three main drivers pursued in the different markets. Their respective priority, and detailed content, however varies depending on the applications:

- Transport applications focus on *cost* and *safety*, with stringent requirements for energy density. This is due mostly to the relatively large amount of energy storage required for electric transportation, generating costs and potential risks due to the energy contained. Mitigation of energy density may be acceptable, as long as it does not impact the need of a minimum autonomy of the vehicle.
- Stationary applications focus on *cost* & *durability*. This relates to the need for low-cost storage solutions for stationary storage to become competitive in the long run.
- Portable batteries focus on *energy density* and *safety*, being a high-value customer-driven market.

Due to the transport sector being the key driver for battery R&D today, efforts are currently put mostly on improving cost and safety, while maintaining/improving performances.

7.1.3 Implications for demand of CRMs

The trend towards Li-ion batteries in transport will increase demand for cobalt, natural graphite and fluoride (derived from CRM fluorspar).

Although lithium supplies are probably sufficient and accessible, bottlenecks may arise along the supply chain, as one supplier, SQM, presently has a dominant position in the market. Due to this corporate and geographic concentration and the fact that some future battery chemistry may use more lithium (e.g.. lithium metal electrode), there is a question in the battery industry whether lithium should also be considered as a “CRM”.

CRM-related drivers

As of today, the impact of CRM-identified materials appears to be limited in the battery industry. No specific efforts or intents have been identified to steer away from these materials. From the industry point of view, although there is a conscience of material criticality, no strong material-related issue is yet affecting energy storage applications. The evolution of battery chemistries and technologies is driven by market needs. A question remains open concerning lithium-related[11] supply risk, mostly due to the importance of this material in today’s Li-ion technology. If supply issues arise, they are assumed to be temporary and would just slow-down deployment in some end-markets. However, neither cobalt, graphite or fluoride (Li-ion) are seen as truly “critical” from the industry point of view, nor are REE (decreasing NiMH market) or antimony (limited growth of lead-acid market).

If actions are taken, these are more in the domain of securing supplies (e.g. company-level, to country-level alliances), rather than carrying out long-term R&D on substitute materials. An effort to reduce the cobalt content exists, but is mostly related to cost-reduction objectives with respect to automotive applications.

7.1.4 Interpretation of the roadmap table

The table below identifies potential substitution technologies that may exist at different time-horizons. These are not intended to be “objectives” to be reached, but aim at identifying potential substitute technologies *that may exist at different time-frames, based on the natural dynamics of the market and research, and may provide an alternative to a potential CRM issue.*

The time scale indicated for the different technologies attempts to capture the maturity of their respective development. Given the multiplicity of potential alternative technologies, no assumption is made whether a given technology has more chances for a “break-through” than another one. Difference may however arise with respect to specific markets, in line with the present perception of the strengths/weaknesses of each technology.

Obviously, the vision of market technologies at the horizon 2030 is highly uncertain, and should be considered as such.

[11] Copper has also been quoted, in the more general context of electric vehicles.

Table 5 - Roadmap for substitution of CRMs in batteries for transport

2015	Substitution Strategy	Horizon 2020	Horizon 2025	Horizon 2030	Facts/Example of actors involved
REGIME: TRANSPORT - MARKETS					
Lead acid batteries dependence on Antimony (Sb):	New technology for substance	- Some reduction of Lead-acid battery market on emerging uses: e.g. Li-ion will equip some stop-start systems - Current 12V Lead-acid batteries likely to maintain their position as start-up-type batteries (standard)	- Reduction of Lead-acid batteries share on emerging use: e.g. increasing Li-ion batteries in transport applications - Current 12V Lead-acid batteries likely to maintain their position as start-up-type batteries (standard) - Possible reduction of Sb in Lead-acid batteries	- Lead acid 12V batteries remaining used (e.g. start-up batteries), but being progressively substituted. Other transport applications with high energy requirements substituted by Li-ion - Progressive replacement of 12V Lead-acid batteries by other technologies - Potential removal of Sb in Lead-acid batteries	EUROBAT study (2014): Lead-acid battery remaining a key technology for automotive industry in the foreseeable future
NiMH dependence on REE & Co	New technology for substance	- Decrease of NiMH market and substitution by Li-ion in the car industry	- Decrease of NiMH market and substitution by Li-ion or possibly NiZn as backup solution in the car industry, related to the increased need for electric autonomy.	- Substitution by other technologies (no perceived long-term niche in transport).	BASF acquired in 2012 Ovonic Battery Company, a leading producer of NiMH battery technology
PEM fuel cells dependence on PGMs	Substance by substance	- Fuel cell car→ PEMFC with Pt based catalyst	- Fuel cell car → PEMFC with reduced Pt catalyst loadings: alloys and core shell nanomaterials (w/ & w/o Pt)	- Fuel cells in several transport media →PEMFC with PGMs free catalyst (e.g. alkaline anion exchange membrane fuel cells)	Toyota's **fuel cell** sedan car will go on sale in Japan and California in 2015, but the company has added the UK, Germany and Denmark to the list.

2015	Substitution Strategy	Horizon 2020	Horizon 2025	Horizon 2030	Facts/Example of actors involved
REGIME: TRANSPORT - MARKETS					
Li-ion dependence on Co, natural graphite & fluorspar	Substance by substance	- New generation Li-ion batteries → Cathode: Substitution of Cobalt by other elements: Mn, Fe, Ni…(eg. LFP, NMC) → Anode: Substitution of natural graphite by synthetic graphite or anode with low Si content → Electrolyte: remains likely F-based	- Advanced Li-ion batteries → Cathode: Reduction of Co by Lithium-rich cathode (low of no Co). Polyanionic compounds (e.g. Fe/Mn/Ni-PO_4/SiO_4/CO_3/BO_3). → Anode: Substitution by silicon or Lithium-metal → Electrolyte: remains likely F-based	- Advanced Li-ion batteries → Electrolyte: Possibly substitution of fluoride based electrolytes (although no specific research on this)	TESLA (the Gigafactory to reach capacity, demand from the battery sector could increase by as much as 152% in the graphite market, 50% in the lithium market and 17% in the cobalt market, relative to 2013 levels) The European Green Car Initiative (EGCI) multi-annual roadmap details the milestones for energy storage systems in order to achieve the overall target for the electric vehicle. There is a particular milestone (by 2020) related to the "availability of batteries providing tripled energy density, tripled lifetime and 20-30 % of 2009 cost and matching V2G".
	New technology for substance (in the case of post-Li batteries like Li-S, metal-air, Na-ion,…)	- Lithium-Metal Polymer technology (no Co, possibly Graphite) - Possibly ZEBRA batteries (no CRM identified), as backup solution, but only for big vehicles - Possibly marginal PEMFC (but Pt use)	- Possibly first Li-S batteries in the automotive market (no CRM). Possible hybridisation with supercaps. - Limited PEMFC (but Pt use)	- Li-S batteries (no CRM) but no advantage in terms of mass, possible hybridisation with supercaps - Metal-air batteries (Li-air, Zn-air, Al-air…)→ without critical materials if cyclability and PGM dependence are solved. - Na-ion, Mg-ion batteries (in case of pressure on Li) - Solid-state batteries (uncertainty on CRM content, but some chemistry should be w/o CRM) - PEMFC cars may take-over the growth over "battery" cars at the 2030 horizon.	Volkswagen, in their roadmap for high energy batteries has identified a short term increase in Li-ion battery energy density to about 220 Wh/kg (compared to the 170 Wh/kg in the today cells) Beyond that, the Group is looking to Li-S (500 Wh/kg) and Li-air (1,000 Wh/kg) as future solutions. SAFT developing FLP batteries. Bolloré Group developing LMP batteries, already used in car sharing. Toyota first mass-market Fuel-Cell car on sale early 2015.

Table 6 – Substitution options in the stationary battery market

2015	Substitution Strategy	Horizon 2020	Horizon 2025	Horizon 2030	Facts/Example of actors involved
REGIME: STATIONARY MARKETS					
Lead acid batteries dependence on Antimony (Sb):	New technologies for substance	- Decrease of Lead-acid battery applications → substitution by Li-ion, NaS and 1st generation redox flow batteries - Decreasing use of Sb in lead-Acid batteries, through the evolution towards valve-regulated lead-acid batteries (no Sb)	- Decrease of Lead-acid battery applications → substitution by Li-ion, NaS, Zn-air, 2nd generation redox-flow and NiZn batteries - Valve-regulated lead-acid batteries (no Sb)	- Only niche markets for Lead-acid batteries in stationary applications (if any) → substitution by Li-ion , NaS, NiZn, Li-S, Na-ion, metal-air and 3rd generation redox-flow batteries…	Battery cost decrease expected for high-performing technologies like Li-ion: $150-200/kWh expected by 2025-2030, making them competitive.
NiCd batteries dependence on cobalt (Co) → 1 % wt. at the cathode	New technologies for substance	- Replacement of NiCd batteries by NiMH and Li-ion batteries			Directive 2006/66/EC: the sale of consumer NiCd batteries is banned within the EU except for medical use; alarm systems; emergency lighting; and portable power tools.
NiMH dependence on REE & Co	New technologies for substance	- Decrease of NiMH market and substitution by Li-ion	- Decrease of NiMH market and substitution by Li-ion, or NiZn	- Possibly only niche markets for NiMH batteries → substitution by Li-ion, or NiZn	Battery cost decrease expected for high-performing technologies like Li-ion: $150-200/kWh expected by 2025-2030, making them competitive. PowerGenix positioning on NiZn batteries for stationary storage

2015	Substitution Strategy	Horizon 2020	Horizon 2025	Horizon 2030	Facts/Example of actors involved
REGIME: STATIONARY MARKETS					
Li-ion dependence on Co, natural graphite & fluorspar	Substance by substance	- New generation Li-ion batteries → Cathode: Substitution of Cobalt by other elements: Mn, Ni, Fe…(eg. NMC) → Anode: Substitution of natural graphite by synthetic graphite or anode with low silicon content → Electrolyte: remains likely F-based	- Advanced Li-ion batteries → Cathode: Reduction of Co by Lithium-rich cathode (low or no Co). Polyanionic compounds (e.g. Fe/Mn/Ni-PO_4/SiO_4/CO_3/BO_3) → Anode: Substitution by silicon or Lithium-metal → Electrolyte: remains likely F-based	- Advanced Li-ion batteries → Electrolyte: Possibly substitution of fluoride based electrolytes (although no specific research on this)	See examples of transport sector for some technologies. German company Gildemeister reportedly sold more than 50 of its edox-flow CellCube devices in Europe and Asia. NGK insulators manufactures and sells NaS batteries. FZ Sonic, a venture from MES-DEA and FIAMM planned to develop a line of Zebra batteries for stationary applications.
	New technology for substance (in the case of post-Li batteries like Li-S, metal-air, Na-ion, etc.)	- Lithium-Metal Polymer technology - NaS batteries → no critical materials - ZEBRA batteries → no critical materials - 1st generation Redox flow batteries (Zn/B, vanadium, etc.) → no critical materials	- Possibly first Li-S batteries in the market (no CRM) - Use of PEMFC as complement or substitution to batteries. PEMFC + supercap hybridation may substitute to batteries - Possible Power-to-gas (hydrogen or methane) in link with market development - Possibly first Na-ion batteries (in case of pressure on Lithium) - 2nd generation Redox flow batteries → no critical materials	- Li-S batteries (no CRM) - Advanced metal-air batteries (e.g Li-air; Al-air, Zn-air…)→ without critical materials if cyclability and PGM dependence are solved. - Mg-ion - 3rd generation Redox flow batteries → no critical materials - Solid-state batteries (uncertainty on CRM content, but some chemistry should be w/o CRM) - Possibly first market introduction for liquid-metal battery technology - PEMFC electrolysis for storage (may take-over the growth over "battery" stationary at the 2030 horizon)	

Table 7 – Substitution options in the portable batteries market

2015	Substitution Strategy	Horizon 2020	Horizon 2025	Horizon 2030	Facts/Example of actors involved
REGIME: PORTABLE MARKETS					
NiMH dependence on REE & Co	New technologies for substance	- Only niche markets for NiMH batteries → substitution by Li-ion	- Li-ion batteries		
Li-ion dependence on Co, natural graphite & fluorspar	Substance by substance	- New generation Li-ion batteries: → Cathode: Reduction of Cobalt by partial substitution by other elements: Mn, Ni…(e.g. NMC). But Co remains important for performances in this market. → Anode: Substitution of natural graphite by synthetic graphite or anode with low Si content → Electrolyte: remains likely F-based	- Advanced Li-ion batteries: → Cathode: Increased reduction of Cobalt by partial substitution by other elements. Cobalt remains important for performances. Possible reduction of Co by Lithium-rich cathode (low or no Co) → Anode: Substitution by silicon or Lithium-metal → Electrolyte: remains likely F-based - Possibly micro-PEMFC (Pt content)	- Advanced Li-ion batteries: → Electrolyte: Substitution of fluoride based electrolytes	
	New technologies for substance			- Possibly Metal-air batteries (e.g. Li-air, Al-air,…), but with performance mitigation and if cyclability and PGM dependence is solved.	

Table 8 - Roadmap for substitution of CRMs in batteries - regulation

Regulations influencing the markets

The following elements identify some examples of regulations influencing the regime-level dynamics.

REGIME: REGULATION	
REGIME: REGULATION	➢ Regulation for storage under review in the EU: The legal framework for governing storage is identified at European level in the 3rd Package Electricity Directive but there are, at national level, other laws under development which will regulate electricity storage application. Where it is regulated, the regulation is done within the ancillary services market. ➢ In May 2013, Germany introduced a €25 million storage subsidy programme, providing financial support to all photovoltaic systems containing battery energy storage (BES) that are installed in Germany in 2013 (with a maximum capacity of 30kW). The programme gives subsidies via low-interest loans from state-owned KfW bank and principal grants from the Environment Ministry. The subsidies amount to €660/kW of solar power for each system, improving the economic logic for BES take-up in the residential and commercial sector. ➢ EU regulations on emissions for transport is an indirect driver for EV/HEV market push. Below a certain level of emissions, which is already in the regulation roadmap, electrification is the only solution to meet the emission requirements. ➢ Combination of regulations like Transport emissions and RES storage may lead to positive business cases for batteries for electric vehicles (as a 1st life) and for stationary RES storage (as a 2nd life), on a "single" product. ➢ In October 2013 the California Public Utilities Commission unanimously approved its proposed mandate[12] that will require the state's big three investor-owned utilities to add 1.3 gigawatts of energy storage to their grids by decade's end. ➢ Progress on the ban of some substances (e.g. Lead, Cadmium) is always possible in the future, but unlikely due to cost constrains and good material recovery today. Some regulatory pressure, like constrains related to REACH (e.g. on Nickel), may however influence the use in non-mainstream technologies. ➢ Possible shift of political majority in countries like the US, with potential impacts on policies on renewable energy, and the consequent market impact.

[12] http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M078/K929/78929853.pdf

Table 9 - Roadmap for substitution of the CRMs in batteries – R&D

The following table identifies the timing of the main R&D efforts with regard to the different technologies considered. It has been considered that this effort takes place with a typical 5-year lead-time with respect to potential market availability of the technology.

Topic		Horizon 2020	Horizon 2025	Horizon 2030	Facts/Example of actors involved
REGIME: R&D					
"Li-ion" batteries	Co-reduced cathodes	Lithium-rich cathode Polyanionic compounds			Joint Center for Energy Storage Research (JCESR) - $120 million over five years to investigate in post-li batteries.
	Anode formulations without natural graphite	Silicon anode Lithium-Metal anode Graphene and novel 2D layered materials			
	Electrolyte		New Fluoride-free/F-reduced electrolyte formulations (if pressure on Fluoride)		
(non-Lithium)-ion batteries		Na-ion batteries	Mg-ion batteries		
Lithium-Sulfur batteries		Li-S batteries			
NiZn batteries		NiZn batteries			
Redox-flow batteries	Not CRM-dependent (except perflourinated membranes in some cases)	2nd Generation Redox batteries	Organic redox flow batteries / 3rd Generation Redox batteries	Ionic liquid flow battery	

Topic		Horizon 2020	Horizon 2025	Horizon 2030	Facts/Example of actors involved
REGIME: R&D					
High-temperature batteries (molten salts)	Not CRM-dependent. Awaiting stationary market development.				
Metal-air batteries	Not CRM-dependent	Zinc-air battery	Iron-air battery Lithium-air battery Sodium-air battery		
"Low-cost" batteries			e.g. Liquid metal batteries		Need for very-low cost storage systems likely to develop in link with RES energy storage.http://www.iflscience.com/technology/new-liquid-metal-battery-will-make-renewables-competitive
Other storage types		Power-to-Gas technology	Solid-state batteries		
PEM fuel cells	Non-PGMs catalysts in the electrodes. 2D-layered materials for the electrodes: graphene, metal dichalcogenides, MXenes)	Mixed oxides with catalytic properties for ORR and OER μ-PEMFC	High-grade quality graphene produced at competitive prices	PEMFC electrodes based on novel 2D layered materials: improved durability and conductivity. Pt-group free catalysts for PEMFC	Graphene Flagship community, see Novoselov 2012 Drexler Univ. (MXenes)

Table 10 - Roadmap for substitution of the CRMs in batteries – niche level

Niche level stimuli

The following examples identify Niche-level small signals that have been identified as possible hints of wider tendencies that could influence the storage market or offering in the future.

Trend	Horizon 2020	Horizon 2025	Horizon 2030	Facts/Example of actors involved
NICHES (Examples)				
Own car in large cities no longer desired / affordable. Development of car-sharing				Urban population (40% of the EU27 population, Eurostat 2012). Limited impact foreseen for the coming 15 years. Due to cycle-life of batteries, development of car-sharing is not seen as decreasing the need for batteries.
3D printing				General method, not specific to batteries. Can be useful for prototyping but not at this point for volume production, which needs speed and high reliability.
Possible multiple life of battery product : e.g. second life of automotive battery in stationary storage. Second-hand market development for batteries (if standards).		Likely to develop with the material deployment of batteries in link with electric vehicles and the end of their first "life-time" (~10 yrs).		
Potential convergence and interaction of stationary and vehicle storage (e.g. smart charging).		Likely to develop once a material EV penetration is reached, and significant need is felt for stationary storage		
Flexible & conformable batteries				

Trend	Horizon 2020	Horizon 2025	Horizon 2030	Facts/Example of actors involved
NICHES (Examples)				
Replacement of stationary batteries by an energy vector conversion: Power-to-Hydrogen, Power-to-Methane and either gas storage or injection in the gas grid. (By 2030)		In link with development of the need for grid-related stationary storage		
Energy efficiency in buildings	To develop in link with decentralized (local/individual) RES production, and the development of the “prosumer” (producer/consumer) trend in RES.			
Unexpected events (ex. fire in an electric transportation), in particular related to safety perception or environmental concerns				Anytime risk. E.g. fires that took place on NaS battery systems in 2010 and 2011. Such occurrence may have strong consequences on the perception of battery use, and thus speed of acceptance for specific applications.

7.2. Summary of substitution potentials: transition pathways

Key storage technologies rely today on CRMs. Some material dependence like NiMH (rare earths) or Lead-Acid batteries (antimony) should not be problematic according to the developed roadmap: the NiMH market is seen as decreasing in the medium term, and the market share of Lead-Acid technology in the growing applications of energy storage is deemed to be limited in the future to antimony-free designs (valve-regulated batteries for stationary storage). Current Lead-Acid battery uses such as 12V automotive batteries are likely to continue, but are already well addressed today in terms of collection and recycling, mitigating the material risk. Li-ion technology on the other hand is considered as the current key technology for the majority of short, medium and possibly long-term applications and suffers from historical dependence on cobalt and natural graphite for the electrodes, and fluoride for the electrolyte. Concerns also exist in the industry on whether lithium itself could be considered a CRM, due to a high geographic and corporate concentration of production in South-America.

In practice, numerous technologies/chemistries co-exist today even within the Li-ion family, with differences in material compositions. Due to huge future market potentials, technology developments are very active and lead to a high diversity of battery chemistries and solutions available today. This is also stimulated by the different markets addressed, each with its specificities: the main ones being transportation (electric/hybrid vehicles), portable electronics, and stationary storage. New generations of batteries are also actively investigated, which creates a rich panel of potential CRM-reduced or CRM-free options for the medium-term, even though these may also have an influence on cost or performance.

With its short-term potential uptake, electric transportation is currently driving technology developments of batteries, with a major focus on security and cost, and to some extent energy density (autonomy). Li-ion is seen as dominant in this market for the coming two decades, with performance drivers currently leading to a reduction of the cobalt use, either partially (e.g. NMC, NCA, etc.) or totally (e.g. LFP). Natural graphite is not seen as a strong issue (possible substitution by synthetic graphite or new generations of anodes - e.g. silicon, Li-metal), but no specific effort is made to reduce the use of fluoride. From 2025 on, other non-Li-ion technologies (e.g. Li-S, Metal-air, hydrogen…) may start to be introduced depending on performances and market conditions, broadening the range of possible technology-based substitution.

Portable electronics is already today a strong market, with continuous strong growth. It is mostly driven by an energy density requirement and has a lower sensitivity to costs, which makes it strongly dependant on cobalt-based Li-ion chemistries. Performance mitigation is seen to be harder in this market, which makes it less favourable to substitution in the short term.

Stationary storage, which is today restricted to specific uses (e.g. industrial sites, hospitals, etc.), is seen as a huge market potential related to the increasing penetration of renewable energy sources (PV and wind energy). There is, however, a high uncertainty on the actual timing of this market opportunity, the 2030 horizon used in the roadmap being possibly the time for such a market shift. The main drivers for such stationary storage are lifetime-cost of storage, along with security. Current storage solutions need to improve their cost/lifetime characteristics to facilitate the development of this market. Li-ion is a possible candidate for such storage, but other technologies exist (e.g. redox-flow batteries, molten-salt batteries) or should become available (e.g. metal-air, hydrogen and more generally power-to-gas) at the foreseen 2025-2030 time horizon, likely waiving any CRM-related constrains, if R&D is able to deliver solutions on time.

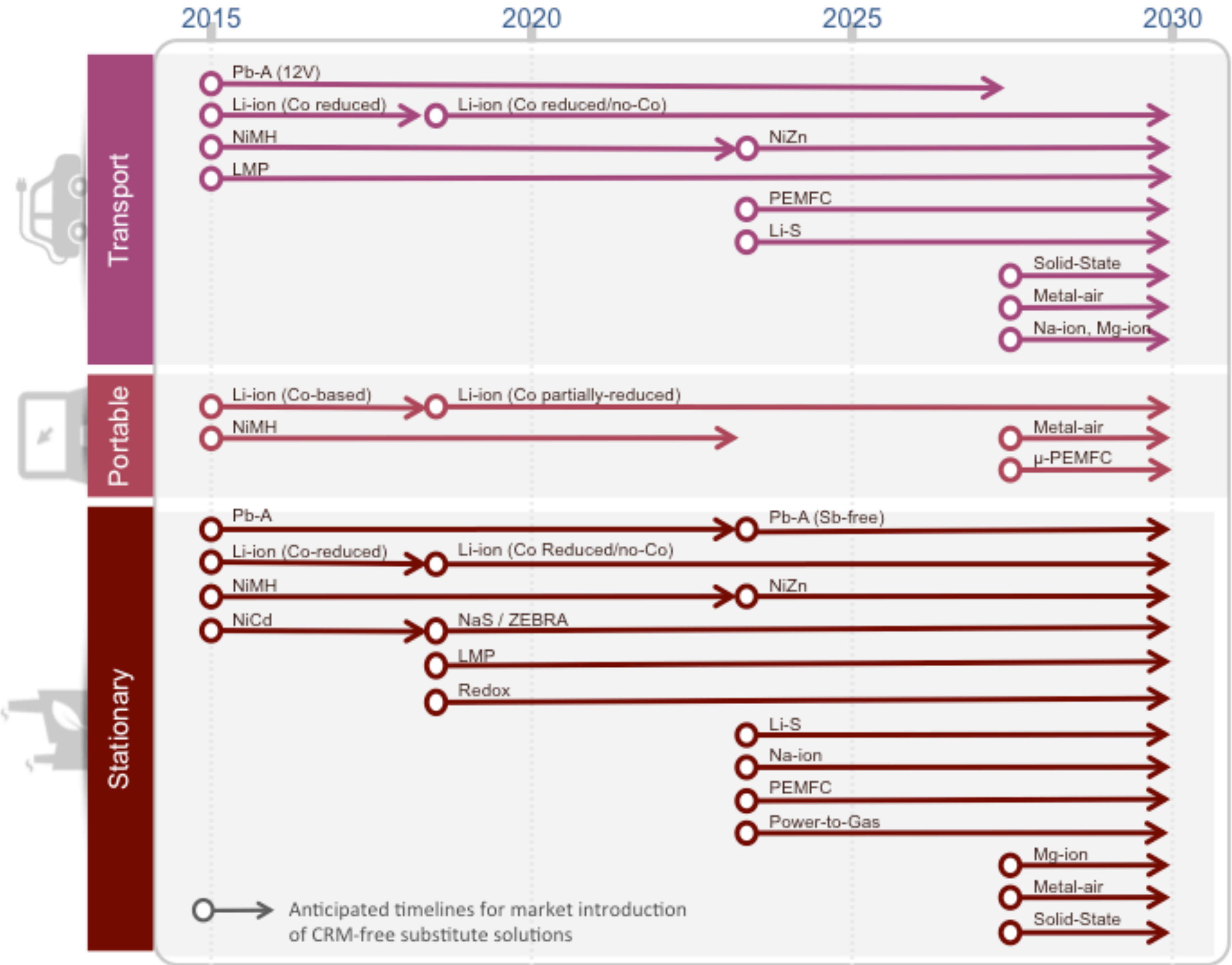

Figure 7 - Transition pathways for CRM substitution in Batteries & Accumulators[13]

Overall, despite the general evolution towards Li-ion, and thanks to the diversity of the Li-ion battery technologies, CRM-related dependence is seen as not highly critical although some constrains exist. Li-ion energy storage offers *some* protection today and in the near future against cobalt- and graphite-related material issues, although this may come with an impact on performances or costs, possibly affecting specific markets. Particularly portable electronics, but also to some extent transport (due to the volume of material required), are seen today as sensitive to cobalt and with no off-the-shelf substitution options with maintained performances available in the short term.

Apart from awaiting new storage technologies, nothing is however done concerning the use of fluoride.

At the medium (2025) or longer (2030) term, several other storage technologies are likely to be introduced, increasing the number of alternatives in case of material issues. If lithium was experiencing supply risks, which is not the case today, short-term and medium term substitutes would be harder to find and significant alternatives would likely only be available around the 2025 timeframes with non-Lithium storage technologies development (e.g. Na-ion, metal-air, hydrogen…).

[13] It is considered in this graphic that a given technology may be substituted by another technology co-existing in the same calendar period. No preferential substitution is assumed.

8. SUBSTITUTION ROADMAP – HIGH-VALUE ALLOYS

8.1. Drivers for substitution

The amount of structural materials produced is several magnitudes bigger than the amount of functional materials. The development of alloys for structural (non-functional) applications is generally a slow process: Alloys used as structural materials like the advanced steel and aluminium alloys used in the automotive sector, the alloys used in medical applications and in aerospace have been developed over the last 50 years. Supply uncertainty, legislation, environmental regulations and price increases are perceived as a driver for substitution, especially in the case of niobium, tungsten and cobalt, but substitution is costly and the return on investment is unclear. Europe’s capacity to respond is furthermore restrained by the fact that many components containing CRMs are imported by OEMs and because companies are not aware of risks in their supply chain. The strongest driver of substitution of CRM is cost and in some cases legislation due to for example toxicity of a substance.

8.2. Landscape developments

There are trends in the use of structural materials, like the focus on lightweight materials in the transport sector that is expected to continue. Experts are not certain about future developments in the aerospace industry, but do not expect major changes to occur before 2030. In the case of material demand by the automotive industry, a greater use of high-strength alloys can be expected, but also of alternative materials, such as aluminium or carbon fibres. The use of higher-strength steel in the automotive industry may face certain challenges related to downstream processing of the advanced high strength steels, such as forming of the body, welding and coating. Weight considerations could work in favour of using greater amounts of aluminium, whereas an extended use of carbon fibres will take time to implement, due to the necessary changes to the overall design of the vehicle.

Figure 8 shows the present trend in steel development and the improvements expected from the new generation of advanced high-strength steels, which the industry expects to gain market shares in the coming years.

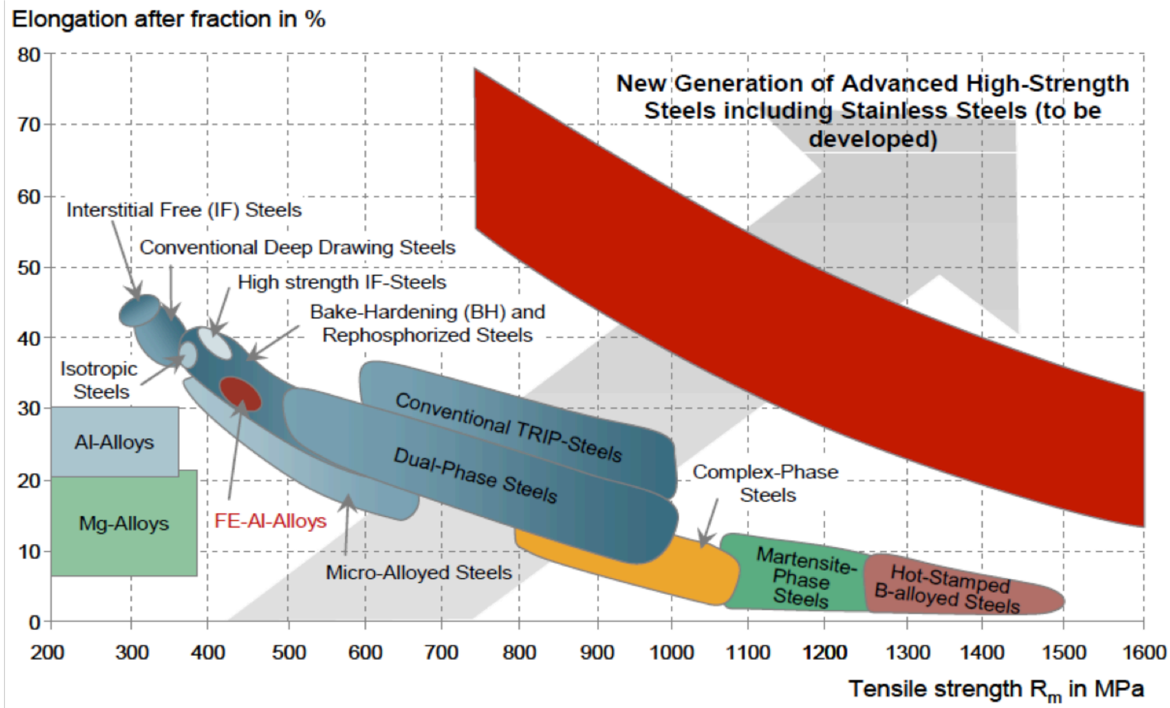

Figure 8 – New generation of advanced high-strength steels. Source: Birat, J.P. (2014)

It should also be observed that material innovation occurs more frequently due to technology transfer between sectors or industrial groups than through specific design for a given application. Recycling is important for structural materials and mentioned several times during the workshop held in May 2014. It is part of the complex relationship between the different strategies for avoiding material scarcity, including mining, recycling, minimization and substitution. But recycling has its own particular challenges and is therefore not within the scope of this roadmap, so that comments from experts on this issue are not further discussed here..

8.3. Regime level changes

On the policy and regulatory level, some minimum standards need to be defined to identify the critical materials in imports. Also, the policy framework needs to be reliable to encourage investments by industry and it should create a level-playing field for European companies, which are subject to more stringent environmental legislation than their Chinese competitors.

The expert groups identified numerous research initiatives aiming at the substitution of critical materials in high-value alloys and other hard metals (mainly W, Co, Mb, Mg and heavy REE, but Ni was also mentioned). Several of the mentioned initiatives aim at accelerating material innovation. Several examples and initiatives in this field were cited, i.e. multi-scale material design, GRANTA material database, Integrated Computational Materials Engineering (ICME), Accelerated Metallurgy (High throughput materials science), which could eventually give a decisive competitive advantage to European industry.

It so recommended that abandoned alloy designs should be revisited to evaluate their potential for substitution. There is a strong link between substitution, material design and changes to industrial metallurgical processes (castings, coatings and novel concepts, such as out-of-autoclave composite curing, self-propagating processes or change of microstructure instead of alloy, i.e. substitution strategy *process* *for substance*), as well as the use of alternative reductants to substitute coking coal[14]. The following approaches are highlighted:

- The use of natural gas as reductant for iron and other metals produced through carbothermic reduction as substitute for coking coal
- Electrolytic production of titanium production avoiding Mg use
- High quality castings to replace CRM containing alloys
- Coatings that reduce the product requirements to the bulk of a product thereby decreasing CRM use
- Novel concepts, such as out-of-autoclave composite curing
- Near net shape technologies/additive manufacturing initiatives
- Low cost solar silicon through metallurgical processes substituting the Siemens process
- Microstructural refinement to improve properties substituting alloy elements

The experts consider that a common European research strategy in the field of metallurgy, metal design and metal processing could improve the continent's competitiveness with China, but that Europe also needs a broader reindustrialization strategy and an excellent workforce to re-gain positions in the world market, since the high level of outsourcing has eroded vital industrial infrastructure in Europe. The expert group propose that Europe (EU and Member States) should dedicate resources into the high-quality education of engineers in fields such as mining, metallurgy and materials science, and that this education should be imparted in close interaction with industry.

8.4. Specific cases

8.4.1. Cutting tools (based on input from Sandvik)

It is difficult to find a substitute for WC-Co (tungsten carbide with cobalt binder) cutting tools. The good wettability between WC and Co is the basis for the good performance. Substituting the binder without substituting the cutting tool or vice versa is therefore difficult.

Many candidate substitutes have been investigated for cutting tools. The challenge is to find substitutes that can compete on price and performance. The latest developments in modelling (e.g. calculation of wettability through calculation of charge density) and microscopy can help the quest for suitable material combinations. Research is being done on Co substitution in the academic environment. But the industry is not prioritising it. It will take long time to introduce a substitute since it will be based on the performance of each and every application. This requires increasing the companies' own knowledge about the new materials.

The cermets that have been developed until now are too brittle to substitute today's cutting tools. In order to start using cermets today, a large change in the manufacturing industry is necessary and that is not anticipated. Moreover, cermets often do not exhibit such good wettability with the Co binder. Without an extra-ordinary research effort it will take at least 20 years before proper substitute materials for each hard metal are ready for commercialisation.

Cobalt is, at this moment, the most critical element for the industry. Some iron-based binders are under development. There is, at this moment, no real driving force for substitution of Co. Co is toxic. A change in legislation will accelerate the pursuit for a Co substitutes. Moreover a price increase will also be a driving

[14] Coking coal is included in the roadmap, although it was not on the original list of the 14 critical materials, which work in CRM_InnoNet parted from. It was added during the first revision of the list due to its vital importance for the steel industry and the uncertainty of supply due to the flooding of coalmines.

force for Co substitution. When it comes to raw materials supply, the focus of the industry is more on recycling than on substitution. Standardisation is not a hurdle for substitution.

In the future, additive manufacturing might bring a big change in the manufacturing industry and thereby change the market for cutting tools.

8.4.2. Materials for aerospace engines (based on input from Rolls Royce)

The aerospace industry has a very conservative, risk averse, culture that makes changes slow and stepwise.

In order to improve the performance of aircraft engines one can either add alloying elements to the Ni to improve its high temperature properties or try to keep the turbine parts cool with cooling systems or coatings.

The most critical elements for turbine parts are mostly the alloying additions to the Ni-alloys like: rhenium, tungsten, tantalum, hafnium and niobium.

Rhenium is a scarce material. There is an ongoing development towards the reduction in the use of rhenium in turbine parts.

By using coatings, some of them containing yttrium oxide and platinum, one can decrease the requirements for the alloy, thereby decreasing the required amount of CRM. When coating is applied, maintenance and recycling are challenging.

Altering the microstructure, like eliminating the grain boundaries through a single crystal, can decrease requirements on the alloy.

It is important that the substitution of materials that are used during production, but that are not included in the final product, is also considered. An example from the past is hexavalent chromium plating which is toxic. Its use has been restricted due to legislation.

There is still a lot of development potential in conventional superalloys. At the same time there is research and development on-going in intermetallic, ceramics and CMC. These new materials have shown promising performances, but only in lab-scale/pilot testing. The aerospace industry is a very conservative industry. Therefore it is not expected that these new materials will take the place of superalloys within commercial aviation any time soon.

The recent developments in atomistic and other modelling can accelerate substitution. Although thorough testing is always a requirement in the aerospace industry.

8.4.3. Steel industry (based on input from ESTEP)

Niobium is used as alloying element. It can be substituted with quite a few other elements that form fine carbides, like Ti. The choice of niobium or alternatives is based on a cost/performance basis. There is ongoing research and development on these types of dispersoid steels, both in industry as well as in academia.

Chromium is essential for stainless steel. The market for stainless steels has not been growing significantly during the past years. Mainly because the corrosion resistant coating for ordinary steels (e.g. galvanization) has been improved so much that the need for stainless steels has decreased. Chromium as alloying element in engineering steels can readily be substituted by other elements.

Fluorspar is less used in the steel industry than previously. The driver for substitution has been environmental concerns and the following legislation. It is still used for slags for Electro-slag remelting (ESR) where it is essential. But this is a very small niche market.

Natural graphite is hardly ever used in the steel industry. It is more common in foundries.

Magnesium can easily be substituted by other desulphurising elements like manganese.

Boron is a powerful hardening element. The amounts used are extremely small and there are many alternative elements with the same function.

Coking coal is included in the roadmap, although it was not on the original list of the 14 critical materials, which work in CRM_InnoNet parted from. It was added during the first revision of the list due to its vital importance for the steel industry and the uncertainty of supply. Coking coal can partly be substituted by injection of coal during blast furnace operation. This is under development and will be used as much as needed. Moreover natural gas can also be injected during blast furnace operation. The use of natural gas reduces also the CO_2 emissions from the industry but natural gas is, in Europe, more expensive than coal. The production of iron with natural gas (Direct Reduced Iron) is not expected to increase so much that it will significantly influence the demand for coking coal. More research on substitutes for coking coal can be of benefit for the whole steel industry.

8.4.4. Beryllium (based on input from Beryllium Science & Technology Association)

The largest use of beryllium is as an alloying element in copper beryllium alloys that are used to make components, which are inert, stable, and do not give off emissions during use. Beryllium-containing alloys are used in critical locations in products where they provide a design solution based upon reliability, miniaturization, improved energy management and/or extending the service life. High reliability electronic connectors incorporate copper beryllium based terminals to carry the current or signal, because of the combination of strength and conductivity provided by this metal.

There are several materials that have equivalent individual properties of strength, ductility, formability, machinability, electrical and thermal conductivity, fatigue resistance, resistance to loss of strength with long term exposure to heat, etc. to those provided by the copper beryllium alloys and nickel beryllium alloys, however, no other alloys offer the same combinations of these properties. In all cases, considerable reduction in the performance of the component article used in the application will occur. There has been research and development effort on the substitution of Be in copper alloys in switches, connectors and other electronic components. Some examples are:

<u>Cu---Ni---Si---Cr alloy</u> (Ampcoloy944 developed by Ampco Metal) is an alloy made by one company in the USA. The material has inferior conductivity, ductility and spring (modulus) properties. Of critical importance to this reference for the replacement of copper beryllium, this alloy is marketed as a bulk product alloy, for use in large sections, and cannot be readily transformed into the ultra-thin strip and rod products that are needed for electronics applications.

<u>Cu---Ti---Fe</u> (NKT 322 Gigalloy, developed by JX Nippon Mining & Metals) alloys match some of the strength and spring properties of copper beryllium, but in combination cannot meet many of the application requirements, and consequently it has gained limited acceptance in the electronics business. Manufacture of these alloys requires specialized, capital intensive manufacturing equipment, which has limited its production to one company that had unused equipment available, and it is sold within a limited supply only in Asia. It is not available in Europe, eliminating its viability as a substitute.

The Cu-Ni-Sn, Cu-Ni-Si and Cu-Ni-Al alloys are very well known, are abundantly available in the EU, and are the alloys of choice for applications that do not require extreme or high reliability or fail safe performance in life safety applications. In particular, for lower strength alloys, with lower levels of ductility and formability, usually in combination with lower electrical or thermal conductivity, designers will be forced to use larger sections, or less sophisticated designs resulting in larger sized, heavier components to achieve equivalent strength, defeating the objective of miniaturization, with the concomitant benefits of weight reduction, energy savings and carbon footprint reduction.

8.5. Roadmap for substituting CRM in high value alloys

The substitution options considered viable after extensive literature review and expert consultation are listed in Table 11. The table identifies potential substitution technologies that may exist at different time-horizons. These are not intended to be “objectives” to be reached, but aim at identifying potential substitute technologies that may exist at different time-frames, based on the natural dynamics of the market and research, and may provide an alternative to a potential CRM issue.

The time scale indicated for the different technologies attempts to capture the maturity of their respective development. Given the multiplicity of potential alternative technologies, no assumption is made whether a given technology has more chances for a “break-through” than another one. Difference may however arise with respect to specific markets, in line with the present perception of the strength/weaknesses of each technology.

Obviously, the vision of market technologies at the horizon 2030 is highly uncertain, and should be considered as such.

Table 11 - Roadmap for substitution of CRMs in high-value alloy applications

2015	2020	2025	2030 & beyond	Comments
LANDSCAPE DEVELOPMENTS				
The new generation of high-performance steels will increase the demand for CRMs	Advanced High Strength Steel (AHSS) available for automotive appliances			Information obtained from NanoSteel Company http://nanosteelco.com/markets/automotive/
Increasing production volume of high-strength low-alloy steels will create pressure on the niobium market	High volume production of high-strength low-alloy steels could create further pressure on the niobium market			Niobium is predominantly used in HSLA. An estimated 4,000tpy of Nb goes into high-performance alloys and superalloys (2012). Source: Niobium: Market Outlook to 2018, Roskill Information Services Ltd. (2013). Niobium's demand has been growing by approximately 8% per annum over the past decade. There are only two Nb producers worldwide, but some new deposits are being developed (http://www.canadiansailings.ca/?p=9786)
Use of steel substitutes in non-structural parts of vehicles	Light-weight vehicles will reinforce the trend towards the substitution of steel by alternative materials (aluminium, magnesium, carbon fibre).			http://www.acemr.eu/uploads/media/Trendstudy_ACEMR_Designmaterials_01.pdf http://www.mckinsey.com/~/media/McKinsey/dotcom/client_service/Automotive%20and%20Assembly/PDFs/Lightweight_heavy_impact.ashx. Carbon fibre is not yet competitive in the automotive industry due to costs (CRM_InnoNet Vision workshop)

Application	2020	2025	2030 & beyond	Comments
REGIME (Markets, Policy & Regulation, R&D): HARD METALS AND CUTTING TOOLS				
Substitution of Co as binder in cutting and wear-resistant tools			Alternative binders such as Ni-base superalloys (or, alternatively, iron-manganese alloys); beyond 2030: nanostructured WC-Cu composites fabricated by mechanical alloying	High level of uncertainty due to long time horizon. Tools with alternative binders show less wear and last longer, but as cutting speed increases, their performance is worse. Source: D. Waldorf, M. Stender, S. Liu, D. Norgan, "Alternative binder carbide tools for machining superalloys", Int. Conf.on Manufacturing Science and Engineering, 2008; and M. Yusoff, R. Othman, Z. Hussain, "Mechanical alloying and sintering of nanostructured tungsten carbide-reinforced copper composite and its characterization.
Substitution of tungsten (W) in high-speed cutting tools. Currently available substitutes for W in high performance steels for cutting tools: Molybdenum, vanadium, chromium…	Substitution by composite of cemented carbide and cermet (TiCN-Co/Ni)			Same level of resistance with reduced tungsten usage of 30%. Developed by Sumitomo Electric Industries, the next step is the development of mass production technique. Source: T. Ishida, H. Moriguchi, A. Ikegaya, “Development of cemented carbide tool of reduced rare metal usage”, SEI Technical review, Nº73, October 2011. Source for currently available substitutes: http://www.glsd.us/cms/lib01/PA01000207/Centricity/Domain/176/2%20Cutting%20Tool%20Materials%20Study%20Guide.pdf
	Polycrystalline Diamond (PCDs) and Polycrystalline Boron Nitride (PCBN)			Increased hardness but lower toughness. Source: http://www.kennametal.com/content/dam/kennametal/kennametal/common/Resources/Catalogs-Literature/Metalworking/Master%20Catalog%20-%20Metric%20Sections/A-11-02679_MasterCat_stationary_PCBN_PCD_inserts_metric.pdf

Application	2020	2025	2030 & beyond	Comments
REGIME (Markets, Policy & Regulation, R&D): BIOMEDICINE				
Substitution of Co-Cr in biomedical applications (artificial joints, prosthesis)	Titanium parts made by additive manufacturing processes			Orthopaedic implants involving knee and hip replacements have already been fabricated by EBM. Acetabular hip shells of Ti-6Al-4V have already been implanted in humans. L.E. Murr, S.M. Gaytan, E. Martinez, F. Medina, R.B. Wicker, "Next generation orthopaedic implants by additive manufacturing using electron beam melting", Int. Journal of Biomaterials, Vol.2012.
Substitution of Ti-Ta alloys in prosthetic devices (hip joints, skull plates, suture clips, stents…)	Additive manufacturing of Ti or Ti64 alloys			Orthopaedic implants involving knee and hip replacements have already been fabricated by EBM. Acetabular hip shells of Ti-6Al-4V have already been implanted in humans. L.E. Murr, S.M. Gaytan, E. Martinez, F. Medina, R.B. Wicker, "Next generation orthopaedic implants by additive manufacturing using electron beam melting", Int. Journal of Biomaterials, Vol.2012.

Application	2020	2025	2030 & beyond	Comments
REGIME (Markets, Policy & Regulation, R&D): STEEL INDUSTRY				
Process: Slag chemistry: fluorspar	Alternatives already in place due to environmental concerns around the use of fluor			
Process: Desulphurisation: Mg	Manganese			
Process: coking coal (reductant)		Lower quality coal and natural gas		Coking coal was not considered as critical material in the initial list of CRMs, but was introduced during the revision of the list of CRMs
Alloying elements for hardening: Boron	Other hardening elements are readily available			"Report on resources for the steel industry prepared by ESTEP's WG4,
Alloying element - carbide formers: Nb and Cr	Other carbideformers like Ti			ftp://ftp.cordis.europa.eu/pub/estep/docs/wg4-resources-report-2012-09.pdf "
Alloying element for corrosion resistance: Cr	Improved coating technology is improving the corrosion resistance of low-alloyed steels			"Report on resources for the steel industry prepared by ESTEP's WG4,

Application	2020	2025	2030 & beyond	Comments
REGIME (Markets, Policy & Regulation, R&D): AEROSPACE (high temperature materials)				
Substitution of alloying elements in Ni based superalloys: Re, W, Ta, Hf and Nb	Single crystals to increase creep resistance			
Substitution of alloying elements in Ni based superalloys: Re, W Ta, Hf and Nb	New coatings to reduce the requirements to the base materials			
Substitution of Ni based superalloys: Intermetallics			Intermetallics: Refractory metals (Mo and Nb-based silicide multiphase alloys and Silicon nitride based ceramics	Silicides have been under development for a long time, but the problems with brittleness at low temperature has not been solved. Tasks to be carried out: composition optimisation for simultaneously enhanced mechanical props and oxidation/corrosion resistance, improvement of available protective coatings, control of the microstrucure and implementing of a cost effective industrial manufacturing route. Source: S. Drawin, J.F. Justin, "Advanced lightweight silicide and nitride based materials for turbo-engine applications", Journal Aerospace Lab n°3, November 2011
			CMCs (Oxide-Oxide or SiC-SiC)	Demonstration of CMCs is currently underway on some military aircraft. Rolls-Royce has designed and tested some static components. Source: SBAC Aviation and Environment Briefing Papers. Advanced Aircraft Materials. In 2010 GE reported that the company was able to make CMC rotating parts and test CMCs-based turbine blades. In 2012, IHI announced that they would finalize mass-production technology of CMC parts for jet engines in 2015, but industry sources estimate that use in aerospace will require another 10 - 15 years. Source: K.L. Luthra, "Ceramic Matrix Composites (CMCs) for gas Turbien Applications" / S.Hidaka, "Superalloys versus ceramics" and industry interviews
			New ceramic materials	

8.6. Transition Pathways

The scope of the roadmap is limited to alloys that contain elements that are on the list of critical raw materials or that need materials from this list to be produced[15]. The prioritized areas are the steel industry (because of the large amounts of materials processed), cutting tools and materials for aerospace turbines; the latter two due to the important role of CRM in these high performance materials. The time horizon for the roadmap, 2030, is quite narrow, as the development of new, substitute materials and its acceptance in a rather conservative market, such as the aerospace industry, takes longer (about 20 years) and thus has been extended to 2050.

A graphical representation of the main findings is shown in Figure 9. It is recommended that abandoned alloy designs should be revisited to evaluate their potential for substitution. A strong link was established between substitution, material design and changes to industrial metallurgical processes (castings, coatings and novel concepts, or change of microstructure instead of alloy, i.e. substitution strategy process for substance), as well as the use of alternative reductants to substitute coking coal.

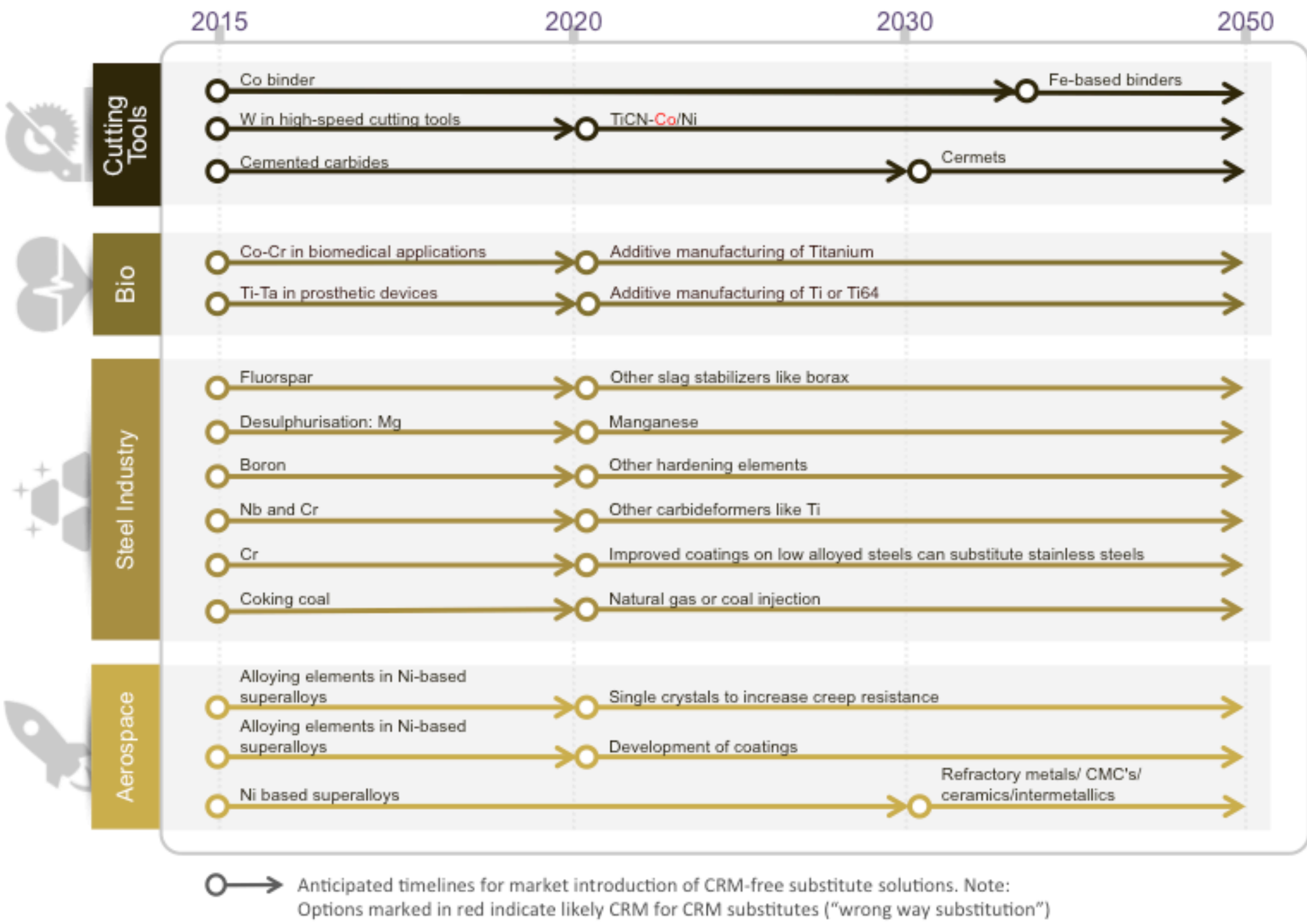

Figure 9 – Transition pathways for CRM substitution in High-value Alloys

[15] With the exception of coking coal.

9. SUBSTITUTION ROADMAP – PHOTONICS & HIGH-END OPTICS

9.1. General considerations about CRM substitution in photonics

CRM's are a group of critical materials, mostly named as single elements, that are metals, at risk of supply constraints, have environmental implications, are financially costly, experience price volatility, deemed economically important and substitution offers opportunities but remains challenging as a result of the material unique properties or for economic reasons. These critical materials – metals, are used in engineering, technology applications and product designs (Peck et al 2015).

The material requirements of products and technologies has become more 'omnivorous'[16] with one large, global, engineering and technology company stating they use at least 70 of the first 83 elements listed in the Periodic Table of Elements[17]. This reflects a range of industries that have seen rapid technological developments over the past 30 years using an ever increasing range of materials in order to meet the performance requirements in new products. These connected activities have contributed to material supply changes that can be observed through disruptions to supply and price volatility. This is true in the case of photonics.

For new product development, the key engineering design steps involve choosing a suitable product lay-out, deciding which parts will be designed specifically for the product and which components will be bought in from stock (i.e. the 'make or buy-decision'), and then detailing the specific parts and choosing the right stock components – with design iterations where needed. For adapting existing products – that constitutes the majority of all product development – some of these steps can be skipped, and material choices are partially implicit in the system, barely if at all debated by the OEM manufacturer. Also, note that products are rarely designed as stand-alone items but more commonly as members of product families, sharing lay-outs, bought-in components and even product-specific parts (ibid.). Implementing such 'product platform design' is a strategic choice that rarely involves designers / engineers only: more commonly the whole product development team is involved.

For product-specific parts, material choice follows from a process of gradual elimination, and for these parts, the designers can indeed be the main decision makers, explicitly choosing carefully to determine the optimal compromise between requirements of functionality, quality and cost.

The question also arises about how do new materials make it into products. Ashby and Johnson in their 2010 publication, Materials and Design (Greenfield et al 2013), propose that new materials emerge through commercialisation via science driven development. In other words, the materials scientist pushes the material into the awareness of the product designer / engineer who uses the material in a creative way. This push of materials from materials lab to product appears logical. There is in most cases a symbiosis between the new material development activity and the application into products. The demands of product end users are translated into technical requirements at which point changes in materials can make a significant impact. In those cases there is a clear pull of new materials out of the materials lab. In any case there has to be a commercial case for the development of new materials.

[16] Understanding the "Rare Earth" Material Problem http://www.efficientenergyllc.com/_Rare_Earth_Problem.html
[17] White organic light emitting diodes: Status and Perspectives http://arxiv.org/pdf/1302.3435v1.pdf

The 'conscious' selection of critical materials falls to materials scientists working either in scientific research or in the R&D labs of a materials company. The technical designers (engineers) working in component companies that use critical materials will also be aware as they design such components to meet the performance requirements of upstream customers. The 'less / unaware' choice of critical materials is usually made by the sub-assembly and final product designer / engineer together with the rest of the product development team.

The complexity of the situation is well demonstrated when one looks at the photonics application sectors. This is done by the design engineer who has been, over recent years, driven by market demand to make designs smaller, lighter, faster, higher performing, more power efficient and robust. This has driven the selection of components that use critical materials.

To summarize: currently product designers / engineers are certainly not the only ones who make material choices, and when it comes to components, they usually choose the constituent materials only implicitly. They select at the level of materials, not at the level of elements. There is however a range of substitution strategies that, if the product designer / engineer (and others) were more aware of, could be used to address CRM challenges.

9.2. Detailed Presentation of Roadmap

9.2.1 CRM substitution in photonics – the scope

The field of photonic is broad, and developing a roadmap for substitution of CRMs in photonics in a fully homogeneous way is a challenge within the framework of this project. It is foreseen that this work will extend beyond the end of this project. The majority of photonic technologies contain at least one CRM, although the precise number and the importance of the CRM vary significantly from one application to another. This roadmap therefore focuses on the photonic technologies that have been identified as the most critical regarding their use of CRMs and their importance in the global photonics market.

This approach means that a number of market application areas are significant under the term 'photonics'. These are:

- Health equipment sector: scanning, sensing, biophotonics, light guided / light activated therapies, wearable electronics, chip based sensing devices and LED
- Manufacturing equipment sector: measurement, automated vision and LED
- ICT sector (mobile devices): touchscreens, flat panel display and LED
- Renewable energy generation sector: photovoltaic panels
- Industrial / technical equipment: lasers

Correspondingly the critical materials that are considered in more detail are:

- Indium
- Rare earth elements (REEs)
- Gallium
- Germanium

9.2.2 CRM substitution in photonics – an overview

One of the most widespread concerns regarding CRMs in photonics is the indium supply risk and price volatility. Indium is an essential component of ITO (Indium Tin Oxide) coatings used in flat panel displays and photovoltaics. Given that (i) these two sectors together account for 40% of the total world market for photonics, and (ii) at the current rate of ITO consumption the US Geological Survey suggests that indium will be highly critical[18], this problem could seriously affect the photonics sector The market is cautiously reacting to this issue by proposing alternatives to ITO based on carbon nanotubes (CNT), conductive polymer films, and copper solutions. CRM_InnoNet highlights the use of fluor tin oxide (FTO) as an existing and graphene as one of the most promising, research substitution strategies for ITO.

Another important line of substitution strategies for CRMs in photonics is the use of rare earth elements (REEs), gallium, and indium in light emitting diodes (LEDs). Here we have to make a distinction between white LEDs used for lighting applications and red, green, and blue LEDs used for flat panel displays. In the case of lighting the increasing market demand for LEDs is being reinforced by the EU policies focused on phasing out of incandescent bulbs and seeking low energy alternatives. Industry supports the substitution of existing LEDs, which are highly CRM dependent, through the use of organic LEDs (OLEDs)[19]. But even if OLEDs develop as an excellent candidate to produce eco-friendly CRM-free flexible displays and lighting sources, the current cost and luminous efficacy issues are delaying its commercial deployment and give rise to doubts about OLEDs taking up a significant market share from LEDs by 2030. Another solution driven by the industry is the development of LEDs using quantum dots instead of REEs.

The laser market does not seem to be clearly reacting to the potential price volatility of the REE yttrium. Some experts believe, and this affects also to other fields of photonics, that the problems with the supply of rare earth elements will not be very critical for laser technologies, due to the small amounts of REE needed. However, in the event that the future means yttrium shortages or acute price peaks there are readily available high-power fibre laser solutions that could replace the widely used Nd:YAG laser for industrial applications such as marking and welding, even in some medical applications, such as surgery[20].

Finally, the photovoltaic (PV) market has also given rise to some concerns regarding the use of CRMs. There are particular PV technologies that use CRMs as their critical active material, amongst them copper indium gallium selenide (CIGS) and single and multi-junction GaAs cells. CIGS technology is one of the established thin film technologies, whose main advantage is that it can be grown in flexible substrates. Multi-junction cells on the other hand are by far the most efficient PV technology, but their cost is also much higher. Amorphous and crystalline silicon are not CRM dependent and constitute a viable alternative for thin film CIGS cells, although they cannot be grown in flexible substrates. For the high efficiency sector, there is no other commercial PV technology that matches multi-junction. There are, however, promising research strategies to improve the efficiency of thin film cells by using photonic crystals that aim at efficiency values closer to the ones achieved with multi-junction.

[18] Note that information provided by Indium Corporation to this Consortium directly shows a much more positive perspective in terms of indium reserves and potential for more capacity/output increases. However, we have to reflect the market trends, and these show a clear concern for indium price volatility and supply shortage.
[19] Except for phosphorescent OLEDs that are also strongly dependent on REEs
[20] See for example IPG Photonics TLR-200 Thulium CW Fiber Laser

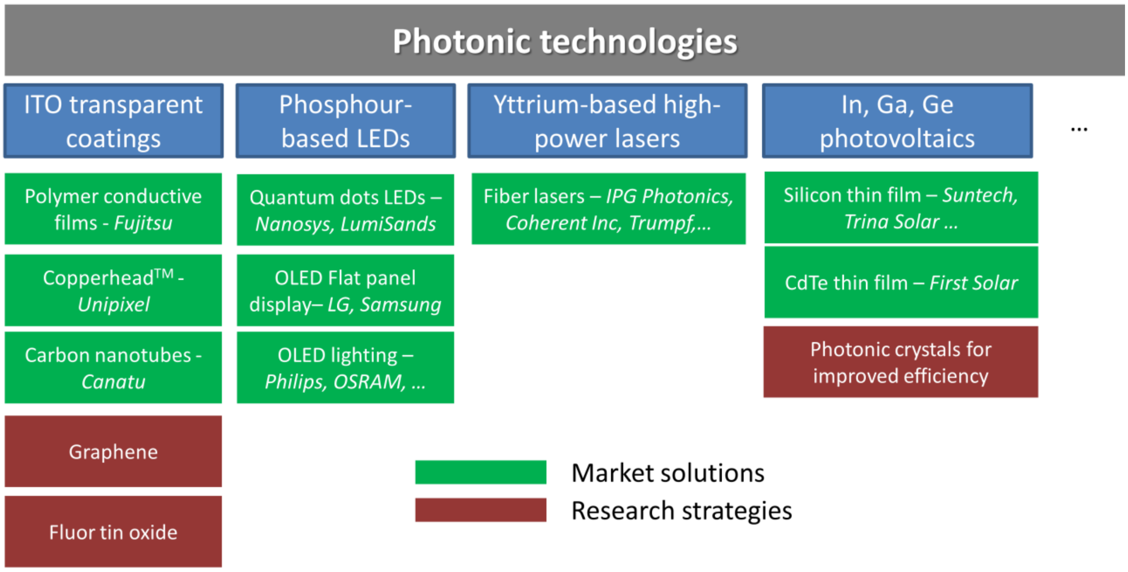

Figure 10 - Substitutive solutions identified in the photonics roadmap

Finally, it has been observed that technological developments are mainly driven by industry, but research organisations can also play a leading role in cross-cutting solutions, such as the search for graphene alternatives to ITO and the use of photonic crystals for improved solar cell efficiency.

9.2.3 CRM substitution in photonics – landscape developments

The table below identifies potential substitution technologies that may emerge in 3 different time-horizons. These are not intended to be "objectives" to be reached, but aim at identifying potential substitute technologies *that may exist at different time-frames, based on the natural dynamics of the market and research, and may provide an alternative to a potential CRM issue.*

Given the multiplicity of potential alternative technologies, no assumption is made as to whether a given technology has more chances for a "realisation" than any other. Differences may however arise with respect to specific markets, in line with the present perception of the strength/weaknesses of each technology.

Given the rate of scientific and technological developments, the vision of market technologies in the 2030 time point is highly uncertain, and this reflects a typical 'divergence' of scenarios in longer term timeframes.

Table 12 - Roadmap for substitution of CRMs in photonics

Trend	2020	2025	2030	References/Actors involved
LANDSCAPE: DRIVERS FOR SUBSTITUTION				
Increasing demand in the health sector for, scanning, sensing and imaging devices, biophotonics for applications such as early diagnosis of diseases with minimal or no invasion, light-guided and light-activated therapies, wearable electronics or chip-based sensing devices	Given developments in Europe and Worldwide in the health sector the demand for CRM's will increase. The field of wearable electronics poses great opportunities for companies but where the electronics are embedded into textiles / footwear the loss rates can be high. Substitution activity in both the wearable electronics sectors and chip-based sensors is currently low and challenges in CRM supply and price volatility could challenge this position in the 2020 timeframe.	If widespread substitution activity were enacted in 2015-2016, by 2025 results would start to be diffused into products. During the period 2015 to 2025 personal health devices will see significant expansion and this will present new challenges to the supply of CRM's in the field.	As global population increases / ages the demand for CRM will grow.	
Increased demand for measurement and automated vision in industrial applications and manufacturing,	The smart manufacturing initiatives in the EU are an indicator of developments. The current use of CRM's in the sector is evolving and substitution is low and challenges in CRM supply and price volatility could challenge this position in the 2020 timeframe.	The trend for increased automation resulting from cost pressures and the erosion of low cost manufacturing base in developing countries will continue. As developing economies seek to develop domestic markets the pressure on CRMs will increase.		

Trend	2020	2025	2030	References/Actors involved
LANDSCAPE: DRIVERS FOR SUBSTITUTION				
Increased demand for information technologies	The increased demand for ICT will move ahead into the 2020 timeframe and demand on CRM's will continue. Specific actions on substitution will continue but action will depend on security of supply issues and price volatility.	The rapid expansion of mobile ICT based on touchscreens - in particular small mobile devices will continue. The development of internet access across Africa and other developing economies will mean the demand for CRM's in such devices will grow significantly. Substitution activity will need to correspond in growth rate to ensure demand is met.	Demand continues to grow and substitution must be widespread to meet CRM demands.	
Developments in photovoltaics	See below			
Concerns with regard price volatility in the indium and the yttrium market. The increasing demand for yttrium in other industrial sectors could negatively affect laser production	Whilst clean energy demand for Yttrium could flatten in the West the prospects for ROW demand rising are high. For Indium the Chinese domestic demand could cause challenges going forwards.	The Chinese domestic market could see significant development in this timeframe along with other emerging markets. This could increase pressure for substitution activity.		

Application	2020	2025	2030	References/Actors involved
REGIME: MARKETS				
Substitution of Germanium in fibres for telecommunication	The massive fibre optic deployments for telecommunications continue to use standard germanium-doped optical fibre cables. Only timid attempts to use to enter the telecommunications market with pure silica (Ge-free) core fibres have been observed so far.	None of the major fibre optic cable producers has claimed its intention to substitute Ge in standard telecommunications fibres. In our opinion, the community is not concerned about the Ge potential shortage given the fact that this material is just used as a dopant in the silica core, and only small amounts are needed.		Major fibre optic cable producers (Corning, Draka, Nexans, Sumitomo, YOFC, AFL Telecommunications, OFS, JFOPT). The new players pushing Ge-free fibres for telecommunications are: Fiberore and Fibertronix. http://www.fibercore.com/
Substitution of Germanium in Photovoltaics	The general PV market is going to silicon-based photovoltaic technologies, as proved by the fact that the top 5 solar module players use this technology.	Germanium solar cells will probably continue to be used only in niche applications such as on spacecrafts.		Photovoltaic manufacturers: According to PVinsights' market intelligence report, the top 5 solar module players in 2011 in turns are Suntech, First Solar, Yingli, Trina, and Canadian. Source: http://pvinsights.com/ ; Umicore http://www.umicore.com/en/cleanTechnologies/solarCells/; Panasonic: http://panasonic.net/energy/amorton/en/solar_battery/
OLED (Organic LEDs) appear as an eco-friendly and CRM-free (except for the case of phosphorescent OLEDs) alternative to LEDs in lightning applications	In the short time only a small fraction of the market will be taken by OLED giving it´s reduced luminous efficacy.	There is a high-level of uncertainty regarding the significant market uptake for OLEDs according to the experts´ opinion (See Results of the Online Survey)		Merck, Philips, Osram, Panasonic and Lumiotec are some of the world´s most proactive developers of OLED lighting. Sources: Trends and forecasts in the OLED lighting market, 2010-2020 http://www.digitimes.com/news/a20120514RS400.html?chid=2.;

Application	2020	2025	2030	References/Actors involved
REGIME: MARKETS				
OLED (Organic LEDs) appear as an eco-friendly and CRM-free (except for the case of phosphorescent OLEDs) alternative to LEDs in flat panel displays.	LG Display recently said that the flexible OLED market will reach $41 billion in 2020. Smartphone: Samsung has announced that in a 3-year period the cost of the technology will be competitive in the mass market.	There is a high-level of uncertainty regarding the significant market uptake for OLEDs according to the experts´ opinion (See Results of the Online Survey). In the Display market, as opposite to the lighting market, the main barrier for OLEDs' market uptake is cost. E.g. Sony and Panasonic decided to stop their OLED-TV development, because they did not reach the production costs goal.		Sources: On-line survey, http://www.oled-info.com/lg-display-details-their-flexible-oled-process-expects-flexible-oled-market-reach-41-billion-2020; http://news.oled-display.net/oled-tv/; http://www.lg.com/es/OLED; http://www.samsung.com/us/video/oled-tv
Substitution of ITO by polymer conductive films	Fujitsu Ltd. already has started using conductive polymer for some of its resistive-type touch screens.			http://www.fujitsu.com/us/news/pr/fcai_20040525-01.html
Substitution of ITO by copper	UniPixel, a leader in mastering and manufacturing high-performance flexible electronics, has a copper-based alternative to ITO.			http://www.unipixel.com/home/products/intouch-sensors-2/

Application	2020	2025	2030	References/Actors involved
REGIME: MARKETS				
Yttrium-free lasers: high-power fibre lasers	The laser market does not seem to be strongly reacting to the potential price volatility of Y. Some experts believe that the problems with the supply of REEs will not be very critical for laser technology, due to the small amounts of REE needed. Alternatives to Nd:YAG lasers, already available in the market are: - Nd:Fiber lasers for marking			IPG Photonics, Coherent Inc, Newport Corp, Rofin-Star, Trumpf as the leading supplier of fibre lasers. http://www.rp-photonics.com/spotlight_2014_06_27.html
Thin film PV	Thin film technology is a commercial reality already (e.g. First Solar technology is thin film).		In the last 20 years the efficiency of this technology has presented a very moderate enhancement. Extrapolating this trend to the future suggests that unless an unpredicted technology breakthrough occurs (see nanostructured solar cells in the research section) these types of solar cells will remain below 25%.	First Solar, one of the world's largest thin-film PV companies, announced that it set a world record for cadmium-telluride (CdTe) PV cells, converting 20.4% of the sun's energy into electricity. The cell was built at the company's Perrysburg, Ohio, factory. First Solar, one of the world's largest thin-film PV companies, announced that it set a world; Sources: NREL Best Research-Cell efficiencies; http://www.firstsolar.com/en/technologies-and-capabilities/pv-modules/first-solar-series-3-black-module/cdte-technology

Application	2020	2025	2030	References/Actors involved
REGIME: POLICY & REGULATION				
Phasing out of incandescent bulbs in the EU and other markets	Phase out in the European Union, Switzerland, and Australia began in 2009. Other phase-outs: Argentina and Russia 2012, United States, Canada, Mexico, Malaysia and South Korea in 2014. By October 2016 possibly banned in China. Possibly India 2020		1. Japan predicts to replace 60% incandescent bulbs by LED/OLED before 2030.	1. Source: LED News.org http://www.lednews.org/japan-incandescent-bulbs-led-oled-2030/
Other policies may unintentionally increase the demand of CRM materials for photonics. Alternatively they could be seen as a driver for substitution. Such is the case of the fibre optic benefits from the U.S. program FTTH (fibre-to-the-home), which aims to deliver fibre optic cables to every U.S. home, or the EU27 Fibre Investment.	FFTH and FFTB being expanded in developed countries at various rates up to 2020.		Possibility of FFTH widespread	Source: FTTH council http://www.ftthcouncil.eu/documents/Reports/FTTH_Finance_Report.pdf
REACH policy, dealing with materials that could entail a potential risk for health, could affect substitution strategies	Growing understanding of potential risks associated with CRM's, including in some cases radioactivity issues	Likelihood of further controls on substances hazardous to health being introduced are high		Source: VISION Workshop for Photonics Summary Report
Photonics21 and the recently funded PPP in Photonics can influence the demand for CRMs	1. Photonics 21 aims to deliver on its commitment of an overall investment of 7 Billion Euros in a Photonics Public Private Partnership (PPP) by 2020			1. Source www.photonics21.org

Application	2020	2025	2030	References/Actors involved
REGIME: POLICY & REGULATION				
Other strategies such as service for product use coming into plat -such as a closed loop / circular economy.	Promotion of closed loop/ circular economy package from the European Commission (version 2) up to the 2020 timeframe. 1. Companies making a clear connection with CRM risks and circular opportunities.	Promotion of closed loop/ circular in the H2020, EIT Raw Materials over the 2020 - 2025 timeframe providing a widespread substitution contribution		1. Ellen MacArthur Foundation CE 100

Application	2020	2025	2030	References/Actors involved
REGIME: R&D				
ITO substitution by FTO (fluor tin oxide)	1. Research ongoing at Fraunhofer, Germany			1. http://www.iws.fraunhofer.de/de/geschaeftsfelder/chemische_oberflaechen_reaktionstechnik/chemische_oberflaechentechnologie/projekte/subito.html
ITO substitution by CNT (carbon nanotubes)	Indium Shortage Could Advance Carbon Nanotube Technologies	According to Gartner analyst Dean Freeman, the most likely replacement for ITO will be carbon nanotubes, or CNTs. But that technology isn't quite ready yet. Carbon nanotubes are cylindrical carbon molecules with novel properties which make them potentially useful in many applications in nanotechnology, electronics, optics, and other fields of materials science, as well as potential uses in architectural fields		Apple, Samsung,… and mobile phone/ portable devices producers, which use ITO in their displays. www.azonano.com/news.aspx?newsID=20360
Silicon solar cells (Nanostructured and photonic-crystal based silicon solar cells with improved efficiency)	The efficiency rates of CRM containing solar PV technologies are high compared to non-CRM alternatives. Substitution research on-going.			D. Zhou and R. Biswas,"Photonic crystal enhanced light-trapping in thin film solar cells," J. Appl. Phys. 103, 093102 (2008); Guldin et al. " Dye-sensitized solar cell based on a three-dimensional photonic crystal". Nano letters, 10(7), 2303-2309.(2010

Application	2020	2025	2030	References/Actors involved
REGIME: R&D				
Graphene-based transparent conductors as substitute of ITO	The available Roadmap for Graphene foresees that medium quality display applications could be ready by 2020		According to the same roadmap, high-quality graphene devices for electronic applications won´t be a reality until 2030.	Source: Novoselov et al. "A roadmap for graphene" Nature 490, 192-200 (2012). http://www.nature.com/nature/journal/v490/n7419/full/nature11458.html Park et al. "Doped graphene electrodes for organic solar cells" Nanotechnology vol. 21, No 50 (2010). Koh et al. "The Potential of Graphene as an ITO Replacement in Organic Solar Cells: An Optical Perspective", Selected Topics in Quantum Electronics, IEEE Journal of (Volume:20 , Issue: 1) (2014) "Graphene to replace ITO in LCDs" in Electronics Weekly (April 2008) http://www.electronicsweekly.com/news/research/materials-rd/graphene-to-replace-ito-in-lcds-2008-04/
Substitution of Germanium in fibre optics by new types of fibre, different than the standard germanium-doped silica, is being investigated. ZBLAN [zirconium (Zr), barium (Ba), lanthanum (La), aluminium (Al), sodium (Na) fluoride], for example, has the potential to carry 100 times as much information as silica fibre.	Substitution research on-going			Sources: USGS http://pubs.usgs.gov/of/2004/1218/2004-1218.pdfCeramoptec - http://www.ceramoptec.com/pure-silica-core-fiber.php; FiberLabs http://www.fiberlabs-inc.com/fiber-index.htm; Fibertronix; http://www.fibertronix.com/pure-silica-core-polyimide-coated-singlemode-fiber; Le Verre Fluore http://leverrefluore.com/

9.2.4. Transition pathways

The transition pathways for photonics that arise out of the roadmapping exercise are shown in figure 11 below. Following the roadmapping exercise the market application areas were adapted from:

- Health equipment sector: scanning, sensing, biophotonics, light guided / light activated therapies, wearable electronics, chip based sensing devices and LED.
- Manufacturing equipment sector: measurement, automated vision and LED.
- ICT sector (mobile devices): touchscreens, flat panel display and LED
- Renewable energy generation sector: photovoltaic panels
- Industrial / technical equipment: lasers

To:

- Telecom (ICT sector, mobile devices): touchscreens, flat panel display and LED
- Renewable energy generation sector: photovoltaic panels (PV)
- Lighting: LED
- Lasers: Industrial / technical equipment
- ITO substrates

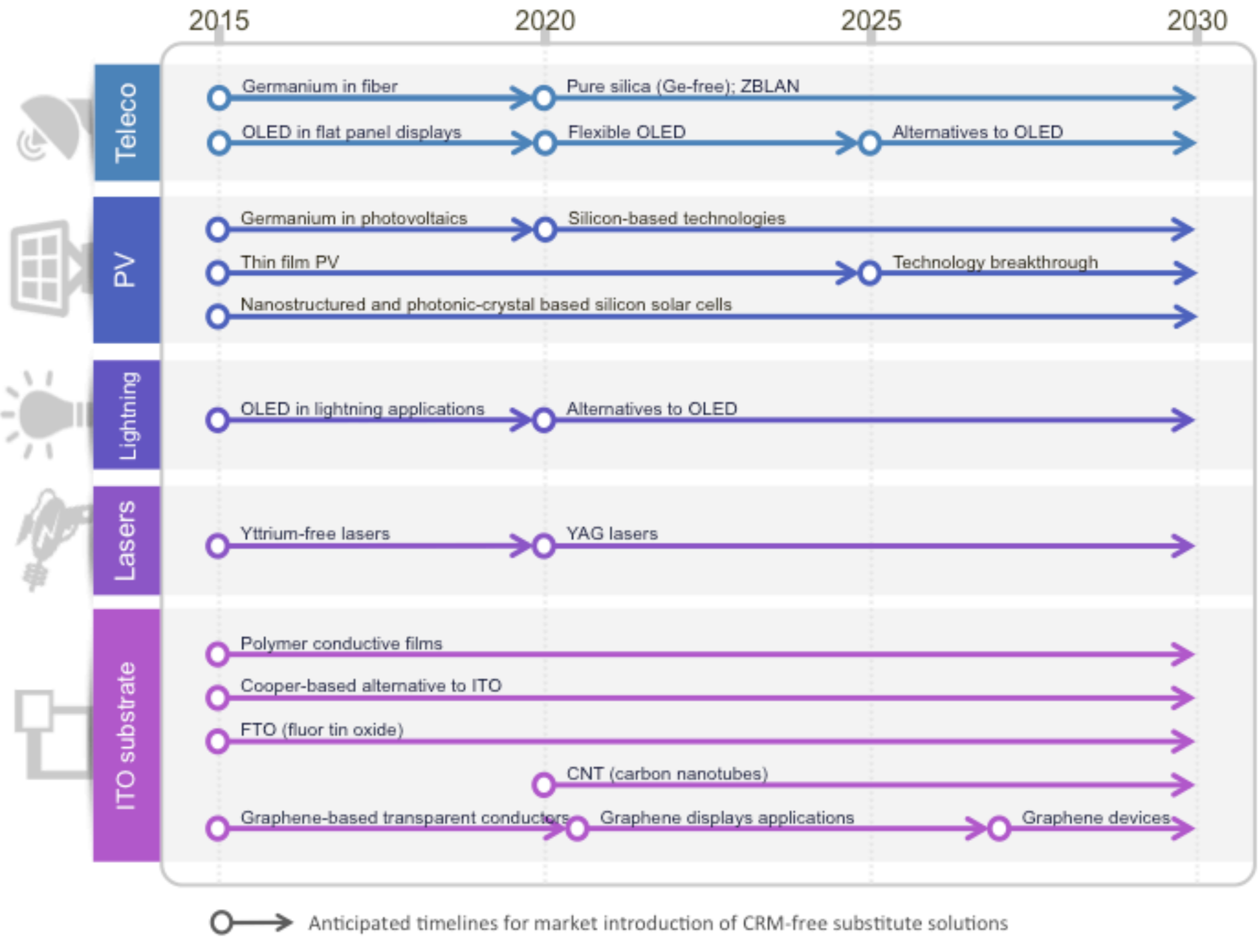

Figure 11 – Transition pathways for CRM substitution in Photonics

The challenges to realise the proposed changes are significant and should not be underestimated. In particular in order to have an effect in addressing the challenges of critical materials it would be necessary to not only have a new technology in production but to see it in widespread uptake in the market.

Of the 4 substitution strategies shown in figure 2 only service for product was not proposed by experts as a viable substitution strategy, even when prompted. This having been said some companies which use photonics based technologies in their products are beginning to explore the possibility of using approaches such as closed loop / circular approaches. Little work on actually changing product designs to facilitate this has been completed.

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