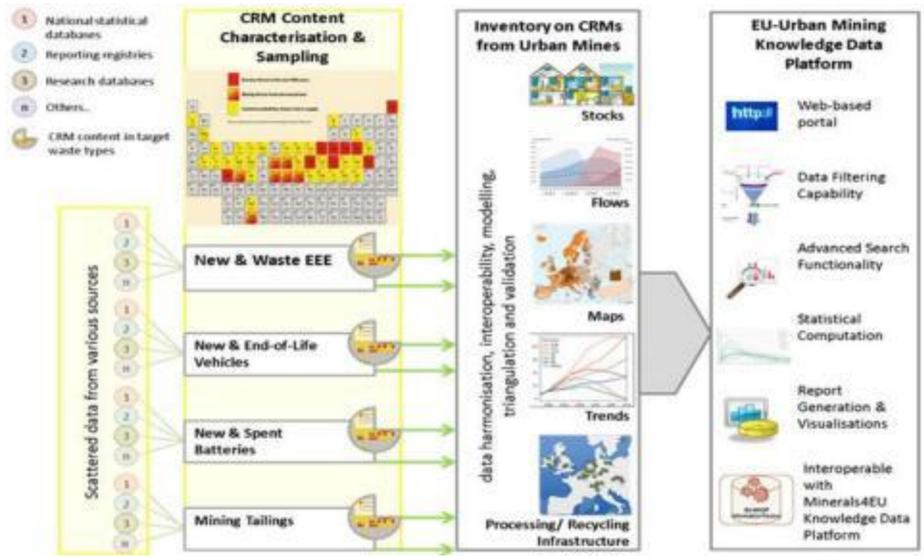
Identify factors affecting the CRM parameters of products and components: Deliverable 2.3



Project	Prospecting Secondary raw materials in the Urban mine and Mining waste
Acronym	ProSUM
Grant Agreement	641999
Funding Scheme	Horizon 2020
Webpage	http://www.prosumproject.eu/
Work Package	Work Package 2
Work Package Leader	Dr. Patrick Wäger
Deliverable Title	Identify factors affecting the CRM parameters of products and components: Deliverable 2.3
Deliverable Number	2.3
Deliverable Leader	Delft University of Technology
Version:	1
Status	1st Draft
Authors	Arno Scheepens, David Peck, Patrick Wäger, Amund Løvik, Claude Chanson, Perrine Chancerel, Maria Ljunggren Söderman
Reviewed by	Project Management Team
E-mail	Arno Scheepens a.e.scheepens@tudelft.nl
Scientific Coordinators	Dr Jaco Huisman, Scientific Advisor, UNU – IAS SCYCLE Nikolaos Arvanitidis, Chair of the EGS Mineral Resources Expert Group
E-mail	Huisman@unu.edu, Nikolaos.Arvanitidis@sgu.se

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 641999.

DOCUMENT CONTROL

Project Coordinator:	WEEE Forum
Work Package Leader:	Empa
Deliverable leader	TU Delft
Due date:	M18 01 July 2015
Date of submission: Note: Extension from 30 June 2016	M18 30 September 2016
Dissemination level:	PU (Public)

Version history			
Ver. no.	**Date**	**Reason for release**	**Responsible**
1	8-7-2016	First draft	Arno Scheepens, David Peck
2	24-09-2016	First final draft	Arno Scheepens, David Peck
3	30-09-2016	Final Report	Arno Scheepens, David Peck, Patrick Wäger, Amund Løvik, Claude Chanson, Perrine Chancerel, Maria Ljunggren Söderman
4	07-10-2016	Revised Final Report	Arno Scheepens, David Peck, Patrick Wäger, Amund Løvik, Claude Chanson, Perrine Chancerel, Maria Ljunggren Söderman

NOTICE

Table of Contents

List of figures

List of tables

PURPOSE

The purpose of this document describes the results of the activities undertaken in Task 2.1.2. The aim of this deliverable is to identify factors affecting the CRM parameters of the selected products and components in the ProSUM project, these being electrical & electronic equipment (EEE), battery (BATT), and vehicle components and products. This report satisfies ProSUM project deliverable D 2.3, which concerns a part (Sub-task 2.1.2) of Task 2.1 of the Technical Annex 1 of the ProSUM Grant Agreement.

1. Introduction

1.1. Aim and scope D2.3

Products constantly change and product / technology trends show the material requirements of technologies in products has become increasingly 'omnivorous' (Greenfield & Graedel, 2013, Tilton, 2001), 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 (Duclos, 2010). This reflects the rapid technological developments over the past 30+ years. The literature does indicate, via product case studies, the changes in the CRM parameters over time. These changes are driven by some key factors. The aim of this deliverable is to identify factors affecting the CRM parameters of the selected products and components in the ProSUM project, these being electrical & electronic equipment (EEE), battery (BATT), and vehicle components and products (ELV).
This report satisfies ProSUM project deliverable D 2.3, which concerns a part (Sub-task 2.1.2) of Task 2.1 of the Technical Annex 1 of the ProSUM Grant Agreement (see Figure 1).

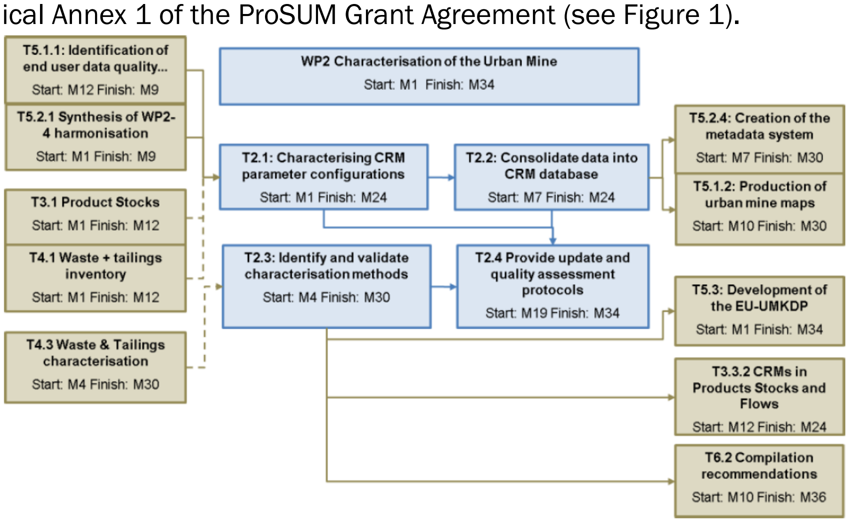


Figure 1: Work Package 2 Pert chart.

The scope of this deliverable is limited to factors relating only to EEE, BATT and ELV. The factors which influence CRM parameters includes the material choices made at the product / component design stage, the development of technologies which affect material choices and the wider materials value chain forces at play at a given time.

In terms of the methodological approach, in line with the scope of the ProSUM project, data mining will address available literature and publications on factors influencing the CRM parameters for component/product composition relevant for the EU member states plus Switzerland and Norway. The time period covers the years 1980 to 2015. In accordance with the description of Task 2.1 in Annex 1 of the ProSUM Grant Agreement, data mining is based on literature, existing open source databases currently in the ProSUM bibliography, expanded with a specific literature which has been found through the literature review for this deliverable.

The CRMs addressed in Deliverable 2.2 correspond to the CRMs defined as critical to the EU. More specifically, for the ProSUM project, critical materials are elements from the periodic table of elements (metals / rare earths), cf. section 7.4 and Annex 5 in D5.3 (Figure 2).

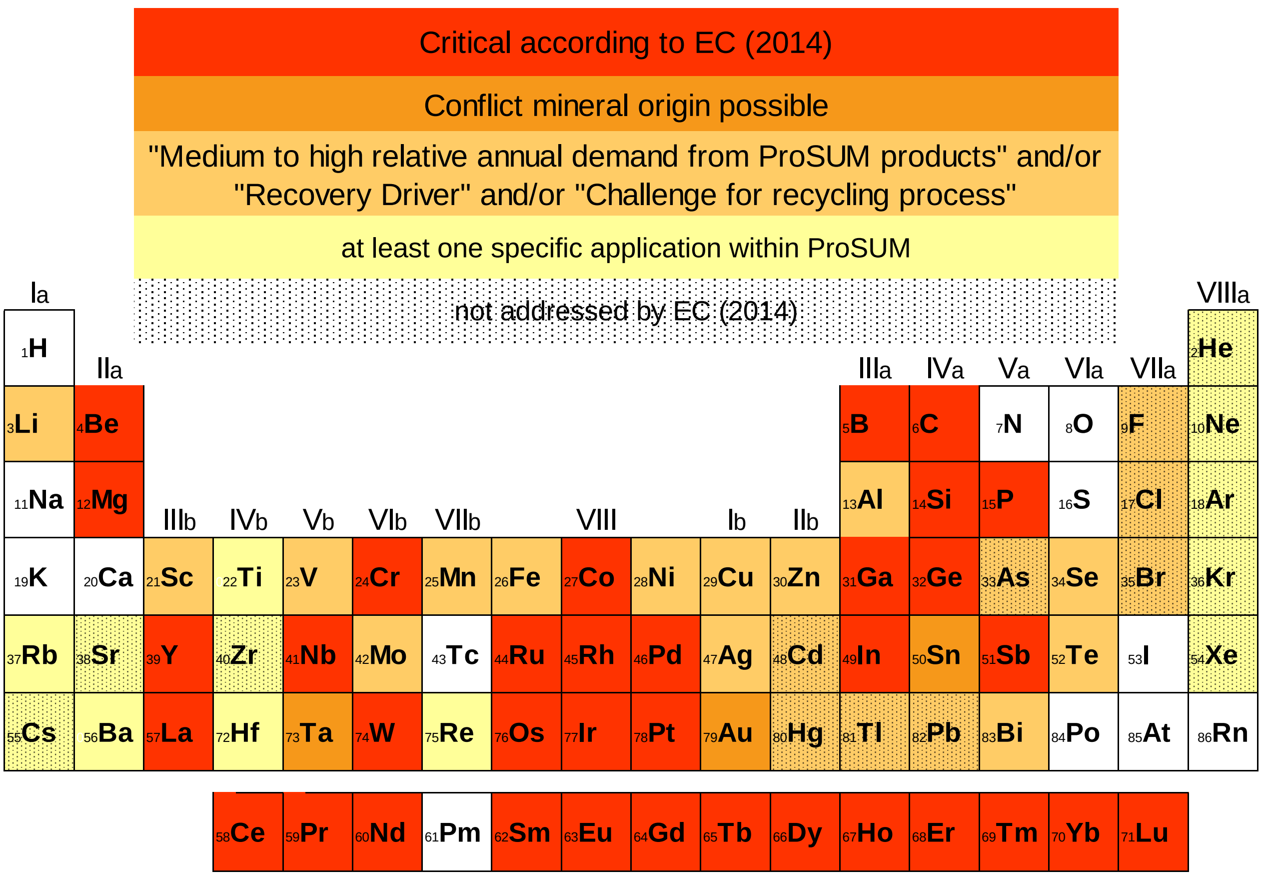


Figure 2: ProSUM project: critical materials are elements from the periodic table of elements (metals / rare earths)

CRM Parameters

The work for Deliverable 2.3 relies on the framework of classification and code lists that were developed in Deliverable 5.3 "Review and harmonisation of data", especially the product keys, component list and material list. In addition to these code lists, a list of CRM parameter labels has been established in D2.2 to enable a precise description of the property represented with numeric data contained in references. The CRM parameters identified in D2.2 are reproduced below.

- **e-m:** Mass or mass fraction of an element in a material
- **e-c:** Mass or mass fraction of an element in a component
- **e-p:** Mass or mass fraction of an element in a product
- **m-c:** Mass, mass fraction or volume of a material in a component
- **m-p:** Mass, mass fraction or volume of a material in a product
- **c-c:** Mass, mass fraction, number, length, volume, area or other extensive property of a component in another component
- **c-p:** Mass, mass fraction, number, length, volume, area or other extensive property of a component in a product
- **p-p:** Mass, mass fraction, number, length, volume, area or other extensive property of a product in another product
- **p:** Mass, length, area, volume or other extensive property of a product
- **c:** Mass, length, area, volume or other extensive property of a component
- **p-f**: Mass, mass fraction, number, length, volume, area or other extensive property of a product in a product flow

Note that *c-c*, and *p-p*, are valid options, since a product, such as batteries, may sometimes appear as a component of other products, and a component can often be subdivided into more components. For example, a populated printed circuit board and its capacitors are both considered components in this system.

2. Methods and Approach

In line with the scope of the ProSUM project, data mining has revealed publications which will provide the data and information on the factors influencing the CRM parameters for component and product composition. Geographically the literature will aim to be principally relevant for the EU. It is recognised that the global nature of materials chains means the geographical scope can be wider.

In accordance with the description of Task 2.1 in Annex 1 of the ProSUM Grant Agreement, data mining is based on literature, existing open source databases currently in the ProSUM bibliography, expanded with a specific literature which has been found through the literature review for this deliverable. The time period of the review covers the years 1980 to 2016.

The approach is to first define the scope: It was decided to focus on CRM content in Permanent Magnets (PM) in Hard Disk Drives (HDD) and vehicles, and CRM content in batteries over time (1980-2016).
The work package contributors then studied cases based upon available literature found in the ProSUM EndNote bibliography (primary focus on most frequently studied products and components identified in the ProSUM bibliography, i.e. computer components, components of vehicles and batteries).

a. PM in HDD (EEE)
b. PM in vehicles (ELV)
c. Batteries (BATT)

Based upon the studied cases, we identified a list of factors based on:

- factors posing significant influence on the CRM content within the parameters of c-c, c-p, e-c and as defined in D2.2. predefined examples of factors are:
  - introduction of new components/products/technologies/regulations/etc. (e.g. lithium batteries)
  - Division by EEE, BATT and ELV.

The final result of this deliverable is an overview of the identified factors in the cases, which are then categorized and generalized for further application in the ProSUM IN.

2.1 Key activities on EEE, Batteries and Vehicles

This phase was divided among the ProSUM partners involved: TUD, Chalmers, Empa, Eucobat, Recharge, TUB. TUD and TUB performed the literature review on EEE time-series, Chalmers and Empa on Vehicles time-series and Eucobat and Recharge focus on a literature review on batteries time-series.

3. Results & Discussion

3.1 Results: Case – Magnet use in passenger cars

Identify factors affecting the CRM parameters of vehicles

Studies on the composition of vehicles with respect to critical metals were identified in deliverable D2.2. None of these studies provide sufficient data for quantifying changes over time in the critical metals composition of vehicles. One study identifies six main application categories for critical metals: steel alloys, aluminium alloys, magnesium alloys, nickel alloys, lubricants, catalytic converters and electric, electronic and magnetic components (Andersson et al. 2016), all of which can safely be claimed to have changed over time. This report focuses on electric, electrical and magnetic applications, which have increased significantly over the past two decades, see Figures 2 and 3. In the following, we give an overview of the factors affecting the choice of magnetic material in vehicles, the historical development of magnetic materials and a summary of the factors identified which influence the content of critical metals in vehicles through their use in magnets. Moreover, we provide an overview of changes in the use of electrical and electronic devices in vehicles in general.

Important properties of magnetic material

The magnetic, physical and chemical properties determine, to a large extent, the selection of magnetic material for different applications. The most important properties in this context are (Constantinides 2012):

- Flux density - B_r [G]
- Resistance to demagnetization - H_{cJ} [Oe]
- Reversible temperature coefficient for B_r – α [%/°C]
- Reversible temperature coefficient for H_{cJ} – β [%/°C]
- Energy product - BH_{max} [GOe]
- Corrosion resistance
- Curie temperature - T_C [°C]
- Physical strength
- Ductility

In addition, the cost of raw materials is important. The four important magnetic materials in use today in passenger cars are alnico (AlNiCo), samarium cobalt (SmCo), ferrite and neodymium-iron-boron (NdFeB). In addition, there are so-called bonded magnets created by embedding any of the former materials in a rubber, thermoplastic, thermoelastomer or thermoset. Table 1 shows an overview of these properties for the four most common magnetic materials: AlNiCo, Ferrite, SmCo and NdFeB.

Material	Properties																	Relative cost at 20°C[10]	Relative cost at 200°C[10]
	Magnetic									Physical									
	Br		HcJ		α	B	BHmax	Usable temperature		Corrosion resistance	Tc	Manufacturing Process							
	kG		kOe		%/°C	%/°C	MGOe	°C			°C			Bonding					
	Min	Max	Min	Max				Min	Max			Casting	Sintering	Injection	Compression	Calendering	Extrusion	$/MGOe	$/MGOe
AlNiCo	5.5	13.5	0.64	1.9	-0.02	-0.01	1.4 to 10.5[4]	-250	425	Excellent	860 to 900[7]	x	x	x				6.95	7.9
Ferrite	2.5	4.1	3.2	4.5	-0.2	0.27[3]	2.7 to 4.0[5]	-40	150	Outstanding	450		x	x		x		3.9	9.15
SmCo	8.8	18	18	-	-0.035 to -0.04[1]	-0.2 to -0.4[1]	18 to 32	-250	525	Good	700 to 810[8]		x	x	x			7.25	8.45
NdFeB	10	13	-	14	-0.07 to 0.13[2]	-0.4 to -0.65[2]	27 to 45[5]	-125	225[6]	Fair	310 to 470[9]		x	x	x	x	x	8.5	10.8

Table 1: Properties of the most common magnetic materials. FeCrCo, CuNiFe and hybrid magnets are not considered because they are not relevant for automotive applications. Data from: (Rooze 2002, Constantinides 2010, Constantinides 2012)

[1] $SmCo_5$ has higher α and β than Sm_2Co_{17} (less temperature stable)
[2] Sintered NdFeB have higher α and β than bonded NdFeB (less temperature stable)
[3] Ferrite magnets have a positive β; they are resistant to demagnetization at high temperatures, but not resistant at low temperatures
[4] Cast Alnico have higher BHmax than sintered Alnico
[5] Bonded type NdFeB and Ferrite have lower BHmax than their sintered types
[6] Higher additions of Dy, Nb, V, Ga and Co, etc. are required above 80 °C
[7] Values for cast Alnico; higher: Alnico grade 5, lower: Alnico grade 8
[8] Sm_2Co_{17} has higher Tc than $SmCo_5$
[9] NdFeB bonded have higher Tc than NdFeB sintered
[10] Material prices from mid 2013

History of permanent magnet materials

The four automotive vehicle magnetic materials were discovered and developed subsequently throughout the 20th century, starting with alnico magnets in the late 1930's, ferrite magnets in the late 1950's, SmCo in the early 1970's, and NdFeB in the early 1980's. The development has been driven by a need for improved magnetic properties and reduced cost. Figure 1 shows how each subsequently developed material has surpassed the earlier ones in terms of energy product, BH_{max} (Rooze 2002), with the exception of ferrite magnets, whose main advantage is the low cost.

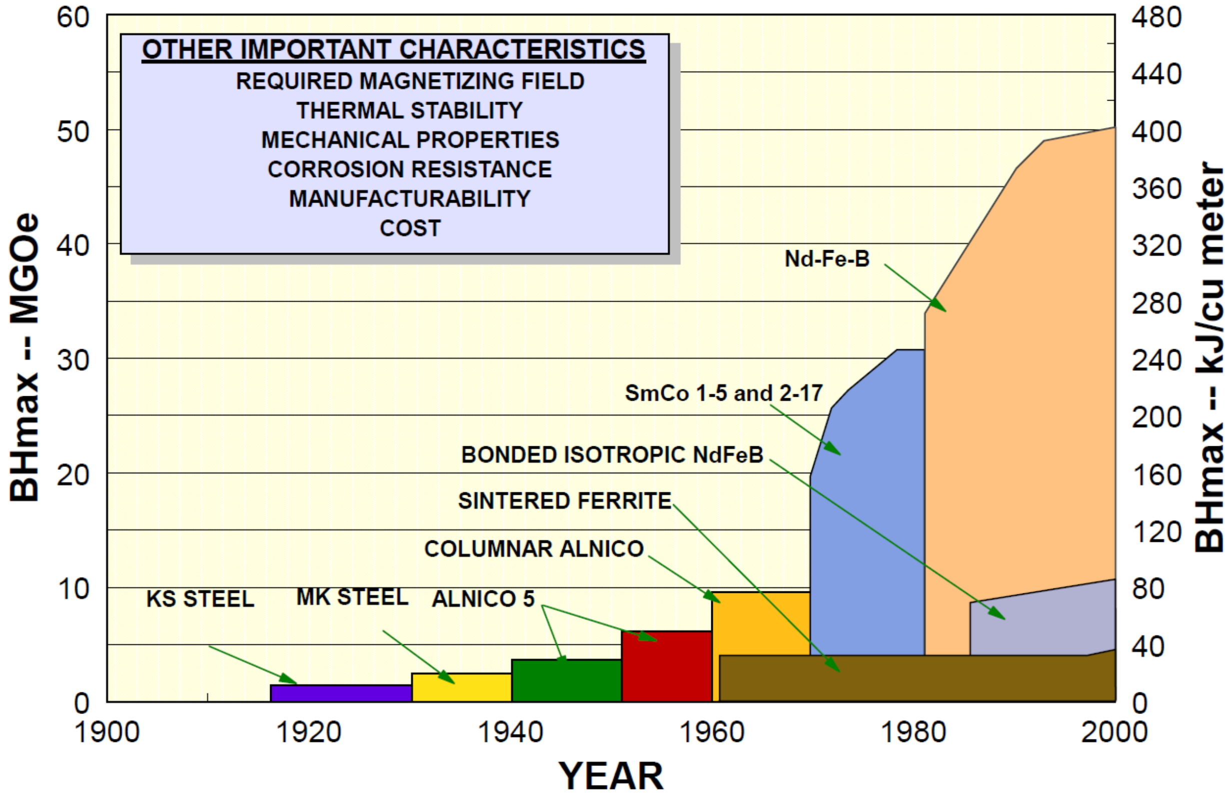


Figure 3 The historical development of magnetic materials and their energy product, BH_{max} (Rooze 2002).

Factors affecting the content of critical metals in vehicles

Magnets in vehicles are used mainly in transducer applications (devices that convert one type of energy to another). They can be divided in three groups: *electromagnetic*, converting electric signals to magnetic signals and vice versa; *electroacoustic*, converting electric signals to sound, and *electromechanical*, converting electric energy to mechanical energy or vice versa. Of these three, electromechanical devices are largest in mass in vehicles. Electromechanical devices include all the electric motors (e.g. power windows, windscreen wipers, fan motor) as well as the alternator. The magnetic materials contain different critical metals, see Table 2.

Magnetic material	*Critical metals*
AlNiCo	Co
Ferrite	La (optional)
SmCo	Sm, Co
NdFeB	Nd, Pr (optional), Dy (optional)

Table 2: Content of selected critical metals in magnetic materials (Howe 1940, Lee 1988, Tabaru and Shimizu 1992, Takami, Kubota et al. 1999)

Ferrite magnets are normally the first choice of magnetic material due to its low cost and outstanding corrosion resistance (Rooze 2002), and is therefore by far the most common magnetic material found in vehicles (Widmer 2015). The more costly material NdFeB is used when a higher energy density is required such as in small speakers, most often found in high-end vehicles. SmCo is rarely used due to the high cost, but can be an option when a high energy product and resistance to magnetization (by temperature or magnetic field) is required, e.g. for safety applications such as the seatbelt adjusters, although this is only known to be used in high-end vehicles.

The choice of magnetic material in vehicle applications has in the past been influenced by the discovery of entirely new materials, such as ferrite magnets and NdFeB. The required magnetic, physical and chemical properties are given by the application in which the magnet is used, and if several materials are suitable the most important factor for selection is the price. Hence, the current change in magnet use in vehicles is mainly driven by the introduction of new devices. The expected penetration of electrified vehicles in the passenger vehicles market is likely to drive the use of magnets significantly, since they often, but not always, use NdFeB magnets for the electric drive motor (Elwert et al 2015). Another factor increasing the use of magnets in vehicles is the penetration of various other electrical and electronic devices.

Electric and electronic devices in cars

The use of electrical and electronic systems in vehicles is increasing and contributes significantly to increasing their content of critical metals. Some electronic systems have reached maturity or even decline, see Figure 2 (Deloitte China Automotive Practice 2013). However, there are also new systems that currently experience rapid growth, such as advanced driver assistance systems (ADAS), gasoline direct injection (GDI) and tire pressure monitoring system (TPMS).

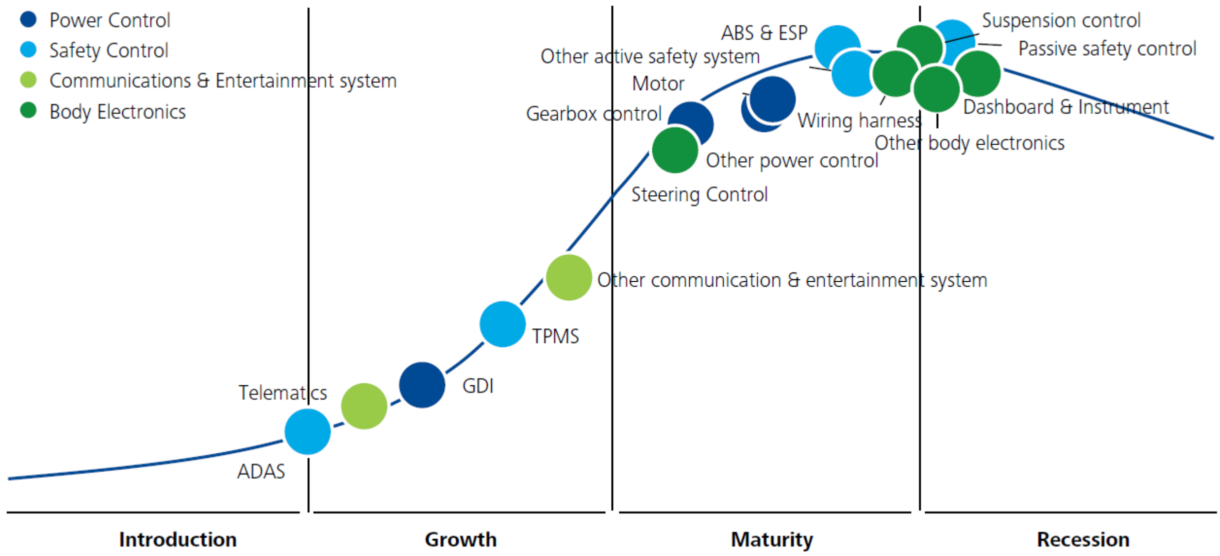


Figure 4: Market penetration of various electronic systems in vehicles (Deloitte China Automotive Practice 2013). ADAS = advanced driver assistance systems, GDI = gasoline direct injection, TPMS = tire pressure monitoring system, ABS = anti-lock braking system, ESP = electronic stability program.

By reviewing market analysis reports and producer catalogues we identified the following main functions driving the increasing use of electronics in vehicles (Bosch , McKinsey & Company 2012, Deloitte China Automotive Practice 2013):

- Safety (considered the most important driver in terms of number of devices)
- Fuel economy
- Emissions control
- Communication and entertainment

- Comfort
- Electrified powertrains

Safety and emissions control are, in turn, heavily influenced by regulatory requirements (Deloitte China Automotive Practice 2013). Figure 3 shows the market penetration of various electronic systems in new cars sold in Germany since 1999 (Deutsche Automobil Treuhand 1999 to 2013 as compiled in (Sander 2014). Many of these systems have now reached a near 100% market penetration and most have reached maturity. It can clearly be seen that the introduction of electronics for safety (ABS and side air bag), comfort (air condition, electric window lift) and entertainment (CD-player) were all significant in the past decade.

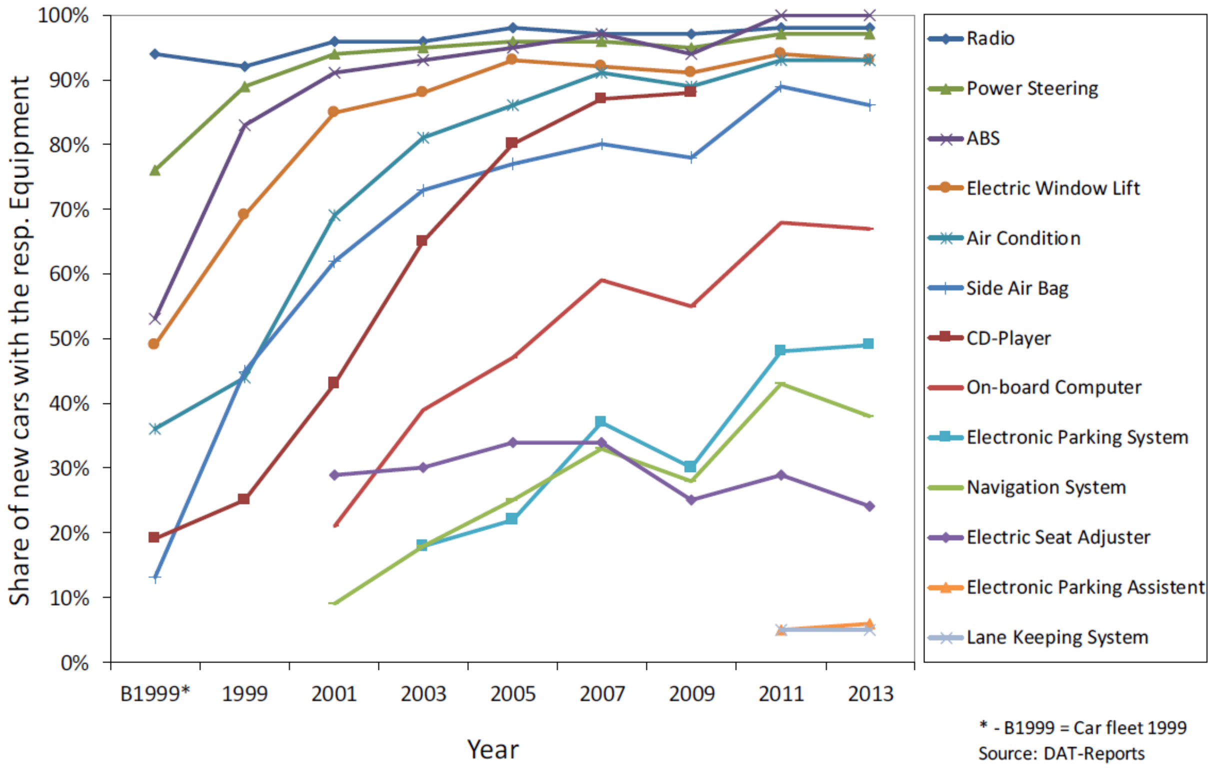


Figure 5: Market penetration of electronic systems in new cars sold in Germany (Sander 2014).

The increase in electric and electronic systems appears to continue, evident in, for example, the equipment of new vehicles on the German market. The following changes between 2014 and 2015 are pointed out:

"Particularly noticeable were the increases in new and used vehicles with on-board computers and rain sensors. In addition, ESP and TPMS were mandatory in new vehicles. Both of these have been required equipment features in all new passenger vehicles and motorhomes in the EU since 1 November 2014. In addition, more vehicles had metallic paint, inbuilt hands-free equipment and adaptive cruise control. In used vehicles, light sensors, side airbags and multifunction steering wheels were the features that saw double-digit increases compared to the previous year. New in the survey for all vehicles were automatic start-stop systems, digital radios, drowsiness detection systems or driver alert systems, electric boot lids and rear-view cameras."(Deutsche Automobil Treuhand 2016)

3.2 Results: Case study on Batteries

Introduction to the outcomes

Basically, there are four CRMs that can be found in batteries:

- Cobalt in main types of lithium-ion batteries and in NiMH batteries
- REE in NiMH batteries (Ce, La, Nd, Pr) (and in low concentrations in lead-acid batteries (Pr))
- Antimony in lead acid batteries mainly;
- And natural graphite in a large proportion of the Li-ion batteries.

The following **factors** may have a significant influence on changes to the CRM parameters:

- Economic requirement: battery price. This is particularly true for batteries containing Co, where price can represent a significant part of the battery cost.
- Technical requirements:
    - Battery specific energy
    - Charge/Discharge rate capability
    - Lifetime and calendar life
    - Battery volumetric energy

  For example, slightly different performances can be observed when using artificial graphite for the Lithium-ion batteries cathode, when compared to natural graphite.
- Legislative requirements: Article 4 of the Batteries Directive 2006/66/EC prohibits the placing on the market of portable batteries or accumulators that contain more than:
    - 0,0005 % of mercury by weight, excepting button cells with a mercury content of no more than 2 % by weight
    - 0,002 % of cadmium by weight

In general, the decisive factors for the development of the average material composition of batteries are not a result of changes in the composition of batteries with a specific electrochemical system, but market shifts from an electrochemical system to another.
(Rydh & Svärdb, 2002) summarised the production of portable rechargeable batteries for the years 1989 to 1999, with a projection up to 2009 (Figure 6). (Patrício, 2015) in Sweden and (Meisenzahl & Sittig, 2010) in Germany published more recent data on the market shares of the different electrochemical systems (Figure 8 and Figure 9). These data do not include industrial and automotive batteries. The data shows a decrease in the production of NiCd batteries, an increase in the production of Li-ion batteries and a trend towards a decrease in the production of NiMH batteries.

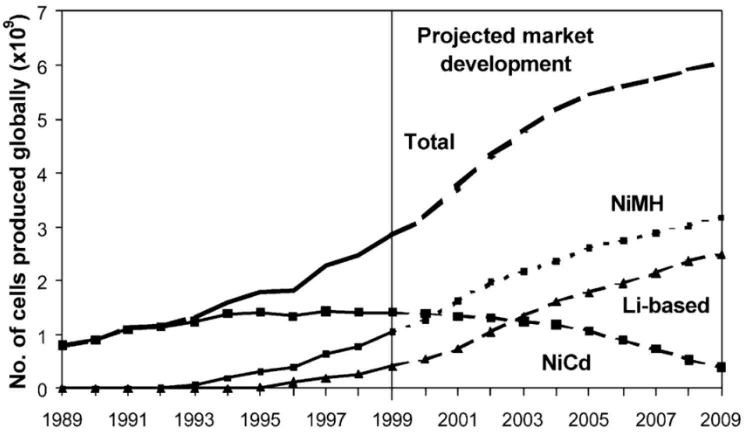


Figure 6: Global production of portable rechargeable batteries 1989–1999 with projected market development from 2000 to 2009 (Rydh & Svärdb, 2002)

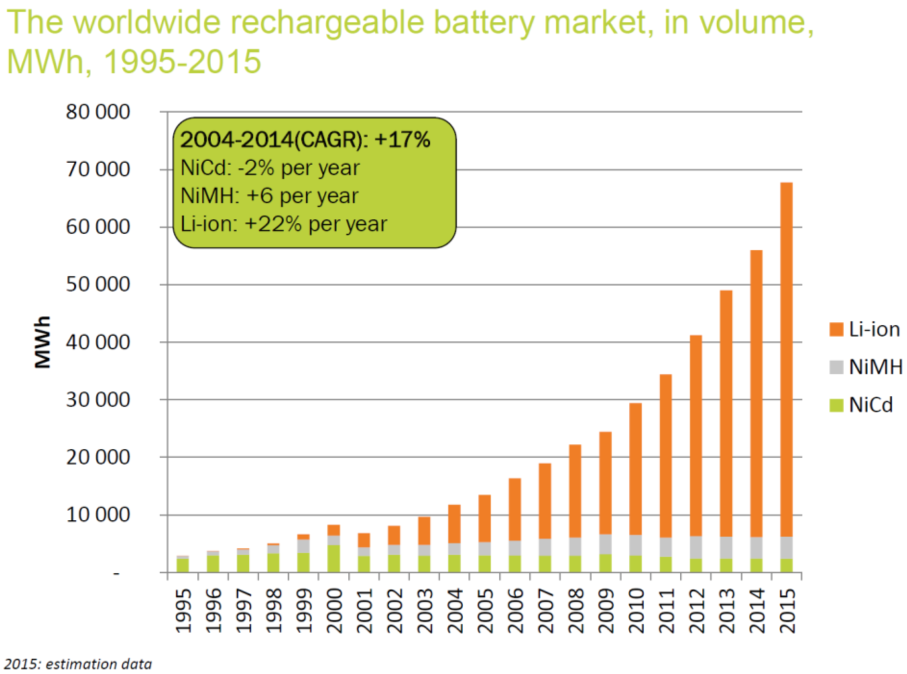


Figure 7: Global production of portable rechargeable batteries 1995-2015 (Pillot, 2014)

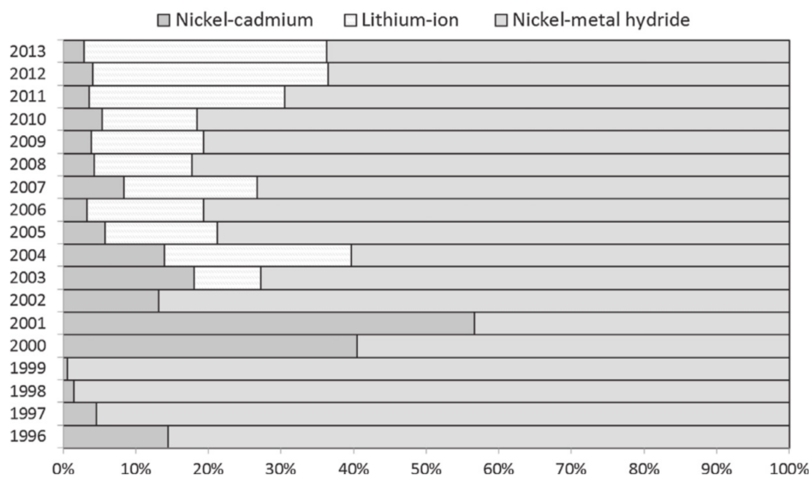


Figure 8: Share of number of secondary batteries consumed by electrochemical composition in Sweden (Patrício, 2015)

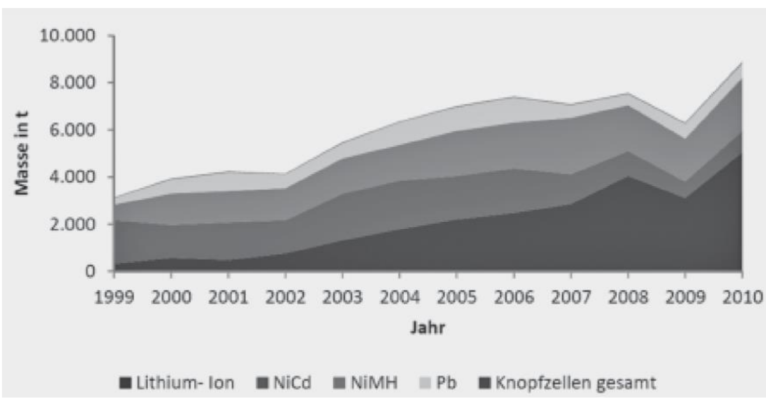


Figure 9: Weight of secondary batteries put on the market in Germany 1999-2010 (in tons) (Meisenzahl & Sittig, 2010)

The shifts in the development of electrochemical systems reflect changes on the market for products, in which the batteries are used, such as the case of compact electronic products like smartphones, leading to changes to the technical and economic requirements of batteries. (Patrício, 2015) illustrated the changes of the EEE share for consumed batteries in Sweden for 1996–2013 (Figure 10).

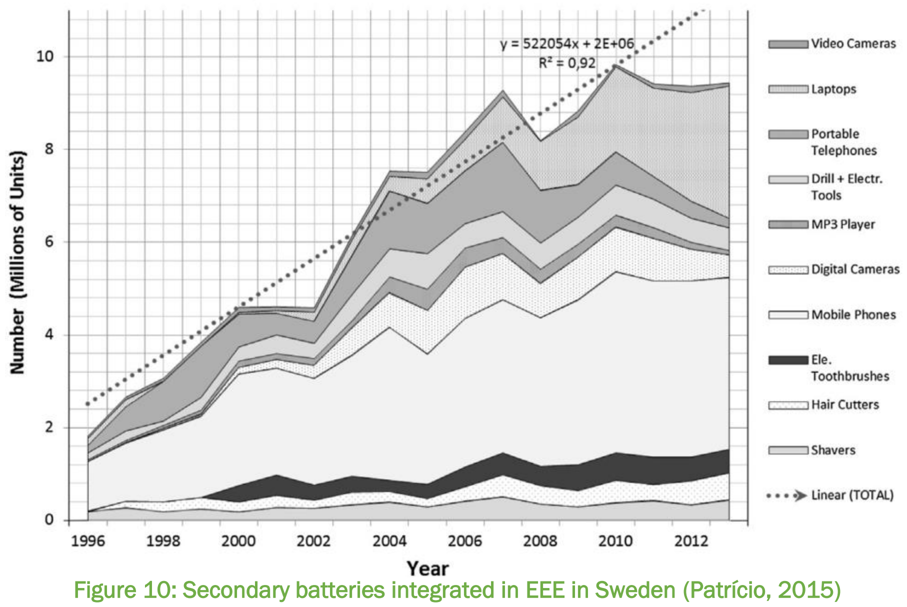


Figure 10: Secondary batteries integrated in EEE in Sweden (Patrício, 2015)

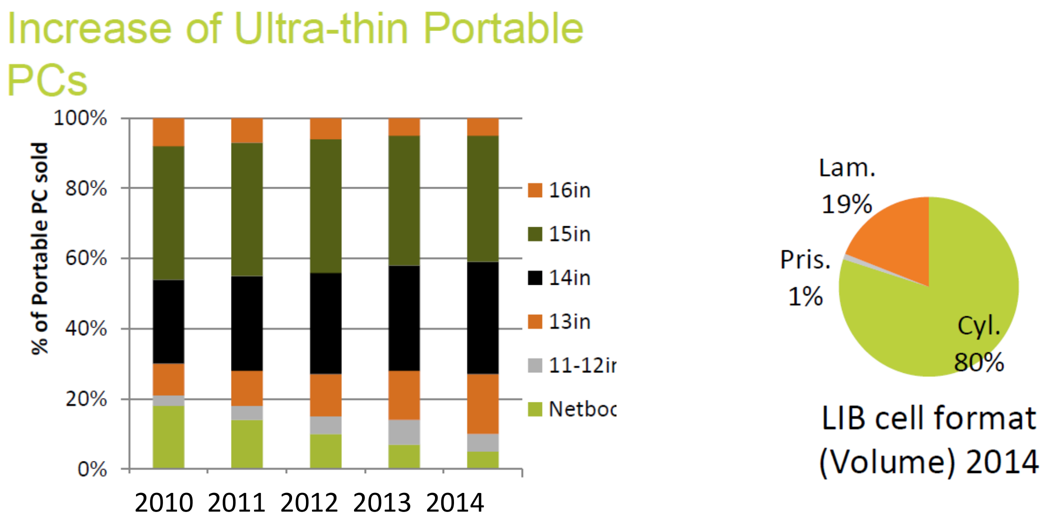


Figure 11: % of portable PC's according their thickness (in inches) placed on the market from 2010 to 2014, and proportion of laminate, prismatic and cylindrical cells in 2014 (Pillot, 2014) (LIB = Li-Ion Battery)

Another example is the shift of portable personal computers (PC) towards thin and "ultraportable" notebooks. As a result, the traditional battery shape used for portable PC, since the 90's, can no longer be used in these new products: the battery shape was based on a standard cylindrical shape Li-ion cell having a diameter of 18 mm. The new batteries design requires a maximum thickness of 10 mm or less, and therefore, requires the development of new battery technologies. As indicated in the

, the new format (called here laminate batteries) represents 19% of the global market and this is increasing. This new requirement is one of the reasons for the shift observed in the batteries chemistry from Li-CoO2 type to Li-NMC type (Figure 12)

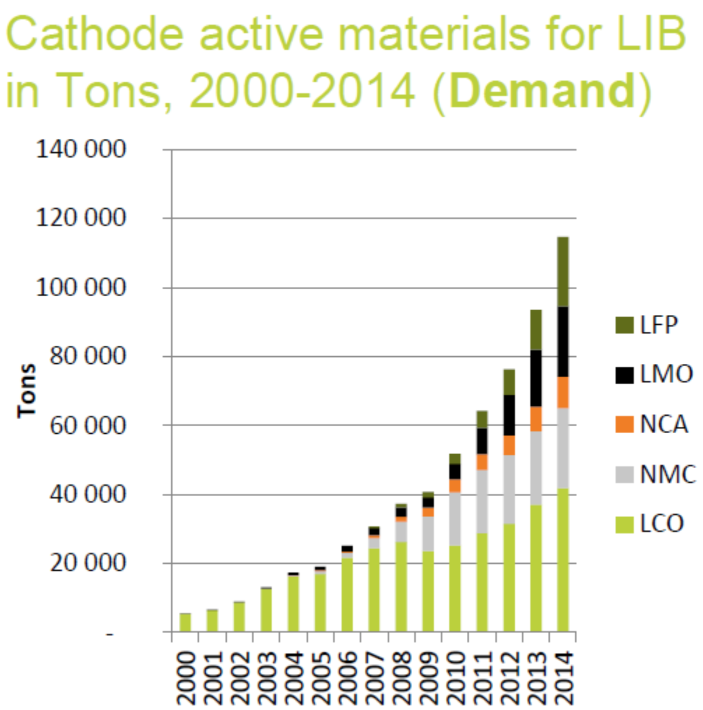


Figure 12: trends in the usage of cathode active material of Li-ion battery set from 2000 to 2014, (Pillot, 2014)

Overview of the factors and their time of introduction to the market for selected BATT types

This section presents an overview of the factors, the date of introduction to the market and the development of material composition for following BATT types selected for the amount of CRM they contain and their relevance to battery markets:

- Cobalt in lithium-ion batteries (LIB);
- REE in NiMH batteries (Ce, La, Nd, Pr) ;
- Antimony in lead acid batteries;
- And natural graphite in Li-ion batteries (LIB).

Cobalt in lithium-ion batteries

The composition of the electrochemical systems of the different lithium-ion batteries does not significantly vary over time, but the uses of materials has changed as a consequence of the introduction and diffusion in the market of new electrochemical systems (Figure 13). Cobalt is contained in the cathode, of several lithium-ion battery types, in different concentrations.

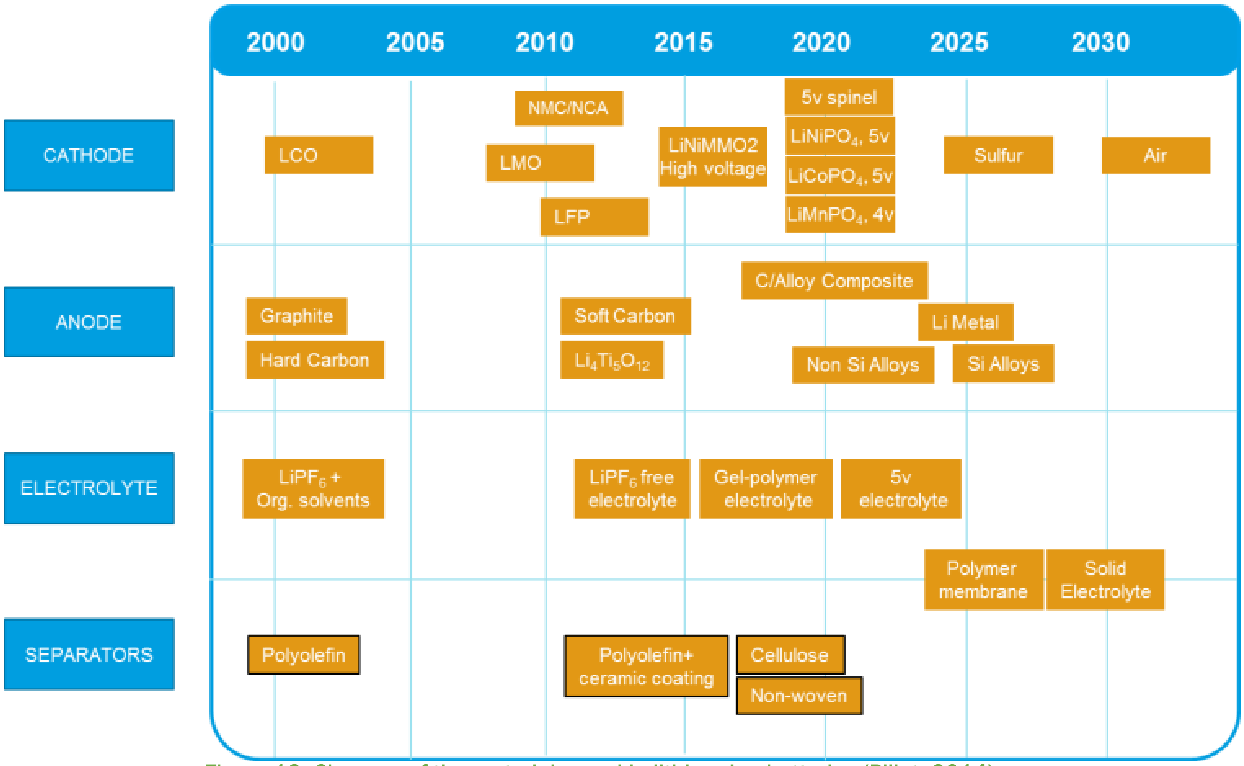


Figure 13: Changes of the materials used in lithium-ion batteries (Pillot, 2014)

Avicenne market data (Avicenne, 2015) show market shifts from the cobalt-rich LCO batteries to other types of lithium-ion batteries which contain less cobalt, such as NMC and LMO. This is reflected in the data on material composition of different types of batteries compiled by RECHARGE in work package 2 (**Error! Reference source not found.**).

Battery type	Mass fraction of cobalt in battery (wt- %)
Lithium nickel manganese cobalt (LiNMC)	4%
Lithium Cobalt (LCO))	14%

Table 3: Mass fraction of cobalt in different types of batteries

The overview of the cobalt concentration in lithium-ion batteries contained in WEEE shown in **Error! Reference source not found.** was provided by (Sommer, Rotter, & Ueberschaar, 2015).

Battery type	*Average cobalt content in wt.%*	*Error*
Li-ion LCO	14.0	±2
Li-ion NCA	2.5	±1.5
Li-ion NMC	4.0	±2

Table 4: Average cobalt content in Li-ion batteries based on literature evaluation (Sommer et al., 2015)

As discussed above, the drivers for changes for Cobalt content are mainly the new battery shape requirements (thin batteries) and the cost of cobalt. These incentives for change will probably remain valid in the coming years. Accordingly, it is proposed to use these trends for the assessment of the products placed on the market in the coming years.

REE in NiMH batteries

An average of 10 weight % in NiMH batteries in WEEE consists of rare earth elements (Sommer et al., 2015). NiMH batteries with an average of 3.5 kg of REEs are also contained in hybrid electric vehicles (Alonso et al., 2012), where sales volumes are significant since 2010 and continuously increasing (Yano, Muroi, & Sakai, 2015).

The rare earth elements used in Ni-MH batteries are not selected as single rare earth elements, but based on a mixture called Misch Metal. This Misch Metal composition depends on the raw material used. Based on the typical Mish Metal used in the market, the following average compostion for the REE content of a battery can be calculated (see material composition of different types of batteries compiled by RECHARGE in task 2.1.1, described in the D2.2 report for the ProSUM project):

Ce	*Cerium*	*1%*
La	Lanthanum	9%
Nd	Neodymium	0,3%
Pr	Praseodymium	0,2%

Table 5: Calculated REE content of NiMH batteries

The trends for the change in this composition is mainly cost optimisation: due to the high price increase of some of the rare earth elements specifically used in other applications (such as neodymium in permanent magnets NdFeB), the Misch Metal producer can propose neodymium-depleted Misch Metal.

Conversely, there are few incentives for change to the CRM content in Ni-MH batteries coming from market requirements. The two main markets for Ni-MH are:

- The automotive market, where they are used in Hybrid Electric Vehicles. The trend in this market is a progressive substitution by Li-ion batteries for most of the new products placed on the market.
- The portable rechargeable battery market (substitution of small primary cells). This market is relatively stable, and is not pushed by highly competitive technical requirements.

In both cases, there is globally limited R&D spending for development leading to changes to battery design and composition.

Therefore, it is proposed to use a stable composition as the trend for products placed on the market in the coming years.

Antimony in Lead-acid batteries

Antimony has been used for years in Lead-acid batteries as an additive to lead grids in order to improve their mechanical strength as electrode support. Although not all Lead-acid batteries use antimony, both technologies based on lead-calcium and lead-selenium grid alloys still add antimony, in the range of 2 to 6%.

Based on the type of batteries placed on the market, according to their usage, a calculation of the average amount of antimony has been proposed for the two selected categories of lead-acid batteries (see material composition of different types of batteries compiled by RECHARGE in task 2.1.1, described in the D2.2 report for the ProSUM project):

Lead-acid (Pb), sealed	Sb	antimony	0,10%
Lead-acid (Pb), vented	Sb	antimony	2%

Table 6: Antimony content in Lead-acid batteries

Concerning the trend for changes, a lot of published literature is available that describe the use of antimony in lead acid batteries, which underline the current R&D efforts to optimize the use of antimony in this application.

At the moment, there is no clear identification of possible substitution of antimony in current technologies of lead acid batteries. Therefore, it is proposed to keep the trend for antimony content constant for batteries.

Natural graphite in Li-ion batteries

Graphite is the main material used for the anode of the Li-ion Batteries (LIB). It comes from two sources: natural graphite and artificial graphite (Figure 14).

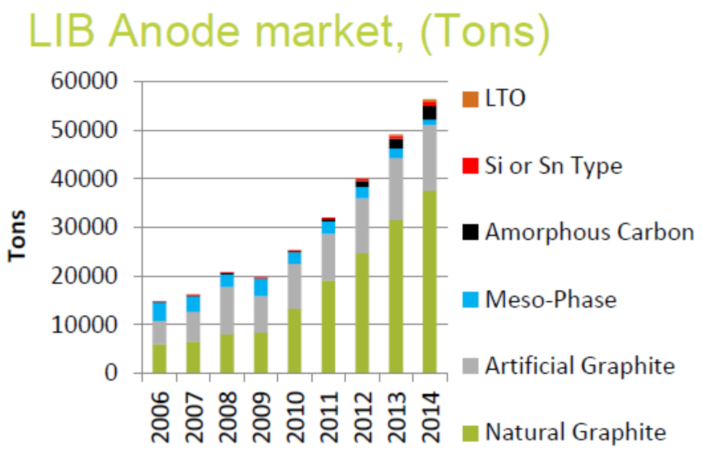


Figure 14: Changes of the materials used in lithium-ion batteries anode (Pillot, 2014)

As can be seen in Figure 14, the use of both natural and artificial graphite are growing, but the major choice is natural graphite. As both types are competitive from a cost and technical point of view, and sometimes used as a mixture, there is no clear indication that this trend will change. Nevertheless, external markets may play an important role: the natural graphite used in batteries represents about one quarter of the total natural graphite in industrial usage. Therefore, in the case of a large increase in Li-ion batteries, material consumption, a shift towards artificial graphite can be foreseen. The situation in this case can be considered as different from the case of cobalt or lithium, which substitution in Li-ion or Ni-MH batteries is more difficult or impossible.

As a result, it seems likely that the trend in the future years is similar to the present one, until the amount of Li-ion batteries placed on the market is doubled or tripled and the sourcing of natural graphite becomes more critical.

3.3 Results: Case study – Permanent Magnets in Hard Disk Drives

The graph below (Figure 15) depicts the time-series analysis for permanent magnets (PM) of the material composition of PM in terms of the elements used to produce them over time. In the 1930's AlNiCo magnets are introduced (Zepf, 2013) mainly consisting of the elements Fe, Al, Ni, Co, and Cu. In the late 1960's, the FeSmCo magnets were developed, due to a demand for increased magnetic properties whilst maintaining or reducing weight. These so-called Samarium-Cobalt magnets were a significant advance in PM technology. High prices of both samarium and cobalt were important factors for the subsequent development of the NdFeB PM, which is currently the materials composition of choice for PM's in HDD's.

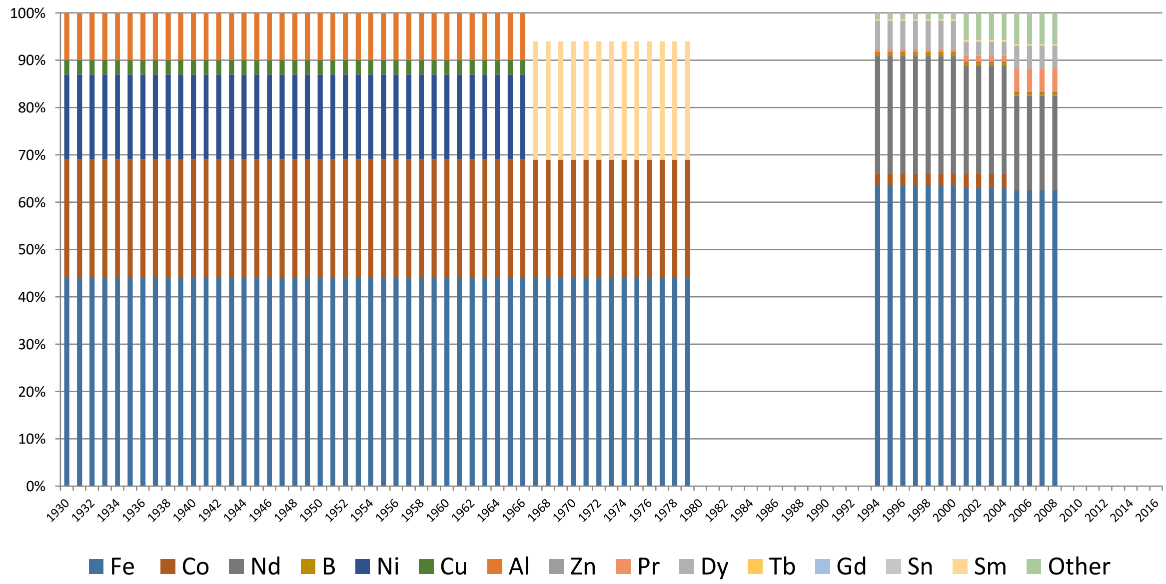


Figure 15: analysis over time of permanent magnet compositions on elemental level

HDD were introduced due to the introduction of computers in the eighties. This immediately introduces the "market" factor: customers embraced computers, and from there created the demand for more and better storage for desktop computers. The industry's response was a HDD, which quickly became an integral part of PC's. The best analysis of PM material composition in HDD's over time is from (Ueberschaar & Rotter, 2015). The time-series analysis based upon this publication is shown in Figure 16.

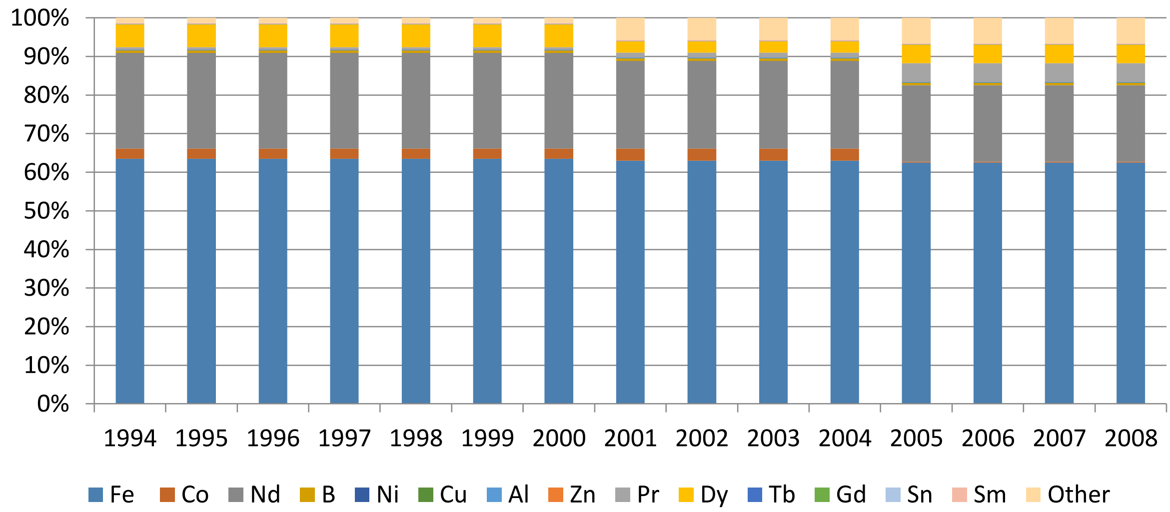


Figure 16: the composition of NdFeB PM used in HDD's over time (Überschaar & Rotter, 2015)

In terms of CRM's, Neodymium has the biggest share in the composition. It plays an important role in the magnet performance. The use decreased slightly to 25.5 % between 1994 to 2000. In the years 2000 to 2008 it dropped to 22.5 %. This drop correlates to a general reduction in the REE overall content in NdFeB magnets.

Ueberschaar and Rotter, 2015, go on to show how Dysprosium in spindle motor magnets also reduced in the period 2000-2005. Similar results are seen for Praseodymium. In the period 2000–2008, Neodymium decreased to under 20 %. At the same time Praseodymium and Dysprosium were substitutes but were now using smaller quantities. Cobalt appears to be similar. Between 1994 to 2004 higher content of Cobalt was seen (3 %), but after 2005 it fell to well below 1 %.

Literature from Ueberschaar and Rotter, 2015, demonstrates how, in the case of voice coil magnets, there was an increase in Praseodymium in voice coil magnets until 2005 due to lower prices. When prices raised sharply in 2005/6 use decreased. A similar trend can be seen for Cobalt where a drop was seen from 3% in 2000 to 1.4 – 1.6% in 2008.

Alternative blending approaches were taken for both spindle motor magnets and voice coil magnets and this was in turn affected by desired technical performance and prices.

3.4 Discussion: Summary of identified factors for the 3 case studies

Categorisation of factors

The different factors from across the three case studies are grouped into economical, technological, regulatory, social and other categories to analyse which types of factors e.g. occur most, have the most impact on CRM use and concentration (either positive or negative). It is also used to attempt to describe which type of effect on CRM use and concentration will be generated by each of the factor types.

The approach to generating this table was firstly to seek keywords in the text which relate to the factors. These are shown in the first column titled "Keywords in Literature indicating a factor". These keywords were then grouped together into "Factor category" headings. Thirdly any "Potential underlying reasons" were generated. Indicative "CRM affected" are listed.

Keywords in literature indicating a factor	**Factor category**	**Potential underlying reasons**	**CRM affected**	**Vehicles (magnets)**	**Battery**	**EEE (magnets in HDD)**
"due to size" "compact" "shape" "thin" "Ultraportable" "diameter"	Technological - dimensions	Miniaturisation. Customer demand	All CRM	x	x	x
"Power" "Charge / discharge rate"	Technological – power out, higher energy density	Product features Customer demand	Co, La, Sm, Nd, Pr – many CRM	x	x	x
"Weight" "Ultraportable"	Technological - Mass	Product features Customer demand	Co, La, Sm, Nd, Pr – all CRM	x	x	x

"resistance to temperature"	Technological – Temperature	Product features Customer demand	Co, La, Sm, Nd, Pr - all	x	(x)	x
"corrosion"	Technological – chemical and or electrochemical reaction	Product features Customer demand	All CRM	x	x	x
"other devices" "shifts in system"	Technological – system interface with other devices	Product features Customer demand	Co, La, Sm, Nd, Pr - all	x	(x)	x
"economy"	Technological – system power requirements	Product features Customer demand	Co, La, Sm, Nd, Pr - all	x		x
"market" "maturity" "volumes"	Business – market forces	Company internal forces, Forces between companies. Customer demand. Conflict materials, geopolitics and regional instability, insecurity of supply.	All CRM	x	x	x
"Economic requirement"	Business – cost / price forces	Company internal forces, Forces between companies. Market systemic forces. Customer demand	All CRM	x	x	x
"Lifetime" "calendar life"	Business – market forces	Company internal forces, Forces between companies. Market systemic forces. Customer demand	All CRM	x	x	x
"Legislative requirements" "mercury"	Governmental forces – toxic and mining, process and product waste controls	Toxic & hazardous materials, Pollution, waste, eco- protection, shipments of waste, protection of 3rd countries, bio diversity.	Cd, Hg All CRM	x	x	x
"safety" "standards" "vehicle requirements"	Governmental forces – Legislative – product regulations – industry standards	consumer safety protection	All CRM	x	x	x
"R&D spend"	Business – R&D investment. Also Governmental - policy – inter-governmental, defence and fiscal	Sizes of markets, payback periods, business confidence, costs of new technology development, global financial systems, stock markets, banking sector, central bank policy, interest rates, shift in loci of economic power (W to E), Defence spend. global debt.	All CRM	x	x	x

Table 7: Overview of identified factors in the selected case-studies

It should be noted that the keywords, factors, and underlying reasons are not static or nor independent from each other. For example; the market demand for miniaturization leads to a weight reduction. The corresponding size reduction however leads to challenges in battery life. At the same time a conflict or trade dispute erupts which has another effect. All this can be happening at the same time and is dynamic and difficult to predict.

From the table above the factors that affect CRM parameters of products and components (Vehicles, Batteries and EEE) can be grouped into 3 overarching categories; technological, business and governmental. Societal factors, it could be argued, are seen via the business and governmental factors.

Discussion

There appears to be a pronounced spectrum of factors that affect CRM parameters of products and components (Vehicles, Batteries and EEE). The technological factors are the most pronounced in the literature, in particular the demand to reduce size and mass whilst increasing performance. These factors are in turn measurable and therefore scientific approaches are taken to achieve the required aims in the product / component. As the literature is scientific, then the focus tends to be on the technological factors.

This is a bias which is observed in the literature which defines critical materials. Peck et al 2015 and Peck, 2016 observes that a review of definitions of critical materials (1999 to 2014), establishes that the majority of the critical materials definitions were not written with the aim to engage R&D activity. Increasingly, however, R&D based approaches are being proposed by governments to help address the critical materials challenge, as seen for instance in the proposed EU circular economy package in 2015.

Peck, 2016 goes on to show via research conducted on the 29 companies, that the level of familiarity of the term and the role of CRM's is high. The majority of the companies are, however, in their own opinion, following wider developments in CRM's 'poorly'.

Both the definition of CRM / R&D and following CRM developments more widely can be observed in the results of the factors that affect CRM parameters review in this report. The core focus of analysis of factors is around the size, mass and performance of product in order to deliver product which will perform well in the market.

Less reported on and rarely welcomed by companies is the imposition of regulation by governments. This does however have a significant effect on changes to CRM composition in product. The same can be said of extending product life / durability.

Even less reported on is the interlinkage between governmental policy and CRM composition in product. International disputes, conflicts and embargos can have a rapid and significant effect on CRM composition in product. These are however seen as temporal factors, difficult to define concisely and impossible to predict. It concerns the actions of states and this human factor makes the link with scientific / technological factors difficult to assess.

It is unwise to attribute the label of 'most important' factor because it appears more often in the literature. As explained from Peck above the literature can have a bias, depending on which field it comes from. It has been seen that international disputes can have as a dramatic effect as steady technological changes. In the case of these two they are often interrelated, as most of the factors are.

4. CONCLUSIONS AND OUTLOOK

4.1 General findings

From the literature the factors that affect CRM parameters of products and components (Vehicles, Batteries and EEE) have been grouped into 3 overarching categories; technological, business and governmental. In more detail the factors are:

Technological

- Dimensions
- Higher energy density
- Mass
- System interface with other devices
- Temperature
- System power requirements

Business

- Market
- Cost / Price
- Business – R&D investment.

Governmental

- Toxic and controlled materials. Mining, process and product waste controls
- Legislative – product regulations – safety of users
- Policy – national, inter-governmental, defence /security and fiscal

Societal factors, it could be argued, are seen via the business and governmental factors.

The interlinkage between governmental policy and CRM composition in product is much less reported on, but can have a significant effect.

4.2 Next steps

This report takes a backwards look from 1980-2014 to assess the factors that affect CRM parameters of products and components (Vehicles, Batteries and EEE).

The next report will take these factors and look forwards into the near term future and aim to predict the factors that affect CRM parameters of products and components (Vehicles, Batteries and EEE).

5. REFERENCES

1. Andersson, Ljunggren Söderman and Sandén (2016) Are scarce metals in cars functionally recycled?, Waste Management, http://dx.doi.org/10.1016/j.wasman.2016.06.031
2. Deutsche Automobil Treuhand (2016) DAT report 2016, http://www.dat.de/fileadmin/media/download/DAT-Report/DAT- Report-2016-English-Version.pdf, accessed 2016-09-12
3. Bosch Product Information Automotive: Gasoline Systems, Bosch.
4. Constantinides, S. (2010). The Magnetic Material Challenge. ARPA-E Workshop Rare Earth and Critical Materials.
5. Constantinides, S. (2012). The Demand for Rare Earth Materials in Permanent Magnets. 51st Annual Conference of Metallurgists.
6. Constantinides, S. (2012). Material Matters. Keynote presentation at the opening of Motor and Power Electronics Laboratory at the Technical University of Graz, Austria, Arnold Magnetic Technologies.
7. Deloitte China Automotive Practice (2013). Trends and outlook of the auto electronics industry, Deloitte.
8. Howe, G. H. (1940). Sintered permanent magnet.
9. Lee, R. W. (1988). Iron-rare earth-boron permanent.
10. McKinsey & Company (2012). The Future of the North American Automotive Supplier Industry: Evolution of Component Costs, Penetration and Value Creation Potential Through 2020, McKinsey & Company.

11. Rooze, J. (2002). The Arnold Engineering Company TechNotes: How to Select the Appropriate Permanent Magnet Material, The Arnold Engineering Company.
12. Sander, K. (2014). Separation of components and materials from end-of-life vehicles aiming at the recovery of critical metals. W. Kaerger, M. Groke, M. Bergamos and R. Kohlmeyer. DEU, Oekopol.
13. Tabaru, K. and M. Shimizu (1992). Rare earth permanent magnet, method of heat treatment of same, and magnet body.
14. Takami, T., Y. Kubota and Y. Ogata (1999). Ferrite magnet and process for producing the same.
15. Widmer, R. (2015). Scarce Metals in Conventional Passenger Vehicles and End-of-Life Vehicle Shredder Output. Environmental science & technology. X. Du, O. Haag, E. Restrepo and P. A. Wager. CHE, American Chemical Society.
16. Greenfield A, Graedel TE. The omnivorous diet of modern technology. Resource Conservervative Recyclcling 2013;74:1–7, 2013.
17. Tilton J E, Depletion and the long-run Availability of Mineral Commodities, Report published by IIED for WBCSD, Washington D.C., 2001
18. Duclos S, GE Global Research Subcommittee on Investigations and Oversight of the House Committee on Science and Technology, USA, February 10, 2010
19. Peck. D, Kandachar. P, Tempelman, E, Critical materials from a product design perspective, Journal of Materials and Design, Volume 65, January 2015, Pages 147–159
20. Peck D, Prometheus Missing: Critical Materials and Product Design, Published by Delft Academic Press, Delft University of Technology, Delft, The Netherlands, 2016
21. D. Pavlov, B. Monakhov, M. Maja, N. Penazzi, Mechanism of action of Sn on the passivation phenomena in the lead-acid battery positive plate (Sn-free effect), J. Electrochem. Soc., 136 (1989) 27
22. D. Pavlov, B. Monakhov, M. Maja, N. Penazzi, Sn-Free Effect at the Positive Lead Acid Battery Plates, Revue Roumaine de Chimie, 34 (1989) 551
23. T. Laitinen, K. Salmi, G. Sundholm, B. Monahov, D. Pavlov, The Effect of Antimony on the Anodic Behaviour of Lead in Sulphuric Acid Solution. 1. The Behaviour of Lead-Antimony Alloys During the Early Stage of Oxidation, Electrochim. Acta, 36 (1991) 605-614
24. D. Pavlov, B. Monahov, G. Sundholm, T. Laitinen, The Effect of Antimony on the Anodic Behaviour of Lead in Sulphuric Acid Solution. 2. Phase Composition of the Anodic Layer in Dependence of the Oxidation Potential, J. Electroanalyt. Chem., 305 (1991) 57-72
25. D. Pavlov, A. Dakhouche, T. Rogachev, Influence of Arsenic, Antimony and Bismuth on the Properties of Lead/Acid Battery Positive Plates, J. Power Sources, 30 (1990) 117
26. D. Pavlov, Effect of Dopants (Group V) on the Performance of the Positive Lead-Acid Battery Plate, J. Power Sources, 33 (1991) 221
27. D. Pavlov, A. Dakhouche, T. Rogachev, Influence of Antimony on the Electrochemical Behaviour and the Structure of the Lead Dioxide Active Mass of Lead-Acid Batteries, J. Power Sources, 42 (1993) 71
28. B. Monahov, D. Pavlov, Influence of Antimony on the Structure and Degree of Hydration of the Anodic PbO2 Layer Formed on Pb-Sb Electrodes, J. Electrochem. Soc., 141 (1994) 2316
29. D. Pavlov, Premature Capacity Loss (PCL) of the Positive Lead/Acid Battery Plate: Phenomena. New Concept., J. Power Sources, 42 (1993) 345
30. D. Pavlov, Suppression of premature capacity loss by methods based on the gel-crystal concept of the PbO2 electrode, J. Power Sources, 46 (1993) 171
31. D. Pavlov, Effect of the corrosion layer on the phenomena causing premature capacity loss (PCL), J. Power Sources, 48 (1994) 179
32. M.K. Dimitrov, D. Pavlov, Location of the phenomena of premature capacity loss during cycling of lead/acid batteries with lead grids, J. Power Sources, 46 (1993) 203
33. D. Pavlov, Methods for Suppressing the Phenomena Causing Premature Capacity Loss (PCL) Based on the Gel-Crystal Concept of the PbO2 Electrode, Proceedings of the International Conference LABAT'93, 7-11 June 1993, Varna, Bulgaria, p. 11

34. D. Pavlov, A theory of the grid/positive active mass (PAM) interface and possible methods to improve PAM utilization and cycle life of lead/acid batteries, J. Power Sources, 53 (1995) 9
35. D. Pavlov, A. Dakhouche, T. Rogachev, Influence of antimony ions and PbSO4 content in the corrosion layer on the properties of the interface grid/active mass in positive lead-acid battery plates, J. Applied Electrochem., 27 (1997) 720
36. T. Rogachev, D. Pavlov, Influence of CaSO4 on the properties of the positive lead-acid battery plates, Proceedings of extended Abstracts, LABAT'96 International conference, p.29, Varna, June 1996
37. T. Rogachev, D. Pavlov, Influence of cycling on the nature of the positive active mass of lead-acid batteries and effect of CaSO4 on the behaviour of the positive plates, J. Power Sources, 64 (1997) 51
38. Ueberschaar, M. & Rotter, V.S. J Mater Cycles Waste Manag (2015) 17: 266. doi:10.1007/s10163-014-0347-6
39. V. Zepf, 2013. Rare Earth Elements, Springer Theses, DOI: 10.1007/978-3-642-35458-8_5, Springer-Verlag Berlin Heidelberg