SCRREEN

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Report on major trends affecting future demand for critical raw materials

Authors : Mr. Antoine MONNET (LGI), Amar AIT ABDERRAHIM (LGI Consulting)

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Solutions for CRitical Raw materials - a European Expert Network Dimitrios Biliouris

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Summary

Report on major trends affecting future demand for critical raw materials Following the publication of the list of critical raw materials (CRMs) at the EU level, different European projects have studied the value chain of several CRMs. However, the knowledge produced remained mostly disseminated, and some CRMs have not been studied as much as others. The project SCRREEN was launched to gather all CRM initiatives into an Expert Network, which could centralise and assess existing knowledge, fill in possible knowledge gaps and eventually provide policy and technology recommendations for decision-makers. This study aimed at assessing the major trends affecting future demand for CRMs. Rather than addressing this topic through a CRM-by-CRM approach, an approach based on industrial applications and sectors was preferred. This approach facilitated the identification of demand drivers since the consumer preferences, the economics, the technological, environmental, legal and even political aspects related to an application are easier to analyse than those related to the macro-sectors used to analyse CRM demand in top-down approaches. Besides, the analytical framework of a CRM-by-CRM approach is usually unsuitable to emerging applications and breakthrough technologies and unfamiliar for the general public and decision makers. Thus, based on appropriate practical and theoretical tools (multi-level perspective, PESTEL framework), this study pursued 4 main objectives: - Analyse a series of applications covering the broadest part of future CRM requirements - Identify a series of drivers affecting the future demand of CRMs in these applications - Involve experts to validate these drivers and quantify the trends as much as possible - Compile the drivers affecting a whole sector and highlight the most important; provide a synthesis of the trends per CRM for those involved in several applications. In the end, this study covered 12 applications involving 20 CRMs. 5 CRMs have been covered not for their main applications (B, Ba, Hf, W, V) but because they are involved in the main application of other CRMs. As a result, the study covers a low share of their consumption. The coverage rate (percentage of current EU apparent consumption R1 covered in the study) for natural graphite is also low but the reason is different: the applications involving this CRM are emerging and the future requirement for these applications are expected to exceed the total current consumption by 2035...

Approval

Date	By
2018-05-22 19:31:42	Dr. Luis TERCERO (Fraunhofer)
2018-05-23 09:00:18	Mr. Stéphane BOURG (CEA)

CORRIGENDUM

A few minor calculation errors and inaccuracies have been identified in the original report. Please note that consequently, this report was revised on February 26th, 2019. The following corrections were included with no impact on the overall conclusion of the study.

Page 50

Correction

Table 9 – CRM significance indicators for electric vehicles

CRM	Application use in 2015 (t)	EU apparent consumption[1] (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Nd	48	1,000	5%	2,500	250%
Pr	16	230	7%	800	350%
Dy	16	180	8%	800	420%
Co	620	13,000	5%	29,500	230%
C	2,340	80,900	3%	118,500	150%
Li	830	26,100	3%	35,600	140%

(…). In 2015, CRM demands are calculated to be a small fraction of EU demands for these CRMs (indicator R1)

Original

Table 9 – CRM significance indicators for electric vehicles

CRM	Application use in 2015 (t)	EU apparent consumption[1] (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Nd	2	1,000	0%	2,200	220%
Pr	1	230	0%	700	300%
Dy	1	180	1%	700	390%
Co	20	13,000	0%	25,500	200%
C	70	80,900	0%	98,400	120%
Li	20	26,100	0%	35,000	130%

(…). In 2015, CRM demands are calculated to be negligible compared to global demands for these CRMs (indicator R1)

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Pages 63 to 64

Correction

A recent study by Oakdene Hollins confirmed resource efficient material flows for magnesium metal, and in comparison to earlier studies (MSE), included the recycling loop of magnesium (as alloying element) in the Aluminium industry.

It is also important to mention, that beside the use of magnesium as alloying element in Al alloys, it's also used for several automotive body applications in form of Mg alloys (usually 5-9% aluminium as alloying element). Large parts like door inners or multi-material light-weight solutions in lift-gates are only a few examples with high potential future growth in this segment.

(…). Mg alloys, Mg alloyed Aluminium and Nb steel grades offer lighter alloys with equal or improved mechanical properties.

(…). Continuous research to reduce vehicle weight is expected to require more Mg and alloys, Mg alloyed Aluminium and Nb steel grades

(…). Even if the functional recycling (old and new scrap) of Magnesium used as Mg alloys and Aluminium alloys in automotive applications is estimated at 58%, there is room for improvement specially in the field of EoL scrap. Niobium is not recycled at all at the moment (European Commission 2018b).

Original

A further analysis reveals that at least for magnesium, there might be additional sources of uncertainties (other than the assumptions related to the reference scenario). It is important to point out that there are large amounts of Mg deposited as waste in landfills and tailings. Such amounts could explain (part of) the difference between apparent consumption (import minus export) and actual use for the industry. It could also account for differences between our reference scenario and results from other studies.

(…). Mg and Nb offer lighter alloys with equal or improved mechanical properties.

(…). Continuous research to reduce vehicle weight is expected to require more Mg and Nb

(…). Indeed, niobium is not recycled at all at the moment (European Commission 2018b).

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Page 70

Correction

Table 14 – Share of CRM uses covered in this study

CRM	Current total use covered (t)	Current EU apparent consumption (t)	% (R1)	Total expected use covered in 2035 (t)	% of expected use vs current total (R2)
Co[2]	2,600	13,000	20%	36,200	280%
Natura Graphite C[2]	2,440	80,900	3%	159,000	200%
Dy (HREE)[2]	230	180	120%*	1080	580%
Pr (LREE)[2]	150	230	60%	1070	460%
Nd (LREE)[2]	2,060	1,000	210%*	5,700	570%

Original

Table 14 – Share of CRM uses covered in this study

CRM	Current total use covered (t)	Current EU apparent consumption (t)	% (R1)	Total expected use covered in 2035 (t)	% of expected use vs current total (R2)
Co[2]	2,000	13,000	20%	32,200	250%
Natura Graphite C[2]	160	80,900	0%	139,000	170%
Dy (HREE)[2]	210	180	120%*	980	530%
Pr (LREE)[2]	130	230	60%	970	420%
Nd (LREE)[2]	2,000	1,000	200%*	5,400	540%

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Pages 74 to 80

Correction

The main four applications (wind turbine, EVs, smartphones & computers, domestic appliances) account for around 210% of the EU apparent consumption of neodymium according to Table 14. In 2035, they could grow up to 570%. (…)

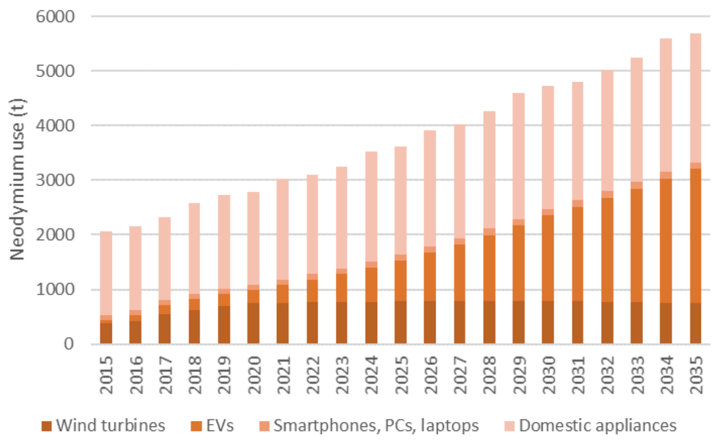

Figure 22 – Neodymium use in the applications covered in this study

(…). In 2035, they could grow up to 460%. (…)

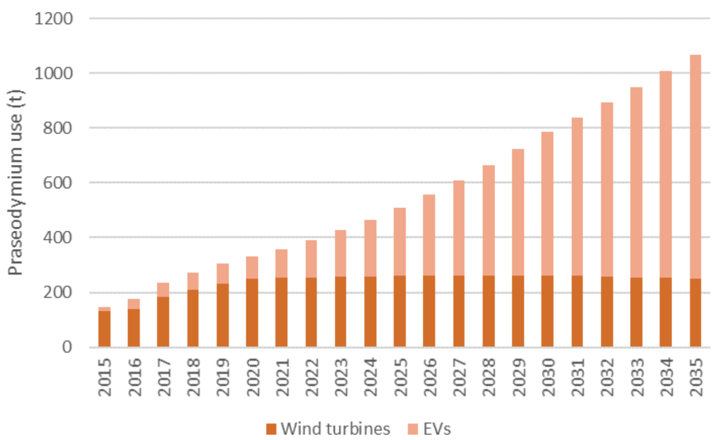

Figure 23 – Praseodymium use in the applications covered in this study

(…). In 2035, they could grow up to 580% of current consumption. (…)

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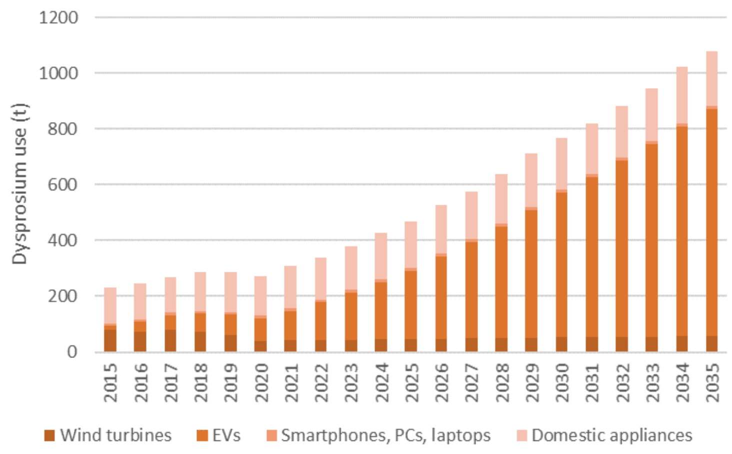

Figure 24 – Dysprosium use in the applications covered in this study

(…). Yet, in 2035, the applications covered in this study could represent 280% of current consumption. (…)

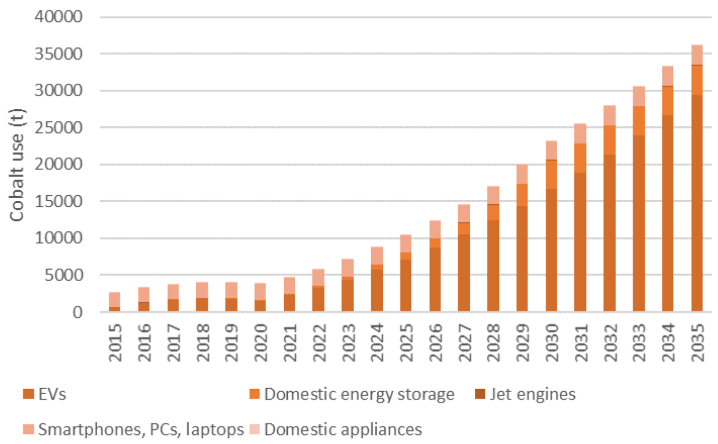

Figure 25 – Cobalt use in the applications covered in this study

(…). These applications (EVs, domestic energy storage) currently account for 3% of the EU apparent consumption of natural graphite according to Table 14. Yet, in 2035, the same applications could represent 200% of current consumption. (…)

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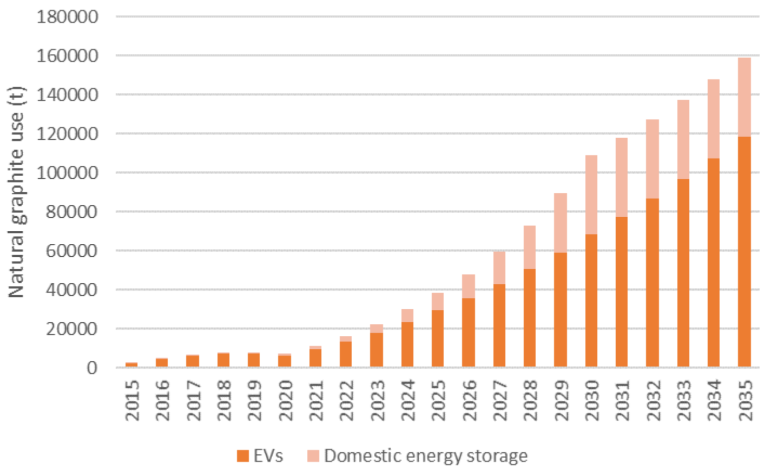

Figure 26 – Natural graphite use in the applications covered in this study

Original

The main four applications (wind turbine, EVs, smartphones & computers, domestic appliances) account for around 200% of the EU apparent consumption of neodymium according to Table 14. In 2035, they could grow up to 540%. (…)

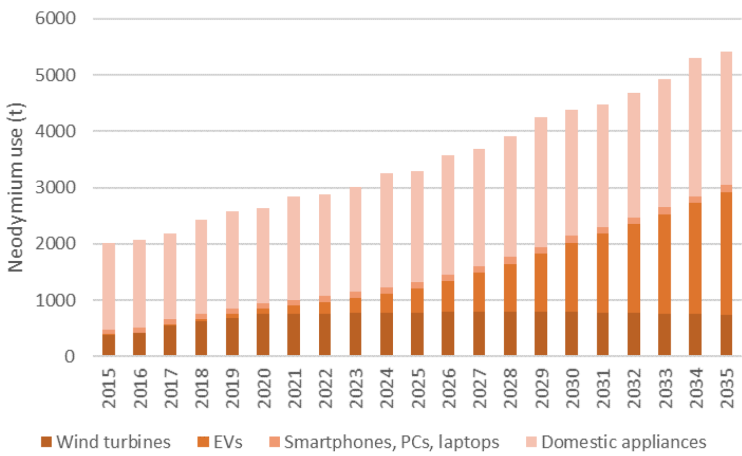

Figure 22 – Neodymium use in the applications covered in this study

(…). In 2035, they could grow up to 420%. (…)

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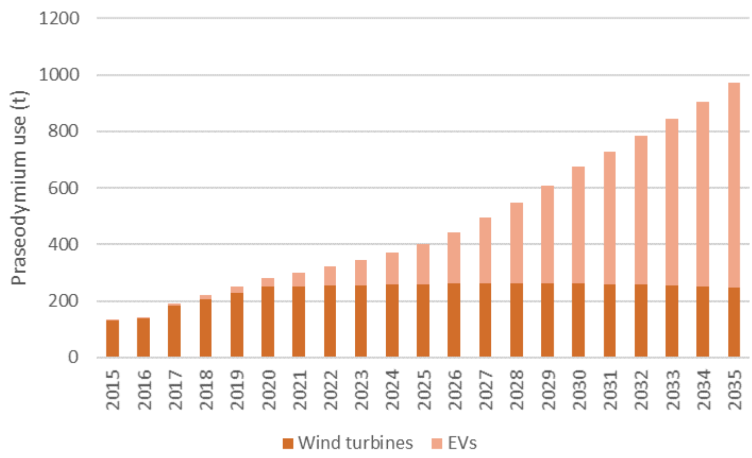

Figure 23 – Praseodymium use in the applications covered in this study

(…). In 2035, they could grow up to 530% of current consumption. (…)

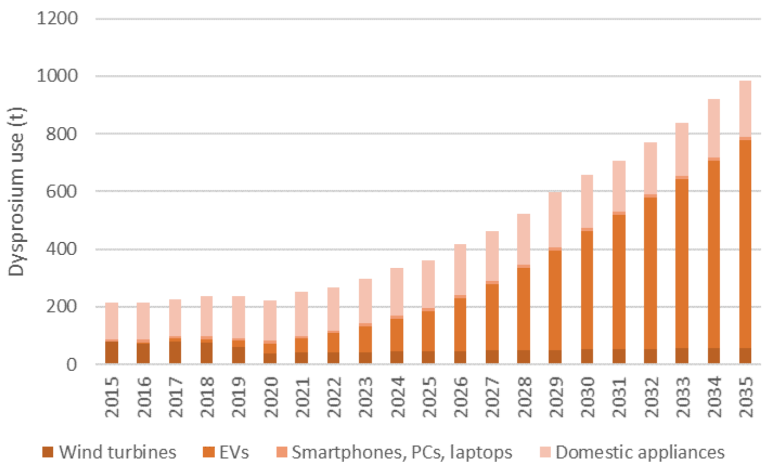

Figure 24 – Dysprosium use in the applications covered in this study

(…). Yet, in 2035, the applications covered in this study could represent 250% of current consumption. (…)

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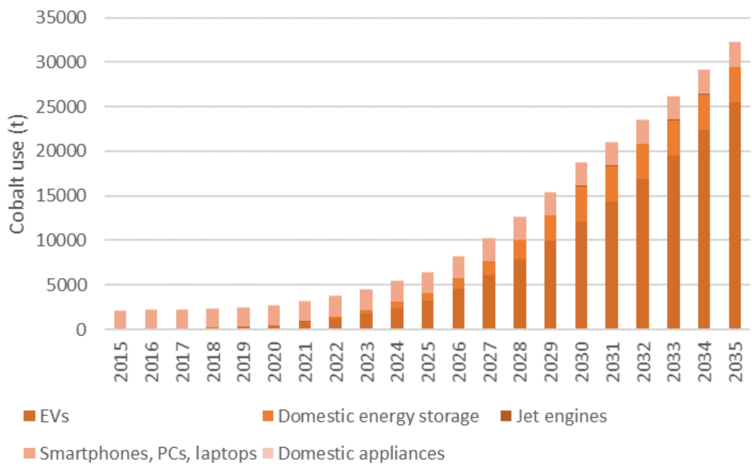

Figure 25 – Cobalt use in the applications covered in this study

(…). These applications (EVs, domestic energy storage) currently account for less than 1% of the EU apparent consumption of natural graphite according to Table 14. Yet, in 2035, the same applications could represent 170% of current consumption. (…)

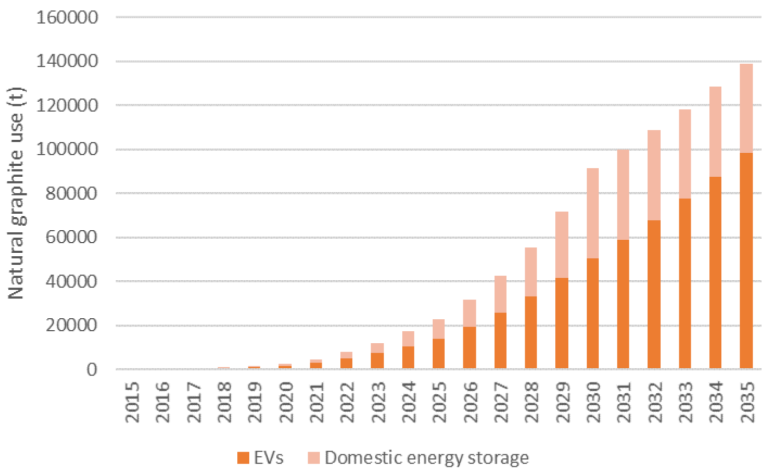

Figure 26 – Natural graphite use in the applications covered in this study

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SCRREEN
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Start date: 2016-11-01 Duration: 30 Months

DELIVERABLE 2.2 – REPORT ON MAJOR TRENDS AFFECTING FUTURE DEMAND FOR CRITICAL RAW MATERIALS

AUTHOR(S): AMAR AIT ABDERRAHIM, ANTOINE MONNET (LGI CONSULTING)
CONTRIBUTORS(S): T. BROWN, G. GUNN, J. NADEN, E. PETAVRATZI, R.A. SHAW (BGS), S. DEETMAN, N.A. MANCHERI (CML LEIDEN UNIVERSITY), M. KIVINEN, B. LÅNGBACKA (GTK), S. MANFREDI (JRC), L. TERCERO (ISI FRAUNHOFER)

1 CONTENT

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2 EXECUTIVE SUMMARY

Following the publication of the list of critical raw materials (CRMs) at the EU level, different European projects have studied the value chain of several CRMs. However, the knowledge produced remained mostly disseminated, and some CRMs have not been studied as much as others. The project SCRREEN was launched to gather all CRM initiatives into an Expert Network, which could centralise and assess existing knowledge, fill in possible knowledge gaps and eventually provide policy and technology recommendations for decision-makers.

This study aimed to assess the major trends affecting future demand for CRMs. Rather than addressing this topic through a CRM-by-CRM approach, an approach based on industrial applications and sectors was preferred. This approach facilitated the identification of demand drivers since the consumer preferences, the economics, the technological, environmental, legal and even political aspects related to an application are easier to analyse than those related to the macro-sectors used to analyse CRM demand in top-down approaches. Besides, the analytical framework of a CRM-by-CRM approach is usually unsuitable to emerging applications and breakthrough technologies and unfamiliar for the general public and decision makers.

Thus, based on appropriate practical and theoretical tools (multi-level perspective, PESTEL framework), this study pursued 4 main objectives:

- Analyse a series of applications covering the broadest part of future CRM requirements
- Identify a series of drivers affecting the future demand of CRMs in these applications
- Involve experts to validate these drivers and quantify the trends as much as possible
- Compile the drivers affecting a whole sector and highlight the most important; provide a synthesis of the trends per CRM for those involved in several applications.

In the end, this study covered 12 applications involving 20 CRMs. 5 CRMs have been covered not for their main applications (B, Ba, Hf, W, V) but because they are involved in the main application of other CRMs. As a result, the study covers a low share of their consumption. The coverage rate (percentage of current EU apparent consumption R1 covered in the study) for natural graphite is also low but the reason is different: the applications involving this CRM are emerging and the future requirement for these applications are expected to exceed the total current consumption by 2035. The other 14 CRMs covered have an average coverage rate of 70%. Moreover, the CRM requirements related to the applications covered in this study grew by 260% on average (excluding natural graphite whose growth rate is much higher as it is only involved in emerging applications have almost no current requirements).

Based on literature review, a reference scenario including quantitative data was provided for each application and more than 70 drivers helped to qualify the trends and their potential future evolution. Both scenarios and drivers were validated by experts. Among the most important findings of this study, a synthesis of both quantitative and qualitative key points was provided by sector.

In the energy sector, the development of wind power (involving REE) and domestic energy storage (mainly cobalt and natural graphite) are expected to drive up the CRM requirements in the coming decades. On the contrary, the requirements related to the deployment of PV panels (mainly silicon, indium and gallium) should become less critical by 2035, especially thanks to material efficiency. Important drivers to monitor in this sector include policies to further reduce CO_2 emissions, incentives for distributed power generation, power and storage requirements related to the deployment of EVs.

In the transport sector, the need to debarbonise mobility and reduce air pollution is closely tied to the emergence of hybrid and electric vehicles and the persistent dependence on autocatalysts for ICE vehicles. The

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deployment of EVs is expected to drive most of the growth of CRM requirements (mainly REE, cobalt and natural graphite) in this sector by 2035. The search for better performing materials to replace existing ones, especially in terms of weight and performance in extreme conditions (ceramics for jet engines, Al-based alloys for car bodies), should also impacts the sector: Ta, Mg, Nb are the main CRMs concerned. Finally, the increasing demand for mobility, especially in emerging countries, and newer forms of mobility (MaaS), are not to be overlooked.

In the sectors of telecoms and electronics, the global expansion of digital networks and services implies that more people have access to the internet, thus fuelling the need for connected equipment and fibre optics that Europe could produce and export. Therefore, the demand of CRMs in this sector should either level off (indium for screens) or keep increasing (REE, Ta, Pd for electronic devices & appliances, Ge for optic fibres). Important drivers to monitor in the future include miniaturisation of components, measures against planned obsolescence and restrictions on exports of e-waste. In addition, the search for better performing and cheaper materials or components of electronic appliances fosters substitution, making future demands more unpredictable in the sector.

In the sector of agriculture, the global population growth (moderate in Europe) will foster the need for a more efficient agriculture, thus increasing reliance on fertilisers and potentially encouraging European exports. On the contrary, various sources of phosphorous are likely to be considered (animal manure, but also sewage sludge and food waste chain) to reduce dependence on phosphate rocks. At last, the emergence of precision agriculture, helped by new technologies, might improve the efficiency of the use of fertilisers, in a context where agriculture tries to reduce its environmental footprint.

Finally, some recommendations were made to provide guidance for further research.

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3 MAIN ACRONYMS

AFV	Alternative fuel vehicles
Ag	Silver
Al	Aluminium
B	Borate
Ba	Barium
BEV	Battery electric vehicles
C	Natural graphite
Cd-Te	Cadmium telluride photovoltaics
CIGS	Copper indium gallium selenide solar cell
Co	Cobalt
CRM	Critical Raw Material
DD-PMG	Direct-drive Permanent Magnet Generator
DSO	Distributed System Operator
Dy	Dysprosium
EV	Electric Vehicle
FCV	Fuel cell vehicles
FPD	Flat Panel Display
Ga	Gallium
GDP	Gross domestic production
Ge	Germanium
GHG	Greenhouse Gases
HEV	Hybrid electric vehicles
Hf	Hafnium
ICE	Internal combustion engine
In	Indium
IoT	Internet of Things
ITO	Indium tin oxide
LCD	Liquid-crystal display
Li	Lithium
LIB	Lithium-Ion Battery
MaaS	Mobility as a Service
Mg	Magnesium
MLP	Multi-Level Perspective
MS/HS-PMG	Medium-speed / High-speed Permanent Magnet Generator
Nb	Niobium
Nd	Neodymium
OLED	Organic light-emitting diode
P	Phosphate rocks
Pd	Palladium
PESTEL	Political, economic, social, technological, environmental and legal analysis framework
PGM	Platinum Group Metals
PHEV	Plug-in hybrid electric vehicles
Pr	Praseodymium
Pt	Platinum
PV	Photovoltaics
REE	Rare Earth Element
SDG	Sustainable Development Goal
Se	Selenium
Si	Silicon metal
SS	Sewage sludge (secondary fertiliser)
SSP	Shared Socio-economic Pathways
Ta	Tantalum
Te	Tellurium
TF	Thin-film solar cell
TSO	Transmission System Operator
V	Vanadium
W	Tungsten
WEEE	Waste Electrical and Electronic Equipment

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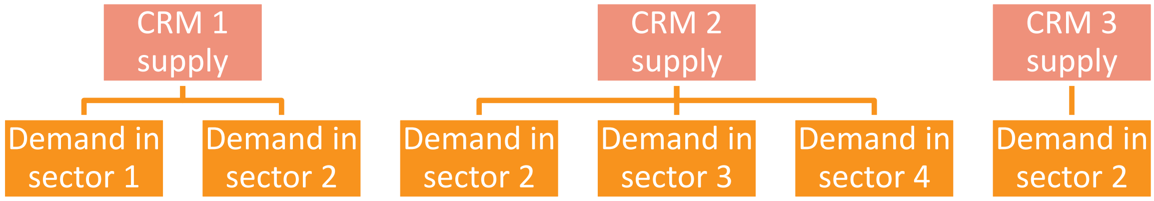
4 INTRODUCTION

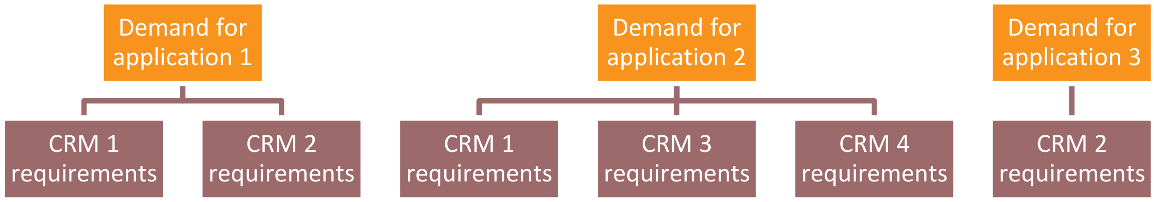
4.1 GENERAL APPROACH

The general approach of task 2.2 is to investigate demand trends by sectors and applications. For each Critical Raw Material (CRM), the overall demand is considered as a sum of partial demands coming from various applications. There are two ways to address these partial demands:

- CRM-by-CRM approach, i.e. answering the question from the *supply* point of view: "What share of EU supply for a specific CRM will be dedicated to each sector and related applications?"



- Sector-by-sector approach, i.e. answering the question from the *demand* point of view: "What will be the requirement of each application using a given CRM?"



T2.2 builds the analysis on the second approach. Describing the demand for CRMs from the point of view of end-users (consumers or manufacturing industries) has several advantages:

- Since the overall demand results of convoluted processes strongly influenced by consumer preferences as well as technology and regulation, it is easier to assess it in a sector-by-sector approach starting from individual needs (consumers' or manufacturers' needs) rather than a CRM-by-CRM approach. It is also easier to take new applications into account while they would probably find no category to fit in the classification of a top-down approach, especially if their supply chain relies on new industrial channels.
- Since this approach starts by investigating the CRM requirements of specific end-products or applications, it is meant to be easily understood by the consumers of these products or the manufacturers involved in their value chain. It is also easier to understand by the general public or policy makers than any approach analysing individual CRM markets which are often abstract and complex due to the number of sectors they usually supply. Thus, the method can involve the most relevant stakeholders (consumers, manufacturers and corresponding market/policy experts) to bring insights on the expected trends in terms of consumer preferences, technology and regulation in their domain.

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In line with this thinking, task 2.2 relied on two analytical tools: the PESTEL analysis framework combined to the multi-level perspective (MLP) theory to facilitate the contribution of the SCRREEN Network (e.g. Market Expert Group) in giving their insights on the drivers for change.

Besides, to make sure the most significant sectors have been covered, a specific analysis was done at the beginning and at the end of the assessment.

4.2 MULTI-LEVEL PERSPECTIVE THEORY

The multi-level perspective theory was developed by Geels (Geels 2002). It is a means to understanding the interactions of stakeholders with their environments (economic, political, social, etc.) and how innovations can modify these interactions. It describes a system thanks to 3 distinct layers: the landscape (macro-level), the regime (meso-level) and the niches (micro-level).

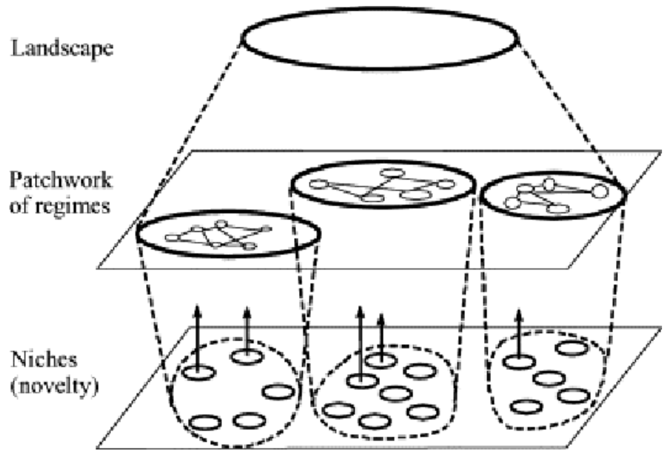

Figure 1 – The 3 levels of the MLP theory (Geels 2002)

The **regime** refers to the 'rule-set' of processes, technologies, skills, corporate cultures that are embedded in the current system (the value chain of individual applications requiring CRMs in this case). The regime refers to dominant rules that pertain in a domain. It enables and constrains activities within communities, giving them stability and guiding decision making. Modifications in the regime result from a cascade of changes over time.

The **niches** are places where new things are done and tested, where radical innovation happens. They act as incubation rooms from normal market forces and allow research and learning through experience.

The **landscape** forms the external structure or context for interactions of stakeholders. It consists of the social values, policy beliefs, worldviews, political coalitions, built environment (factories, etc.), prices and costs, trade patterns and incomes. It contains a set of heterogeneous factors such as oil prices, economic growth, wars, immigration, broad political coalitions, cultural norms and environmental problems.

The three levels can impact each other: the regimes put pressure on the landscape through industrial networks or strategic games. The landscape can impact the regimes when events such as economic or environmental crisis occur. Similarly, niches can modify regimes when an innovative solution becomes a mainstream technology, product or service (successful start-up or R&D program). Finally, uncertainties within a given regime may boost the development of a dedicated niche.

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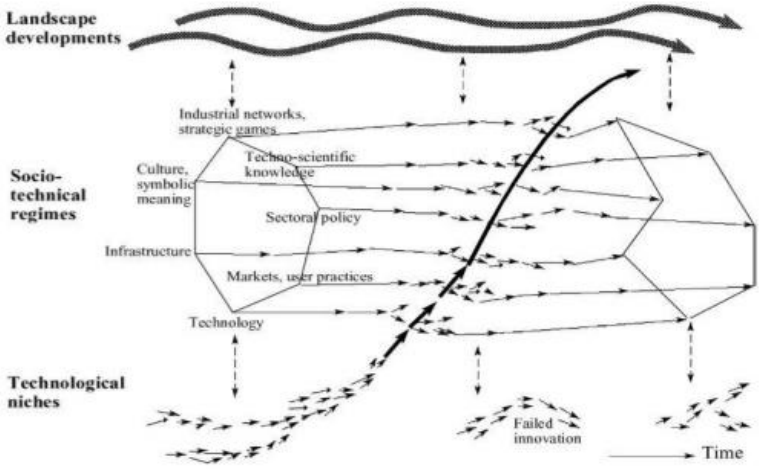

Figure 2 – Influences and interactions between the 3 levels (Geels 2002)

In this study, the *regime* mainly gathers the set of parameters related to the current and future demand of specific CRM through specific applications (e.g. current and expected sales of CRM-intensive products, current and expected CRM content of those products, current and expected market shares, etc.).

As it refers to the dominant rules established in a domain, the *regime* is usually easy to describe. The *landscape* and the *niche innovations* are more difficult to depict:

- *niche innovations* usually refer to disruptive innovations (successful start-ups, R&D programs): the difficulty is to anticipate which of these innovations will succeed;
- *landscape* usually refers to more continuous change: it is less likely to miss a *landscape* trend than a *niche innovation,* but it can be more difficult to cover the whole landscape.

4.3 PESTEL FRAMEWORK

While it is impossible to predict the success of start-ups or R&D programs (niche innovations) at their early stages or if they do not exist yet, exploring the landscape can be facilitated by using the PESTEL framework.

The PESTEL analysis consists in assessing the macro-economic environment of a system (i.e. its *landscape*) by classifying into one of the 6 following categories every driver affecting the system[1]:

- **Political** drivers (e.g. fiscal policy, foreign trade)
- **Economic** drivers (e.g. economic cycle, discount rate, inflation, lack of qualified workforce)
- **Societal** drivers (e.g. raising awareness of pollution-related health issues in urban areas, preference for sustainable products)

[1] The examples given in the following are very generic. More specific drivers will be identified when analysing the different CRM-intensive applications.

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- **Technological** drivers (e.g. new materials fostering the substitution of CRM, new techniques improving the CRM content/intensity of some systems)
- **Environmental** drivers (e.g. increasing share of renewable energy systems with high CRM contents, increasing effort to decarbonize the mobility sector using electric vehicles)
- **Legal/regulatory** drivers (e.g. increasing constrains in mining, obligation to treat all end-of-life products and industrial waste containing certain materials)

In this study the MLP theory was combined to the PESTEL framework with three main objectives:

- Identify and categorise drivers for change coming from *landscape* innovations
- Highlight which demand-related parameters will be affected by these drivers
- Characterise the expected variation of the given parameters and quantify whenever it is possible.

These objectives will be fulfilled by involving all task partners so that the SCRREEN Network (e.g. Market Expert Group) will only need to validate and complement the results of this subtask (drivers for change identified, quantitative information on potential variations of the demand-related parameters).

4.4 OBJECTIVES OF TASK 2.2

Task 2.2 aimed to identify trends in the future demand for CRM by analysing the requirements of individual applications or sectors. As much as possible, the objective was also to give quantitative insights in these trends.

Since SCRREEN is not a research project and has limited resources, this objective was limited to most important applications and sectors for which appropriate information is available. To allow specific research to fill the gaps in the existing knowledge, this task also estimated the share of overall demand covered and it provided a list of applications for which information is missing, requiring deeper research efforts.

The main objective was divided intro the following 4 objectives:

- **Objective 1**: To identify a **series of industrial applications** (forming the *regime*) which are connected to different sectors and all together expected to form most of CRM requirements in the next 20 years. For each application, the objective was also to identify the **most important parameters driving the demand** (annual sales of corresponding technologies, CRM content of these technologies, etc.) and to check whether enough information is available to conduct a quantitative analysis.
- **Objective 2**: To identify a **series of drivers for change** (from *landscape* and from *niche* innovations) that could modify the demand-related parameters of the most important applications, and therefore affect the current *regime* under which demand is changing.
- **Objective 3**: To **involve SCRREEN Network (market/policy experts)** in order to qualify the evolution of demand-related parameters in major applications for the next 20 years based on the drivers for change. The objective was also to quantify these trends whenever sufficient information is available to the expert group. Since part of this objective requires quantitative inputs, the objective is also to give recommendations to conduct further research when those inputs were missing, in order to cover more applications and gather usable data.
- **Objective 4**: To highlight the **key drivers for demand** in each sector covered in the study and to provide a synthesis of the trends per CRM for those involved in several applications.

Besides, this task was also meant to be useful for other tasks and work packages, in line with the main objective of the SCRREEN project: gather all CRM initiatives into an Expert Network, which could centralise and

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assess existing knowledge, fill in possible knowledge gaps and eventually provide policy and technology recommendations for decision-makers. Thus, the quantitative data obtained in this study will serve as input to task 2.3 when conducting the assessment of raw material needs. Besides, both quantitative and qualitative results will feed the work of WP9, in particular the reflection on the extension of the 'MICA' expert system (task 9.4).

To reach these objectives, a specific methodology is used including an assessment of the *regime*, meaning the current state of the parameters driving the demand of CRM in major applications and their expected evolution in a baseline scenario. The multi-level perspective helps us to identify some factors affecting the baseline scenario. This exercise has been continued by workshops involving the SCRREEN Network (e.g. market expert group) to validate the qualitative (and as far as possible quantitative) trends introduced by these drivers for change. Finally, sector demand scenarios are built based on the results from previous stages and the share of overall demand covered by the study is assessed.

5 METHODOLOGY

The methodology for task 2.2 has been divided into 5 subtasks:

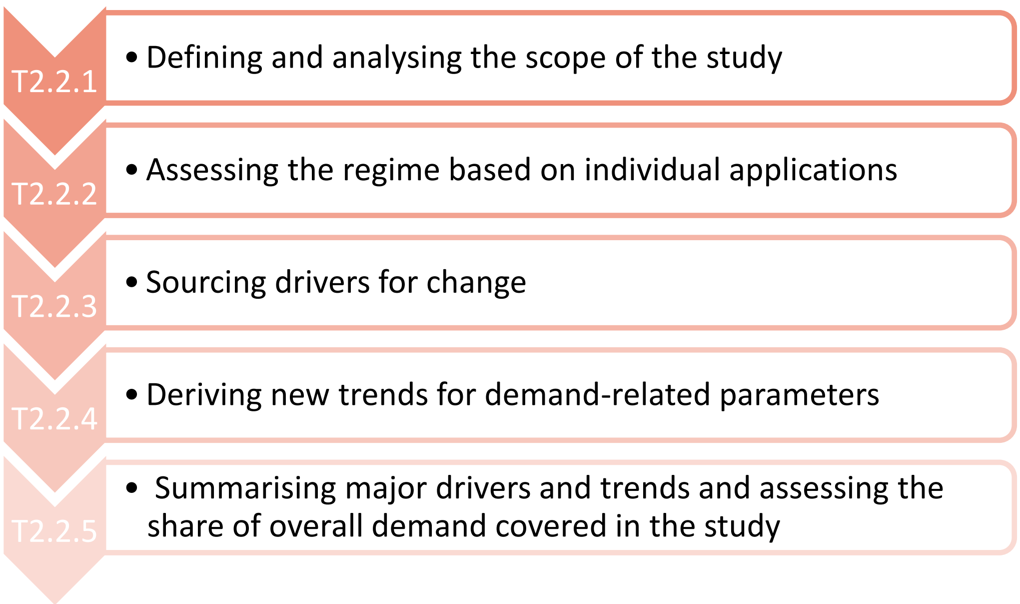

Figure 3 – Simplified workplan of T2.2

The first subtask was done by LGI. All partners in task 2.2 were then involved in the next 2 subtasks. Efforts were allocated to each partner based on individual applications. LGI provided an example of deliverable expected from each partner. In this draft, LGI applied the general methodology to one of the applications to be considered so that every partner could easily reproduce the same workflow. JRC provided state-of-the-art information (reports, data, forecasts, etc.) to the other partners.

LGI led the last 2 subtasks (workshop with the SCRREEN Network, e.g. Market Expert Group, final analysis). LGI was also responsible for all follow-up activities and coordination of the production of the final deliverable.

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The results of this study were gathered in this report. Apart from the scope of the study and its synthesis, the way results are presented does not follow the subtasks described hereafter. Rather, all results related to a specific application or sector have been grouped. This choice was motivated by the fact that these subtasks were completed in parallel for each application and by the general approach to this task, that is describing the demand for CRMs from the point of view of end-users. The final synthesis also includes a summary of the main results grouped by CRM.

5.1 DEFINING AND ANALYSING THE SCOPE OF THE STUDY

5.1.1 DEFINING DEMAND

To define the scope of this study, the first step was to clarify the terms “CRM demand”, “CRM consumption” or “CRM total use”. We considered that all these terms would refer to the same economic meaning: **apparent consumption**, i.e. the **sum of imports, production subtracting exports**. This definition is very common and was also adopted in one of the main references used in this study (Deloitte et al. 2017). It can be used to track the economic balance or the material flow balance of CRM trade. Yet, in the latter case (this study uses the material flow approach), it raises some issues as raw materials appear in different forms along the value chain: primary raw materials, secondary raw materials, processed materials, end products, wastes. For instance, a country importing primary materials and exporting 50% of it as processed materials would have the same “apparent consumption” as a country exporting 50% as end products, while their economic balance would certainly be different.

As often as possible (based on available information), it was therefore decided to use data specifying the forms of raw materials. Indeed, apparent consumption is often confused with “material content of end products used locally” which omits other materials flows like wastes & losses (which can be significant in applications involving processing industries). Imports data can also be misleading in the case of materials imported both in primary form and as end-products.

Besides, it was decided to **complement apparent consumption data with further indicators** (imports, total supply, dominant form of CRM in imports and exports). In particular, a couple of situations required specific analysis:

- Applications in processing industries: not considering wastes and losses, these industries have a neutral material balance, although they may have a very important role in the local economy. If they are the only element of the value chain in the country, their CRM apparent consumption is always close to zero and therefore not a good indicator to monitor future growth. Total imports or exports would complement the analysis. The same applies to integrated value chains in countries exporting most of their production (e.g. PGM for autocatalysts): most added value remains local (high economic importance) while apparent consumption is low (whatever the trends).
- Applications using recycled materials: while these materials are essential to the applications, they are not accounted in total apparent consumption figures since their material flow is neutral (e.g. cobalt in lithium-ion batteries). Total supply (sum of imports, extraction and recycled materials) would complement the analysis.
- Applications with high waste production or significant losses along the value chain: for such cases, an additional piece of information is provided such as the amount of waste added to landfills and tailings (e.g. indium in flat panel displays).

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5.1.2 SELECTING APPLICATIONS

As the purpose of this study is to identify and analyse future trends in the EU demand for CRM, only industrial applications using CRM have been included in the analysis. However, analysing every EU activity involving CRM would be beyond the capacities of the resources allocated to this task. As a result, a specific approach was adopted to prioritise the applications to analyse, taking into account the availability of information.

First, the main three applications of every CRM were grouped by sector:

- Transport
- Energy
- Electronics & telecommunications
- Metallurgy
- Chemical industry
- Agriculture
- Other industrial applications

This list was built from the last publication of CRM factsheets (Deloitte et al. 2017). From there, a focus was made on the three sectors gathering most CRM and applications. Starting from the list of the most CRM-intensive applications and considering the information available, this approach allowed to narrow the scope of the study to less than ten applications. Additionally, the main applications of a few CRMs have been analysed in detail because the factsheets report no substitution option for these CRMs. Finally, some applications for which information was available have been included in the analysis based on their significance indicators (assessed in the next step of the methodology):

- Applications using more than 30% of at least one CRM total apparent consumption, with a constant or increasing trend.
- Applications using little amounts of CRM (compared with each CRM total apparent consumption) but having a strong growth perspective (expected use of at least one CRM above current total apparent consumption or 5 times higher than the current use in this application).

In total, this study covered a dozen of the most CRM-intensive applications, defined in the following sections.

5.2 ASSESSING THE REGIME BASED ON INDIVIDUAL APPLICATIONS

Based on the scope of the study defined in the first subtask, each partner proposed to cover and to be responsible for the rest of the workflow of a couple of applications, taking into account its own expertise. All propositions were submitted and validated in coordination with LGI to prevent any overlap between partners and to ensure that most important applications are covered.

Figure 4 provided a guidance to subdivide individual applications into technologies and sub-technologies so that all partners could share a common analysis framework.

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Example

To illustrate the diagram of Figure 3, let's consider the application "Wind turbines" which was used as an example in all documents provided by LGI as guidelines. In 2017, wind power installed capacities outreach 150 GW in Europe. By 2035, they are expected to increase up to 380 GW. To make it generic, we refer to the corresponding annual growth as the "application sales". Here, application sales are the annually installed wind power capacities. Besides, wind turbines can be categorised in two groups of technologies: on-shore and off-shore wind turbines.

Every category has its own **market share** in the current situation and this share is expected to **change until 2035**. Within the technology groups, there may be sub-technologies involving different sorts or different quantities of CRMs:

- On-shore
  - Medium & High-speed Permanent Magnet Generator turbines (MS/HS-PMG)
  - Direct-drive Permanent Magnet Generator turbines (DD-PMG)
- Off-shore
  - Direct-drive Permanent Magnet Generator turbines (DD-PMG)

Again, every sub-category has its own **market share** in the current situation and this share is expected to **change until 2035**. In addition, sub-technologies have additional parameters: the quantity of every CRM contained in this technology (often called **CRM contents** or CRM intensities). These parameters are also expected to **change until 2035** if technological improvements allow substituting the CRM.

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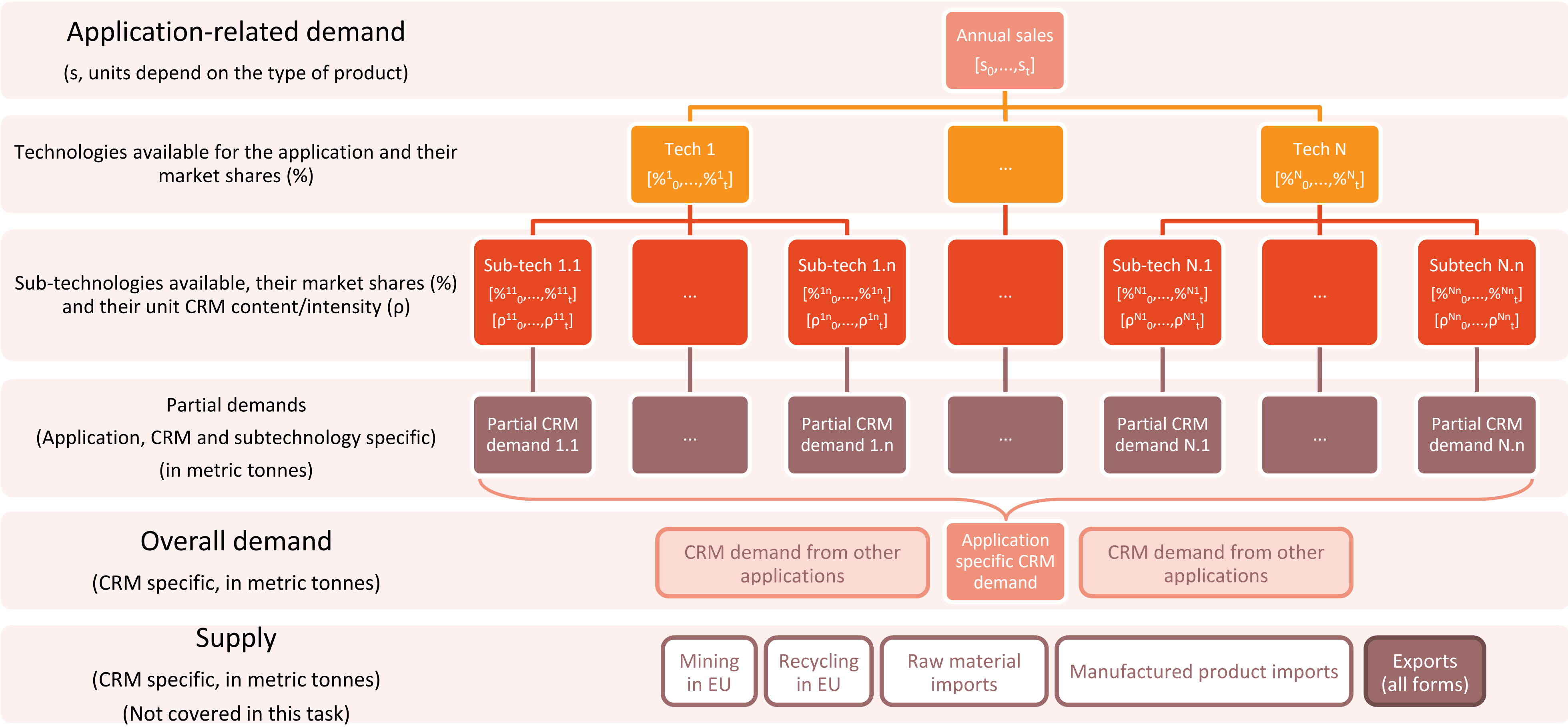

Figure 4 – Diagram of the assessment of the demand for CRM related to a specific application

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Finally, in this framework all applications can be described referring to a list of generic parameters driving a part of the demand of CRM:

- annual sales for the whole application;
- market shares of technologies;
- market shares of sub-technologies if necessary;
- CRM contents of sub-technologies;
- expected future value of these parameters.

In the **second stage** of this subtask, partners identified these **demand-related parameters** and **assigned them relevant information**. For every parameter, the partners looked in priority for the following information and paid attention to referencing the sources of information (or lack thereof):

- Current information (current value of the parameter)
- Prospective information
    - Quantitative trends to 2035 (scenarios or expected future value)
    - Failing this, quantitative trends to any time horizon, complemented with an inter- or extrapolation to 2035
    - Failing this, partially quantitative or detailed qualitative trends to 2035 (e.g. business-as-usual evolution, following historical trend, continuous increase for 10 years before stabilizing, sharp decrease)
- Historical information
    - Historical data to 2017
    - Failing this, qualitative evolution in the recent years

Desktop research and interviews with experts were two options used to find information.

Based on the information collected for each application, two indicators were chosen to highlight the significance of the current and future use of each CRM:

- R1: Percentage of each CRM apparent consumption in EU (as defined by the European Commission in (Deloitte et al. 2017)) currently dedicated to a specific application
- R2: Ratio between expected use of each CRM for a specific application in the future (based on prospective scenarios found in the literature) and the current apparent consumption of the CRM in EU.

The assessment of each application (list of technologies, sub-technologies, list of demand-related parameters, qualitative and quantitative information, references, etc.) were gathered in individual Excel files delivered by the partners. An example of such file was provided as a guidance by LGI in the case of "Wind turbines".

5.3 SOURCING DRIVERS FOR CHANGE

The objective of subtask n°3 is to identify and categorize **a series of drivers for change,** which could modify the evolution of the demand-related parameters in every CRM-intensive application. In the framework of the Multi-Level Perspective (MLP) theory, subtask n°2 described the *regime* (current and expected state of demand-related parameters) while subtask n°3 has looked for *landscape* elements that could modify the *regime*. This approach was complemented by the PESTEL framework in order to sort the drivers affecting the *regime* of each application.

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Each partner of task 2.2 applied this workflow to the applications under its responsibility. All drivers identified by the partners were gathered in individual Excel files. LGI will provided an example of the drivers identified for a specific application.

5.4 DERIVING NEW TRENDS FOR DEMAND-RELATED PARAMETERS

Subtask n°4 aims at deriving trends for every demand-related parameter based on the previous ranking of the drivers for change, on available scenarios and considering the historical trend when appropriate. The SCRREEN Network (e.g. Market Expert Group) was involved to validate these trends during the project workshops. For every parameter of the most important applications, the experts validated or modified the ranking obtained in the previous subtask.

To do so, a canvas (Figure 5) was provided to the experts and they were asked to give their opinion on the baseline scenario of every demand-related parameter. For instance, if the baseline scenario had foreseen that the sales of a product containing CRM would double by 2035, experts could disagree with this trend and could point at a specific driver that would revise the trend upward or downward. Experts were asked to vertically position these drivers on the canvas (a high position would mean that the trend would require a significant upward revision while low positions would mean a significant downward revision is necessary). They were also asked to categorise the drivers (PESTEL category, demand parameter they refer to: sales, CRM content, market shares, etc.) and to evaluate their confidence in their judgement from low to high certainty.

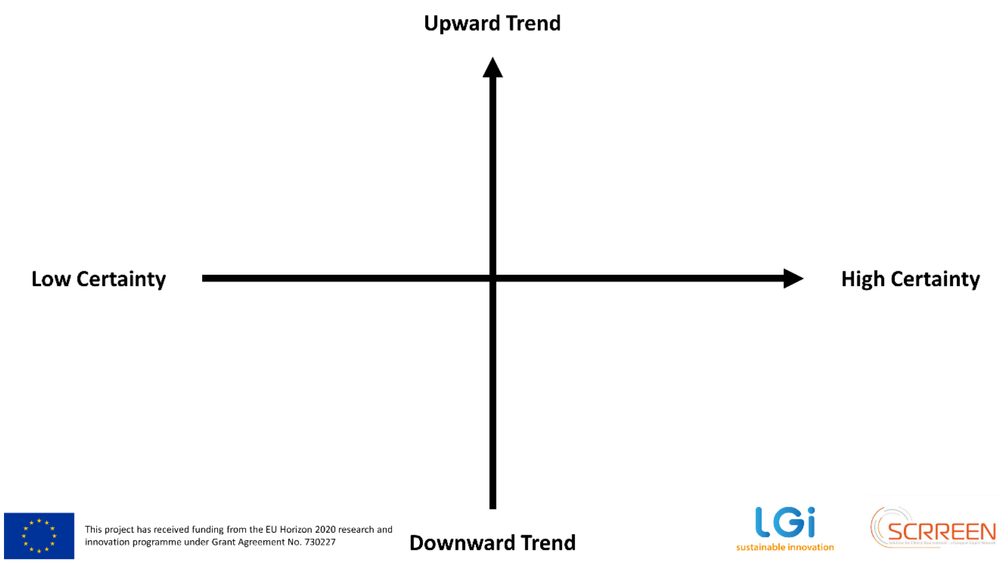

Figure 5 – Canvas submitted to expert groups to qualify the baseline scenarios of demand-related parameters in each CRM-intensive application

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5.5 SYNTHESIS ON MAJOR DRIVERS AND TRENDS FOR FUTURE CRM DEMAND

The **first stage** of the last subtask aimed to summarise the results of the study by highlighting the most important drivers expected to shape the future trends of CRM demand in Europe. First, these results are recalled following the general approach of this task, that is application by application. Then, most significant trends are grouped by CRM and, considering for each CRM the relative weight of the application covered in this study, the most significant trends to monitor in the future will be discussed.

The **second stage** of the last subtask aimed to assess the share of the overall CRM demand covered in this study. Based on the quantitative data gathered during the assessment of the different CRM-intensive applications, the total demand of every CRM is evaluated and compared to the overall apparent use of this CRM. Based on these results, recommendations are made to cover additional applications in future works and conduct specific research on significant applications for which little information is available.

6 SCOPE OF THE STUDY: MOST SIGNIFICANT INDUSTRIAL APPLICATIONS FOR FUTURE CRM DEMAND

Based on the last publication of CRM factsheets (Deloitte et al. 2017), the main applications of every CRM were gathered in Table 15 (Annex 14.1).

Table 1 – Number of CRM-intensive applications by sector

	Energy	Electronics & telecoms	Transport	Metallurgy	Chemical industry	Agriculture	Other industrial applications
Number of applications	18	14	13	12	11	2	26

In total, energy, transport and electronics are the top 3 sectors gathering most CRM and applications. Besides, because energy, electronics & telecoms and transport gather more end-user focused applications and most of the available information, most applications analysed in this study are related to these sectors.

Yet, metallurgy and chemical application should not be overlooked and the closing analysis of the study (§ 11) will recall the importance of these sectors when dealing with critical raw material supply: they should receive more attention and research efforts to track CRM quantities along the value chain, even though the end-user is often not directly involved.

The applications from the top 3 sectors analysed in the following were chosen either because they represent a large share of (at least) one CRM total apparent consumption (with constant or increasing trend) or because they use little amounts of CRM (compared with each CRM total apparent consumption) but have a strong growth perspective. Apart from these applications, a few additional applications were selected as they are major end-uses of a CRM for which no substitution option has been reported so far (e.g. phosphate rocks for fertilisers, silicon for PV panels, yttrium for lighting).

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7 ENERGY SECTOR

7.1 WIND TURBINES

7.1.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

Wind energy is one of the most advanced and mature renewable energy technology, and it will play a significant role in meeting the Europe 2020 and 2030 climate and energy goals. The EU has long been a leader in wind power generation. At the end of 2015, on average, wind power produced about 315 TWh of electricity, representing 11.4 % of the EU's total electricity production, through the cumulative installed capacity of 142 GW (of which 11 GW is offshore) (EWEA 2016).

The EWEA's new Central Scenario forecasts an installed wind capacity of 192 GW in 2020, increasing to 320 GW by 2030, of which 254 GW will be onshore and 66 GW offshore (EWEA 2015). Wind turbines market development is helped by a decrease in manufacturing and operating costs, as well as improved efficiency: the current cost of onshore wind energy attained a lower price than that produced from coal and gas in several European countries (Bloomberg Finance L.P. 2017).

Different wind turbine types are used depending on the various specific onshore and offshore site conditions. They are specifically designed to enhance their performance in terms of energy production, reliability, operation, maintenance, capital cost and transportation. Modern wind turbines integrate a series of highly optimised components to produce the lowest possible energy costs. The rare-earth elements neodymium, praseodymium and dysprosium are key ingredients in the most powerful magnet material, namely neodymium-iron-boron (NdFeB). This magnet is used to manufacture permanent magnet synchronous generators (PMSG), which are used in all major wind turbine configurations: low speed (direct drive), mid speed and high speed.

The wind turbine technologies using permanent magnets are below. Onshore and offshore are not separated because of physical properties of wind turbines, but because market trends are different: for instance, offshore market advantages direct-drive models, since they require less maintenance. This is why all scenarios give installed capacity forecasts for onshore AND offshore. Then, the difference between sub-technologies concerns the drive train. Direct-drive models do not have a gearbox, while other REEs-using wind turbines combine a gearbox and a permanent magnet synchronous generator and have therefore a lower permanent magnet content than direct-drive models.

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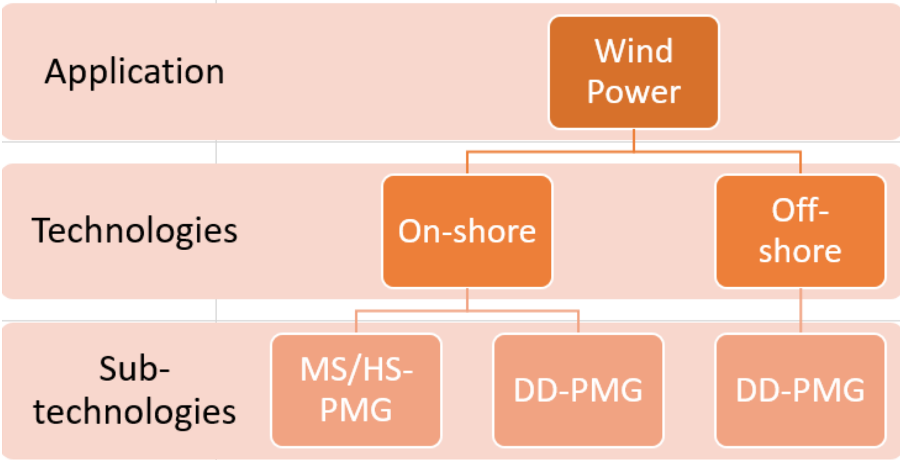

Figure 6 – Wind turbines technologies using permanent magnets, classified according to localisation and drive-train. MS/HS-PMG = Medium-Speed/High-Speed Permanent Magnet Generator; DD-PMG = Direct-Drive Permanent Magnet Generator

Table 2 gathers recent data for the EU apparent consumption of the CRMs in question. Based on historical data for the different turbine technologies, for their CRM content and for their annual growth rate (Blagoeva et al. 2016), the first indicator (R1) was evaluated to assess the relative importance of this application. Then, using a prospective scenario on the expected growth rate of each technology (Blagoeva et al. 2016) and expected CRM content taking into account technological improvement (Blagoeva et al. 2016), the second indicator (R2) was calculated to assess the future trend and its significance.

Table 2 – CRM significance indicators for wind power

CRM	Application use in 2015 (t)	EU apparent consumption[1] (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Nd	390	1,000	40%	750	80%
Pr	130	230	60%	250	110%
Dy	80	180	40%	60	30%

[1] 2013 for neodymium and dysprosium (BIO by Deloitte 2015) and average from 2010 to 2014 for praseodymium (Deloitte et al. 2017)

Even though there might be minor inconsistencies between the two data sets (2015 and 2010 to 2014), the first indicator shows that wind turbines already represent a significant share of EU apparent consumption for neodymium and praseodymium.

Besides, the second indicator suggests that in 2035, the annual CRM requirements in the wind power sector could nearly double. This is based on the assumptions of the European Commission central scenario (Blagoeva et al. 2016). This rise is explained by the fact that for Nd and Pr, decreasing material contents are not sufficient to counter the effects of a growing fleet (constant annual wind turbines installations) combined with growing market shares for permanent-magnet models. Therefore, the demand grows, then levels off around 2035.

It should be noted that dysprosium does not follow the same trend: this can be explained by technical improvement and the development of Dy-free magnets. In effect, Dy is a heavy REE, which is far less common than its two light REEs counterparts, thus encouraging the substitution effort. Therefore, the EC refence scenario assumed that the percentage of Dy in a permanent magnet would sink from 4.5 % to 1 % in 2020, then

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stays constant at 1 %. Hence, despite the growth of wind power installed capacities, the consumption of dysprosium for this application should decrease in the long term.

7.1.2 DRIVERS FOR CHANGE

7.1.2.1 POLITICAL DRIVERS

- **EU & national policies in terms of CO_2-free power production (low certainty – upward trend)**

The EU has proved a strong collective political will to reduce greenhouse gases (GHG): it committed to the Kyoto Protocol and is on good track to reach the 2020 targets of Copenhagen pledge (reducing emissions by 20% below 1990 levels). In 2011, even more ambitious objectives were endorsed by European countries to satisfy the former 2°C warming limit agreed in Copenhagen: Europe would reduce GHG emissions by 80 to 95% below 1990 levels by 2050. Yet, the recent commitments endorsed after the Paris agreement are more restrictive and so far, Europe has faced difficulties to keep on track to fulfil these objectives (only 1.5°C as a new warming limit and 40% reduction of GHG emissions below 1990 levels) (Climate Action Tracker 2017). Therefore, further climate action and more ambitious renewable energy deployment scenarios could be expected in the future in EU.

- **Measures in favour of smart grid developments (low certainty – upward trend)**

The lack of flexibility of variable renewables is a barrier known to hinder their development. The EU plans to replace 80% of electricity meters with smart meters by 2020 (European Commission 2017). The development of these devices enables a fine monitoring of electricity consumption and explains a growing number of smart grid projects combining demand monitoring, renewable electricity production and smart electricity distribution based on the variability of demand and production. Developing TSO and DSO roles (and their interactions in a single market) could also foster smart grid developments (ENTSO-E 2015). Besides, some technological improvements based on digital solutions are expected to further improve the efficiency of network management (big data, IoT…) and thus provide more flexibility to electricity systems even when they integrate a high share of renewables. Consequently, the adoption of smart grid distribution solutions in electricity systems could foster further development of variable renewable electricity sources.

7.1.2.2 ECONOMIC DRIVERS

- **Development of electric mobility (medium certainty – upward trend)**

In 2035, the development of electric vehicles (EVs) could represent a growth of electricity demand around 5% (European Environment Agency 2017). Considering the previous driver on CO_2 emission reduction policies and the fact that electric mobility is one of the few solutions to decarbonise the transport sector, there is a good chance that climate actions will foster the adoption of EVs which in turn would support the growth of renewable power production. This trend could be strengthened considering the fact for now EU non-ETS sectors (including transport and buildings) are less constrained than EU ETS sectors to meet the GHG emission reduction objectives (Climate Action Tracker 2017). In the future, further measures in favour of electric mobility might be required to remain on the tracks of the objectives described in the first political driver.

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7.1.2.3 SOCIETAL DRIVERS

- **Not in my backyard perception (medium certainty – downward trend)**

NIMBYism refers to local opposition to projects designed for public interest and accused to have a negative impact on its surroundings (noise, pollution, technological risk, etc.): the NIMBYs often agree with the project philosophy but would rather move its location further from their personal interests. In some European countries, this type of opposition has significantly slowed down the development of wind power (McCaffery 2011) with various arguments put forward (noise and visual pollution, competition with farming or fishing activities). In the future, if no effort is made to better involved local population and achieve their acceptance, NIMBYism may keep limiting the development of wind power, especially as the number of favourable sites with little opposition reduces.

7.1.2.4 TECHNOLOGICAL DRIVERS

- **Improvement of material efficiency or substitution solutions for permanent magnets (medium certainty – downward trend)**

As highlighted in the EC reference scenario, the material efficiency of magnets used in wind turbines is expected to improve in the coming decades, thus limiting the growth of CRM demand associated to the growth of installed wind power capacities. On closer examination of expected improvement, it seems that dysprosium has the highest efficiency improvement potential. On the other hand, a study shows the use of neodymium and praseodymium for wind turbines could also slightly decrease by 2020 if component substitution solutions are adopted: magnet-free technologies, currently under development, seem more promising than improving Nd & Pr material efficiency in existing components (Pavel et al. 2017).

In this situation, despite the trend toward less CRM requirements in this application, a potential rebound effect should be mentioned: is less critical raw materials are necessary, there is a chance that more wind power plants are installed to respond to the CO_2-emission objectives mentioned in the first driver.

7.1.2.5 ENVIRONMENTAL DRIVERS

- **Protection of on-shore and off-shore landscapes and biodiversity (high certainty - Strong downward trend)**

Apart from the impacts mentioned in the NIMBYs driver, wind farms have environmental impacts going beyond personal interests:

- Land use: one argument of wind farm opponents is that it impacts landscapes as a public good
- Impact of wild life: while it has been demonstrated that on-shore wind farms had rather limited impact on local biodiversity (National Wind 2010), offshore farms would have either positive or negative impacts during operation and would require particular measures to limit the impacts during their construction phase (Bergström et al. 2014).

In the second situation, the trend on the growth rate of CRM demand could be even stronger as offshore farms are based on the most CRM-intensive technologies.

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7.1.2.6 LEGAL DRIVERS

- **Obligation to recycle products containing CRM used in wind turbine manufacturing (low certainty – downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future.

Currently no specific regulation points at wind turbines, but there recycled rare-earth magnets from other regulated applications (see electronics, electric motors) that could be reused or refurbished for the manufacturing of new wind turbines in the future. This would pull down rare earth imports.

7.2 PHOTOVOLTAIC PANELS

7.2.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

This application analyses photovoltaic technologies and some of their constituent raw materials. It does not cover concentrated solar power. Photovoltaic energy technologies convert solar energy into electricity and could represent a viable path for generating clean energy. For years, its high cost represented a major drawback, but in recent years, a combination of technological innovations, economies of scale and manufacturing experience led to a strong decline in manufacturing costs. This decline has been accompanied by increased efficiency of solar cells. The global installed capacity has risen from 1 GW in 2000 to 39 GW in 2010 and almost 300 GW in 2015 (approximately 100 GW in Europe), according to IEA data (IEA 2017).

Commercial PV technologies include wafer-based **crystalline silicon (c-Si)** (either mono-crystalline or multi-crystalline silicon) and **thin-film (TF)** using amorphous silicon (**a-Si**), copper-indium-diselenide-disulphide (**CIGS**) and cadmium-telluride (**Cd-Te**). The various technologies assessed in this study are presented below.

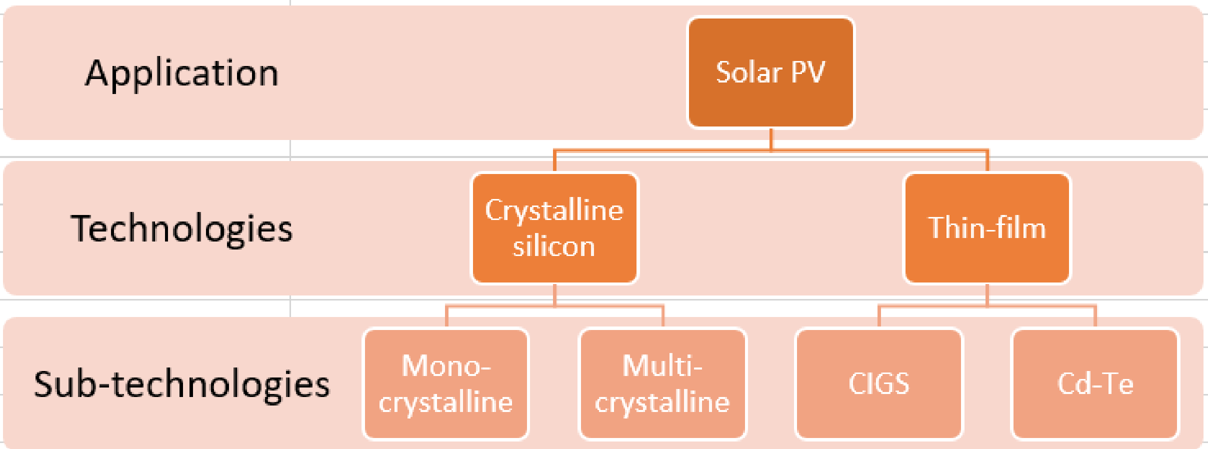

Figure 7 – Technologies assessed for solar cells

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For c-Si technologies, we have investigated the demands of the CRM **silicon metal** (which is the only source of crystalline silicon used in silicon wafers) and the non-CRM silver (Ag). For thin-film technologies, the CRMs **indium** (In) and **gallium** (Ga) and the non-CRMs copper (Cu), selenium (Se) and tellurium (Te) were investigated. Silicon demand for a-Si technology was not assessed because the quantities involved are far less important than the silicon quantities for c-Si (about 1000 times less (Blagoeva et al. 2016)).

Most data and assumptions used for this assessment were taken from a report on EU potential material supply bottlenecks (Blagoeva et al. 2016):

- Emerging PV technologies were not taken into account, due to uncertainty around market adoption.
- Market shares for each technologies and sub-technologies were kept at their 2015 levels: the idea is that thin-film technologies will not replace the mature crystalline silicon technologies. We assumed that stakeholders in the PV industry would rather invest in more mature technologies (c-Si mostly) to optimise some of their value chain steps than spend money on newer, more uncertain technologies.
- A decreasing material content for all technologies and all raw materials. It is assumed that technological improvements and/or substitution efforts will decrease the number of CRMs and other raw materials assessed here needed for 1 GW installed.

Table 3 gathers recent data for the EU apparent consumption of CRMs. Based historical data for the different PV technologies, their CRM content and their annual growth rate (Blagoeva et al. 2016), the first indicator (R1) was evaluated to assess the relative importance of this application. Then, using a prospective scenario on the expected growth rate of each technology and expected CRM content taking into account technological improvement (Blagoeva et al. 2016), the second indicator (R2) was calculated to assess the future trend and its significance.

Table 3 – CRM significance indicators for photovoltaic panels

CRM	Application use in 2012 (t)	EU apparent consumption[1] in 2012 (BIO by Deloitte 2015) (t)	% (Deloitte et al. 2017) (R1)	Waste and losses	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Si	34,900	582,000	6%	360,000	12,700	2%
In	7	22	30%	55 (excl. zinc ores[1])	2	10%
Ga	4	80	5%	52 (excl. bauxite ores[1])	1	1%

[1]: data from the MSA study. For indium, two flows were excluded from the apparent consumption calculation as they referred to indium embedded in zinc ores extracted in Europe and indium embedded in zinc refinery waste. While these quantities of indium are not properly “consumed”, it is worth mentioning their existence (around 100 t) as they could be used to reduce imports and develop a European indium production. For gallium, all quantities not intended for the gallium industry (700+ t of gallium embedded in imported bauxite ores) were excluded.

Indicator R1 shows that solar cells represent only a small fraction of total end-uses for Si and Ga (based on 2012 data). In the case of gallium, the high amount of waste in the material balance suggests that the bottom-

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up approach used to calculate the “application use” probably underestimates the actual requirements (the 4t are derived from end-product gallium content rather than manufacturing input requirements).

What is all the more striking is that in this scenario (Blagoeva et al. 2016), the share of all CRMs in solar cells would decline by a factor of 3 to 5 (indicator R2) by 2035. This may come as a surprise since the reference EU scenario shown below forecasts a growth in PV capacities (we took an average annual installation rate to match this cumulative scenario). However, this overall cumulative capacity growth is counterbalanced by a strong reduce in material content (along with constant market shares). Technical progress in material efficiency would therefore constitute the main reason behind the falling CRM demands for solar applications. Hence, under the hypothesis taken here, PV emergence would not constitute a major trend for any of these CRMs.

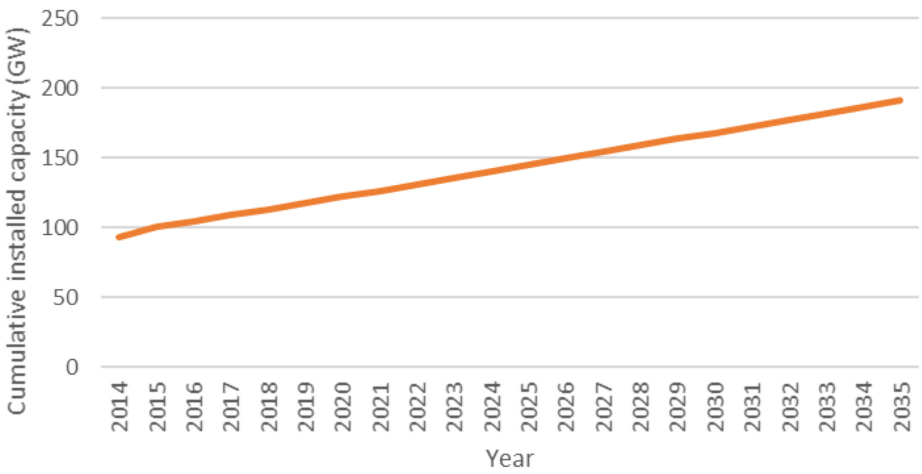

Figure 8 – EU reference scenario for PV deployment

7.2.2 DRIVERS FOR CHANGE

7.2.2.1 POLITICAL DRIVERS

- **EU & national policies in terms of CO_2-free power production (low certainty – upward trend)**

The EU has proved a strong collective political will to reduce greenhouse gases (GHG): it committed to the Kyoto Protocol and is on good track to reach the 2020 targets of Copenhagen pledge (reducing emissions by 20% below 1990 levels). In 2011, even more ambitious objectives were endorsed by European countries to satisfy the former 2°C warming limit agreed in Copenhagen: Europe would reduce GHG emissions by 80 to 95% below 1990 levels by 2050. Yet, the recent commitments endorsed after the Paris agreement are more restrictive and so far, Europe has faced difficulties to keep on track to fulfil these objectives (only 1.5°C as a new warming limit and 40% reduction of GHG emissions below 1990 levels) (Climate Action Tracker 2017). Therefore, further climate action and more ambitious renewable energy deployment scenarios could be expected in the future in EU. For instance, EU is pushing for solar auto-consumption.

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- **National/EU funding to the R&D&I sector – impact on material efficiency (medium certainty – downward trend)**

The European Commission identifies two main challenges for solar PV: reducing the electricity generation costs and increasing the efficiency of converting sunlight into electricity. The Commission funds research projects aiming to identify new materials, better design photovoltaic cells and increase the efficiency of solar panels. It also facilitates cooperation between researchers, industries and manufacturers to rebuild EU technological leadership in the sector (European Commission n.d.). Funding programmes include H2020 projects (CrowdFundRES, Solar Bankability, RECP…) and European Regional and Development Fund among others.

7.2.2.2 ECONOMIC DRIVERS

- **Average cost of MWh produced by solar installations (high certainty - upward trend)**

From 2010 to 2017, the cost (both investment cost and average levelized cost of electricity - LCOE) of solar PV energy has dropped: -64% in Germany, -71% in France, -75% in Italy and -67% in UK (LCOE) (IRENA 2018). Two factors explain this trend: the investment costs have dropped (PV panels are cheaper), and the cell efficiency has improved. In the most recent years, the cost reduction has been more limited than in the early 2010s: the trend is not as strong as it used to. Yet, despite this apparent stabilisation of PV costs, some studies still foresee further cost reduction in the coming decades (ETIP-PV 2017). This could foster a higher adoption rate.

7.2.2.3 SOCIETAL DRIVERS

- **Willingness to adapt power consumption during the day – demand response (low certainty – upward trend)**

Due to the higher penetration of renewable, intermittent energy sources (esp. wind and solar), electricity production is becoming more uncertain, resulting in more volatile prices. As a consequence, the energy demand of a production system has to become more flexible, i.e. to adapt itself to volatile energy prices. Different demand response instruments aim to achieve changes in electric usage by end-use customers (price-based and incentive-based demand response). Examples can be: adaptation of process starts, of machine scheduling, of order sequence, of staff-free time, of shift times, interruption of processes and storage of energy (Graßl and Reinhart 2014). Industrial customers are prime targets for demand response, because of higher power consumption, existing infrastructure for control and communication and in certain cases, ability to adjust demand quickly.

7.2.2.4 TECHNOLOGICAL DRIVERS

- **Emergence of new solar cell technologies (low certainty – variable trend)**

Nowadays, the main technology on the market is the silicon-based cell. Other technologies, such as thin-film cells (Cd-Te, CIGS…) and organic solar cells, hardly account for a few % of market shares. While crystalline silicon is likely to remain the dominant player in the next decade at least, significant progress has been made on a new technology: metal halide perovskites, which has achieved a 22.7% efficiency in laboratory (higher than Cd-Te). Lightweight and flexible modules could be produced at a lower cost than Si-based cells. Furthermore, perovskite-silicon tandems could be used to increase c-Si cells efficiency: lower quality Si would

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therefore be needed, resulting in potential huge changes in the CRM demands (Brown et al. 2017) (upward or downward depending on the new dominant technology). Such deployments are however subjects to high uncertainty as these technologies have not hit the market yet.

7.2.2.5 ENVIRONMENTAL DRIVERS

- **Local impact of large solar projects (high certainty – downward trend)**

Utility-scale solar projects necessitate large areas for collection of energy. This may interfere with existing land uses (agriculture, farming, industry, real estate…), or have a negative impact on the ecosystem or the landscape. Building solar facilities can also impact the soil (erosion, compaction, risk of acid drainage or spilling of chemicals…) or water resources (for cooling purposes) (greenmatch.co.uk 2015). In addition, the extraction of raw materials for the manufacture of panels has an environmental impact which is more and more taken into account by end-users.

7.2.2.6 LEGAL DRIVERS

- **Feed-in tariff for solar PV electricity production (low certainty – variable trend)**

Feed-in tariffs (FITs) are the most widely used policy in the world for accelerating renewable energy deployment. A FIT drives market growth by providing companies long-term purchase agreements for the sale of electricity generated from PV sources. These agreements often provide a price per kWh of electricity and are structured with contracts ranging from 10-25 years. Prices can be differentiated according to source quality, project location or other parameters. FIT payments can also be given as bonus above the market prices. FIT policies typically include access to the grid, long-term agreement and payments based on the cost of electricity generation(Fogarty and Lamb 2012). However, a lack of clear FIT policies, or a changing legislation in general, can impact negatively the deployment of solar energy since It increases the legal and economic risk for companies willing to develop such projects.

- **Obligation to recycle end-of-life products (medium certainty - downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future.

In the case of PV panels, recycling is already mandatory and falls in the framework of the EU WEEE[2] Directive (European Commission 2012). Yet, since the first significant PV installations started in the 1990s with a 25 to 30-year lifespan, the recycling flows of panels are still limited. These flows will follow a strong upward trend in the coming years, thus reducing the amount of primary material to import.

[2] Waste Electrical and Electronic Equipment

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7.3 DOMESTIC ENERGY STORAGE

7.3.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

Residential energy storage are devices that allow to store energy inside a household, for later consumption. In this application, only batteries storing electricity were considered, as they are the most widespread technology in Europe. There are two main operating modes for these devices: on-site generation, where the electricity produced by solar cells, for instance, is stored for later usage (e.g. recharging electric vehicles during the night); and differential tariffs exploitation, where the device is charged during off-peak hours, when the electricity is cheaper. The main advantages provided by such batteries are supporting the energy grid during high-demand periods and mitigating the intermittency of solar panels production.

Various battery technologies could be suitable for small to medium-size electricity storage applications:

- Lead-acid batteries, the historical dominating technology for vehicles, which nowadays has a low market share in domestic storage due to its low energy and power density compared with Li-Ion batteries (Robson and Bonomi 2018).
- Li-Ion batteries, the technological standard today for new systems. They currently exceed 90% market share (Hill 2016a) and were assumed to maintain a high market share (~95%) until 2035 (Cookson 2015).
- Sodium batteries, benefiting from higher efficiency and good energy density. They require high temperature offer limited power. New concepts are still being developed (Robson and Bonomi 2018).
- Flow batteries. Still under development and demonstration, these concepts still offer quite low efficiency and energy density (Robson and Bonomi 2018).

The market for domestic ("behind the meter") energy storage is currently very dynamic and rapidly expanding (Cookson 2015). Access to detailed market information is behind "paywalls" (e.g. Bloomberg New Energy Finance "Global Energy Storage Forecast" (Bloomberg New Energy Finance 2017)). However, summary reports provide information that can be used to estimate market growth. To estimate how much Co, C and Li will be required on an annual basis to supply the European market for behind the meter storage, estimates the following parameters are required:

- Co, C and Li content of batteries (280 g/KWh for Co, 2870 g/KWh for C, 286 g/KWh for Li)
- Energy storage market growth between 2015 and 2035 and the proportion of it that is "behind the meter"
- EU share of the global market
- Proportion of Li-ion batteries used in domestic energy storage (there is some very limited use of Pb-acid batteries in mainly off-grid domestic energy storage)

Concerning the non-hydro global energy storage market, on 20th November 2017 Bloomberg New Energy Finance stated that it "will double six times between 2016 and 2030, rising to a total of 125 gigawatts/305 gigawatt-hours" (Figure 1) (Bloomberg New Energy Finance 2017). This represents a compound annual growth rate of 35%. In a separate report, "Global Energy Storage Forecast" (Deign 2016), they also predict that by 2024 "66% of all storage will be behind the meter, compared to just 16% at present". This corresponds to a compound annual growth rate of 19%. In terms of the EU market share of the sector, there are no publicly available definitive data. However, Figures 1 and 2 provide some guidance as to what the percentage share

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could be. A crude estimate can be arrived at by measuring the cumulative area proportions for each EU country depicted in Figure 2. The relative area proportion for France, Italy Germany and the UK is 29%.

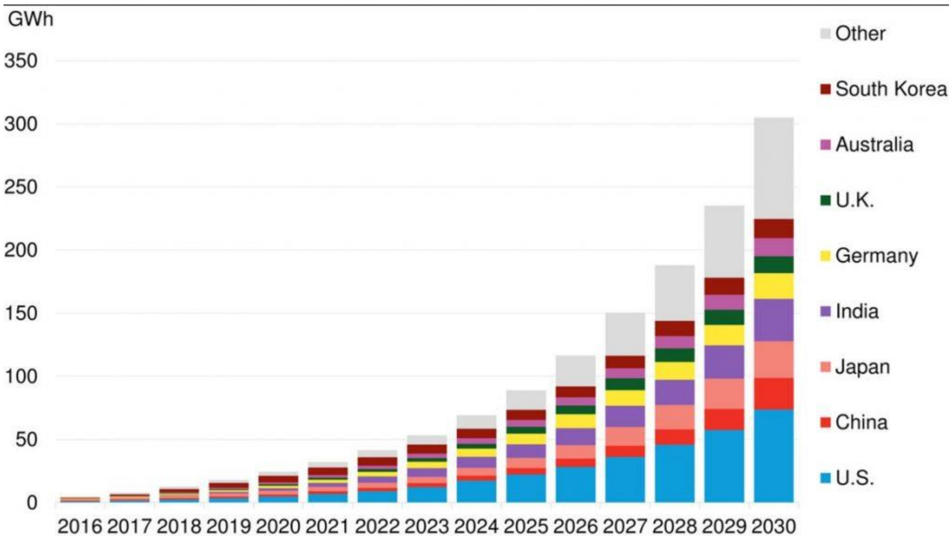

Figure 9 – Global cumulative storage deployments (Bloomberg New Energy Finance 2017)

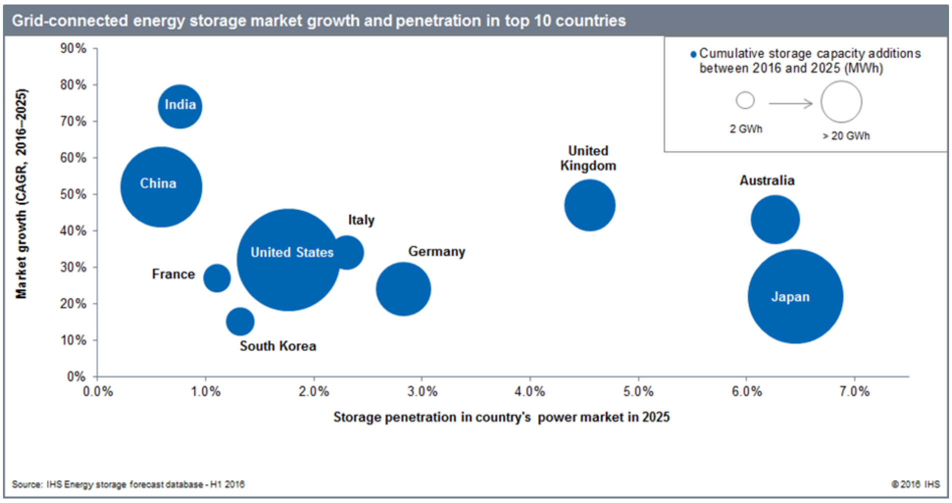

Figure 10 – Grid connected energy storage market growth in top 10 countries (Hill 2016b)

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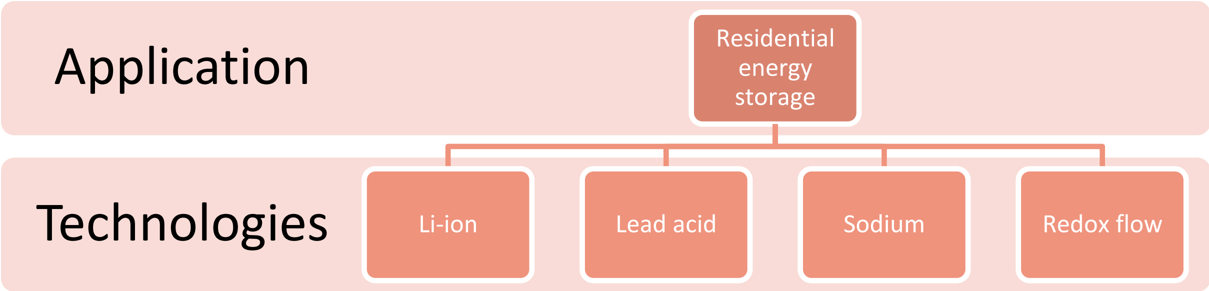

Figure 11 – Technologies for residential energy storage

Apart from Li-Ion batteries, some alternative technologies include CRMs (e.g. Antimony in lead-acid batteries, phosphorus, germanium or antimony in some sodium battery concepts, vanadium in some flow battery concepts). Yet, considering the high expected market share of Li-Ion batteries, the assessment only considered the CRMs contained in this technology.

In order to assess the future demands in Co, C and Li (not a CRM), the following assumptions were made:

- The compound annual growth rate for all global energy storage capacities is 35% p.a. with an initial value of 5 GWh in 2016 (back calculated to 3 GWh for 2015), corresponding to 300 GWh cumulative capacities installed in 2030 (Bloomberg New Energy Finance 2017). Post 2030 sales are assumed to be constant with 78 GWh installed per annum around the world (around 15 GWh p.a. in Europe).
- The compound annual growth rate for behind the meter sales as a proportion of all energy storage was estimated at 19% p.a. with an initial value of 16% in 2016 (back calculated to 13% in 2015). Post 2024 behind the meter sales as a proportion of total energy storage are assumed to be constant at 66%. Europe is assumed to represent around 30% of the global market all the time (Deign 2016).
- Second use of batteries from battery electric vehicles was not factored into the calculation. However, the assumption of constant sales post 2030 and constant market share of behind the meter sales would reflect some of this market.
- Li-ion batteries make-up 95% of the behind the meter sales energy storage market from 2015 to 2035 (Hill 2016a).
- Exact composition of various products (e.g. Tesla Powerwall) are commercial secrets. However, batteries have similar power requirements as battery electric vehicles. As some BEVs can be “recycled” for second use in domestic electricity storage (e.g.Nissan xStorage (Nissan n.d.)), this indicates that this a reasonable assumption. Thus, the average car battery composition detailed in (Blagoeva et al. 2016) is used as an estimate of the Co, C, and Li content for domestic batteries.

These assumptions can be used to estimate the quantities of CRMs used in this application currently. Based on this estimation and recent data for the apparent consumption of the main raw materials (Co, C, Li), the first indicator (R1) has been evaluated to assess the current relative importance of this application. Then, using the prospective data in above mentioned references, (expected growth rate of storage systems sales, market share of behind the meter systems, etc.), the second indicator (R2) has been calculated to assess the future trend and its significance.

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Table 4 – CRM significance indicators for domestic energy storage

CRM	Application use in 2015 (t)	EU apparent consumption[1] (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Co	10	13,000	0%	4,000	30%
C	100	80,900	0%	41,000	50%
Li	10	26,100	0%	4,000	20%

[1] 2012 for cobalt and natural graphite (BIO by Deloitte 2015), and 2012 for lithium which is currently not considered as a critical raw material (BIO by Deloitte 2015).

The situation here is typical of CRM demand for emerging uses: presently, energy storage consumes virtually nothing with regard to the total demand for Co, C and Li (indicator R1). However, the demand is forecasted to grow quite significantly up until 2035, with Co demand at 30% and C demand at 50% of current demand (indicator R2). The main reason behind this growth is the massive deployment of residential storage solutions (35% growth per annum in this scenario), vastly reliant on Li-Ion batteries.

Finally, it should be born in mind that analysing the demand of some CRMs is complicated by high amounts of waste in landfills and tailings, and high recycling rates. For instance, the annual apparent EU consumption of cobalt (13 kt) includes a high amount of waste (9 kt) compared to the total supply of 30 kt (incl. 6 kt of recycled material) (BIO by Deloitte 2015). The waste and losses of natural graphite accounted in the EU apparent consumption (80 kt) are also very high (70 kt).

7.3.2 DRIVERS FOR CHANGE

7.3.2.1 POLITICAL DRIVERS

- **Incentives for distributed energy generation involving households and incentives for domestic energy storage (medium certainty, upward trend)**

Distributed generation means that electricity is generated from local sources (often renewable) instead of centralised power plants. Governments can provide incentives to overcome market and regulatory barriers to implementation. Third-party ownership is an example where governments provide power purchase agreements or leases (coupled to tax incentives) to cover the costs of a PV system coupled with a domestic storage solution. In addition, net metering policies allow customers to produce electricity locally and sell excess generation to the utility at a set price (U.S. Department of Energy n.d.) (a battery system can also optimise the earnings by storing electricity to self-consume it at peak time, when electricity coming from the grid might be expensive).

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7.3.2.2 ECONOMIC DRIVERS

- **High electricity price for households along with cost reduction for battery storage solutions (high certainty, upward trend)**

Countries where electricity is expensive for households offer a strong incentive for domestic energy storage. As a matter of fact, high prices mean that it becomes increasingly beneficial to consumers who possess a local source of energy production to store energy when it is produced and use it during peak time, when the electricity from the grid is the most expensive. Reduction in the initial investment for such batteries, as well as increased lifespan and reduced maintenance, could mean a quicker return on investment for consumers, and therefore a stronger incentive for auto-consumption and domestic energy storage. Strong synergies can also be found with the deployment of electric vehicle: EV batteries could work as an auxiliary domestic energy storage solution. The car battery could be charged during the night (wind turbine) at home or during the day at work (PV).

7.3.2.3 SOCIETAL DRIVERS

- **Use of electric vehicles for residential energy storage (medium certainty, downward trend)**

Strong synergies can be found with the deployment of electric vehicle: EV batteries could work as auxiliary domestic energy storage solutions. The car battery could be charged during the night (wind turbine) at home or during the day at work (PV). However, batteries designed for domestic use could enter in competition with EV batteries if they can be used as residential storage solutions, and if society widely adopts electric vehicles. There are ongoing projects testing this possibility (e.g. Nissan xStorage (Nissan n.d.), or the test in TU Delft with a fuel cell electric vehicle (Poorte 2017)), but scaling-up has yet to take place.

7.3.2.4 TECHNOLOGICAL DRIVERS

- **Change in the chemical composition of Li-Ion batteries (medium certainty, variable trend)**

Current R&D aims at optimising battery composition in order to reduce its cost and facilitate the deployment of lithium-ion batteries for energy storage, but also electric vehicles. Due to lack of data sources for residential purposes, we explored trends for Li-Ion batteries for EVs and extrapolated the result for the residential area, thanks to a prospective study (Gert Berckmans et al. 2017).The main idea is that two competing battery types could emerge as market leaders for Li-Ion batteries: lithium Nickel Manganese Cobalt oxide (NMC), and silicon-based Li-Ion battery. Both of them use a variety of CRMs and could therefore have a strong impact on their demands in such a growing market.

7.3.2.5 ENVIRONMENTAL DRIVERS

- **Growth of renewable energy production to cut CO_2 emissions resulting in high variability of power supply (high certainty, high upward trend)**

In order to reduce the carbon dioxide emissions in the power production sector, renewable energy sources (RES) are provided incentives within the EU. Due to the higher penetration of renewable, intermittent energy sources (esp. wind and solar), electricity production is becoming more uncertain, resulting in a high variability

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of power supply and volatile electricity prices. Power storage solutions are essential to sustain the development of intermittent RES and move towards a more flexible energy system. This means that tackling global warming and climate change heavily relies on developing energy storage infrastructure, at industrial scale, but also at a residential scale, in line with the emergence of local, decentralised energy sources (especially PV) (Larive 2017).

7.3.2.6 LEGAL DRIVERS

- **Implementation of the EU circular economy package (medium certainty, downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future.

In the case of batteries, a directive already provides a framework (European Commission 2006) and further circular economy actions could be expected, requiring the industry to do more to recycle batteries. This would lead to a lower CRM apparent consumption even though recycling lithium batteries remains uneconomic in the short term (McCormick 2016).

8 ELECTRONICS & TELECOMS

8.1 SMARTPHONES, LAPTOPS AND DESKTOP PCS

8.1.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

Electronic devices are among the manufactured products that have experienced the highest growth in sales over the last few decades. Starting from the late 1970s, desktop computers became more and more widespread in offices at first, then in homes. In the mid-2000s, there has been a gradual shift in PC sales from desktops to laptops, with the global PC market still growing. Finally, the late 2000s and the early 2010s witnessed the emergence of mobile phones and tablets, devices competing to a certain degree with PCs.

This section focuses on PCs (desktop & laptop) and mobile phones. Due to lack of accurate data, some other electronic devices could not be investigated, e.g. tablets and smartwatches. In addition, demand for indium (mainly incorporated in screens in the form of indium-tin oxide) was investigated in a separate section on flat panel displays.

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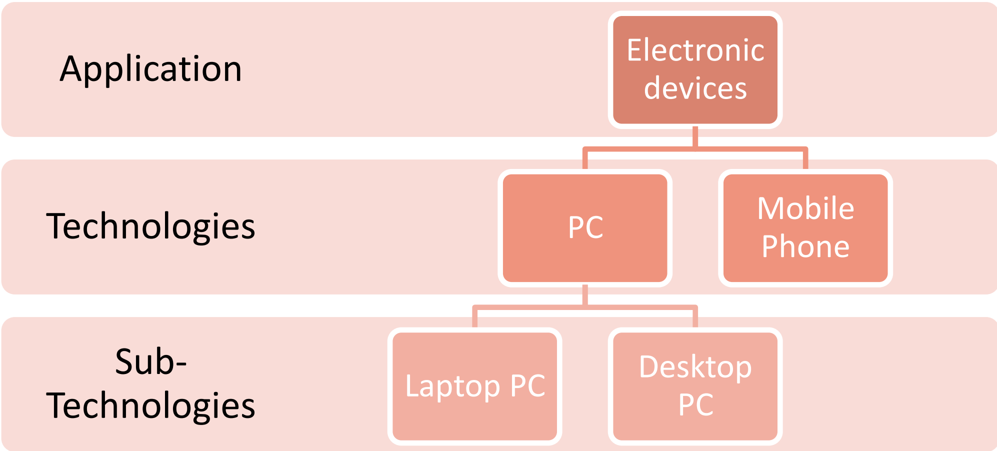

Figure 12 – Technologies assessed for electronic devices

Some hypotheses were made at this point, with a significant number concerning the annual demand scenario:

- The scenarios for device sales are based on (Deetman et al. 2018) (broader study on appliances), deriving the global annual sales of appliances from the ownership-rates found in the IMAGE integrated assessment model (Stehfest et al. 2014), and specifically the sub-model on household energy demand as described in (Daioglou, van Ruijven, and van Vuuren 2012). Though the scenario published in the original paper only presents global figures, the underlying calculations contain regional detail, which were used to extract the European data presented here.
- The main socio-economic drivers for the appliance sales are population & affluence, which are defined by the so called Shared Socio-economic Pathways (or SSPs) (Riahi et al. 2017). This set of scenario specifications was originally developed for climate change research under the Intergovernmental Panel on Climate Change. In particular, the SSP2 baseline was used for the scenarios presented here, this represents a middle-of-the-road scenario in terms of population development as well as in terms of affluence (van Vuuren et al. 2012). In the case of Europe, this means that population will grow only slightly (Jones and O'Neill 2016), so most of the growth in the demand for appliances is attributable to the projected growth in affluence.
- As no specific data were available for smartphones in (Deetman et al. 2018), the growth rate of small appliances was used and applied to historical EU sales (2017).
- Relative market shares for laptops and desktop PCs were assumed to be constant (approx. 60% vs. 40%).
- Since no consensus seemed to appear from literature, a constant material content for all CRMs was used. Contents vary for desktops, laptops and smartphones (Deetman et al. 2018) but remain constant over time. As questionable as this seems, lack of comprehensive, up-to-date data forced us to make this strong hypothesis.

To give a concrete idea of what these central scenarios represent in terms of sales, forecasted sales for smartphones are provided below:

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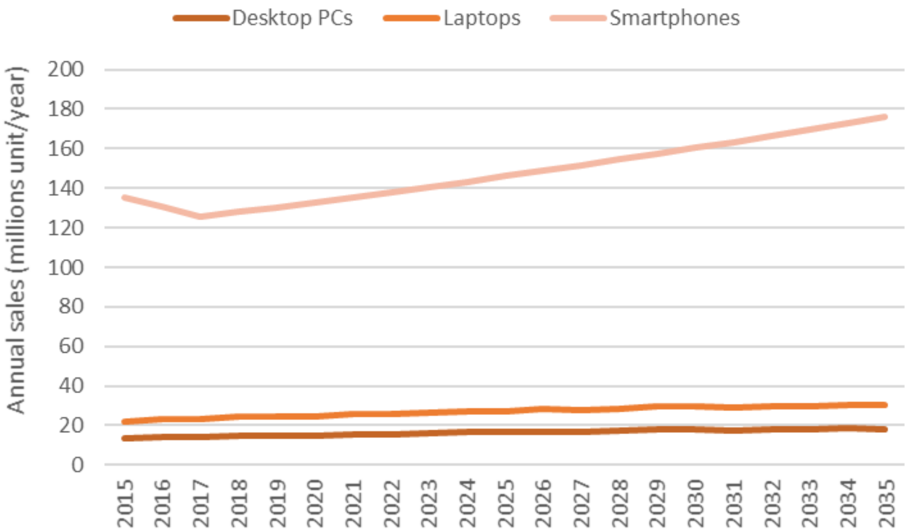

Figure 13: Smartphone & PC sales forecast (adapted from Deetman et al. 2018)

These assumptions were used to estimate the current use of CRMs in this application. Based on this figure and recent data for the apparent consumption of these CRMs, the first indicator (R1) was evaluated to assess the relative importance of this application. Then, using the prospective data in above mentioned references (in particular expected sales for each device), the second indicator (R2) was calculated to assess the future trend and its significance.

Table 5 – CRM significance indicators for smartphones, laptops and desktop PCs

CRM	Application use in 2015 (t)	EU apparent consumption[1] (t)	% (R1)	Waste and losses	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Pd	7	60	10%	14	10	20%
Ba	160	338,330	0%	NA	220	0%
Co	2,000	13,000	15%	9,000	2,650	20%
Ga	4	80	5%	52 (excl. bauxite ores[1])	5	5%
Ta	80	100	80%	NA	110	110%
Nd	90	1,000	9%	190	120	12%
Dy	9	180	5%	50	12	6%

[1] 2015 for palladium, 2017 for tantalum (approximate), average from 2010 to 2014 for barium (Deloitte et al. 2017), 2012 for gallium and cobalt and 2013 for neodymium and dysprosium (BIO by Deloitte 2015). For gallium, all quantities not intended for the gallium industry (700+ t of gallium embedded in imported bauxite ores) were excluded.

Demand trends and their significance are quite different from one CRM to another. If we look at indicator R1, a very significant amount of Ta is used in such appliances (80%), while 10 to 20% of EU net consumption of Pd, Co, Nd and Dy are involved. Despite the growth in sales for some electronic devices, the expected use of related CRMs would either stagnate or rise in relatively limited proportions (Pd, Ga, Dy, Co, Ta, Nd). It is worth noting the case of tantalum for which electronics is currently the main application. This reference scenario

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shows that the electronic applications of tantalum will remain important and could outreach the current use of this material, all applications factored together.

In order to refine the analysis, it should not be overlooked that, for some CRMs, there are additional sources of uncertainties. For cobalt and gallium, there are high amounts of material left as waste in landfills and tailings, and this could suggest that the bottom-up approach used to calculate the “application use” probably underestimates the actual requirements (the 2,000t and 4t are derived from end-product CRM contents rather than manufacturing input requirements). Moreover, the neutral import/export balance and the relatively high recycling rate could also explain differences between our reference scenario and results from other studies, if these material flows are not extensively taken into account.

8.1.2 DRIVERS FOR CHANGE

8.1.2.1 POLITICAL DRIVERS

- **Political measures against planned obsolescence (low certainty – slight downward trend)**

The European Parliament conducted a study on the benefits of longer lifetime products for both consumers and companies in 2016 (Montalvo et al. 2016). The conclusion led more recently to the vote of a resolution (European Parliament 2017a) to fight against planned obsolescence. Concerning critical raw materials, if lifespan of devices is extended, their lower renewal rate will pull down the imports and requirement of CRMs.

8.1.2.2 ECONOMIC DRIVERS

- **Impact of material costs, competition between manufacturers, and renewable rates on sales (low certainty – slight downward trend)**

Thanks to economies of scale, the cost of materials (even CRMs) for electronic device manufacturing are low and the profits of manufacturers (e.g. Samsung, Apple…) high. Recently, new competitors (Chinese brands) gained significant market shares by launching low-priced produced. Now that competitors have settled, prices started rising again (Molla 2018) and the lack of new technological features pull renewal rates down (Meola 2016). Therefore, neither the cost of critical raw materials, the price of devices nor the current technological innovations should deeply impact the demand for electronic devices: only a slight downward trend could be envisaged in the long term.

8.1.2.3 SOCIETAL DRIVERS

- **Growth of demand related to social needs (high certainty – strong upward trend)**

There are strong social drivers behind the use of electronic devices to respond to social needs: the development of social network activities, the growth of on-line/on-app purchases, and on-demand services are expected to drive a strong growth of electronic product demand. Besides, new uses of these devices (e.g. mobile banking, credit card, etc.) and are expected to arise along with many new smaller devices (connected things). As a result, renewal rate of existing devices (smartphones, laptops, etc.) should increase due to more intensive usage, while new devices will create a new demand for CRMs: 20 billion of connected things are expected by 2020 (Hung 2017), and 5G will allow even more Internet of Things (IoT) applications beyond 2020.

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8.1.2.4 TECHNOLOGICAL DRIVERS

- **Smaller and more integrated devices (high certainty – strong upward trend)**

Manufacturers' strategy goes toward smaller and more integrated components (e.g. thinner smartphones, integrated batteries), making recycling more difficult which is a driver for more primary needs: the most cited barriers in recycling electronic devices are the complexity of circuit design and the small size of components (Ueberschaar 2017). Integration also pushes toward higher renewal rates (e.g. battery issues often require full replacement).

8.1.2.5 LEGAL DRIVERS

- **Legal barriers to disposal and incentive measures in favour of reuse, repair and refurbished items (high certainty – downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future.

In the case of electronic wastes, a directive already provides a framework (European Commission 2012) and further circular economy actions could be expected, requiring the industry to do more to refurbish those products. This would lead to a lower CRM apparent consumption. Besides, the imports of "e-waste" from EU into China have been officially banned since 2000 (EFFACE 2015). While this measure has been circumvented until now, the recent decision of China to ban imports of all plastic waste could reinforce controls and accelerate this trend (Latham & Watkins LLP 2018).

8.2 DOMESTIC APPLIANCES

8.2.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

As mentioned in section 8.1, the study of domestic appliances was split into two analyses, each regrouping appliances with similar demand growth. The current section deals with 'larger appliances', not covered in section 8.1, namely air-conditioning, refrigerators, washing machines, TVs. It should be noted some domestic appliances could one day contain significant amount of electronics (and CRMs) due to the development of IoT. These have not been considered in this study.

Hypotheses made for the purposes of this analysis are similar to those detailed in section 8.1 (based on the same original study (Deetman et al. 2018)). In a nutshell, household expenditure (linked with EU GDP per capita) drives the increase in demand for appliances, through the average number of appliances per household. These ownership rates are then converted into annual sales of appliances. Additional hypotheses include the fact that appliances bearing permanent magnets would see their market share increase (due to higher efficiency and lowered costs, as observed currently), and that all TVs contain the same average CRM content

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(due to lack of extensive data covering all TV models and technologies). Indium in TV screens has not been accounted as this is the scope of a dedicated application (see section 8.3).

Regarding CRM content, an extensive review of the available literature has been carried out, including (Habib et al. 2014; Seo and Morimoto 2014; Deetman et al. 2017; Sprecher et al. 2014; Wang et al. 2014). The final CRM content for each appliance was calculated as the mean of different contents available in the literature. For instance, Nd and Dy contents in air conditioners were calculated with (Seo and Morimoto 2014) and (Habib et al. 2014).

One additional comment is that CRM contents are supposed to remain constant while if more appliances become smart objects, the content of some components of printed circuit boards (usually including Ba, Pd, Co, Ta, Ga) could increase.

Based on recent data for the apparent consumption of these CRMs and historical data for the different appliances, for their CRM content and for their annual growth rate, the first indicator (R1) has been evaluated to assess the relative importance of this application. Then, using a prospective scenario on the expected growth rate of each technology and expected CRM content taking into account technological improvement, the second indicator (R2) was calculated to assess the future trend and its significance.

Table 6 – CRM significance indicators for main domestic appliances (AC, fridge, washing machine, micro-wave, TV)

CRM	Application use in 2015 (t)	EU apparent consumption[1] (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Pd	10	60	20%	10	20%
Ba	170	338,330	0%	170	0%
Co	30	13,000	0%	30	0%
Nd	1,530	1,000	150%	2,370	240%
Dy	130	180	70%	190	110%

[1] 2015 for palladium, average from 2010 to 2014 for barium, (Deloitte et al. 2017), 2012 for indium and cobalt, 2013 for neodymium and dysprosium (BIO by Deloitte 2015).

Most significant demand trends occur for Nd (light REE), Dy (heavy REE) and Pd (PGMs). Although there might be some inconsistency between datasets used for this analysis (average of 2010 to 2014 data vs 2015 data), it is relevant to point out that demand for Nd and Dy for appliances already represents a significant part of total demand for these REEs (keeping in mind that Dy global production is small so uncertainties are higher), as is shown by indicator R1. R2 suggests a growing demand for these REEs: appliances may therefore contribute to some extent to the global upward trend in REEs demand (although the rise seems lower than for other end-uses). On the contrary, Pd demand, although significant for this end-use (R1), would stagnate in our scenario until 2035 (R2).

For some CRMs involved in appliances, there may be additional sources of uncertainties (other than those related to the hypotheses and simplifications of the reference scenario). There are high amounts of cobalt laying as waste in landfills and tailings, and this tonnage may account for a significant difference between apparent consumption (import minus export) and actual demand for the industry. In addition, Co and Pd have a neutral import/export balance, and Co has a relatively high recycling rate: this could explain differences between our figures in this reference scenario and results from other studies, if these material flows are not

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taken into account. Regarding neodymium, a couple of reasons can explain why the ratio between application use and EU total apparent consumption (R1) is above 100%:

- The consumption of neodymium has grown fast over the last couple of year, explaining why the use of Nd in 2015 for this application could be close to the total apparent consumption in EU back in 2012.
- Besides, there are uncertainties on the neodymium content of appliances and on the market shares of appliances containing neodymium and of Nd-free appliances. More information is available on CRM-bearing appliances than on CRM-free alterative products. Thus, mean values of CRM content were used whenever possible, but the market shares of appliance sub-technologies were not always available. In some cases, the average CRM content of CRM-bearing appliances may have been used for all sub-technologies, including CRM-free alternatives. This could explain why the CRM use of this application might be overestimated for some appliances.
- There are significant discrepancies top-down (based on production statistics) and bottom-up (mainly based on global magnet production) estimations of demand for neodymium and dysprosium. In that case, the bottom-up estimation also leads to higher demand figures than the top-down estimates. The explanation for the discrepancy at the global level is, besides uncertainties in product content, the existence of significant unquantified production and trade in rare earths. This affects neodymium but also dysprosium (Glöser-Chahoud, Kühn, and Tercero Espinoza 2016).

8.2.2 DRIVERS FOR CHANGE

8.2.2.1 POLITICAL DRIVERS

- **Countries banning the import of e-waste from EU and developed countries (high certainty, downward trend)**

A strong barrier to the further deployment of recycling is its cost: it is often cheaper not to recycle than to implement recycling for end-of-life products. When legislation forbids the abandoning of waste in landfills for instance, some types of waste are exported to countries willing to recycle them because of existing recycling infrastructure, lower labour costs or different legislation. Having the possibility to send abroad problematic wastes decreases the incentives to recycling. However, in a recent move, China has decided to ban the import of 24 categories of recyclables and solid waste (Cole 2017). This could foster recycling initiatives within EU member states, resulting in a higher proportion of waste being recycled in Europe. As a consequence, the apparent consumption of CRMs would decrease.

- **Political engagement against planned obsolescence and class actions (low certainty, downward trend)**

Planned obsolescence participates to the increase in raw materials demand. Several governments and organisations around the world have undertaken action to fight against this phenomenon. For instance, the French government has recently published a report on legal definition and economic stakes of planned obsolescence (Gouvernement français 2017). Different propositions are made: promote the eco-conception of products, encourage companies to build business models enabling the increase of the lifespan of products, increase the legal warranty duration for some products…

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8.2.2.2 ECONOMIC DRIVERS

- **Roughly constant demand corresponding to renewal of appliances in EU (medium certainty, downward trend)**

As mentioned in the reference scenario, in the case of Europe, population will grow only slightly (Jones and O'Neill 2016). Since the bigger economies in the EU are already developed, it is possible that low GDP growth rates would result in a fairly constant demand for appliances, corresponding roughly to the renewal of existing appliances stock. Therefore, the demand for appliances would be lower than the one calculated in this reference scenario. By way of qualifying that, though, Eastern European countries may grow more strongly in GDP and push towards more demand for appliances.

8.2.2.3 SOCIETAL DRIVERS

- **Growth of the number of appliances in households (high certainty, strong upward trend)**

As mentioned in the hypotheses made to build our reference scenarios for appliances, the main socio-economic drivers for the appliance sales are population & affluence, which are defined by the so called Shared Socio-economic Pathways (or SSPs) (Riahi et al. 2017). This set of scenario specifications was originally developed for climate change research under the Intergovernmental Panel on Climate Change. In particular, the SSP2 baseline was used for the scenarios presented here, this represents a middle-of-the-road scenario in terms of population development as well as in terms of affluence (van Vuuren et al. 2012). In the case of Europe, this means that population will grow only slightly (Jones and O'Neill 2016), so most of the growth in the demand for appliances is attributable to the projected growth in affluence. Roughly, the more affluent a population becomes, the more appliances per households it has. Some appliances have a higher upward trend than others, there is a trend to have more screens in appliances for instance.

- **Individual living (medium certainty, upward trend)**

As mentioned in the studied SSPs (Riahi et al. 2017), there is, to a certain extent, a decreasing trend in the number of person per household in most European countries. Part of this trend can be linked with increasing urban populations. In the case of appliances, smaller households mean more appliances per capita. However, this comment should be moderated by the emergence of the sharing economy, in which less people tend to possess appliances.

8.2.2.4 TECHNOLOGICAL DRIVERS

- **Technological improvement in appliance energy efficiency and technologies for connective appliances (IoT, smart appliances) (high certainty, upward trend)**

As a whole, there are two major technological trends in domestic appliances: the improvement of energy efficiency (including smart grid aspects) and the emergence of connective appliances (smart appliances, linked with the Internet of Things) (Pickett 2018). This may cause an upward trend of CRM demands because of an increased renewal rate linked to a novelty effect (people want to have the newest features) and a higher CRM content for smart, energy-efficient appliances (e.g. Ba, Pd, Ta, Ga since they are components of printed wire boards).

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8.2.2.5 ENVIRONMENTAL DRIVERS

- **Restrictive certifications to assess environmental impact of appliances (medium certainty, low upward trend)**

In many regions of the world, governments try to incentivise appliances which are more respectful to the environment, in particular energy-efficient ones. These appliances may therefore be favoured by consumers, resulting in changes in the CRM demands depending on their specific composition. For instance, the European Commission manages a system of energy labelling for appliances such as washing machines or refrigerators. Depending on their energy consumption, appliances are classified on a scale ranging from A+++ to G (European Commission n.d.). On average, energy-efficient products require more CRMs to improve their performance and limit their energy consumption.

8.2.2.6 LEGAL DRIVERS

- **Implementation of the EU circular economy package (medium certainty, downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future.

In the case of electronic wastes, a directive already provides a framework (European Commission 2012) and further circular economy actions could be expected, requiring the industry to do more to refurbish those products. This would lead to a lower CRM apparent consumption. Besides, the imports of “e-waste” from EU into China have been officially banned since 2000 (EFFACE 2015). While this measure has been circumvented until now, the recent decision of China to ban imports of all plastic waste could reinforce controls and accelerate this trend (Latham & Watkins LLP 2018).Besides, the imports of “e-waste” from EU into China have been officially banned since 2000 (EFFACE 2015).

8.3 DISPLAYS

8.3.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

Flat Panel Displays (FPDs) are a prime example of a technology developed for a few specific markets (mostly laptops and other portable devices) that later found several applications in various markets. The main competitive advantage of FPDs as compared with previous technologies (e.g. cathode ray tubes for TVs) is their reduced weight and volume. This feature, along with gradually reduced costs, helped FPDs to become the dominant technology for TVs, laptops and computer monitors in the 2000s. By the early 2010s, the emergence of other electronic devices such as smartphones and tablets constituted a major trend in FPDs sales (Marscheider-Weidemann et al. 2016).

There are different technologies of FPDs. Two of them were assessed in this study. The first one is the Liquid Crystal Display (LCD), which dominates the FPD market today (Marscheider-Weidemann et al. 2016). Different commercial LCD technologies exist, the main one being the LED-backlit LCD. The other one is the Organic Light-

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Emitting Diodes (OLED), which is commercially available today, although with a lower market share and for niche markets (Marscheider-Weidemann et al. 2016). Plasma Display Panels were investigated but are not detailed in this report, because most manufacturers stopped commercialising them, resulting in low, plummeting market shares. Other emerging technologies, such as Electroluminescent Displays (ELD) or Quantum dot LED (QLED) were not assessed because of high uncertainties in the commercialisation process and lack of quantitative data. However, they should not be overlooked: any significant progress in cost reduction or technological features might result in commercialisation before 2035, thus modifying the market shares of this study.

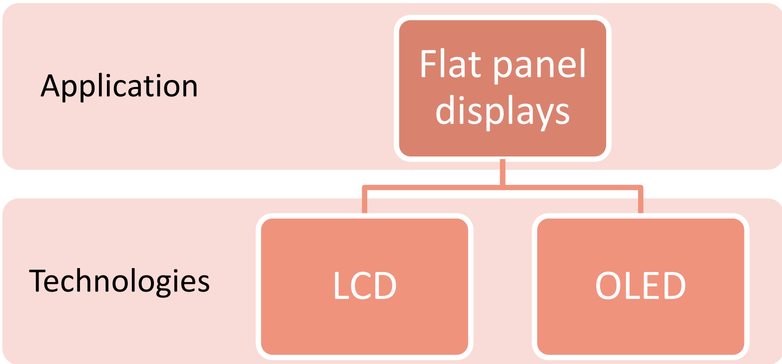

Figure 14 – Flat panel displays technologies

Among the CRMs used in FPDs, two were assessed here: indium and gallium. Indium is primarily used in the form of indium-tin oxide (ITO), which is deposited as a thin film on glass or clear plastic. It functions as a transparent electrode. Gallium is mostly used in the form of GaN-based LEDs (WLED) for LCD backlighting. Some additional indium is present in WLED (3 to 12% of the total amount of In according to our calculations).

In order to calculate the demands for In and Ga used in FPDs, different hypotheses and assumptions were made (Marscheider-Weidemann et al. 2016):

- Market shares and material content were taken from (Marscheider-Weidemann et al. 2016), which foresees that the market domination will gradually shift from LCD to OLED for TVs, monitors, laptops, tablets and smartphones. It also postulates a fixed In & Ga content, depending on the size of the screen (an average size was taken for each device based on (Marscheider-Weidemann et al. 2016)).
- EU data was available for most electronic devices. For TVs, smartphones and laptops, it was assumed that market shares among LCD and OLED were the same as for global sales.
- For Ga, the calculation was a bit different. The market share of WLED – backlit LCDs among all LCDs were taken from (Buchert et al. 2012), as well as the % of In for background illumination vs ITO and the Ga/In ratio in WLED.

Based on recent data for the apparent consumption of these CRMs and historical data for the different displays, for their CRM content and for their annual growth rate, the first indicator (R1) has been evaluated to assess the relative importance of this application. Then, using a prospective scenario on the expected growth rate of each technology and expected CRM content taking into account technological improvement, the second indicator (R2) was calculated to assess the future trend and its significance.

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Table 7 – CRM significance indicators for displays

CRM	Application use in 2015 (t)	EU apparent consumption[1] in 2012 (BIO by Deloitte 2015) (t)	% (R1)	Waste and losses	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
In	14	22	60%	55 (excl. zinc ores[1])	14	60%
Ga	0.5	80	1%	52 (excl. bauxite ores[1])	0	0%

[1]: data from the MSA study. For indium, two flows were excluded from the apparent consumption calculation as they referred to indium embedded in zinc ores extracted in Europe and indium embedded in zinc refinery waste. While these quantities of indium are not properly "consumed", it is worth mentioning their existence (around 100 t) as they could be used to reduce imports and develop a European indium production. For gallium, all quantities not intended for the gallium industry (700+ t of gallium embedded in imported bauxite ores) were excluded.

Even though there may be some uncertainties related to the material flows taken into account (see above comment, demand for indium used in FPDs should constitute a significant part of apparent consumption (indicator R1). This situation would not change in our scenario up until 2035 (indicator R2), which would tend to demonstrate that the increasing adoption of FPDs could remain the main driver of indium supply criticality. The amount of gallium used in this application should remain insignificant, even though the high amount of waste in the material balance suggests that the bottom-up approach used to calculate the "application" use probably underestimates the actual requirements (the 0.5t are derived from end-product gallium content rather than manufacturing input requirements).

8.3.2 DRIVERS FOR CHANGE

Only a few drivers are presented in this section as most drivers impacting Smartphone, laptop & PC still apply to this application. Some of these drivers are recalled hereafter.

8.3.2.1 POLITICAL DRIVERS

- **Countries banning the import of e-waste from EU (high certainty, downward trend)**

The imports of "e-waste" from EU into China have been officially banned since 2000 (EFFACE 2015). While this measure has been circumvented until now, the recent decision of China to ban imports of all plastic waste could reinforce controls and accelerate this trend (Latham & Watkins LLP 2018). The trend toward more recycling initiatives in EU could even go faster if other countries follow the Chinese path, thus limiting the EU apparent consumption of CRM.

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8.3.2.2 ECONOMIC DRIVERS

- **Economics of Zinc (high certainty, variable trend)**

Indium is almost entirely produced as a by-product of Zinc. For now, zinc production is high enough to supply the amount of indium required by the display and PV industries which tend to stabilise indium prices. If indium demand goes beyond the zinc production capacities, the indium prices could increase significantly. This does not only depend EU future demand: should the growth of sales remain limited in EU, overseas demand for displays could drive indium demand beyond production capacities. In turn, the price increase would impact the price of displays sold in EU.

8.3.2.3 SOCIETAL DRIVERS

- **Shift in user experience design toward display interaction (high certainty, upward trend)**

While it used to be limited to TVs, computers, tablets and phones, there is currently a trend to integrate touch screens in appliances. Consumers expect interaction with their appliances. Driven by appliance manufacturers' demand, the sales of display would increase. Although this driver is rather certain, there seems to be an emerging trend toward voice-controlled appliances to (e.g. Amazon Alexia, Google Home…), which could revise the impact of this driver downward.

- **Demand for flexible electronics (low certainty, downward trend)**

ITO has great conductivity and transparency properties, but it has limitations in this regard: ITO are hard to fold. Ongoing research look for potential alternative solutions: for instance, silver nanowires could substitute ITO for foldable touch screen applications, but cost is still a barrier (Materials Today 2016). Besides, the demand for foldable display is still uncertain: should this uncertainty and the substitution barriers be overcome, this could represent a significant downward trend for indium demand in the long term.

8.3.2.4 TECHNOLOGICAL DRIVERS

- **ITO sputtering process efficiency, recycling cost of end-of-life products (medium certainty, downward trend)**

The ITO sputtering process is very inefficient: out of the 100 units of primary indium entering the manufacturing process, only 30 units are successfully deposited (Lokanc, Eggert, and Redlinger 2015). This yield has improved thanks to a closed-loop recycling process: manufacturers can obtain a 55% overall efficiency (Lokanc, Eggert, and Redlinger 2015) but there is still room for significant improvements) could significantly decrease the amount of primary indium necessary to the manufacturing of displays. Similarly, ongoing research improves the recycling of end-of-life products to recover indium and reduce the primary supply needs (Smith 2016). In the future, these two drivers could highly reduce the primary indium needs.

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8.3.2.5 ENVIRONMENTAL DRIVERS

- **EU policies and certifications taking into account environmental impact of electronic manufacturing from the design phase even for imported products (high certainty, downward trend)**

To a certain extent, those policies have been taken into account by the overseas manufacturing industry, resulting in more environmental friendly designs (Lin, Chung, and Wang 2005). Since they are seen as potential barriers to international trade, foreign industries adapt their methods to comply with new regulations. Further environmental constrains in certifications could produce similar effects: in particular, is recyclability constrains are reinforced from the design phase, it could reduce future requirement of primary materials.

8.3.2.6 LEGAL DRIVERS

- **Legal barriers to disposal and incentive measures in favour of reuse, repair and refurbished items (medium certainty, downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future.

In the case of electronic wastes, a directive already provides a framework (European Commission 2012) and further circular economy actions could be expected, requiring the industry to do more to refurbish those products. This would lead to a lower CRM apparent consumption. Besides, the imports of “e-waste” from EU into China have been officially banned since 2000 (EFFACE 2015). While this measure has been circumvented until now, the recent decision of China to ban imports of all plastic waste could reinforce controls and accelerate this trend (Latham & Watkins LLP 2018).

8.4 FIBRE OPTICS

8.4.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

An optical fibre is a flexible and transparent fibre made of glass or plastic. These fibres are bundled together to form the core of a cable. This core is surrounded by a cladding material and a jacket for protection. Such cables are used to transmit information from one place to another by sending pulses of light. Fibre is preferred over electrical cabling when high bandwidth, long distance or immunity to electromagnetic interference are required.

There are different technologies of fibres, which differ mainly by the materials they use. Two main types of fibres exist: glass optical fibres and others. Glass optical fibres are made of silica glass for most applications (other glass fibres, such as fluoride fibres, are used in niche applications and not covered in this study). They can be either multi-mode (large core diameter) or mono-mode (thinner core diameter), resulting in different

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properties (e.g. bandwidth). Non-glass fibres can be polymer optical fibres (mainly used in short-range applications due to a higher attenuation) or multi-component fibres.

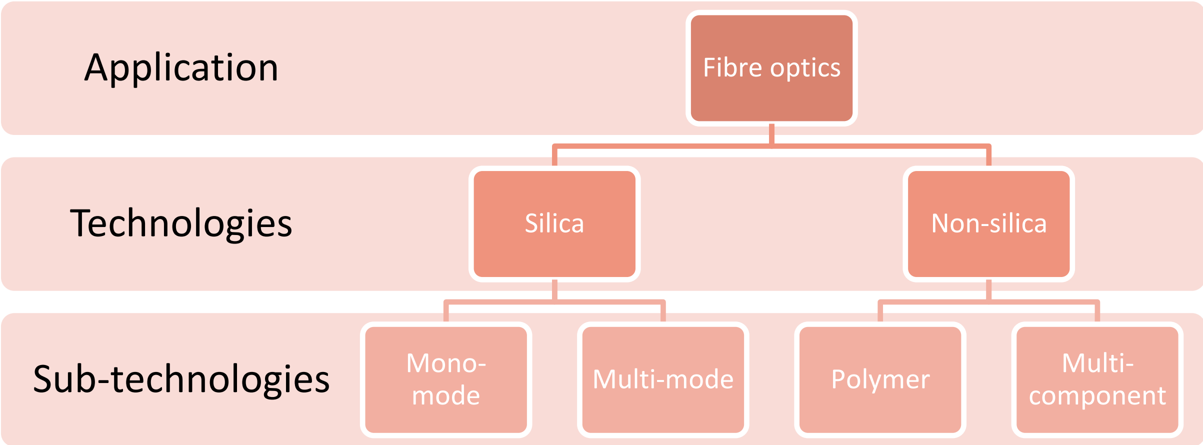

Figure 15 – Optical fibre technologies (only silica incorporates Ge)

Among the different CRMs present in fibre optics, this study concentrates on germanium, of which fibre optics is a significant end-use. Germanium oxide is used as a dopant to silica glass, increasing its refractive index to prevent light absorption and signal loss (Deloitte et al. 2017).

In order to calculate the forecasted demand for Ge in fibre optics, a number of assumptions and simplifications had to be made:

- The only source of germanium is considered to be silica glass. Although there are other glass fibres on the market, silica glass dominates the market for most applications.
- Germanium oxide is assumed to be the only dopant used for silica glass fibres. Although other dopant exist (titanium dioxide, aluminium oxide, rare-earth…), germanium oxide appears to be an industry standard for most applications (Marscheider-Weidemann et al. 2016).
- The unit used for this application was the weight of germanium per length of optical fibre cable (ton/million km). The reference scenario for the global deployment of cables was taken from (Marscheider-Weidemann et al. 2016). It appears inappropriate to give a fixed figure for the Ge content of a km of optical fibre; instead, an average was taken and assumed to be representative.

Based on recent data for the apparent consumption of Ge (total consumption and dedicated use for optics fibre), the first indicator (R1) has been evaluated to assess the relative importance of this application. Then, using a prospective scenario on the expected growth rate of each technology and expected CRM content taking into account technological improvement, the second indicator (R2) was calculated to assess the future trend and its significance.

Table 8 – CRM significance indicators for fibre optics

CRM	Application use[1] (t)	Total apparent consumption[2] (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Ge (global)	60	150	40%	120	80%
Ge (extrapolated for EU)	15	40		30[3]	

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[1] 2015 for the world, extrapolated from R1 and apparent consumption for EU. [2] 2012 for the World and for EU (BIO by Deloitte 2015; Deloitte et al. 2017). [3] extrapolated from R2 for EU.

Unfortunately, no specific EU data has been found for this study. Global data was calculated with the hypotheses and simplifications mentioned above, and EU data was extrapolated conserving the ratio between total EU and global consumption. Besides, even though European countries only represent a small share of the global market, global trends may also impact countries importing primary germanium to export fibre cables (France for instance is the European leader in fibre optics cable manufacturing).

Even though there might be some inconsistency between datasets (2015 vs 2012 data), indicator R1 shows that germanium demand for fibre optics represents about 40% of total EU demand for Ge. The reference scenario used in this study concludes that demand for Ge would approximately double by 2035 (indicator R2), thus representing a significant proportion as compared with today's figures. This is mainly due to the deployment of optical fibre cables around the world, linked with the strong demand for increased bandwidth. The deployment of such cables would therefore constitute a major trend for germanium demand.

Finally, it should be born in mind that analysing the demand of germanium is also complicated by the fact that in a high amount of Ge is left as waste in landfills and tailings, and by the significant amount of Ge recycled in Europe. Indeed, the annual apparent EU consumption (40 t) includes a high amount of waste (30 t) compared to the amount of germanium exported (around 40 t) and the total supply of 95 t (incl. 15 t of recycled material) (BIO by Deloitte 2015).

8.4.2 DRIVERS FOR CHANGE

8.4.2.1 POLITICAL DRIVERS

- **Cyber-security threats related to submarine cables (medium certainty, variable trend)**

99% of current transoceanic traffic uses fibre optics cables rather than satellite communications as they remain a cheaper solution (even though a transoceanic cable can easily cost several hundred million dollars). Fibre optics cables are concerned by two serious vulnerabilities. The first one deals with surveillance programs of national security agency (Timberg 2013). The privacy of transoceanic communications can be compromised by these programs. Besides, there is a threat of attacks on submarine cables (Barker 2018): if several cables get cut at the same time, the web traffic of whole countries could be heavily congested. Those threats could either lower the demand for new submarine cables if alternative solutions become cheaper, but it could also foster the deployment of new cables if cheap solutions using fibre optics are found (e.g. in the case on surveillance: encryption of sensitive data which increases the necessary bandwidth).

8.4.2.2 ECONOMIC DRIVERS

- **Emerging middle class especially in rapidly growing Asian and Latin American countries (high certainty, high upward trend)**

As mentioned for smartphones and connected devices, there are strong social drivers driving the development of social network activities, the growth of on-line/on-app purchases, and on-demand services. Besides, new smaller connected devices (IoT) will produce a very large amount of data in the coming decades: 20 billion of

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connected things are expected by 2020 (Hung 2017). New broadband communication capacities will therefore be required, mostly in fast developing countries. This should impact countries importing fibre cable, including European countries even though they only represent a small share of the global market. It should also impact countries importing primary germanium to export fibre cables (France for instance is the European leader in fibre optics cable manufacturing).

8.4.2.3 SOCIETAL DRIVERS

- **Digital content of higher quality (sound, video) and new ways to access it and higher expectations on content availability (high certainty, upward trend)**

This driver refers to the content that is available: as the quality/definition of the content gets higher, it requires more bandwidth. Besides, as stressed before, the development of on-demand services, IoT, and cloud storage/cloud computing has dramatically increased the amount of data processed remotely. This is evidenced by the fact that the storage capacity of notebooks and PCs remains roughly constant. As these services become more popular, people tend to use them more intensively and require a higher quality of service. The consequence is that higher bandwidth is necessary and fibre optics become the only option. This does not necessarily mean that cable sales will increase as much as web traffic: fibre optics networks are long lasting and provide outstanding capacities everywhere it has already been deployed which is why most demand growth is expected in developing countries.

8.4.2.4 TECHNOLOGICAL DRIVERS

- **Continual improvement of fibre optics (high certainty, downward trend)**

There are continuous R&D efforts improving the fibre capacities, i.e. the ability to send more data using the same amount of fibre: in particular, multiplexing technologies helped to multiply the capacity of current fibre optics by 100 (wavelength division multiplexing) to 1,000 times (time division multiplexing) (Mizuno and Miyamoto 2017). Multiplexing does not require more raw materials and the current trend is to multiply capacities 10 every 4 years which fully benefits to material efficiency (Richardson 2016).

9 TRANSPORT SECTOR

9.1 ELECTRIC VEHICLES

9.1.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

Because of overall concerns about the supply of certain materials, this study aims to assess whether the widespread deployment of electric vehicles in the EU could be hindered by the potentially insecure supply of materials along their supply chain. We focus here on two key components:

- ***Rechargeable batteries***, which allow on-board storage of electrical power from the grid and releasing it when requested. Among the options in terms of rechargeable batteries, lithium-ion batteries (LIB) are expected to dominate the market for EV in medium to long-term. LIB can employ as cathode different chemistries such as LCO (lithium-cobalt-oxide), NMC (nickel-manganese-cobalt), LMO

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(lithium, manganese, phosphate) or LFP (lithium-iron-phosphate), with performances suited to different applications. Natural graphite is the reference anode material for LIB. The following materials will be thus analysed: lithium, cobalt and graphite. Other CRMs involved in LIBs (e.g. phosphate) are not assessed because the quantities involved are lower compared to C, Co and Li (Battery University n.d.);

- ***Electric traction motors*** are used for the propulsion of electric vehicles. The majority of traction motors use high-performance rare-earth magnets which contain neodymium, praseodymium and dysprosium.

Besides, there is a large diversity of electric powertrains available on the market. We will focus here on:

- Hybrid Electric Vehicles (HEV): combine an internal combustion engine (ICE) and one or more electric motors;
- Plug-in Hybrid Electric Vehicles (PHEV): include rechargeable batteries that can be plugged into an external electric power source for charging; they also have ICE to extend the range of vehicles;
- Battery Electric Vehicles (BEV): run exclusively with one or more electric motors; they are powered by a rechargeable battery, thus using energy stored in the grid.

The different technologies and sub-technologies considered in this study are shown below. The different commercial models for HEV are studied in detail because we cannot assess the input parameters of the model using mean values, as is done for PHEV and BEV, because of different LIB penetration rates, as will be explained in the next sub-section. Fuel-cell electric vehicles are not included in this study.

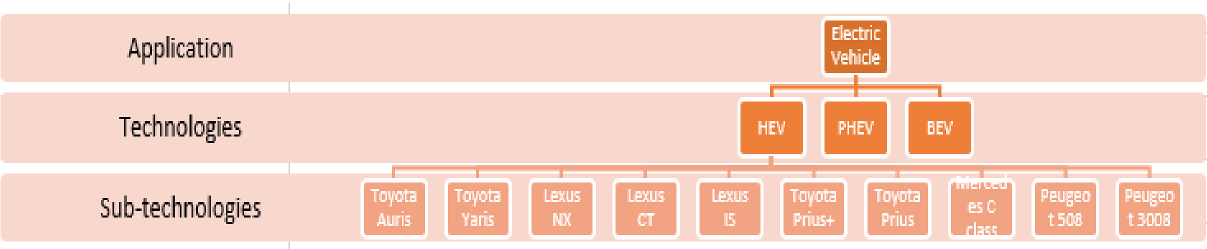

Figure 16 – Electric & Hybrid vehicles technologies. HEV are split according to different commercial models to account for different LIB penetration rates. PHEV and BEV are assessed using mean values

Several assumptions are made in (Blagoeva et al. 2016) and recalled hereafter:

- For HEV, two assumptions are made:
  - It is assumed that the 2015 market shares between the existing commercial models will remain the same: no constructor will really dominate the market. This hypothesis can be debated: the market may consolidate, some constructors may acquire a bigger market share, others may disappear. But since no forecast of market shares within HEV models was available, we stuck to this assumption;
  - The vast majority of constructors would eventually adopt LIBs. The current situation is that most constructors of HEV use NiMH batteries. The report assumes that all of them will switch to LIB, mainly because of increased performances (autonomy, weight…) and cost reductions, but not at the same rhythm;
- For PHEV and BEV, two assumptions are made:

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- An average material content per model is used, based on 2015 data. In detail, the report gives an average CRM tonnage/kWh of battery (depending on the type of chemistry for the LIB, with some not including Co), and an average battery capacity for PHEV and BEV;
- Material content is assumed to be constant: no technological improvements and/or substitution efforts. This is arguable: if some CRMs used in LIB were to come short of supply, it is sure that tremendous efforts would be done in the field of substitution for instance. We stuck to this assumption because no information on this topic was available.

Table 9 – CRM significance indicators for electric vehicles

CRM	Application use in 2015 (t)	EU apparent consumption[1] (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Nd	48	1,000	5%	2,500	250%
Pr	16	230	7%	800	350%
Dy	16	180	8%	800	420%
Co	620	13,000	5%	29,500	230%
C	2,340	80,900	3%	118,500	150%
Li	830	26,100	3%	35,600	140%

[1] average from 2010 to 2014 for praseodymium (Deloitte et al. 2017), 2012 for cobalt and natural graphite, 2013 for neodymium and dysprosium (BIO by Deloitte 2015), and 2012 for lithium which is currently not considered as a critical raw material (BIO by Deloitte 2015).

Therefore, this reference scenario predicts that the CRM demands for LIB batteries would increase dramatically. In 2015, CRM demands are calculated to be a small fraction of EU demands for these CRMs (indicator R1). In 2035, demands are forecasted to exceed the current EU consumption for all of them, with the most exceeding values coming from REEs and cobalt.

This is related to the high annual sales increases and to constant material content. The latter can be criticized: there are always, to some extent at least, technological improvements, and there could also probably be substitution efforts, provided some incentives are given (high prices for Li for instance). This would lead to a decrease in CRM tons used per kWh. On the other hand, a possible increase in battery sizes to gain more autonomy could counter the improved material efficiency (not necessarily the case: if HEV win huge market shares, light hybridation would only require small batteries, and could be sold at a cheaper price).

Finally, it should be born in mind that analysing the demand of some CRMs is complicated by high amounts of waste in landfills and tailings, and high recycling rates. For instance, the annual apparent EU consumption of cobalt (13 kt) includes a high amount of waste (9 kt) compared to the total supply of 30 kt (incl. 6 kt of recycled material) (BIO by Deloitte 2015). The waste and losses of natural graphite accounted in the EU apparent consumption (80 kt) are also very high (70 kt).

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9.1.2 DRIVERS FOR CHANGE

9.1.2.1 POLITICAL DRIVERS

- **European and national policies to accelerate the deployment of fast charging infrastructures (high certainty, strong upward trend)**

Charging infrastructure is indispensable for the deployment of a large fleet of electric vehicles in the EU. Even though most buyers would recharge their vehicles at home, and vehicles tend to have increased ranges, drivers need to be reassured they will find charging stations at publicly-accessible locations. This include charging stations distributed along the main road networks, and not only in large urban areas. Amongst the proposals of the 2nd Clean Mobility Package were an action plan and investment solutions for the trans-European deployment of Alternative Fuels Infrastructure (AFI) to enhance the deployment of alternatively fuelled vehicles. Member States (MS) were required to notify the Commission by 18/11/2016 on their strategy for deployment of AFI in their National Policy Frameworks (NPF). An analysis (Platform for electro-mobility 2018) of these plans was carried out, and recommendations include that countries should have about one charging point for 10 to 15 EVs.

- **EU & national policies to cut GHG emissions in the transport sector (high certainty, upward trend)**

Transport represents almost a quarter of Europe's GHG emissions (not mentioning air pollution). Contrary to other sectors, emissions started to decline only after 2007. Europe's objective for 2050 is to reduce GHG emissions in the transport sector by at least 60% compared with 1990 levels. The Commission identifies 3 priorities (European Commission 2016):

- Increasing the efficiency of the transport system.
- Speeding up the deployment of low-emissions alternative energy for transport.
- Moving towards zero-emission vehicles.

9.1.2.2 ECONOMIC DRIVERS

- **Cost of raw materials in Li-Ion batteries (medium certainty, strong variable trend)**

In order to ensure a minimum range for HEVs and BEVs, expensive batteries are needed: this explains their current high prices, which limit their adoption. Therefore, a significant decrease in the cost of batteries would foster the massive adoption of HEVs and BEVs. An article on cost projection for batteries (Gert Berckmans et al. 2017) forecasts a strong downward trend for the cost of lithium batteries, driven partly by falling material costs. Wider adoption of BEV will drive down costs. Considering two technologies (NMC and silicon-based lithium-ion batteries), the article calculates that the 100$/kWh limit would be reached in 2020-2025 for silicon-based batteries and in 2025-2030 fir NMC batteries. Such low prices for batteries are likely to drive upwards the demand for EVs, and thus the demand for batteries. However, possible tensions on Co, C or Li markets, resulting in increasing or volatile raw materials prices, could have the opposite effect: carmakers would not be able to sell cars at lower prices, and EVs would remain a niche product.

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9.1.2.3 SOCIETAL DRIVERS

- **Expansion of residential power generation and incentives for domestic energy storage (low certainty, upward trend)**

Strong synergies could be found between the deployment of electric vehicles and the emergence of residential energy storage (linked with power self-consumption): EV batteries could work as auxiliary domestic energy storage solutions. The car battery could be charged during the night (wind turbine) at home or during the day at work (PV). This could benefit EV users by providing sources of revenues which could balance the higher cost of EVs (by reducing consumption from the grid, or by selling energy to utilities in countries where a legal premium tariff has been set). There are ongoing projects testing this 'vehicle to grid' (V2G) possibility (e.g. in TU Delft with a fuel cell electric vehicle (Poorte 2017)), but scaling-up has yet to take place.

9.1.2.4 TECHNOLOGICAL DRIVERS

- **Technological improvements in batteries, material efficiency and substitution (high certainty, variable trend)**

Technological features of batteries will have a crucial importance regarding mass adoption of EVs. Range, weight and price/kWh are some key characteristics which will determine the future success of EVs. Current R&D aims at optimising battery composition in order to reduce its cost and facilitate the deployment of lithium-ion batteries for electric vehicles. According to a prospective Dutch study (Gert Berckmans et al. 2017), two competing battery types could emerge as market leaders for Li-Ion batteries: lithium Nickel Manganese Cobalt oxide (NMC), and silicon-based Li-Ion battery These two technologies would see their costs (especially material costs) decrease significantly over time, as EVs become more and more widespread. Both of them use a variety of CRMs and could therefore have a strong impact on their demands in such a growing market. However, there is still a high uncertainty on which technologies will be on the market in 2035 and what their CRM contents would be like. If a gradual increase in material efficiency is perhaps likely, it is not sure whether the same CRMs will remain in future battery technologies, resulting in variable trends depending on the composition of the future main market players. A potential rebound effect is not to be overlooked either (more efficient batteries, but more battery capacity in each car to increase its range and/or performances).

9.1.2.5 ENVIRONMENTAL DRIVERS

- **European threshold for particulate matters and policies to ban ICE vehicles from city centres (high certainty, upward trend)**

A large set of policy measures and instruments have been adopted at EU level, national level and inside urban areas in order to cut down air pollution and CO_2 emissions. Objectives in terms of CO_2 emission reduction were presented in the second political driver. Regarding air pollution, EU has produced a number of directives on this topic (European Commission 2018e), many EU countries have initiated specific actions (e.g. subsidies on price; scrappage schemes for ICE vehicles, etc) and several European cities are pursuing policies against ICE vehicles (8 cities among the most active in this domain are European (Garfield 2018)). These actions are expected to drive down the sales of ICE vehicles in the future, thus fostering their gradual replacement by hybrid and electric vehicles.

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9.1.2.6 LEGAL DRIVERS

- **Implementation of the EU circular economy package (medium certainty, downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future. In the case of batteries, a directive already provides a framework (European Commission 2006) and further circular economy actions could be expected, requiring the industry to do more to recycle batteries. This would lead to a lower CRM apparent consumption even though recycling lithium batteries remains uneconomic in the short term (McCormick 2016).

9.2 JET ENGINES

9.2.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

Jet engines are engines that move an aircraft forward by sending hot air and gases under pressure out behind it. Although they are also used in high speed cars and cruise missiles for instance, the main users of jet engines are jet aircrafts. This study focuses on the demand for CRMs in jet engines used in aircrafts. The demand includes both the replacement of the existing aircraft fleet and the forecast growth in fleet sizes, as described in the chart below.

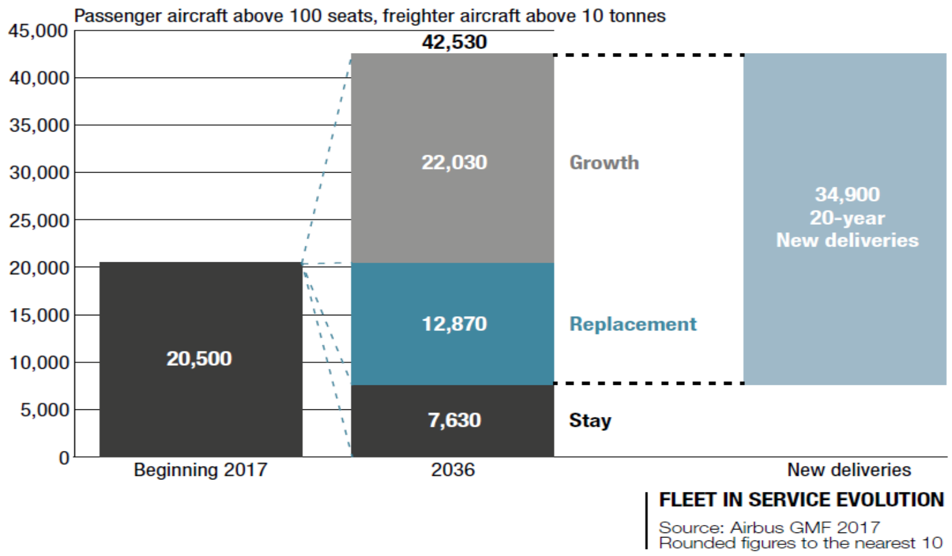

Figure 17 – Forecasted evolution of global aircraft fleet

For the evolution of the fleet, some hypotheses were made:

- Increase in plane fleet is calculated for 2018-2035 by using a compound annual growth rate (CAGR), based on Airbus data (Airbus 2017).
- However, additional new planes will be needed to replace those retired; Airbus estimations were used for the replacement of the existing fleet (Airbus 2017).

- Each aircraft will have 2 or 4 engines, with the majority at 2: an average of 2.12 engines per plane is taken based on Flightglobal Ascent Online Fleets database (Flightglobal 2015).

There are approximately 12 manufacturers of jet engines globally, although the majority (96%) of engines in service are made by 5 companies (CFM International; General Electric, Rolls Royce, Pratt & Whitney, International Aero Engines). However, there are approximately 35 different jet engine types in use globally and this number does not include different *variants* of these types. In addition, there are a very large number of different alloys that can be used for the various components within the engines. Each individual alloy specification contains a slightly different weight percentage of a range of metals, both those which are listed as 'critical' and those which are not. In some cases, the description of metal content of an alloy gives a minimum and maximum for a particular element rather than an exact weight percentage. Furthermore, material specifications for individual engine types are confidential to each manufacturer, which is understandable in this highly competitive market. **Consequently, it is not possible to be entirely accurate when considering metal contents of jet engines.**

To simplify the task, several assumptions were made:

- All the engines types use similar quantities of materials even though there are very distinct design differences, as well as a range of sizes (and hence weights) of engine (the Rolls Royce Trent 800 was used as the 'typical' engine).
- Only a relatively small number of alloys are used in the engines (nine in this example) and the 'recipes' of these alloys remain the same over time.
- Specific named alloys were assigned to particular components based on descriptions of properties.

The number and approximate dimensions of certain key components were obtained from personal communication with Mr J Logan (an Aerospace Engineer), while names of alloys, metal content and densities were obtained through a literature review (Mukai, Li, and Fang 2004; Davis 1997; Muktinutalapati 2011; Supra Alloys n.d.; AZO Materials 2002, 2008; MatWeb 2018; ASM Aerospace Specification Metals Inc. n.d.).

Even relatively small adjustments to the alloys used for different components of a jet engine could make a significant change to the CRM contents.

Having the aircraft deployment scenario and CRM contents, CRM demands forecasts can be calculated. The following chart summarises the results:

Table 10 – CRM significance indicators for jet engines

CRM	Application use in 2018 (t)	EU apparent consumption[1] (t)	% (R1)	Waste and losses	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
V	130	71,000	0%	NA	730	1%
Si	1	582,000	0%	360,000	5	0%
Nb	60	10,400	1%	2,100	350	3%
Co	10	13,000	0%	9,000	80	1%
W	10	13,400	0%	10,600	80	1%
Ta	3	100	3%	NA	15	15%
Hf	30	33,000	0%	NA	180	1%
B	0.2	74,000	0%	80,000	1	0%

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[1] 2012 for silicon, niobium, boron, tungsten and cobalt (BIO by Deloitte 2015), 2017 for tantalum (approximate), and average from 2010 to 2014 for hafnium (Deloitte et al. 2017).

Indicator R1 shows that, although there are 8 CRMs used for jet engines production, none of them has a demand representing more than a few percent of EU apparent consumption. Even though CRM demands for jet engines are forecasted to grow in this reference scenario, only Ta demand could become significant as compared with current use (indicator R2). This tends to indicate that, even though a constant material content was used, the growth in aircraft fleet (and its refurbishment) would not constitute a major trend for any of the involved CRMs, with the possible exception of tantalum used in superalloys.

However, there may be additional sources of uncertainties for some of these CRMs (apart from the assumptions and simplification already mentioned). As a matter of fact, Co, W and B all have in common a relatively high amount of material stored as waste in landfills and tailings. This amount could explain some difference between the apparent consumption (import + extraction minus export) and the actual demand for industrial use (estimated based on end product CRM content). In addition, Co and W both have a neutral import/export balance and a relatively high recycling rate, which could account for significant differences between our numbers and other studies if these materials flows are not taken into account.

9.2.2 DRIVERS FOR CHANGE

9.2.2.1 POLITICAL DRIVERS

- **Potential new Chinese competitor among civil airplane manufacturers (low certainty – low variable trend)**

The civil aircraft market is largely consolidated. Airbus and Boeing are the two main manufacturers, with other significant ones being Embraer and Bombardier. However, a Chinese newcomer intends to disrupt the market: COMAC. While it has only one regional plane commercialised and another on plan for 2021, COMAC has announced that it will choose the LEAP (Leading Edge Aviation Propulsion) engine, designed by CFM International (a 50/50 joint-venture between GE Aviation and Safran Aircraft Engines) for its newest model (Trimble 2018), potentially driving upward the industrial demand in EU (Safran assembles LEAP in France). On the contrary, if these new manufacturers produce their engines locally, this might have a downward effect on CRM demands for the EU. However, since the market is still largely dominated by the previously mentioned companies, the impact within a time horizon of 2035 seems to be limited.

9.2.2.2 ECONOMIC DRIVERS

- **Economic growth and increase in consumer spending (high certainty – strong upward trend)**

The emergence of a middle-class in developing countries with vast populations, such as China or India, will have an impact on the total number of air passengers. As mentioned in a prospective study from the IATA ('IATA - 2036 Forecast Reveals Air Passengers Will Nearly Double to 7.8 Billion' 2017), by 2036, China will be the first country in terms of passenger numbers, while India will become third. This will strongly impact the global demand for aircraft, and consequently the components manufactured in Europe.

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- **Low air fares (high certainty, upward trend)**

Within Europe, the emergence of several low-cost companies, especially on short-distance flights (Ryanair, EasyJet…) has driven the air fares down. By making air transport more accessible to the middle class, this fall in costs constitutes a strong trend towards more air travellers within Europe. Such low-cost companies have helped in the raise in leisure trips in the EU but are also gaining market shares among business travellers.

9.2.2.3 SOCIETAL DRIVERS

- **Growth of air passenger traffic and demand rise from developing countries (high certainty – strong upward trend)**

Starting from 4 billion passengers in 2017, the international air passenger traffic is expected to grow and reach 7.8 billion passengers in 2036, according to a recent study by the International Air Transport Association (IATA) ('IATA - 2036 Forecast Reveals Air Passengers Will Nearly Double to 7.8 Billion' 2017). The biggest driver will be the Asia-Pacific region, with more than half the new passengers over the next two decades. China would surpass the US in 2022. This strong growth will have a tremendous impact on CRM demands for jet engines.

9.2.2.4 TECHNOLOGICAL DRIVERS

- **Development of alternative high-speed transportation modes (high-speed trains, hyperloop…) (medium certainty, slight downward trend)**

Air transportation has very few competitors. On short to medium-distance trips, high-speed trains could constitute an alternative means of transport. For instance, China has developed recently the largest high-speed rail system in the world over a relatively short period of time, with further lines under construction. In this country, high-speed trains are increasingly viewed as a threat for domestic airlines, due to an efficient rail network compared to crowded airport hubs, more likely to cause delays (He 2017). Airline companies are gradually concentrating their offer on international destinations. As important as this trend may seem (especially in such a growing market as China), high-speed rail is scarcely developed around the world, and few projects are in construction, so the trend is likely to remain low.

Other competitors could arise from transportation systems such as the hyperloop. However, such systems are still in test periods, far from the market. In addition, they might rely themselves on CRMs…

- **Substitution of superalloys (medium certainty, strong downward trend)**

One important trend in the materials used for gas turbines in jet engines is the potential replacement of superalloys by new materials. Prime candidates are ceramic-matrix composites. As a matter of fact, their properties – low density, high strength and toughness, high-temperature capabilities – make them good candidates to replace superalloys, as they could bring reduced weight and enhanced lifetime for gas turbines (Zok 2016). CFM LEAP engines have started incorporating ceramics. Technological competition between superalloys and ceramics could impact downwards the future demand for superalloys in jet engines. However, it is important to bear in mind that these ceramics might also incorporate CRMs (Si for instance).

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9.2.2.5 ENVIRONMENTAL DRIVERS

- **GHG emissions reduction and air quality concerns (medium certainty, downward trend)**

Within the EU, the transport sector is committed to reduce it GHG emissions of 60% by 2030 compared to 1990 levels. This commitment has been backed with a series of measures, such as the inclusion of the aviation sector in the EU Emission Trading System and the development of an aircraft CO_2 standard (European Aviation Safety Agency, European Union, and European Environment Agency 2016). Regarding air pollution, two important pollutants in the aviation sector are nitrogen oxides and particulate matter. Binding national limits for emissions of the most important pollutants have also been established in the EU, but not all aviation activities are included. In addition, there are increasing concerns about aircraft trails which may increase the contribution of air traffic to global warming (Barnett 2008).

9.2.2.6 LEGAL DRIVERS

- **Implementation of the EU circular economy package (medium certainty, downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future.

Jet engines falls within the framework of the EU directive on end-of-life vehicles (European Commission 2000). Significant experience gained in the aerospace industry has led to very high recycling rate: up to 99% for jet engines components (Chandler 2013) and usually more than 80% for the whole aircraft (European Commission 2011). Further recycling seems hard to achieve but transfer of recycling technologies from this industry to other applications using the same CRM or similar alloys could be envisaged: significant improvements would be needed for tantalum (the current EU recycling rate is only 1% (European Commission 2018b)) for instance, and even for the most recycled CRM in EU (vanadium and tungsten recycling rates hardly exceed 40% (European Commission 2018b)).

9.3 AUTOCATALYSTS

9.3.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

Platinum-group metals (PGMs) are used in autocatalysts to control the emission of hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx). These so-called three-way catalysts use a mixture of some or all of three PGM, platinum (Pt), palladium (Pd) and rhodium (Rh), the latter in lesser quantities.

This analysis is restricted to passenger car production in the EU (excluding commercial vehicles). All cars produced in the EU were classified according to their powertrains, with two main categories: cars using an internal combustion engine (ICE) and others. The ICE group was subdivided into petrol-powered cars and diesel-powered cars (different PGM content). The non-ICE group includes electrically chargeable vehicles (battery electric vehicles (BEVs) and extended-range electric vehicles (EREVs)), plug-in hybrid vehicles (PHEVs), full and mild hybrid electric vehicle (HEVs) and fuel cell electric vehicle (FCEVs). Together, they are referred to

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as alternative fuel vehicle (AFVs). Market shares in the EU for some AFV classes are currently very small and largely unquantified, and future market penetration in the EU is highly uncertain.

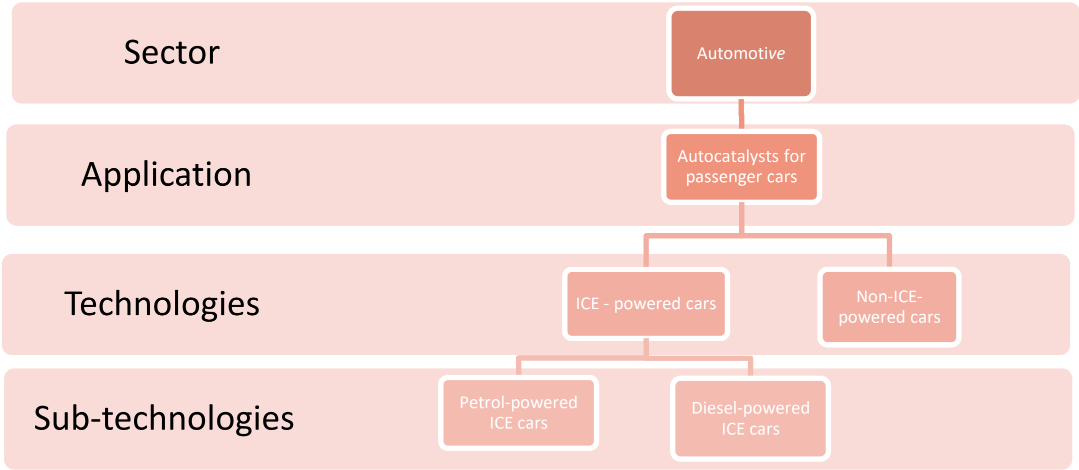

Figure 18 – Classification of cars used in this study

For this application, car production data are used rather than vehicle sales or registrations because they reflect the actual consumption of CRMs in the EU. Data for sales/registrations will include vehicles imported to the EU which are not relevant to EU consumption. EU production data include some cars produced within the EU but exported for sale outside the EU.

For the production scenario, an annual growth rate of 0.8% was taken (LMC AUTOMOTIVE 2018), starting with 2016 data from ACEA (ACEA 2018), although such rate has varied over the past years. Numerous drivers will influence the future level of car production within the EU, the breakdown by powertrain type and the consequent demand for PGM. The relative importance of these is likely to vary considerably in time and space, but quantifying this variation is associated with very high levels of uncertainty.

Regarding market shares and CRM contents, various hypotheses were made:

- EU production data for cars by powertrain type derived from Eurostat PRODCOM database (Eurostat 2018a).
- Given the wide variation in the make-up of autocatalysts used by individual manufacturers across their vehicle range and likely future changes to the amount and relative proportions of PGM used, it is challenging to quantify future changes in demand either for all three PGM together or individually. Accordingly, in this analysis it has been assumed that the total PGM loading in an autocatalyst will remain constant. For a petrol-powered vehicle this has been taken as 2.5 g PGM, while for a diesel system 7.5 g PGM per vehicle has been used (International PGMs Association, n.d.). No attempt has been made to break this down into demand for the individual PGM in question (Pt, Pd and Rh).
- In Alternative Fuel Vehicles (AFVs) it is assumed that autocatalysts are used only in hybrid powertrains. A small share of the market is taken by diesel-hybrids, with petrol-hybrids dominant. This division of market share is expected to continue, although the proportion taken by petrol-hybrids could increase further as sentiment against diesel hardens further. It is assumed that battery electric vehicles (BEV) and other forms of AFV do not use autocatalysts. It should be noted, however, that fuel cell technologies currently used in Fuel Cell Vehicles (FCV) actually use PGM, chiefly platinum, as a catalyst. FCVs currently have a very small share of the global car market (a few thousand units per

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annum) and are not taken into account in this analysis. The future market share of FCVs is highly uncertain and will depend essentially on the balance between a range of technical, economic and environmental factors relative to other powertrains.

- There is considerable geographical variation in the current market shares of BEV and Plug-in Hybrid Electric Vehicles (PHEV). In some countries, such as China, Norway, France and Japan, BEV dominate the AFV market, while elsewhere, for example in UK, Germany, Sweden and the Netherlands, PHEV are dominant (Eurostat 2018a). No data were found which provided a breakdown of EU production of AFVs by type. Accordingly, for the purposes of this analysis EU production is assumed to be 50% BEV and 50% PHEV. Further, in the absence of any data to the contrary, this ratio has been assumed to remain constant to 2035.

The main results are given in this chart. It should be noted that the two main PGMs involved are platinum and palladium.

Table 11 – CRM significance indicators for autocatalysts

CRM	Application use in 2015 (t)	EU apparent consumption in 2015 (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
All PGM	80[1]	120	66%	30[1]	25%

[1] Only includes vehicles manufactured in EU (derived from (International Platinium group metals Association 2015; Eurostat 2018a; ACEA 2018)). Including imported cars in 2015, the amount of PGM in autocatalysts exceeds 100 t (incl. 50 t of palladium and 50 t of platinum) (Deloitte et al. 2017).

Contrary to many other end-uses studied within this task, the demand for PGMs in autocatalysts is forecasted to decrease in our scenario: from 66% of total demand in 2015 (R1) to a mere 25% vs current use in 2035 (R2). Despite a 0.8% growth rate for all cars production, the assumption that petrol and diesel cars will see their market share decrease, associated with a constant PGM content, provokes such a decrease in demand. Therefore, within this scenario, although still significant, demand for PGMs would not contribute to increase the total EU demand for PGMs in the future.

However, it should be noted that such a forecast is subject to high uncertainties. We already mentioned the various hypotheses, assumptions and simplifications used to elaborate this reference scenario. But in addition, platinum group metals have some characteristics which add sources of uncertainties to our figures: they have a neutral import/export balance and a relatively high recycling rate. If these materials flows are not taken carefully into account with relevant data, it might explain (part of) the difference between our figures and results from other studies.

9.3.2 DRIVERS FOR CHANGE

Only a few drivers are presented in this section as most drivers from the Electric Vehicles attend to the same application, often with opposite effects: most drivers increasing the demand for electric vehicles drives down the demand for autocatalysts. Yet, some drivers affect both applications the same way: those related to road mobility in general. Most important drivers from these two categories are recalled hereafter.

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9.3.2.1 POLITICAL DRIVERS

- **Urban, national and EU policies on air pollution, emissions reduction and promotion of non-ICE cars (high certainty, variable trend)**

There are policy measures to cut down air pollution and CO_2 emissions at both EU, national and urban levels. Objectives in terms of CO_2emission reduction were presented in the electric vehicle application. Regarding air pollution, EU has produced a number of directives on this topic (European Commission 2018e), many EU countries have initiated specific actions (e.g. subsidies on price; scrappage schemes for ICE vehicles, etc) and several European cities are pursuing policies against ICE vehicles (8 cities among the most active in this domain are European (Garfield 2018)). While these actions are expected to drive down the sales of ICE vehicles in the future, which would reduce the CRM necessary for autocatalysts, they can also have an opposite consequence: as some policy measures impose pollutant emission limit values, car manufacturers may tend to increase the CRM content of autocatalysts to reduce the emissions of new ICE vehicles.

9.3.2.2 ECONOMIC DRIVERS

- **Decreasing cost of non-ICE vehicles (high certainty, strong downward trend)**

Most studies if not all predict that the cost of electric vehicles will keep decreasing in the coming decades, mainly due to battery improvement (both on economics and technical performances) (Robson and Bonomi 2018; Farrell and Weinmann 2017). Some say they will be competitive against ICE vehicles in 2018, or in the mid-2020 (Farrell and Weinmann 2017; Campbell 2017). As non-ICE vehicles become competitive, the demand for autocatalysts will slow. Thus, demand for PGM should follow the same trend, even though the demand of other CRM could rise with the adoption of non-ICE vehicles (see § Most studies if not all predict that the cost of electric vehicles will keep decreasing in the coming decades, mainly due to battery improvement (both on economics and technical performances) (Robson and Bonomi 2018; Farrell and Weinmann 2017). Some say they will be competitive against ICE vehicles in 2018, or in the mid-2020 (Farrell and Weinmann 2017; Campbell 2017). As non-ICE vehicles become competitive, the demand for autocatalysts will slow. Thus, demand for PGM should follow the same trend, even though the demand of other CRM could rise with the adoption of non-ICE vehicles (see § 9.1).

9.3.2.3 SOCIETAL DRIVERS

- **Changing use patterns and ownership models for cars: growth of mobility as a service (high certainty, downward trend)**

The emergence of digital platforms offering mobility services has diversified companies' and individuals' transportation options. While the adoption of these services makes no doubt, it is uncertain whether there will be a clear shift from the vehicle ownership model to Mobility-as-a-Service (MaaS) or nor. Such transition would slow the renewal rate of all types of vehicles and thus reduce the CRM requirement for autocatalysts: some studies estimate that for every car offering ride-sharing 5 to 15 individual cars would be replaced (Transport & Environment 2017; NRMA 2017). Other studies temper this trend showing that young people still strive for car ownership, in Germany for instance (McKinsey&Company 2012). Besides, in some cases, car sharing services rather compete with collective transportation like rail than with individual cars.

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9.3.2.4 TECHNOLOGICAL DRIVERS

- **Increasing efficiency and cleanliness of ICE powertrains (high certainty, upward trend)**

Over the last decades, the CRM content of catalysts in individual cars seems to have increased (Murray 2011). Besides, from the late 1990s to the late 2000s, the total consumption of PGM for this application doubled (Murray 2011). While global car production hardly rose by 10 million units over this period (less than 10% of annual production), two factors can explain this trend:

- The PGM content of catalysts rose to increase the efficiency and cleanliness of vehicles
- The size of vehicles increased and the PGM content of autocatalysts rose consequently to maintain an equivalent efficiency and cleanliness performance.

The main consequence of further improved cleanliness standard in the future would then be a higher PGM requirement for this application. This could also improve the image of ICE cars and increase the demand for clean ICE vehicles, but on the other hand this higher CRM content would certainly make them less affordable.

9.3.2.5 ENVIRONMENTAL DRIVERS

- **Replacement of ICE cars by non-ICE on grounds of environmental performance and “dirty” image of ICE vehicles (high certainty, downward trend)**

As described in previous drivers, some political measures may accelerate the uptake of non-ICE over ICE cars (e.g. ban of ICE vehicles in city centres). The uptake of electric vehicles is also fostered by consumer preferences: all studies reviewed in this paper report that environmental awareness has a significant positive impact on EV preference (Liao, Molin, and Wee 2017).

9.3.2.6 LEGAL DRIVERS

- **Increasingly strict emission control legislation (high certainty, downward trend)**

It is rather certain that emission control standards will remain restrictive in the EU (Institute for European Environmental Policy 2016). They could even get more restrictive, especially in urban areas where health issues add up to GHG concerns. Yet, the short-term impact of this policy on PGM demand for autocatalysts is uncertain. Indeed, this driver may increase the PGM content of catalysts in the short term (thus limiting pollutant emissions). Even if ICE car sales remain constant, this would increase the total CRM requirement for this application. It could also increase the demand for performant autocatalysts along with the renewal rate of most polluting vehicles, while the recycling rate of end-of-life catalysts would bring secondary PGM resources. In any case, the expected long-term impact of this driver should be the growth of electric vehicles, mitigating any short-term increase of PGM requirement.

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9.4 PASSENGER CAR BODIES

9.4.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

Regardless of the numerous new developments in the automotive industry, where emerging technologies often depend on a large number of CRMs, the latter can also be found in the metals composing the car bodies. This study focuses on two CRMs (niobium and magnesium) found in steel and aluminium-based alloys. Technologies and sub-technologies have not been specified because both steel and Al-alloys are used in all makes and models of passenger vehicles, irrespective of power train type, vehicle size or costs, etc. The main reasons for the adoption of Nb in steel and Mg in aluminium-based alloys are that they make the car bodies lighter (therefore the car consumes less energy and pollutes less in the case of ICE) and possess good mechanical qualities.

In order to calculate the demand for Nb and Mg used in passenger car bodies, hypotheses were made for both the annual car production scenario and the car content of CRMs:

- A 0.8% growth rate was assumed for car production within the EU (LMC AUTOMOTIVE 2018), starting with 2016 car production data from ACEA (ACEA 2018).
- Mg-content was calculated using the weight of Al-alloy used in a 'typical' passenger car body (European Aluminium Association n.d.), the Mg-content of different Al-alloy types (with a literature review (AZO Materials 2013, 2005; Alam and Ansari 2017) (AZO Materials 2005)) and the % of each alloy type used in a 'typical' passenger car body (European Aluminium Association n.d.). For Al-alloys, although numerous alloys exist, three are commonly used in passenger car bodies. The study combined a forecasted amount of Al-alloy used in a ‘typical’ car body (increasing from 181 kg in 2015 t 354 kg in 2035 (Alcoa n.d.)) with an evaluation of the different shares of the three types of alloys and assumed that the Mg content of each alloy would remain constant until 2035.
- Nb-content was calculated using the weight of steel used in a 'typical' passenger car body (UBS 2017), the Nb-content of different steel alloy types (with a literature review (NiobelCon 2017b; Ispat Guru n.d.; NiobelCon n.d.; Bleck, Frehn, and Ohlert 2001; Bhattacharya 2016; Jian et al. 2015)) and the % of each alloy type used in a 'typical' passenger car body (NiobelCon 2017a). It was assumed that the amount of steel used in passenger car bodies would decrease in line with the increase in al-alloy use.

Table 12 – CRM significance indicators for passenger car bodies

CRM	Application use in 2015 (t)	EU apparent consumption in 2012 (BIO by Deloitte 2015) (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
Mg	14,900	128,000	10%	34,900	30%
Nb	3,700	10,400	40%	4,400	40%

For passenger car bodies, demands for CRMs witness an increase from 2015 to 2035 in this scenario, albeit in different proportions. The rise is moderate for Nb: steel for car bodies is nevertheless a major end-use for Nb in 2015 (indicator R1), with a slight increase in 2035. The surge is more important for Mg, roughly tripling its share of global 2015 demand in 2035 (indicator R2). The difference in these trends is mainly due to the assumption that the amount of steel would decrease and gradually be replaced by aluminium-based alloys.

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A recent study by Oakdene Hollins confirmed resource efficient material flows for magnesium metal, and in comparison to earlier studies (MSE), included the recycling loop of magnesium (as alloying element) in the Aluminium industry.

It is also important to mention, that beside the use of magnesium as alloying element in Al alloys, it's also used for several automotive body applications in form of Mg alloys (usually 5-9% aluminium as alloying element). Large parts like door inners or multi-material light-weight solutions in lift-gates are only a few examples with high potential future growth in this segment.

9.4.2 DRIVERS FOR CHANGE

Only a few drivers are presented in this section as most drivers from the Electric Vehicles and autocatalysts applications still apply to this application. Some of them are recalled, and others complete the analysis, in particular by focusing on the role and the magnesium and niobium contents in alloys.

9.4.2.1 POLITICAL DRIVERS

- **National and EU policies on air pollution, emission reduction and promotion of non-ICE cars (high certainty, upward trend)**

There are policy measures to cut down air pollution and CO_2 emissions at both EU, national and urban levels. Objectives in terms of CO_2 emission reduction were presented in the electric vehicle application. Regarding air pollution, EU has produced a number of directives on this topic (European Commission 2018e), many EU countries have initiated specific actions (e.g. subsidies on price; scrappage schemes for ICE vehicles, etc) and several European cities are pursuing policies against ICE vehicles (8 cities among the most active in this domain are European (Garfield 2018)).

Mg alloys, Mg alloyed Aluminium and Nb steel grades offer lighter alloys with equal or improved mechanical properties. Lighter vehicles improve energy efficiency and therefore, reduce fuel consumption, CO_2 and pollutant. Unlike for autocatalysts, this driver is not expected to reduce CRM requirement in this application because light alloys benefit to both ICE and non-ICE vehicles[3].

9.4.2.2 ECONOMIC DRIVERS

- **Development and adoption of electric vehicles (high certainty, upward trend)**

The weight of the battery in EVs is typically offset by light weighting other parts of a motor vehicle (e.g. sub-frame, body panels, etc.). Continuous research to reduce vehicle weight is expected to require more Mg and alloys, Mg alloyed Aluminium and Nb steel grades, and this trend could be accelerated by the adoption of EVs (see more details on this application in section 9.1).

- **Growth of population and GDP (medium certainty, upward trend)**

[3] In the case of non-ICE vehicles, it does not improve pollutant emissions and it still improves the battery life.

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The European population and GDP are increasing slightly (Eurostat 2018b), which could ultimately result in increased car sales. The European population and GDP are increasing slightly (Eurostat 2018b), which could ultimately result in increased car sales. Unlike the other two applications related to the road mobility sector, car bodies are necessary for both ICE and non-ICE vehicles, which ensures a more predictable demand growth. Yet, this driver is counterbalanced by mobility as a service (see next driver).

9.4.2.3 SOCIETAL DRIVERS

- **Changing use patterns and ownership models for cars: growth of mobility as a service (high certainty, downward trend)**

As described in the autocatalyst application, MaaS could reduce the renewal rate of all types of vehicles: some studies estimate that for every car offering ride-sharing, 5 to 15 individual cars would be replaced (Transport & Environment 2017; NRMA 2017). Other studies temper this trend showing that young people still strive for car ownership, in Germany for instance (McKinsey&Company 2012).

9.4.2.4 TECHNOLOGICAL DRIVERS

- **Car safety requirements (high certainty, upward trend)**

Motor vehicles are required to pass stringent safety tests. Over the past decades, the trend has continuously improved the overcall vehicle safety (van Ratingen et al. 2016). This is typically achieved by manufacturing vehicles from lighter, yet stronger materials that deform in a desirable fashion when subjected to impact. Mg and Nb offer this type of alloys.

9.4.2.5 ENVIRONMENTAL AND LEGAL DRIVERS

- **Recyclability and implementation of the circular economy package (high certainty, downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future.

Alloys are already significantly recycled in the automotive industry and economic interest in reusing Mg & Nb alloys could foster further recycling in the future, especially in the framework of the End of Life Vehicles Directive (European Commission 2000). Even if the functional recycling (old and new scrap) of Magnesium used as Mg alloys and Aluminium alloys in automotive applications is estimated at 58%, there is room for improvement specially in the field of EoL scrap. Niobium is not recycled at all at the moment (European Commission 2018b).

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10 AGRICULTURE

10.1 FERTILISERS

10.1.1 TECHNOLOGIES, CURRENT AND EXPECTED USE

Why are phosphate fertilisers being assessed?

- Mineral phosphate is a critical raw material
- EU has high import reliance on mineral fertilisers from extra-EU countries
- Population growth means that greater quantities of food and fertiliser will be required
- Environmental protection is key and reducing leakages of phosphorus into the soil, air and water by using waste as a resource can provide important environmental gains.
- In Europe nutrient recovery and reuse from secondary sources can provide an important diversification of sources of phosphorus and increase Europe's resilience.

Aim

To identify and assess the potential for secondary P-fertilisers to substitute mineral phosphate fertilisers in Europe.

Approach

Demand for P-fertilisers in Europe is assessed for 4 different materials, mineral phosphate, animal manure, sewage waste and food chain waste. Some of the secondary P-sources are already in use, in particular animal manure, but others too depending on the rules of individual Member States.

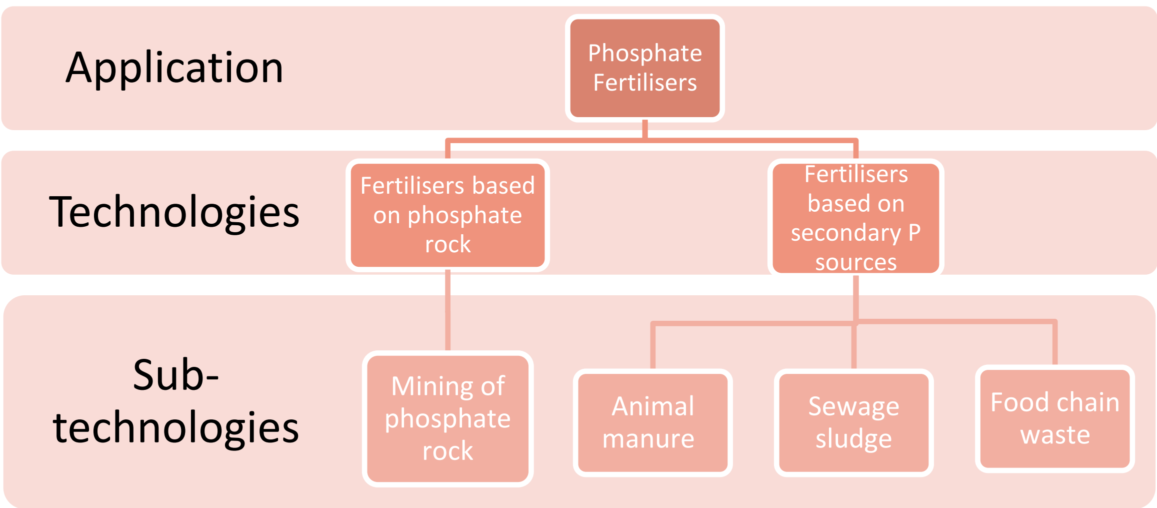

Figure 19 – Types of P-fertilisers

There is another important P-source that is not taken into account related to the accumulation of P into agricultural soil. It is estimated that around half of the mineral P-input is currently stored in agricultural land, which is not taken into account during the application of fertilisers, resulting in excess amounts P associated

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with eutrophication issues. Data related to accumulation of P in soils are scarce and only a small number of estimates have currently been undertaken, hence this is not included in our analysis.

Data availability & hypotheses

Different hypotheses and assumptions were made to evaluate the demand for phosphate fertilisers:

- Application sales figures represent estimated EU total demand for P-fertiliser including mineral fertilisers and fertilisers from secondary P-sources. Mineral fertiliser consumption figures were estimated by calculating apparent consumption for the EU-28 member states using the BGS World Mineral Production statistics (BGS 2017) and trade data from Eurostat (European Commission n.d.). The figures for secondary P-sources consumptions are taken from the (van Dijk et. al, 2016) paper (van Dijk, Lesschen, and Oenema 2016). A CAGR of 1.6% has been calculated for European P-fertiliser demand growth from the FAOSTAT 'World fertilizer trends and outlook to 2020' report (Food and Agriculture Organization of the United Nations 2017), which is applied to project EU demand up to 2035.
- For manure, it is assumed that from 2025 100% recycling will take place, in accordance with (van Dijk, Lesschen, and Oenema 2016), with improvements in handling and processing.
- For SS, the same recycling assumption is made. An average of 1% increase in SS since 1990 is recorded. The same increase rate is used to estimate future increase of sewage sludge (P-content). On top of this the estimated loss is added to the quantity of SS from 2025 onwards. An increase of 1% is also added to the material loss to reflect the increase in production of SS.
- For food waste, we assume for this calculation that from 2025 onwards the loss of P-content food waste is recovered and used, but no increase in the overall stream is projected (the regulatory framework in Europe is looking at reducing food waste).
- The purpose of this case study is to estimate how alternative sources of P (some already in use, but not all) could provide substitutes for mineral fertiliser in the future. For the secondary P-sources, three major sources of waste have been identified as potential P-sources. However, there is also another important P-source that is not taken into account related to the accumulation of P into agricultural soil. It is estimated that around half of the mineral P-input is currently stored in agricultural land, which is not taken into account during the application of fertilisers, resulting in excess amounts P associated with eutrophication issues. Data related to accumulation of P in soils are scarce and only a small number of estimates have currently been undertaken, hence this is not included in the analysis.

Some data is available, for example on future fertiliser trends to 2020, as well as an EU level material flow analysis of P-flows. Several assumptions have been made to estimate market shares and demand up to 2035. They are all documented in the application spreadsheet. With regards to recycling for example, we assume that from 2025, 100% recovery and recycling will take place to avoid nutrient loss. This may well not be the case, but the study is attempting to assess what the substitution potential for mineral P-fertiliser could be following a best-case scenario approach.

It is important to mention that the forecast suggests that SS could provide an important contribution of phosphorous in the future, which will reduce the need for mineral fertilisers. Similar conclusions have been highlighted by other researchers too (Egle et al. 2014).

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Table 13 – CRM significance indicators for fertilisers

CRM	Application use in 2015 (t)	EU apparent consumption in 2012 (BIO by Deloitte 2015) (t)	% (R1)	Expected application use in 2035 (t)	% of expected use vs current EU total (R2)
P	2,688,000	1,643,000	160%	3,632,000	220%

In Table 13, the inconsistency between application use and total EU apparent consumption is due to the fact that the MSA study (BIO by Deloitte 2015) does not include all recycled material (manure in particular). This being said, the annual demand for phosphate in fertilisers increases significantly in 20 years according to this reference scenario. The outcome of the analysis suggests that under this scenario, reliance on mineral fertiliser in Europe by 2035 could be very low. If P-accumulation in soils is taken into account too, then it is possible that no reliance to mineral fertiliser is required at all. As a matter of fact, there are large amount of unused P in soils (landfills, tailings, others…). These amounts add to the uncertainties affecting P demand in this central scenario, as it could account for (part of) the difference between apparent consumption and actual demand for agriculture (and explain differences between our figures and results from other studies).

10.1.2 DRIVERS FOR CHANGE

10.1.2.1 POLITICAL DRIVERS

- **Development of suitable policies for nutrient recovery and reuse (medium certainty, downward trend)**

Nutrient recovery and reuse from waste streams (animal manure, human sewage sludge, food chain waste) can offer an important contribution to support Europe in its transformation to a more circular economy. According to a report from the RISE foundation (Buckwell and Nadeu 2016), there is substantial scope to recover and reuse nitrogen and phosphorus from the European food chain. According to a report from the RISE foundation (Buckwell and Nadeu 2016), there is substantial scope to recover and reuse nitrogen and phosphorus from the European food chain. This would lead to a diversification of the sources of nutrient supply and therefore a better security of supply. The report analysis several policies currently in force (regarding the End of Waste Criteria and the Fertiliser Regulations for instance) and provides policy recommendations to foster the recover and reuse.

10.1.2.2 ECONOMIC DRIVERS

- **Sustainable production and consumption (medium certainty, downward trend)**

The United Nations have developed a sustainable development knowledge platform. This platform presents 17 Sustainable Development Goals (SDGs), among which n°12, 'Responsible Consumption and Production', aims at ensuring sustainable consumption and production patterns (United Nations Sustainable Development Knowledge Platform n.d., 12). To meet this requirement, the UN encourages 'decoupling economic growth from natural resource use'. This would have a downward effect on the consumption of fertilisers based on phosphate rocks, as it would encourage the use of other sources for fertilisers, as well as a decrease in their

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use. However, it remains a general, long-term objective which has few constraining effects (barring the management of hazardous chemicals and wastes).

10.1.2.3 SOCIETAL DRIVERS

- **Population growth (high certainty, low upward trend)**

A growing population will have higher food needs, and therefore a higher dependence on fertilisers. According to the baseline projection of the EU population (figures retrieved using Eurostat Data Explorer (Eurostat 2018b)), the EU28 population would grow until around 2040, then stagnate and eventually start decreasing after 2050. This is very likely to imply a rise in fertiliser demand, therefore in phosphate rocks. However, the rise would remain moderate compared to other regions of the world with a higher population growth.

10.1.2.4 TECHNOLOGICAL DRIVERS

- **Optimisation of P-flows management through precision agriculture (high certainty, downward trend)**

Precision agriculture is a data-based management approach that is characterised by the collection and use of field-specific data. This can then be used to adjust the application of inputs to specific characteristics of small units of cropland and grassland to optimise fuel and input use (and to reduce losses that would otherwise cause pollution). It is based on numerous technologies and infrastructures, such as data gathering and management systems, geographic information systems (GIS), global positioning systems (GPS), microelectronics, wireless sensor networks (WSNs), and radio frequency identification (RFID) technologies (Kritikos, European Parliament, and Directorate-General for Parliamentary Research Services 2017).

Thanks to this development, less fertilizer quantities could be used to obtain the same results, reducing at the same time the environmental footprint of agriculture.

- **Development of secondary phosphate fertilisers like sewage sludge (SS) or food waste (high certainty, variable trend)**

The regulatory framework in Europe is looking at reducing food waste, therefore it is likely that the growth of this stream will be limited and may even reduce further from current levels. We assume that from 2025, 100% recovery and recycling will take place and therefore this loss will not be present anymore. Currently, only a minimum amount of SS returns back to land, although the EU Sewage Sludge directive is meant to encourage its use in agriculture. There are several legislative barriers and social challenges (Project on urban reduction of eutrophication (PURE) n.d.) to be overcome for SS to be utilised more efficiently. There are several legislative barriers and social challenges (Project on urban reduction of eutrophication (PURE) n.d.) to be overcome for SS to be utilised more efficiently. For instance, consumers and land managers may be worried about products that have been fertilised with secondary waste-based fertilisers. Resistance to using them is possible. Cultural barriers should be overcome to enable the move towards nutrient recovery.

In addition, ongoing research (Project on urban reduction of eutrophication (PURE) n.d.) has been conducted in order to address 5 main challenges of SS handling: stabilising, reducing water content and sludge volume, utilising energy potential when feasible, reducing the number of harmful micro-organisms and recovering phosphorus for agriculture. In addition, ongoing research (Project on urban reduction of eutrophication (PURE)

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n.d.) has been conducted in order to address 5 main challenges of SS handling: stabilising, reducing water content and sludge volume, utilising energy potential when feasible, reducing the number of harmful micro-organisms and recovering phosphorus for agriculture. Addressing successfully this last challenge could provide an alternative source of P and therefore reduce imports of phosphate rocks, but it could also foster demand for secondary P (since a lot of recycled P would be potentially available).

10.1.2.5 ENVIRONMENTAL DRIVERS

- **Measures to protect the environment (medium certainty, slight downward trend)**

The main objective is to avoid pollution of air, water, soil and impacts on the climate by gathering up nutrients and recycling them back into agricultural production. Pollution includes eutrophication of water courses, lakes, inland seas and oceans; air pollution with associated impacts on health, greenhouse gas emissions and damage to terrestrial and aquatic biodiversity.

This is related to the policies for the recovery and reuse of nutrients (European Parliament 2017b), and can be contradictory with other drivers like the development of secondary fertiliser. This is related to the policies for the recovery and reuse of nutrients (European Parliament 2017b), and can be contradictory with other drivers like the development of secondary fertiliser. This could lead to a decrease in phosphate rock imports due to the diversification of P sources for fertilisers. However, the quality of these fertilisers varies a lot. Low quality secondary P-fertilisers may increase the risk of P run-off and eutrophication. Secondary P forms vary considerably. Often P is found in complex forms and slowly soluble compounds and it is not therefore readily available to the plant.

10.1.2.6 LEGAL DRIVERS

- **Implementation of the circular economy package; establishment of standards, certification and traceability protocols, best practice (high certainty, downward trend)**

In 2018, the European Commission adopted a new set of measures in the framework of its Circular Economy Action Plan (European Commission 2018a). While the most binding measures concern the recycling of plastics, the plan also included a full assessment of the recycling potential of Critical Raw Materials (European Commission 2018b, 2018c, 2018d), indicating that similar obligations to collect CRM-intensive products and recover valuable and/or hazardous materials could appear in the future.

A new regulation on fertilisers was introduced recently in the framework of the Circular Economy Package. It promotes the use of waste (food and sewage sludge) in agricultural land. Thus, even though the overall fertiliser consumption might grow, the main expected consequence of this policy is a reduction of primary phosphate consumption in favour of secondary sources.

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11 SYNTHESIS ON MAJOR DRIVERS AND TRENDS FOR FUTURE CRM DEMAND

The drivers described in the previous section are not self-fulfilling: they are related to the reference scenarios on which the analysis was based, and they can serve decision makers looking for levers to accelerate the transition toward less dependence on CRMs.

This section will provide a synthesis on drivers and related trends for future CRM demand. As mentioned in section 6, this study focused on a limited number of applications (those involving most CRMs and for which information was available). Important applications were given a high priority to make sure the study cover a significant share of both current and future uses of CRMs. In some cases, one application was enough to cover the majority of current and future uses of a specific CRM (e.g. fertilisers for phosphate). In other cases, the overall consumption of a CRM is the sum of several applications (e.g. magnets in wind turbines and EV motors for praseodymium).

Based on the applications covered in the previous sections, Table 14 summarises which CRMs of the European Commission list have been covered. It also highlights the share of current EU apparent consumption covered by these applications and whether this share is expected to increase or decrease in the coming decades.

Table 14 – Share of CRM uses covered in this study

CRM	Current total use covered (t)	Current EU apparent consumption (t)	% (R1)	Total expected use covered in 2035 (t)	% of expected use vs current total (R2)
Sb	Not covered				
Ba	340	338,330	0%	390	0%
Be	Not covered				
Bi	Not covered				
B/Bo	0.2	74,000	0%	1	0%
Co[2]	2,600	13,000	20%	36,200	280%
Coking Coal	Not covered				
F	Not covered				
Ga[2]	5	80	10%	6	10%
Ge	15	40	40%	30	70%
Hf	30	33,000	0%	180	1%
He	Not covered				
In[2]	22	22	100%	17	80%
Mg	14,900	128,000	10%	34,900	30%
Natura Graphite C[2]	2,440	80,900	3%	159,000	200%
Natural rubber	Not covered				
Nb[2]	3,800	10,400	40%	4,700	50%
P[4]	2,688,000	1,643,000	160%*	3,632,000	220%
Sc	Not covered				

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CRM	Current total use covered (t)	Current EU apparent consumption (t)	% (R1)	Total expected use covered in 2035 (t)	% of expected use vs current total (R2)
Si[1]	34,900	582,000	6%	12,700	2%
Ta[2]	80	100	80%	120	120%
W	10	13,400	0%	80	1%
V	120	71,000	0%	730	1%
Ir (PGM)	Not covered individually				
Pt (PGM)	40	70	60%	15	20%
Rh (PGM)	Not covered individually				
Ru (PGM)	Not covered individually				
Pd (PGM)[2]	50	60	95%	30	50%
Dy (HREE)[2]	230	180	120%*	1080	580%
Other HREEs (Er, Eu…)	Not covered				
La (LREE)	Not covered				
Ce (LREE)	Not covered				
Pr (LREE)[2]	150	230	60%	1070	460%
Nd (LREE)[2]	2,060	1,000	210%*	5,700	570%
Sm (LREE)	Not covered				

[1]: the total use of silicon covered in this study is probably underestimated since no data were found on silicon included in electronic products (smartphones, PCs, laptops, appliances…). Besides, it does not account for the high loss rate of some processes in the value chain (e.g. production of silicon wafer) since the bottom-up approach focused on the CRM content of end products.
[2]: see specific comments in § 11.1.
*: the reason why these ratios exceed 100% are explained in the sections of the main applications of these CRMs (§ 8.2 & 10.1). Besides, as R1 compares apparent consumption (imports – exports) and bottom-up requirements of a specific application, any country importing a CRM for a single application (requirements = total imports) and exporting half of its production would have R1 > 100% (210% in this example).

Since SCRREEN is not a research project and has limited resources, not all industrial applications involving CRMs could be covered. One objective of this task was to point at applications for which further research could be necessary. A couple of recommendations can be made at this point. Further studies could explore:

- The main applications of non-covered CRMs or CRM for which only niche applications have been covered in this study (e.g. Ba, B, Hf, W, V)
- Secondary applications of CRMs showing a quickly growing application (e.g. Co, C, Ge): since the latter is expected to drive up the demand, current applications, even secondary applications, could exacerbate this trend which depending on their own drivers which needs to be assessed.
- Specific processing steps of the CRM value chain: when criticality mainly depends on a specific form of product (e.g. high-grade silicon used for PV and electronic component), a specific study (on silicon refining in this case) may complement a broad analysis as the supply of other forms of this specific CRM may represent much larger volumes and lower criticality.

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In the case of CRMs whose total consumption results of several important applications, a digest of the most important drivers of the future material consumption can usefully complement the analysis done in previous section, depending on the contribution of each application. This is done in § 11.1.

Besides, the future CRM requirements of every European industrial sector will depend on the drivers and trends of the main applications related to this sector. This is why sub-section 11.2 provides a broad picture of the main drivers of CRM requirements in the energy sector, in the transport sector, in the sectors of telecoms, electronics and agriculture. A focus is made on the drivers shared by different applications in the same sector.

11.1 CRM SPECIFIC TRENDS

11.1.1 INDIUM

Based on Table 15, this study covered the main applications of indium except *solders*. The main two applications (flat panel display and solar panels) already account for almost 100% of the EU apparent consumption of indium according to Table 14. Unless a quick adoption of a breakthrough technology using indium changes the picture in the coming years, the trends of future indium demand should be shaped by these two main applications.

More specifically, PV panels and flat displays should both require a slightly decreasing amount of indium towards 2035 (Figure 20). The future indium demand should mainly follow the trends shaped by the current most significant application: flat displays. The main drivers related to flat displays are recalled hereafter (see details in section 8.3.2):

- Drivers expected to accelerate the slight decrease in indium requirements
    - Countries banning the import of e-waste from EU
    - ITO sputtering process efficiency, recycling cost of end-of-life products
    - Legal barriers to disposal and incentive measures in favour of reuse, repair and refurbished items
- Drivers expected to slow the decrease in indium requirements
    - Shift in user experience design toward display interaction
- Other important driver with variable impact
    - Economics of zinc

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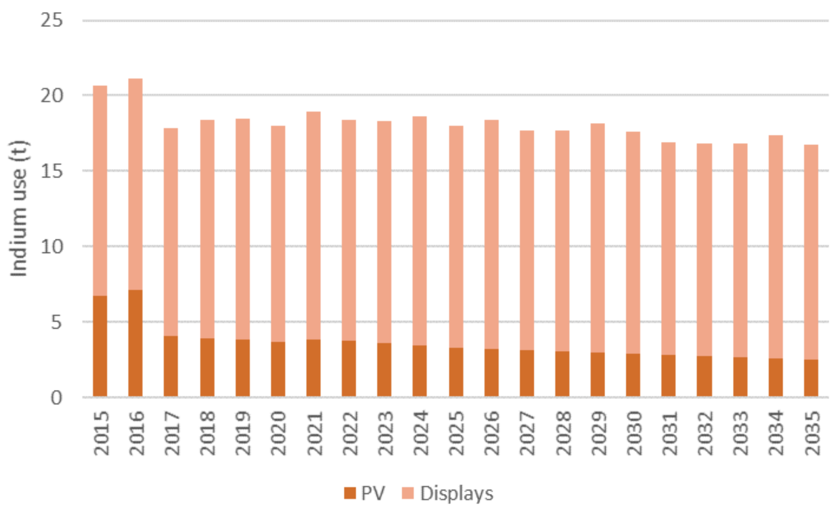

Figure 20 – Indium use in the applications covered in this study

11.1.2 GALLIUM

Based on Table 15, this study covered the main applications of gallium. Yet the three applications covered (smartphone & computers, flat displays and solar panels) only account for around 10% of the EU apparent consumption of gallium according to Table 14. This surprisingly low percentage can be explained by three main factors:

- The application covering smartphones and computers does not account for all integrated circuits (those included in tablets have not been considered for instance).
- The application covering flat displays does not account for all lighting technologies with embedded gallium.
- The high amount of waste in the material balance suggests that the bottom-up approach used to calculate the "application use" probably underestimates the actual requirements (this approach only accounts for the end-product gallium content while the total EU apparent consumption includes all manufacturing input requirements).

Integrated circuits should still drive most of the future gallium demand towards 2035. Based on the quantitative data gathered in this study, a slight upward trend should be expected (Figure 21). The main drivers related to this application (restricted to smartphones and computers in this study) are recalled hereafter (see details in section 8.1.2):

- Drivers expected to accelerate the increase in gallium requirements
  - Growth of demand related to social needs (social network activities, growth of on-line/on-app purchases, on-demand services…).
  - Smaller and more integrated devices
- Drivers expected to slow the increase in gallium requirements
  - Political measures against planned obsolescence
  - Legal barriers to disposal and incentive measures in favour of reuse, repair and refurbished items

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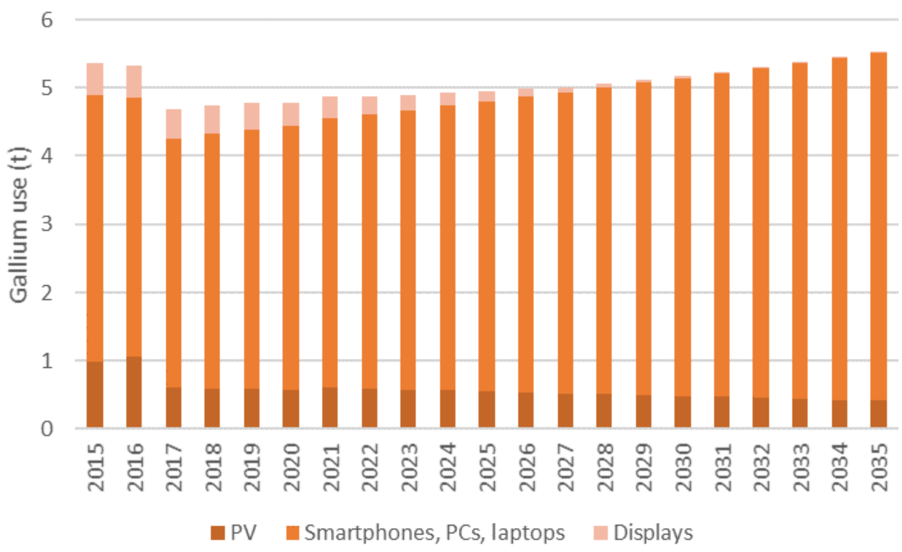

Figure 21 – Gallium use in the applications covered in this study

Since lighting and integrated circuits represent around 95% of gallium requirements, further research should focus on filling the gaps remaining in the analysis of these applications (e.g. considering the gallium content of light bulbs and integrated circuits embedded in tablets or appliances). From the supply point of view, the huge quantities of gallium included in imported bauxite ores should also be borne in mind. Even though their recovery may not be profitable for now, they could be considered as potential resources (850t/y) to reduce the criticality of supply in the future.

11.1.3 NEODYMIUM

Based on Table 15, this study covered the main end products containing neodymium (permanent magnets, batteries, metallic components) even though they were analysed in the framework of applications using these end products (magnets used in wind turbines or EV motors, batteries used for EVs, components used in electronic devices and appliances). The main four applications (wind turbine, EVs, smartphones & computers, domestic appliances) account for around 210%[5] of the EU apparent consumption of neodymium according to Table 14. In 2035, they could grow up to 570%.

Looking at the contribution of each application, it seems that domestic appliances and wind turbines would remain the main share of neodymium demand until 2020 at least (Figure 22). Then, the emergence of electric vehicles could change the picture. By 2035, EVs could represent most of neodymium requirements. Due to the uncertainties in the assessment of each application, it is hard to say when this shift will occur or whether EVs will surpass wind turbines and appliances, but it is pretty certain that this application will drive the growth of

[5] The main reason why these applications exceed 100% of the apparent consumption is a potential overestimation of Nd use for domestic appliances (this reason is detailed in section 8.2.1).

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neodymium demand towards 2035 as the demand for the other two applications should remain rather flat. The main drivers related to the emergence of electric vehicles and their CRM requirements are recalled hereafter (see details in section 9.1.2):

- Drivers expected to accelerate the growth of neodymium requirements
  - European and national policies to accelerate the deployment of fast charging infrastructures
  - EU & national policies to cut GHG emissions in the transport sector
- Drivers expected to slow the growth of neodymium requirements
  - Implementation of the EU circular economy package
- Other important drivers with variable impact
  - Cost of raw materials in Li-Ion batteries
  - Technological improvements in batteries, material efficiency and substitution

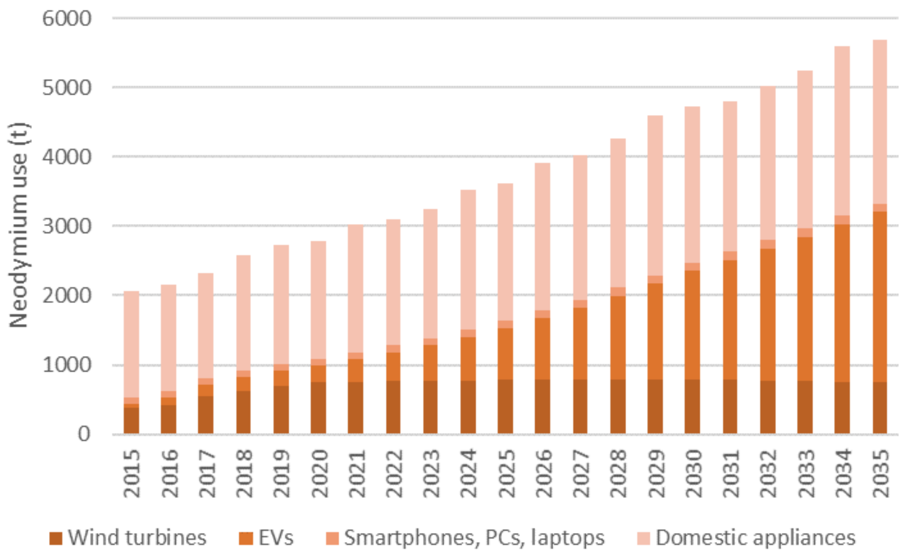

Figure 22 – Neodymium use in the applications covered in this study

11.1.4 PRASEODYMIUM

Based on Table 15, this study covered the main end products containing praseodymium (permanent magnets, batteries) even though they were analysed in the framework of applications using these end products (magnets used in wind turbines or EV motors, batteries used for EVs). The main applications (wind turbine, EVs) already account for around 60% of the EU apparent consumption of praseodymium according to Table 14. In 2035, they could grow up to 460%.

Looking at the contribution of each application, it seems that most praseodymium demand will come from wind turbines until 2020 at least (Figure 23). Then, the requirements for wind turbines will level off and the emergence of electric vehicles could change the picture. By 2035, EVs could represent most of neodymium requirements. Due to the uncertainties in the assessment of each application, it is hard to say when this shift will occur, but it is pretty certain that EVs will drive the growth of praseodymium demand towards 2035. The

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main drivers related to the emergence of electric vehicles and their CRM requirements are recalled hereafter (see details in section 9.1.2):

- Drivers expected to accelerate the growth of praseodymium requirements
    - European and national policies to accelerate the deployment of fast charging infrastructures
    - EU & national policies to cut GHG emissions in the transport sector
- Drivers expected to slow the growth of praseodymium requirements
    - Implementation of the EU circular economy package
- Other important drivers with variable impact
    - Cost of raw materials in Li-Ion batteries
    - Technological improvements in batteries, material efficiency and substitution

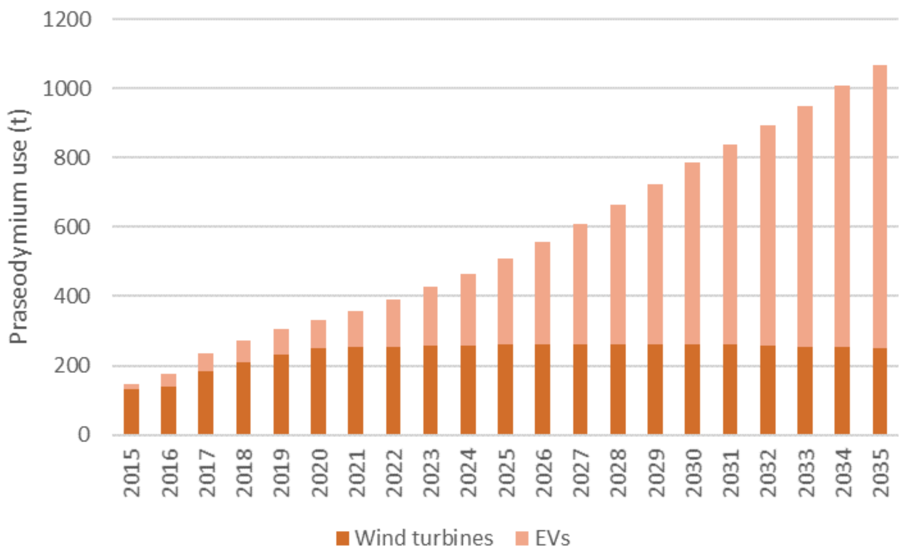

Figure 23 – Praseodymium use in the applications covered in this study

11.1.5 DYSPROSIUM

Based on Table 15, this study covered the main end product containing dysprosium (permanent magnets) even though the framework of analysis included several applications (magnets used in wind turbines, EV motors, components in electronic devices and domestic appliances). The main four applications (wind turbine, EVs, smartphones & computers, domestic appliances) account for around 120%[6] of the EU apparent consumption of dysprosium according to Table 14. In 2035, they could grow up to 580% of current consumption.

Looking at the contribution of each application, it seems that domestic appliances and wind turbines would remain the main share of neodymium demand until 2020 at least (Figure 24). Then, the emergence of electric

[6] The main reason why these applications exceed 100% of the apparent consumption is probably the same as for neodymium (potential overestimation of the CRM requirements of domestic appliances: this reason is detailed in section 8.2.1)

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vehicles could change the picture. By 2035, EVs could represent most of dysprosium requirements. Due to the uncertainties in the assessment of each application, it is hard to say when this shift will occur or whether EVs will surpass wind turbines and appliances, but it is pretty certain that this application will drive the growth of dysprosium demand towards 2035 as the demand for the other two applications should remain rather flat. The main drivers related to the emergence of electric vehicles and their CRM requirements are recalled hereafter (see details in section 9.1.2):

- Drivers expected to accelerate the growth of dysprosium requirements
    - European and national policies to accelerate the deployment of fast charging infrastructures
    - EU & national policies to cut GHG emissions in the transport sector
- Drivers expected to slow the growth of dysprosium requirements
    - Implementation of the EU circular economy package
- Other important drivers with variable impact
    - Cost of raw materials in Li-Ion batteries
    - Technological improvements in batteries, material efficiency and substitution

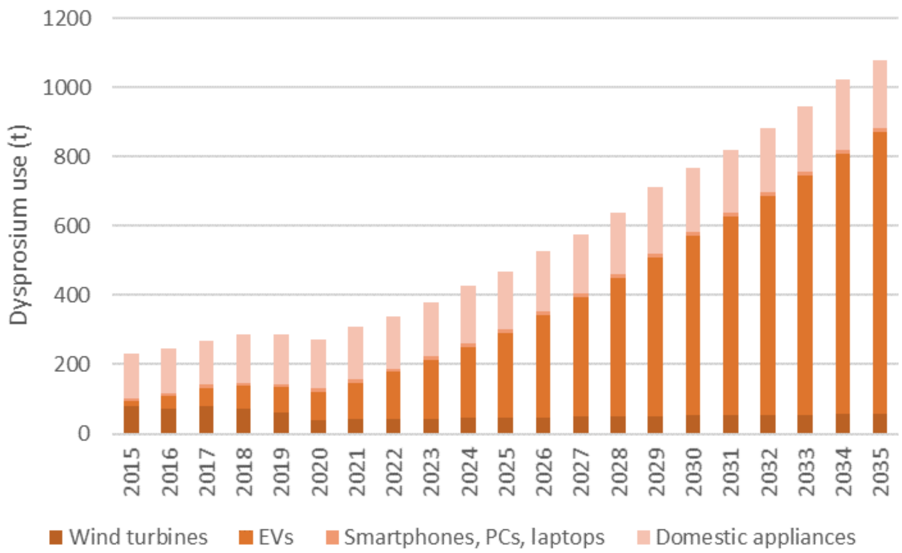

Figure 24 – Dysprosium use in the applications covered in this study

11.1.6 COBALT

Based on Table 15, this study partially covered two main end uses of cobalt (batteries and superalloys): it focused on superalloys in jet engines and batteries for EVs, for domestic use, for smartphones and laptops. These applications (EVs, domestic energy storage, domestic appliances, smartphones & computers, jet engines) only account for around 20% of the EU apparent consumption of cobalt according to Table 14. This current coverage is low because alloys have not been covered while it is the main application in which cobalt is transformed in Europe (Co-bearing batteries are usually imported as end product in EU). Yet, in 2035, the applications covered in this study could represent 280% of current consumption.

Looking at the contribution of each application, it seems that domestic energy storage and electric vehicles will drive the growth of cobalt demand toward 2035 (Figure 25). The main drivers related to the emergence of

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electric vehicles, domestic batteries and their CRM requirements are recalled hereafter (see details in section 9.1.2):

- Drivers expected to accelerate the growth of cobalt requirements
    - European and national policies to accelerate the deployment of fast charging infrastructures
    - EU & national policies to cut GHG emissions in the transport sector
    - High electricity price for households along with cost reduction for battery storage solutions
    - Growth of renewable energy production to cut CO_2 emissions resulting in high variability of power supply
- Drivers expected to slow the growth of cobalt requirements
    - Implementation of the EU circular economy package
- Other important drivers with variable impact
    - Cost of raw materials in Li-Ion batteries
    - Technological improvements in batteries, material efficiency and substitution

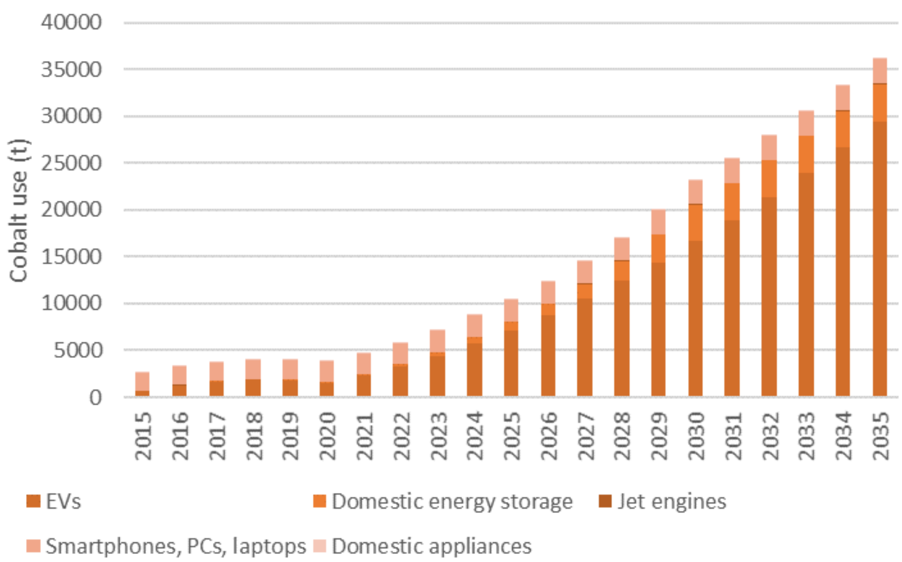

Figure 25 – Cobalt use in the applications covered in this study

11.1.7 NATURAL GRAPHITE

Based on Table 15, this study only covered the third main end uses of natural graphite (batteries): it focused on batteries for EVs and for domestic use. These applications (EVs, domestic energy storage) currently account for 3% of the EU apparent consumption of natural graphite according to Table 14. Yet, in 2035, the same applications could represent 200% of current consumption.

While it seems that EVs will have the main contribution over domestic batteries, both should drive the growth of natural graphite demand toward 2035 (Figure 26). The main drivers related to the emergence of electric vehicles, domestic batteries and their CRM requirements are recalled hereafter (see details in section 9.1.2):

- Drivers expected to accelerate the growth of natural graphite requirements

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- European and national policies to accelerate the deployment of fast charging infrastructures
- EU & national policies to cut GHG emissions in the transport sector
- High electricity price for households along with cost reduction for battery storage solutions
- Growth of renewable energy production to cut CO_2 emissions resulting in high variability of power supply

- Drivers expected to slow the growth of natural graphite requirements
  - Implementation of the EU circular economy package
- Other important drivers with variable impact
  - Cost of raw materials in Li-Ion batteries
  - Technological improvements in batteries, material efficiency and substitution

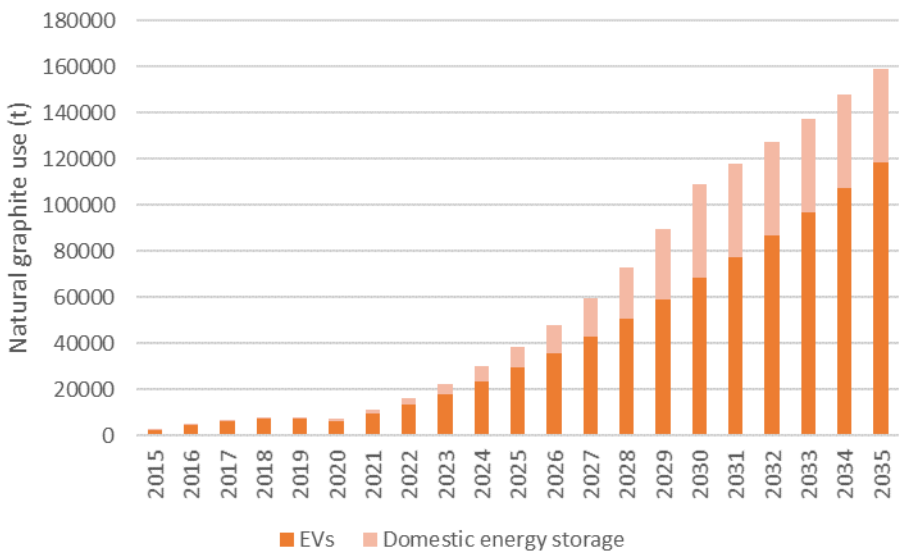

Figure 26 – Natural graphite use in the applications covered in this study

11.1.8 TANTALUM

Based on Table 15, this study partially covered two main end uses of tantalum (capacitors and superalloys): it focused on superalloys in jet engines and capacitors in smartphones and computers. These applications would account for around 80% of the EU apparent consumption of tantalum according to Table 14. In 2035, the same applications could represent 120% of current consumption.

Electronic components in smartphones and computers should drive the future demand of tantalum toward 2035 (Figure 27) even though the growth of demand related to jet engines should be higher at the end of this period. The main drivers related to smartphones and computers and their CRM requirements are recalled hereafter (see details in section 8.1.2):

- Drivers expected to accelerate the increase in tantalum requirements
  - Growth of demand related to social needs (social network activities, growth of on-line/on-app purchases, on-demand services…)

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- Smaller and more integrated devices

- Drivers expected to slow the increase in tantalum requirements
    - Political measures against planned obsolescence
    - Legal barriers to disposal and incentive measures in favour of reuse, repair and refurbished items

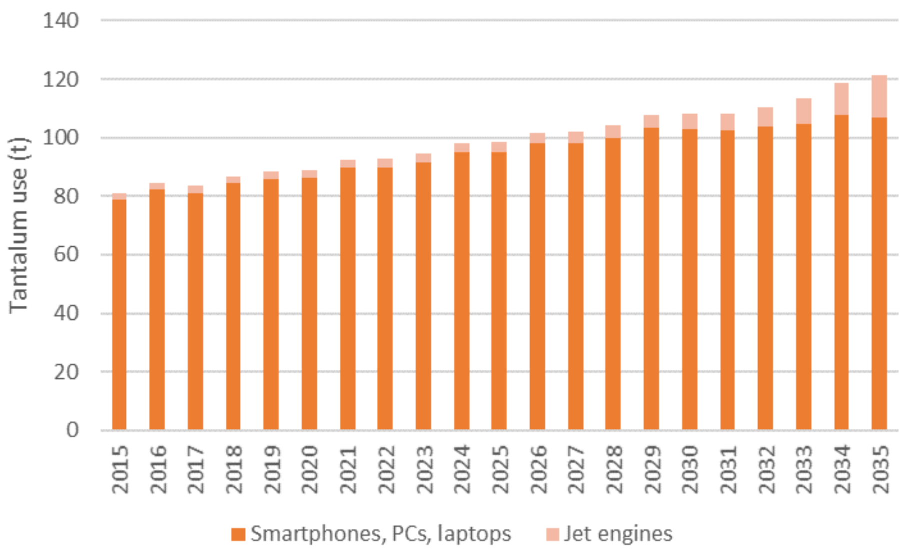

Figure 27 – Tantalum use in the applications covered in this study

11.1.9 PALLADIUM

Based on Table 15, this study covered the two main end uses of palladium (catalysts and electronic components) even though they were analysed in the framework of applications using these end products (autocatalysts, electronic components used in electronic devices or in appliances). These three applications (autocatalysts, smartphones & computers, domestic appliances) account for around 95% of the EU apparent consumption of palladium according to Table 14. In 2035, they may only represent 50% of current consumption.

Looking at the contribution of each application, autocatalysts are and should remain the most demanding application (Figure 28). Yet, it is expected to continuously decline as the emergence of electric vehicles will limit the number of new cars requiring catalysts. Besides the demand for the other two applications should remain rather flat by 2035. The main drivers related to autocatalysts, the emergence of electric vehicles, and their CRM requirements are recalled hereafter (see details in section 9.3.2):

- Drivers expected to accelerate the decline of palladium requirements
    - European and national policies to accelerate the deployment of fast charging infrastructures
    - Decreasing cost of non-ICE vehicles
    - Changing use patterns and ownership models for cars: growth of mobility as a service

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- Drivers expected to slow the decline of palladium requirements
    - Increasing efficiency and cleanliness of ICE powertrains
- Other important drivers with variable impact
    - Urban, national and EU policies on air pollution, emissions reduction and promotion of non-ICE cars

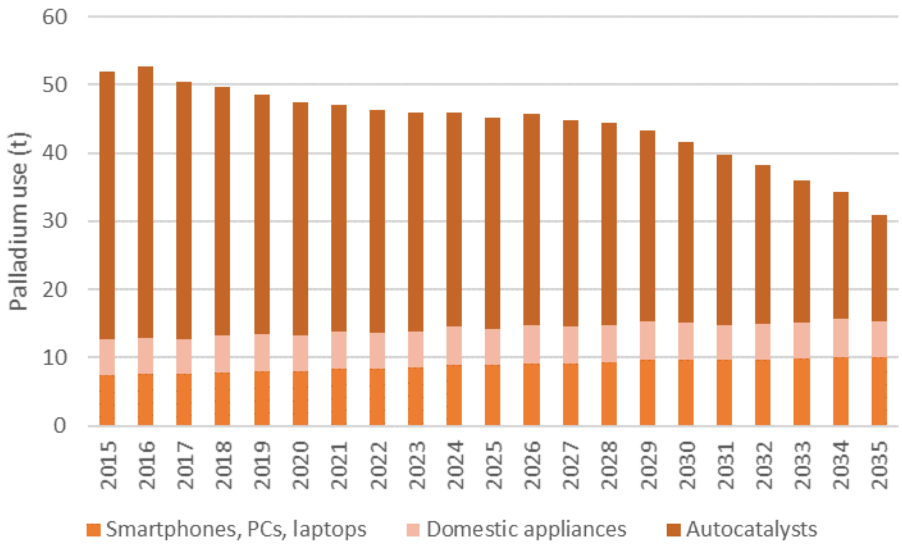

Figure 28 – Palladium use in the applications covered in this study

11.1.10 NIOBIUM

Based on Table 15, this study partially covered the main end uses of niobium (alloy steels): it focused on alloy steels for jet engines and car bodies. These applications account for around 40% of the EU apparent consumption of niobium according to Table 14. In 2035, they could represent around 50% of current consumption.

Looking at the contribution of each application, the demand related to car bodies should remain significantly higher than the demand for jet engines (Figure 29) even though the latter should have the higher growth at the end of this period. The main drivers related to car bodies and their CRM requirements are recalled hereafter (see details in section 9.4.2):

- Drivers expected to accelerate the increase in niobium demand
    - National and EU policies on air pollution, emission reduction and promotion of non-ICE cars
    - Development and adoption of electric vehicles
    - Car safety requirements
- Drivers expected to slow the increase in niobium demand
    - Changing use patterns and ownership models for cars: growth of mobility as a service
    - Recyclability and implementation of the circular economy package

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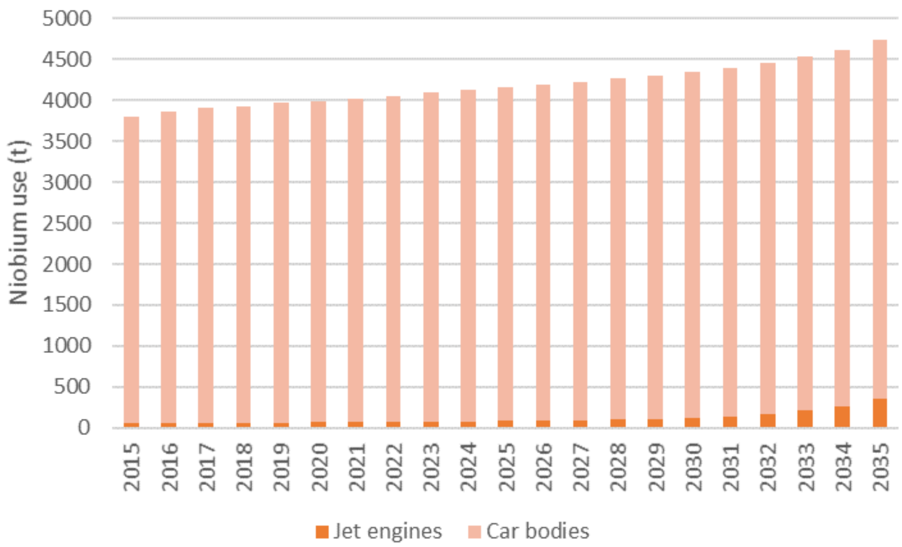

Figure 29 – Niobium use in the applications covered in this study

11.2 SECTOR SPECIFIC TRENDS

11.2.1 ENERGY SECTOR

Three applications of the energy sector have been covered in this study: wind turbines, photovoltaic panels and domestic energy storage. It seems that in this sector, the main trends towards 2035 in terms of CRM demand should be driven by energy transition and renewable energies. Most of these trends seem to push towards a growing CRM consumption:

- To ramp up from around 150 GW of wind power installed capacities in 2015 to more than 320 GW in 2035, more wind turbines are necessary. Even though annual installation may remain stable during this ramp-up period, the market share of CRM-intensive turbine technologies is expected to grow, thus doubling the requirements for some REE (Nd from 400 to 800 t/y and Pr from 130 to 250 t/y approximately). Only dysprosium demand should remain stable (or decrease slightly from 80 to 60 t/y) thanks to improved material efficiency and substitution.
- The installed capacities of behind-the-meter batteries are expected to grow even faster, sales ramping up from less than 100 MWh per year in 2015 to around 15 GWh per year after 2030 in Europe. Even though the initial CRM requirements are low (10 t/y for Co and 100 t/y for natural graphite), they could get 400 times higher 20 years after, reaching 4,000 t/y of cobalt and more than 40,000 t/y of natural graphite.

Only the requirements related to solar panels are expected to decrease despite the continuous increase in PV capacities installed in Europe. Indeed, the annual installed capacities should remain rather stable by 2035, while material efficiency is expected to improve, thus cutting the annual CRM demand by 3 to (from 35 to 23 kt/y for Si, 7 to 2 t/y for In and 4 to 1 t/y for Ga approximately).

These trends are based on reference scenarios depending on a number of strong hypothesis (detailed in section 7). Some drivers will probably impact those scenarios and reinforce or smoothen the trends. In

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particular, political measures may accelerate the growth of CRM requirements (smart grid developments, more ambitious goals to reduce CO_2 emissions, incentives for distributed power generation…). Other important drivers include economics and technology: the adoption of EVs could drive the cost of batteries down and facilitate the grid integration of intermittent energies. The improvement of material efficiency or substitution solutions for permanent magnets and any change in the chemical composition of batteries could also impact the future demand of critical raw materials in this sector.

11.2.2 TRANSPORT SECTOR

Within the transport sector, four applications were covered in this study: electric vehicles, jet engines, autocatalysts and passenger car bodies. Three major trends seem to be influencing the CRM demands in this sector. The first one is the need to decarbonise mobility and reduce air pollution, which triggers the emergence of hybrid and electric vehicles and the strong dependence on autocatalysts for ICE vehicles. The second trend is the search for better performing materials to replace existing ones, especially in terms of weight and performance in extreme conditions (ceramics for jet engines, Al-based alloys for car bodies). The third and last trend is the increasing demand for mobility, especially in emerging countries, which fosters the growth in the overall number of aircrafts and cars.

The first trend can account for the surge in demands of REEs and battery-related materials (Co, C and Li which is not a CRM). The forecasted enormous growth in the annual sales of hybrid and electric vehicles in Europe (from less than 1 million in 2016 to more than 12 million in 2035) associated with the gradual adoption of Li-Ion batteries by most HEVs (due to their performance) and permanent magnet motors by all EVs, explain such growths (e.g. from 2 to 2,200 t/y for Nd, from 20 to 25,000 t/y for Co).

The global rise in the number of aircrafts and cars could explain the growths in demands for CRMs used in car bodies and jet engines. The rate of growth is much slower than for EVs because neither jet engines nor car bodies are emerging CRM uses but the rise is nevertheless steady (from 130 to 730 t/y for V, 15,000 to 35,000 t/y for Mg). For Nb used in car bodies, the demand could stagnate due to a gradual shift from steel to aluminium alloys to decrease weight.

Finally, the demand for PGMs is forecasted to decrease (from 80 t/y in 2015 to 30 t/y in 2035). This is largely due to the decrease in conventional petrol and diesel car sales (see the various hypothesis and assumptions in section 9.3).

However, these CRM demands are obviously subject to heavy uncertainties. To account for this, the main drivers affecting the demands in the transport sector are recalled hereafter (more details in section 9). Some are likely to reinforce the trends described above (upwards or downwards), others may diminish them. Regarding political and environmental drivers, EU & national policies to reduce GHG emissions and tackle air pollution issues in the transport sector will play a major role in the transport sector, while the emergence of Mobility as a Service (MaaS) could have an impact on the societal side. For the economic and technical drivers, driving down the costs and improving the performances of lithium-ion batteries will become essential conditions to the emergence of EVs. As for legal drivers, potential thresholds for GHG emissions or air pollutants for both cars and aircrafts are worth mentioning.

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11.2.3 ELECTRONICS & TELECOMS

Four applications were explored in the Electronics & Telecoms field: smartphones & PCs, domestic appliances, displays and fibre optics. Although these end-uses all have different demand drivers, some common trends seem to influence this sector. First of all, the global expansion of digital networks and services implies that more people have access to the internet, thus fuelling the need for connected equipment. Furthermore, the search for better performing and cheaper materials or components of electronic appliances fosters substitution, making future demands more unpredictable in the sector. In addition, as more and more countries witness a rise in their GDP per capita, increased wealth enables a larger part of the population to gain access electronic equipment and appliances, fostering EU exports of fibre optics for instance.

The global rise in the number of electronic equipment can account for the rise in demands for CRM used in smartphones, PCs and other appliances. Smartphones & PCs will remain an important end-use for Ta especially (from 80 t/y in 2015 to 110 t/y in 2035), while under the hypotheses detailed in section 8.2, Nd and Dy will witness a rise in their demands (from 1,500 to 2,400 t/y for Nd). Displays would remain an important end-use for In, although no further growth in demand is forecasted under our assumptions (see section 8.3).

The rise in internet access around the world also contributes to the increase in Ge demand for fibre optics (15 to 30 t/y).

Severe uncertainties affect the quantitative forecasts described here. In order to have a better understanding of the various factors that could influence future demands, a review of the different drivers for trends was conducted and the most important are given here. Political drivers include engagement against planned obsolescence and restrictions on exports of e-waste, while an important societal driver is the growing number of appliances per household. An important technological trend is the use of smaller and more connected appliances (which may use more CRMs and/or different ones). From the environmental point of view, more action has been undertaken to assess the environmental impact of appliances throughout their life cycle. Finally, binding regulations for recycling waste electrical and electronic equipment are not to be overlooked on the legal field.

11.2.4 AGRICULTURE

The situation of agriculture within this study is different than the other sectors, since only one application is covered: fertilisers. Nevertheless, the use of phosphate fertilisers is crucial and hardly substitutable in agriculture. Some seemingly important trends for fertilisers were assessed. First, the global population growth (moderate in Europe) will foster the need for a more efficient agriculture, thus increasing reliance on fertilisers and potentially encouraging European exports. On the contrary, various sources of phosphorous are likely to be considered (animal manure, but also sewage sludge and food waste chain) to reduce dependence on phosphate rocks. At last, the emergence of precision agriculture, helped by new technologies, might improve the efficiency of the use of fertilisers, in a context where agriculture tries to reduce its environmental footprint.

Although P demand is expected to grow in our scenario (from 2.7 to 3.6 Mt/y in 2035), it is important to mention that the forecast suggests that alternative sources of P could provide an important contribution of phosphorous in the future, which will reduce the need for mineral fertilisers.

There are many uncertainties affecting the quantitative demand forecast for P. So as to better understand the various factors which could drive the demand upwards or downwards compared to this 'central scenario',

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different drivers for trends were identified, some of which are described hereafter. The development of a consistent EU framework for nutrient recovery and reuse is an important political driver, while demand for more organic products may matter at the EU level (more than population growth). On the technological level, the optimisation of P-flows management through precision agriculture could improve the efficiency of fertilisers and reduce their environmental footprint (and perhaps the quantities used). The development of secondary P sources (as mentioned in the previous paragraph) is also an important trend that could reduce dependence on mineral fertilisers. Finally, environmental measures to limit the impact of fertilisers and regulations to ban some chemical products are not to be overlooked.

12 CONCLUSION

This study aimed to assess the major trends affecting future demand for CRMs. Rather than addressing this topic through a CRM-by-CRM approach, an approach based on industrial applications and sectors was preferred. This approach facilitated the identification of demand drivers since the consumer preferences, the economics, the technological, environmental, legal and even political aspects related to an application are easier to analyse than those related to the macro-sectors used to analyse CRM demand in top-down approaches. Besides, the analytical framework of a CRM-by-CRM approach is usually unsuitable to emerging applications and breakthrough technologies and unfamiliar for the general public and decision makers.

Thus, based on appropriate practical and theoretical tools (multi-level perspective, PESTEL framework), this study pursued 4 main objectives:

- Analyse a series of applications covering the broadest part of future CRM requirements
- Identify a series of drivers affecting the future demand of CRMs in these applications
- Involve experts to validate these drivers and quantify the trends as much as possible
- Compile the drivers affecting a whole sector and highlight the most important; provide a synthesis of the trends per CRM for those involved in several applications.

In the end, this study covered 12 applications involving 20 CRMs. 5 CRMs have been covered not for their main applications (B, Ba, Hf, W, V) but because they are involved in the main application of other CRMs. As a result, the study covers a low share of their consumption. The coverage rate (percentage of current EU apparent consumption R1 covered in the study) for natural graphite is also low but the reason is different: the applications involving this CRM are emerging and the future requirement for these applications are expected to exceed the total current consumption by 2035. The other 14 CRMs covered have an average coverage rate of 70%. Moreover, the CRM requirements related to the applications covered in this study grew by 260% on average (excluding natural graphite whose growth rate is much higher as it is only involved in emerging applications have almost no current requirements).

Based on literature review, a reference scenario including quantitative data was provided for each application and more than 70 drivers help to qualify the trends and their potential future evolution. Both scenarios and drivers were validated by experts. The quantitative data will serve as input to task 2.3 when conducting the assessment of raw material needs. Besides, all these results (quantitative and qualitative) will also feed the work of WP9, in particular the extension of the 'MICA' expert system (task 9.4): the objective is to decide the type of information (e.g. main applications, application drivers, certainty about the drivers…) to include in the new ontology, and to disseminate the most important results of the project.

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Among the most important findings of this study, a synthesis of both quantitative and qualitative key points was provided by sector.

In the energy sector, the development of wind power (involving REE) and domestic energy storage (mainly cobalt and natural graphite) are expected to drive up the CRM requirements in the coming decades. On the contrary, the requirements related to the deployment of PV panels (mainly silicon, indium and gallium) should become less critical by 2035, especially thanks to material efficiency. Important drivers to monitor in this sector include policies to further reduce CO_2 emissions, incentives for distributed power generation, power and storage requirements related to the deployment of EVs.

In the transport sector, the need to decarbonise mobility and reduce air pollution is closely tied to the emergence of hybrid and electric vehicles and the persistent dependence on autocatalysts for ICE vehicles. The deployment of EVs is expected to drive most of the growth of CRM requirements (mainly REE, cobalt and natural graphite) in this sector by 2035. The search for better performing materials to replace existing ones, especially in terms of weight and performance in extreme conditions (ceramics for jet engines, Al-based alloys for car bodies), should also impacts the sector: Ta, Mg, Nb are the main CRMs concerned. Finally, the increasing demand for mobility, especially in emerging countries, and newer forms of mobility (MaaS), are not to be overlooked.

In the sectors of telecoms and electronics, the global expansion of digital networks and services implies that more people have access to the internet, thus fuelling the need for connected equipment and fibre optics that Europe could produce and export. Therefore, the demand of CRMs in this sector should either level off (indium for screens) or keep increasing (REE, Ta, Pd for electronic devices & appliances, Ge for optic fibres). Important drivers to monitor in the future include miniaturisation of components, measures against planned obsolescence and restrictions on exports of e-waste. In addition, the search for better performing and cheaper materials or components of electronic appliances fosters substitution, making future demands more unpredictable in the sector.

In the sector of agriculture, the global population growth (moderate in Europe) will foster the need for a more efficient agriculture, thus increasing reliance on fertilisers and potentially encouraging European exports. On the contrary, various sources of phosphorous are likely to be considered (animal manure, but also sewage sludge and food waste chain) to reduce dependence on phosphate rocks. At last, the emergence of precision agriculture, helped by new technologies, might improve the efficiency of the use of fertilisers, in a context where agriculture tries to reduce its environmental footprint.

Finally, some recommendations were made to provide guidance for further research. First, there is still a lack of information on the main application of some CRMs (not covered in this study). Besides, it could be wise to investigate secondary applications of some CRMs when existing studies reveal a quickly growing application (e.g. storage application for cobalt and natural graphite). In these cases, even secondary applications could exacerbate the upward trend of demand. Finally, in specific situations, a focus on some processing steps of the CRM value chain could bring valuable information since the criticality of some CRMs mainly depends on a specific form of product like high-grade silicon used for PV panels and electronic components.

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SCRREEN
Solutions for CRitical Raw materials - a European Expert Network

14 ANNEXES

14.1 MAIN APPLICATIONS OF CRM

Table 15 – List of top-3 applications for each CRM and their relative use (based on (Deloitte et al. 2017))

CRM	1st application	% 1st	2nd application	% 2nd	3rd application	% 3rd	Substitution rank
Sb	Flame retardants	43	Lead-acid batteries	32	Lead alloys	14	2
Ba	Weighting agent in oil and gas well drilling fluids	60	Filler in rubbers, plastics, paints & paper	30	Chemical industry	10	3
Be	Electronics / Telecoms	40	Electronics / Automotive	16	Automotive components	16	3
Bi	Chemicals	62	Fusible alloys	28	Metallurgical additives	10	3
Bo	Glass	49	Ceramics & frits	15	Fertilizers	13	1
Co	Battery chemicals	42	Superalloys, HSS	23	Hard materials	10	3
F	Steel & iron making	33	Refrigeration & air con	17	Aluminium making & metallurgy	14	4
Ga	Integrated circuits	70	Lighting	25	CIGS	5	3
Ge	Infrared optics	47	Optical fibers	39	Satellite solar cells	13	2
Hf	Base metals	45	Machinery parts	26	Chemical products	13	5
He	Cryogenics	29	Welding	17	Semi-conductors, optical fibers	14	3
In	Flat panel displays	56	Solders	10	PV cells	8	3
Mg	Transport	58	Desulfurisation agent	12	Packaging	7	3
C	Steel making (refractories)	52	Refractories for foundries	14	Batteries	8	3
Natural rubber	Automotive	75	Furniture	12	Sportswear	5	2
Nb	Steel (structure)	31	Steel (automotive)	28	Steel (pipeline)	27	4
Ir	Electrical	43	Electrochemical	27	Other	23	4
Pd	Autocatalysts	75	Electrical	10	Chemical	5	3
Pt	Autocatalysts	69	Jewellery	9	Chemical	6	3
Rh	Autocatalysts	82	Chemical	8	Glass	4	3
Ru	Electrical	61	Chemical	17	Electrochemical	15	4
P	Fertilisers	86	Food additives	10	Fireworks and detergents	4	1
(REEs total)	(Catalysts)	(42)	(Glass additives)	(18)	(Metallurgy)	(12)	3
Ce	Autocatalysts	35	Glass & ceramics	33	Polishing powders	11	4
Dy	Magnets	100					2
Er	Optical applications	74	Lighting	26			3
Eu	Lighting	96	Other	4			4

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CRM	1st application	% 1st	2nd application	% 2nd	3rd application	% 3rd	Substitution rank
Gd	Magnets	97	Medical/optical	3			2
Ho, Lu, Yb, Tm	Optical	100					5
La	Fluid cracking catalysts	67	Glass & ceramics	13	Batteries	10	3
Nd	Magnets	37	Batteries	13	Metal	12	3
Pr	Magnets	24	Ceramics	15	Batteries	12	3
Sm	Magnets	97	Medical/optical	3			3
Tb	Lighting	68	Magnets	32			5
Y	Lighting	46	Ceramics	35	Alloys	7	1
Sc	Fuel cells (SOFC)	90	Alloys	9	Other	1	5
Si	Chemical applications	54	Alloys (Al)	38	Solar applications	6	1
Ta	Capacitors	33	Superalloys	22	Sputtering targets	17	3
W	Mill & cutting tools	31	Mining & construction tools	21	Other wear tools	17	3
V	HSLA	60	Special steel	30	Superalloys	3	5

The relative use of each application was estimated as the ratio between the volume of a specific CRM used in this application and the total apparent consumption of this CRM.

The substitution rank was derived from the information contained in the CRM factsheets. The interpretation leading to each grade is explained in the following table:

Grade	Interpretation
1	No direct substitution option for the main applications (there might still be indirect alternatives: completely different technology partially responding to the needs or recycling options to recover the CRM)
2	Substitutes exist for most applications but are more expensive and have lower performances,
3	Substitutes exist but are more expensive or have lower performances
4	Substitutes exist but have little techno-economic incentive to become dominant (e.g. because they rely on others CRM from the same group such as REEs or PGMs) *or,* No direct substitution option but an alternative technology exists and better respond to the needs
5	Substitutes exist with the same level of performance and limited extra-cost

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