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Report on the economic assessment of substitution trajectories

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Summary

Report on the economic assessment of substitution trajectories

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REPORT ON THE ECONOMIC ASSESSMENT OF SUBSTITUTION TRAJECTORIES

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CONTENT

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1 INTRODUCTION AND SUBSTITUTION TRAJECTORIES

This report provides an overview of substitution trajectories assessment in economic terms in order to identify the relevance of CRMs substitution for the European economy and future opportunities for European actors. The economic assessment is based on an application-led/value chain approach (as opposed to material-led). The work presented in this report follows the logic of previous work performed in CRM_InnoNet project.

Substitution trajectories are selected based on knowledge gained in SCRREEN project on current and future use of CRMs, CRMs' applications and their substitutability. The trajectories selected for economic assessment are the following ones:

- Accumulators in electric cars and stationary energy storage applications
- Alloys in transportation sectors in automobile and aircraft applications
- Catalytic converters in vehicles application
- Electrical components in
- Permanent magnets in energy sector in wind turbine application and in transport sector in electric vehicles application

Selected trajectories are analysed through their value chains, the approach is shown detailed in Figure 1. The following aspect are analysed for each trajectories:

- CRM availability: CRMs used in the application and does their availability pose a risk for the European economy
- Economic relevance: Statistical economic data analysis over the value chain and the main actors (companies) identifying in the value chain
- Availability of substitution solutions: Substitution solutions and their effect on the economic value chain

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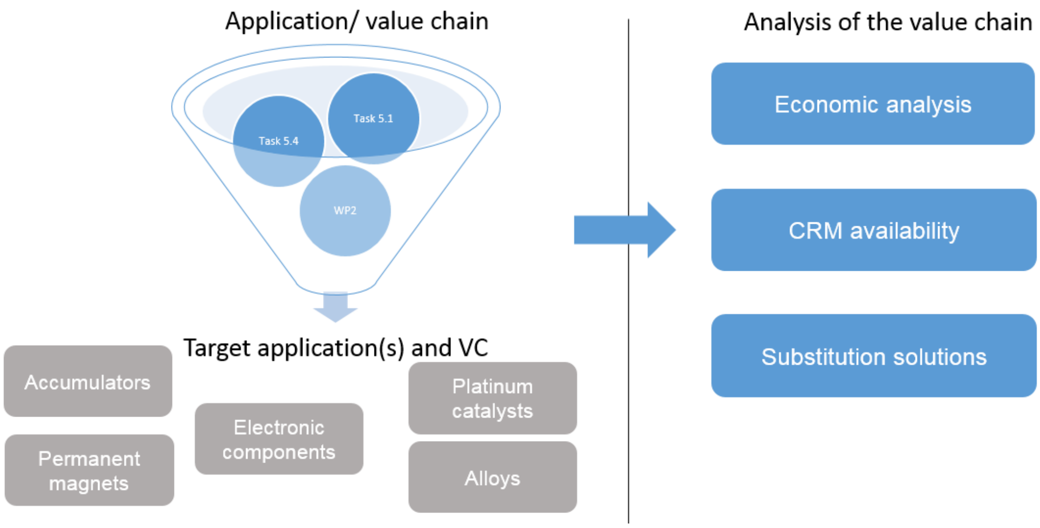

Figure 1. Approach used for economic assessment.

Depending on the applications, like shown in Figure 2, the value chain is widening both to raw material end as well as to industrial sector end.

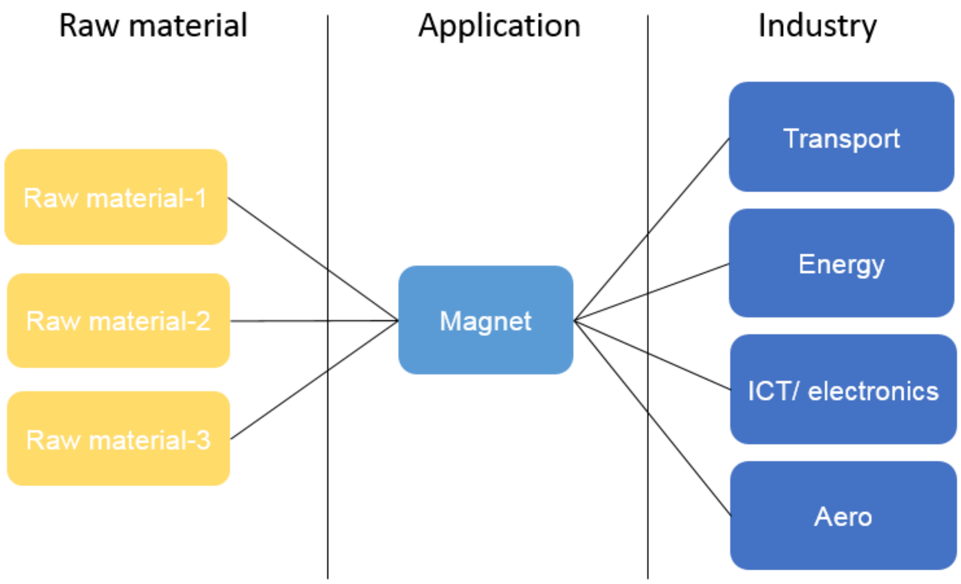

Figure 2. Raw materials, application, industry sectors chains.

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2 METHODOLOGY

For all trajectories, literature review has been used as main tool for gathering the data for CRM availability and substitution solutions combined to experts' own knowledge.

In the examination of European economic importance, information from Eurostat's PRODCOM database [1] has been used. At first, a structural composition of each trajectory/application had to be produced where CRM containing components, parts and materials are listed. After this the trajectories/applications, components and materials identified were 'matched' with the most relevant group/product according to PRODCOM's classification system. In some cases, there is not an obvious match and an application might be spread across many several PRODCOM groups. Where multiple PRODCOM groups are relevant to a particular application, those groups are aggregated. An example of the structural composition with corresponding PRDOCOM groups has been presented Table 1.

Table 1. Structural composition of catalytic converter with PRODCOM codes and names

Application	*Component*	*Sub component*	*Materials*	*Prodcom code and name*
Automobile				*29103000 Motor vehicles for the transport of <= 10 persons* *29102100 Vehicles with only spark-ignition engine of a cylinder capacity <= 1 500 cm³* *29102230 Motor vehicles with only petrol engine > 1 500 cm³ (including motor caravans of a capacity > 3 000 cm³) (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)* *29102230 Motor vehicles with only petrol engine > 1 500 cm³ (including motor caravans of a capacity > 3 000 cm³) (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)* *29102330 Motor vehicles with only diesel or semi-diesel engine > 1 500 cm³ but <= 2 500 cm³ (excluding vehicles for transporting >= 10 persons, motor caravans, snowmobiles, golf cars and similar vehicles)*
	Exhaust silencer			*29323063 Silencers and exhaust pipes; parts thereof*
		Platinum catalyst		*24413070 Platinum catalysts in the form of wire cloth or grill*
			PGM	*24413030 Platinum, palladium, rhodium, iridium, osmium and ruthenium, unwrought or in powder form* *24413050 Platinum, palladium, rhodium, iridium, osmium and ruthenium, in semimanufactured forms (excluding unwrought or in powder form)*

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The information form PRODCOM database were examined through economic status figure (import-production-export) for year 2017 and through production indicator (production/(production + import)) figure from last three years (Figure 3).

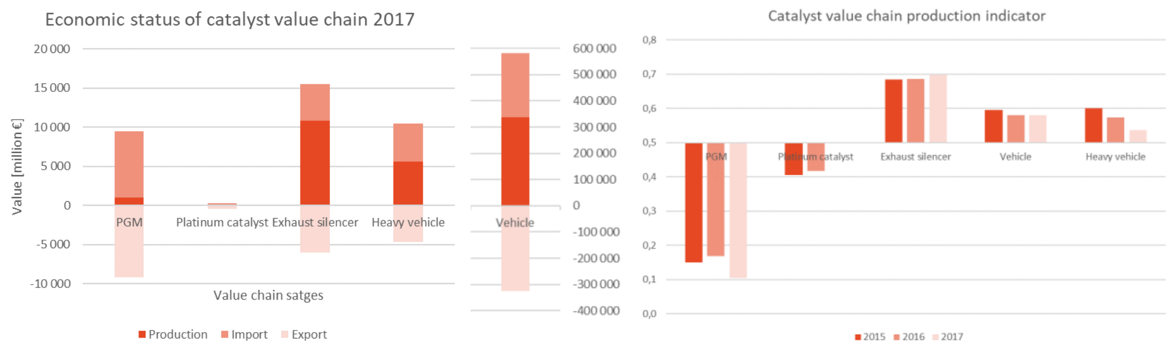

Figure 3. Example of the economic status figure (left) and production indicator figure (right).

In some cases there are some similar elements and product groups used in the chains which means that the graphs can partly similar since the value of a product/application specific component or material cannot be differentiated. However, this is not seen as a restriction since the relevance of a value chain phase for European manufacturing (industry) is the key outcome of the analysis.

In next sections, trajectories assessment are reported one by one.

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3 ACCUMULATORS

The general term accumulator refers to a device for energy storage. Devices accepting, storing and releasing energy through electrochemical reactions are called batteries. This report concentrates on the value chain of rechargeable batteries, or secondary batteries, in electric cars and stationary energy storage applications, and on the substitutability of the critical raw materials these types of batteries contain. The study mainly covers lithium ion (Li-ion) batteries as a battery technology and the critical raw materials involved with this technology, namely cobalt (Co), natural graphite and to some extent, silicon (metal). However, nickel metal hydride (NiMH) batteries are also shortly discussed due to the employment of critical rare earth elements (REEs), namely lanthanum (La), cerium (Ce), praseodymium (Pr) and neodymium (Nd) in this technology. [1], [2]

For battery-driven electric vehicles, the most critical factor is specific energy and therefore Li-ion battery is used in these vehicles. For hybrid electric vehicles, however, more important is the continuous charging/discharging cycle and ability to release power. Therefore, a NiMH battery is more suited for hybrid vehicles. [3] Due to this preference, the use of Li-ion batteries in vehicles is expected to outnumber that of NiMH batteries so that the share of batteries based on Li-ion technology will be more than 90% in all types of electric vehicles by 2020 [4]. It has also been estimated that EVs will make up the majority of new car sales worldwide by 2040, rising from the 3% share to be seen in 2020. In number of cars this translates to an estimated increase from a couple of million vehicles sold in 2020 to over 60 million new EVs sold in 2040. [5] Thus, the demand for Li-ion batteries during the next couple of decades is expected to be immense.

The increasing use of renewable energy sources raises the need to even out the modulating energy production from time to time and integrating the energy sources into the grid smoothly and safely. Balancing the electricity generation and demand between daytime and night time is also a significant aspect in optimised grid utilization. Therefore, a large-scale energy storage system (ESS) is an increasingly important means to shift electrical energy from peak to off-peak periods. A number of potential technologies have been proposed for ESS, but the secondary battery technique is one of the most promising means for storing electricity on a large-scale because of flexibility, high energy conversion efficiency and simple maintenance. The major parameters of stationary batteries for ESS are significantly different from those of power batteries used in EVs. Long cycle life, low cost, and high safety are the most important parameters. [6]

Li-ion batteries have dominated and are anticipated to dominate in future also in ESS applications, whereas NiMH batteries will only have a negligible share. The whole stationary battery market is estimated to see a significant expansion, as the global battery storage capacity in stationary applications is estimated to rise from 11 GWh (2017) to 100-170 GWh by 2030, which means a considerable increase in Li-ion battery demand. [6]–[8] Due to the above-mentioned reasons, this report emphasis the value chain study and substitution solutions of Li-ion batteries over those of NiMH batteries.

The battery technologies are first presented before discussing the statistical data and value chain related to the automotive and stationary energy storage applications relying on these technologies.

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LI-ION BATTERIES

Development of high-energy-density Li-ion battery started in the 1970s. Current Li-ion batteries do not contain metallic lithium and are therefore much safer than the earlier primary lithium-metal design of cell. In Li-ion batteries, lithium ions travel between anode and cathode during charge and discharge processes, [9] as illustrated in the following figure.

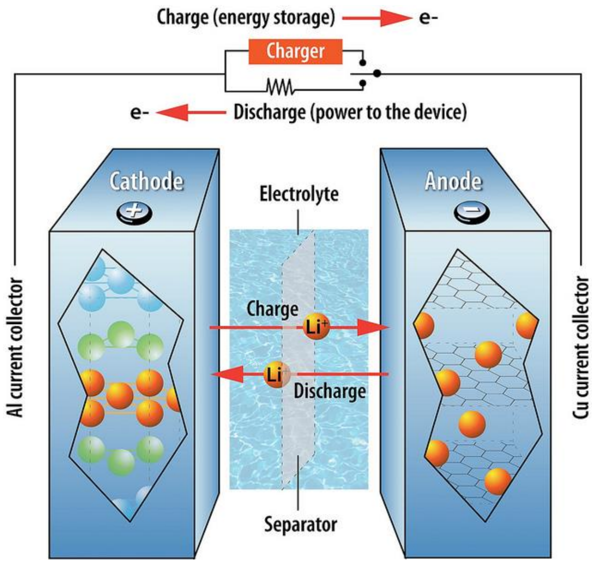

Figure 1. The principle of a lithium ion cell. Figure: Argonne National Laboratory.

The cathode material is typically lithium cobalt oxide ($LiCoO_2$) or lithium manganese oxide ($LiMnO_2$), but other metal oxide based materials are also used, such as $LiMn_2O_4$, $LiFePO_4$, and $LiNi_{1-x-y}Mn_xCo_yO_2$. [9]

Currently, natural or synthetic graphite-based materials are used on the anode side. The electrolyte is composed of an organic-based solvent and dissolved salt (such as $LiPF_6$, $LiBF_4$, or $LiClO_4$), and a microporous polymer sheet works as the separator between the positive and negative electrode. [9]

The most important advantages of the Li-ion cell are high energy density, from 150 to 200 Wh/kg (250-530 Wh/l), high voltage (3.6 V), good charge-discharge characteristics, and relatively long cycling life with acceptable self-discharge (less than 10% per month). Comparing with Ni-based secondary batteries, Li-ion battery shows no memory effect, as well as better high-rate charging performance. The major disadvantage for Li-ion battery is the high price. There also must be a controlled charging process, as overcharging or heating above 100°C causes the decomposition of the positive electrode and the electrolyte with liberation of gas. [9] Despite these currently predominant drawbacks, Li-ion and post Li-ion chemistries are considered the most promising and relevant chemistries for electrochemical energy storage in the time frame up to 2030. [1]

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NI-MH BATTERIES

NiMH battery was first studied in the 1960s and was commercially introduced in 1989. Since then, NiMH cells have become a dominant commercial rechargeable battery system in high-volume production for multiple consumer applications. In recent years, the application of NiMH battery has expanded from portable applications to hybrid vehicle use [9], such as the one presented in next figure.

Figure 2. An example of an automotive NiMH battery. Figure: Public domain.

In NiMH battery, the negative electrode is a hydrogen-storing alloy, while the positive electrode is β-NiOOH, which also contains Co and Zn. The electrolyte is aqueous KOH solution containing some LiOH. The overall process consists in the reversible transfer of a proton from an electrode to the other [9], as illustrated in the next figure.

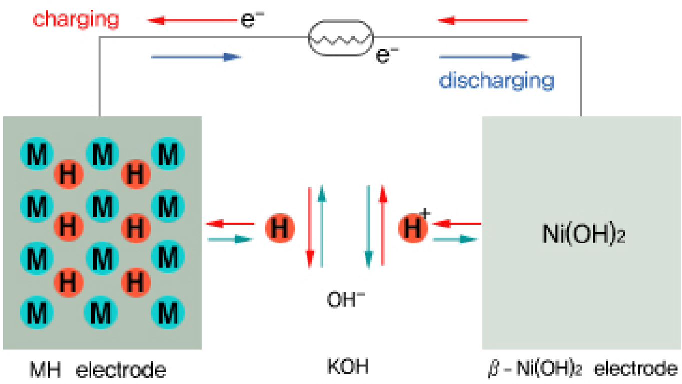

Figure 3. The principle of a nickel metal hydride battery. Figure: Sebang Global Battery.

The negative electrode materials are either AB_5 or AB_2 type alloys, such as $LaNi_5$ or ZrV_2. The advantages of both types of alloys cover wide operating temperature range, high capacity, long cycle life, and high hydrogen diffusion rate. [9] In average, REEs account for more than 30 wt% of a NiMH battery [2].

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In the $LaNi_5$ alloy, using a naturally occurring mixture of rare-earth elements, La, Nd, Pr, and Ce, instead of pure La, enhances the resistance to alkali and reduces costs [9]. A typical mischmetal, designated with A in electrode alloys, is $La_{5,7}Ce_{8,0}Pr_{0,8}Nd_{2,3}$ [3]. Nickel in $LaNi_5$ can be partially substituted by Co, Mn, and Al. AB_5 type alloys show capacities of about 300 mAh/g, which is less than those exhibited by AB_2 type alloys (A: Zr, Ti; B: V, Ni plus minor amounts of Cr, Co, Mn, Fe). However, AB_5 alloys show better performance in wider working temperature range with demanding discharge rates. AB_5 alloys are also less susceptible to self-discharge and, as they are cheaper and easier to use, are still preferred especially in automotive applications. [3], [9]

In optimized NiMH cells, the energy density can approach 100 Wh/kg and 300 Wh/l. The drawback of NiMH batteries is that long-term storage at high temperatures causes permanent damages to seals and separator resulting in reduced cycle life. [9]

VALUE CHAIN

The value chain of Li-ion and NiMH batteries used in EVs and stationary energy storage is presented in Figure 4.

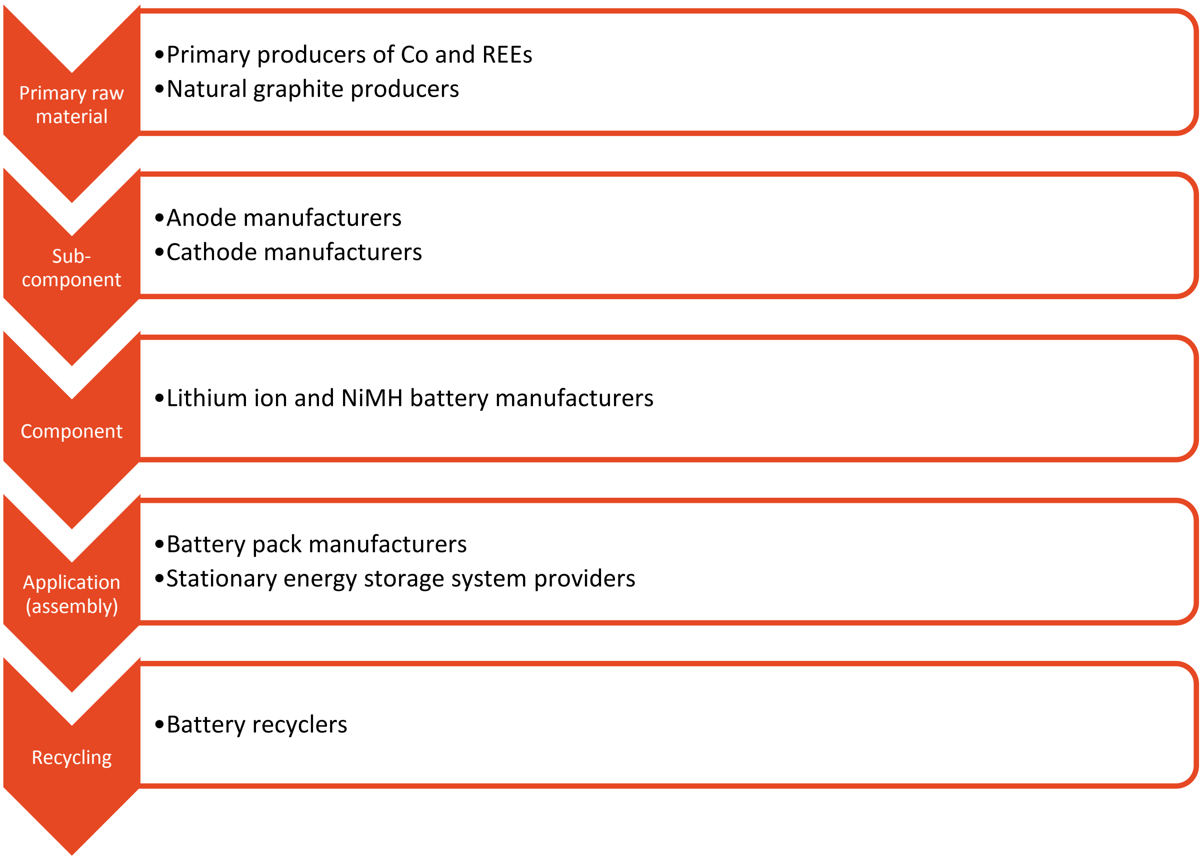

Figure 4. Value chain of Li-ion and NiMH batteries used in EVs and stationary energy storage.

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3.1 ECONOMIC ANALYSIS OF ACCUMULATOR VALUE CHAIN

STATISTICAL DATA

The economic analysis based on statistics (Eurostat, PRODCOM-data base) of the batteries value chain is presented next. For the analysis, the structural composition of the application has been produced in the table below. Based on these divisions, the schematic economic value chain description has been produced and presented separately in the next section.

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Table 1. Structural composition of battery with PRODCOM codes and names.

Application	*Component*	*Sub component*	*Materials*	*Prodcom code and name*
Battery				*27202300 Nickel-cadmium, nickel metal, hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators*
	Battery Cell			*27201100 Primary cells and primary batteries* *27201200 Parts of primary cells and primary batteries (excluding battery carbons, for rechargeable batteries)*
		Cathode/Anode/Electrolyte		*27202400 Parts of electric accumulators including separators*
		Inductor		*27115080 Inductors (excluding induction coils, deflection coils for cathode-ray tubes, for discharge lamps and tubes)*
		Plates, films, sheets…		*22214230 Non-cellular plates, sheets, film, foil, strip of condensation or rearrangement polymerization products, polyesters, reinforced, laminated, supported/similarly comb. with other materials)*
		Anodizing metal		*25612250 Anodizing of metals*
			Co	*20121930 Cobalt oxides and hydroxides; commercial cobalt oxides*
			Graphite	*20132130 Carbon (carbon blacks and other forms of carbon, n.e.c.)* *23991400 Artificial graphite, colloidal, semicolloidal graphite, and preparations*
			REE (La)	*20132300 Alkali or alkaline-earth metals; rare-earth metals, scandium and yttrium; mercury* *20136500 Compounds of rare-earth metals, of yttrium or of scandium or mixtures of these metals*
			Li	*20121950 Lithium oxide and hydroxide; vanadium oxides and hydroxides; nickel oxides and hydroxides; germanium oxides and zirconium dioxide*

The battery value chain composes of 10 groups which can be divided roughly to four stages which are materials, sub-components, components/parts and end applications. More detailed division together with PRODCOM codes and names can be seen in Table 1. In Figure 5 the relationship between production, import and export based on the statistical data has been presented. The positive values present how much value has been either generated and imported to Europe while the negative value present how much leaves as export from Europe.

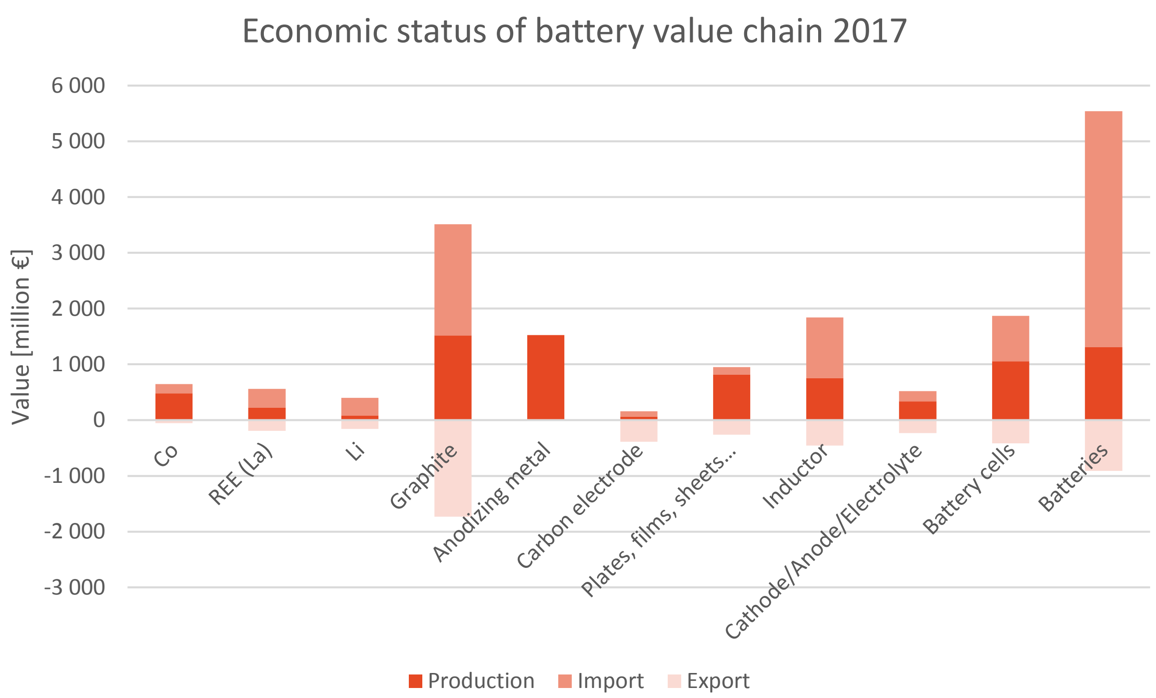

Figure 5. Relationship between production, import and export values for batteries, components and materials in Europe 2017. Note that the values present the whole industry volume not specific to batteries. [10]

The overview of battery value chain describes that the value which is produced, imported and exported is on a higher level in the component/part and end application stages compared on raw materials with exception of graphite. For the batteries significant share of the value is imported which supports the general perception of battery manufacturing focusing outside Europe [1]. However, there is still production in Europe but the demand of batteries in different end applications and products exceeds the production. For the battery cell in component stage, the seems to be some production as well as import. However, since battery manufacturing is mostly located outside the Europe, the battery cell markets can be somewhat limited. This can reflect also to the sub-component groups. Regarding anodizing metal group there is no statistical data on import and export which appears in single production bar.

For materials stage the graphite distinguishes from the other materials clearly. For it the production and export values are somewhat on the same level while the import has slightly larger ones. It should be noticed that graphite do not present the mined natural graphite but so called artificial graphite which is already a semi-

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manufactured material which explains the difference compared with the outcome in CRM-list 2017 which states heavy import reliance [11]. A great share (~65 %) of graphite is utilized in refractories for steelmaking and for foundries [11] at which time the value related to batteries value chain is in reality less. For other materials the values are notably lower. Cobalt has diverse distribution of the value with a relatively large production share. The PRODCOM-group for Cobalt compose of oxides and hydroxides so it describes the situation for processed materials not mined concentrates. In addition, reliability of statistical data on cobalt has been raised since trade figures might be on a rather coarse level [11]. Therefore, precaution should be considered when doing further conclusions. Even though lithium is not on the Critical Raw Materials list, it has been presented in the analysis since it is relevant material for battery industry. In this regard the values are significantly lover compared to other groups in the value chain. In addition, it should be noticed that in the PRODCOM-group of lithium there is also other materials such as vanadium oxides and hydroxides; nickel oxides and hydroxides; germanium oxides and zirconium dioxide which affects the trade figures.

The relation between production and import in Figure 6 expresses how dependent Europe is of import compared to the production. If the production is larger than import the indicator gets positive bar in Figure 6. It can be noticed that there is rather much fluctuation in the production-import relation entire value chain and no distinct pattern or trend in terms of production clustering within Europe can be identified. For some groups such as cobalt, plates and cathode there the indicator shows fairly high figures while for lithium and batteries the figures are lower. Rest of the groups receive figures around 0.5 indicating somewhat similar size of import and production values. It should be noted that Anodizing metal group has been left out from since no data on import has been completed in the statistics.

For cobalt figures there has been reported concerns on the statistical data as was discussed earlier. This might appear in unnecessary positive figures and therefore should be regarded with a critical viewpoint. As for plates, films and sheets there is rather strong production in Europe. However, in this group especially it should be noted that the products are not solely connected to the batteries but also to other industries. As a result plates and films utilized in other end applications are also counted in the figures which most likely increases the values. Cathode, anodes and electrolytes belong to the PRODCOM-group of Parts of electric accumulators including separators at which time the figures might contain some other part as well. Even though, the positive indicator value indicate that there is seem to be some markets for the parts. However, it should be noted that the overall values of production, import and export for this group is quite low (Figure 5).

Low production indicator value for batteries indicate rather heavy reliance on import which is fairly logical since the PRODCOM-group contains many different type of batteries which are used in different end application and large amount of battery manufacturers are situated outside Europe. For lithium, other type of oxides and hydroxides (e.g. vanadium, nickel, germanium, zirconium) are included in the PRODCOM-group which may affect and change the indicator value.

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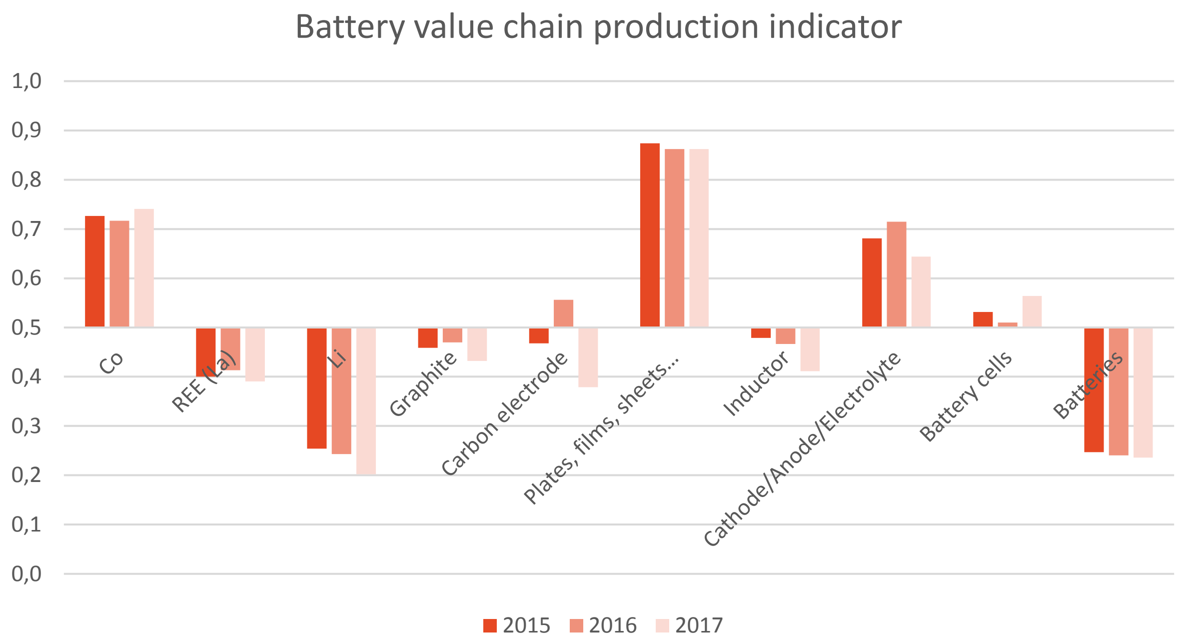

Figure 6. Production indicator (prod / imp + prod) for battery value chain in 2015, 2016 and 2017. [10]

The production/import share has for many groups remained to some extent on same level during the three years. Some fluctuation can be detected for carbon electrode, cathode and battery cells groups, however, the changes are not major. In addition, for lithium and indicator group there is a trend of decrease in the indicator during the last three years. In both cases the production has stayed at the same level while the import has increased which has resulted in the decrease in the indicator figure.

FUTURE PERSPECTIVES ON THE MARKET

The forecasted market balance for cobalt, covering all applications until 2020, indicates that supply matches demand within 1 %. Longer term projections for penetration of electric vehicles up to 2050 show that the cumulative demand for cobalt would require all the resources known today, even considering its relatively high recycling rate in the battery sector. However, this estimation is based on the assumption that the Li-ion technology relying on cobalt continues to be widely used up to 2050, which is unlikely as gradual introduction of other cobalt-free chemistries is expected to be seen during this time-frame (see section 3.2). [1]

The high purity of artificial graphite makes it desirable choice for Li-ion battery applications, but it is also more expensive [12]. Only moderate increase is expected to be seen in the demand of natural graphite because new applications rely more on artificial graphite. However, the price will decrease fast because the supply is abundant. There is already over supply in China and a lot of new projects in China and Canada are under way. [13]

The cathode materials market is in the state of becoming more scattered with more and more companies entering the market and providing a share of the global supply [1]. In addition, many of the major battery cell

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manufacturers such as Panasonic, LG Chem and BYD have started to develop their own in-house cathode materials production in order to better control the quality of the cathode material. [8] The average price of cathode active materials is likely to fall as manufacturers work toward replacing high cost cobalt metal with low cost nickel and manganese metals. [12]

ACTORS IN THE VALUE CHAIN

The main actors related to the value chain of Li-ion batteries used in EVs and ESS are discussed in this section. NiMH batteries are left out of this scope due to their smaller significance in vehicle and stationary energy applications. Some notes related to the geography of manufacturing of each part of the value chain are given first, followed by a list (Table 2) compiling the key companies.

RAW MATERIAL PRODUCTION

Production of cobalt is highly concentrated. Democratic Republic of Congo is the world's leading source of mined cobalt with 51% of the cobalt market volume, while China, Russia, Canada and Australia each have a share of about 5%. However, over 90% of cobalt import into the EU comes from Russia. [1]

Natural graphite is extracted from mines and exists in three forms including amorphous, crystalline and flake types. Flake type is the one used in Li-ion batteries. [12] Production of natural graphite is highly concentrated in China, which produces 66% of the natural graphite market volume. Other important producer countries are India (14%) and Brazil (7%). The majority of natural graphite import into the EU comes from China (57%) followed by Brazil (15%) and Norway (9%). [1]

Silicon metal and silicon alloys are emerging as anode active materials for Li-ion battery cells, but at present their share is negligible compared to other applications [1]. Therefore, silicon metal producers are not included in the accumulator value chain study.

COMPONENT MANUFACTURING

The production of anode active materials has long been dominated by Japan and China. EU-based companies such as SGL (DE), Imerys (CH) and Heraeus (DE), as well as US-based 3M, DuPont, Dow, Dow Corning, and Envia have also recently shown interest in the anode active materials market for Li-ion batteries, but they do not possess a significant share of the global supply yet. [1]

Production of cathode active materials is also dominated by Asia: of the total amount of cathode materials (by weight) in 2015, China produced 39%, Japan 19% and South Korea about 7%. EU-headquartered suppliers, Umicore and Johnson Matthey, together produced approximately 13% (by weight) of the global supply of cathode materials in 2015. [1] Umicore and Johnson Matthey are planning to further expand their production capacities of cathode materials (NCM, LFP and LCO) in Asia in order to tap into the demand from EV and consumer electronics applications [12].

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Companies such as BASF (DE), Dow (US), 3M (US), DuPont (US), Mitsubishi (JP) and LG Chem (KR) have recently shown interest or made acquisitions on installations to enter the cathode market but do not play a significant role in the global supply of the cathode active materials yet. [1]

CELL MANUFACTURING

Cell manufacturing for automotive applications is concentrated in Japan, South Korea and China, which haves significantly increased their manufacturing capacities even further in recent years. China plans further expansion of its manufacturing capacity for Li-ion battery cells and has announced construction of extra 19.3 GWh manufacturing capacity in addition to its 30.4 GWh. The manufacturing capacity of USA increased almost tenfold from 2014 to 2016 thanks to the construction of Tesla Gigafactory. [1]

In Europe the Li-ion cell manufacturing capacity has been moderate, but new facilities are under construction or have been announced. The expected evolution of manufacturing capacity in the EU is presented in Figure 7. The largest installation is announced by NorthVolt (SE), which plans to expand its production from 8 GWh (2020) to even 32 GWh in 2023. [8]

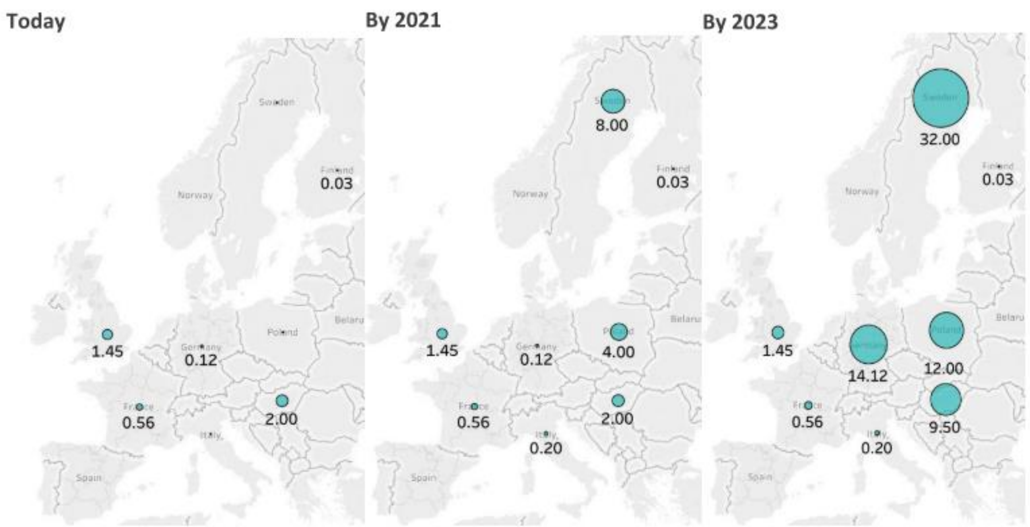

Figure 7. Expected progress of production capacity (in GWh) of Li-ion cells for mobility and stationary storage applications in the EU. Note: The representation is excluding the announcement made by TESLA, as the location was not revealed. Adopted from [8].

BATTERY PACK MANUFACTURING

Different strategies exist among car manufacturers in whether to invest and develop the required pack manufacturing capacity in-house or to outsource it. For example, GM (US) has completely outsourced the cell and pack manufacturing to LG Chem (KR), whereas other US-based company Tesla is planning to shift the manufacturing of cells, pack design and manufacturing in-house. Also joint venture type approaches are used:

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for example, Automotive Energy Supply Corporation (AESC) is jointly owned by Nissan and the Japanese electronics firm NEC. [1]

RECYCLING

At present recycling of Li-ion batteries is mainly limited to portable batteries since still there are no big volumes of battery waste originating from vehicles or ESS that have reached their end-of-life. Spent Li-ion (and NiMH) batteries are industrially recycled in many regions globally. [1]

The actors in the above-described parts of the Li-ion battery value chain are summarised in Table 2.

Table 2. Main actors in the value chain of Li-ion and NiMH batteries in EV and ESS use. Country code in parentheses represents the country of the headquarters of the company. The columns titled Europe and Rest of world refer to a significant presence of production facilities in these geographical regions. [1], [12]–[14]

Part of the value chain	Europe	Rest of world
Raw material production		Cobalt: Glencore (CH), China Molybdenum (CN), Fleurette Group (NL), Vale (BR), Gécamines (CD), Nornickel (RU), ERG (LU)
		Triton Minerals (AU), Hexagon Resources (AU), Focus Graphite (CA)
Sub-component production (anode and cathode materials)	Umicore (BE), Johnson Matthey (GB), BASF (DE)	Graphite anode: BTR (CN), Mitsubishi Chemicals (JP), Hitachi Chemicals (JP), Nippon Carbon (JP)
		NMC: Umicore (BE), Nichia (JP), Ningbo ShanShan (CN), Xiamen Tungsten (CN)
		NCA: Sumimoto (JP), Toda Kogyo (JP)
		LFP: Pulead Technology Industry (CN), Johnson Matthey (GB)
		LMO: Mitsui (JP), POSCO Chemtech (KR), JGC (JP)
Component manufacture (Li-ion cells)	Samsung SDI (KR), Nissan (JP), Bolloré (FR), Leclanche (CH)	Sanyo-Panasonic (JP), Samsung SDI (KR), LG Chem (KR), BYD (CN), AESC (JP), GS Yuasa (JP), Li Energy Japan (JP), Wanxiang (CN), Lishen Tianjin (CN), Toshiba (JP)
Application assembly (battery packs for EVs, ESS)	Johnson Matthey Battery Systems (GB), Deutche ACCUMOTIVE (DE), Kreisel Electric (AT)	In-house/Joint venture: BYD (CN), Nissan (JP), Mitsubishi Motors (JP), Tesla (US), AESC (JP), Lithium Energy Japan (JP)
		Outsourced: Samsung SDI (KR), LG Chem (KR)

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Recycling (battery)	Umicore Battery Recycling (BE), Accurec Recycling (DE), Glencore (CH), Valdi (FR)	Glencore (CH), Retriev Technologies (CA), AERC Recycling Solutions (US), GEM (CN), JX Nippon Mining and Metals (JP), Hunan BRUNP (CN)

3.2 SUBSTITUTION SOLUTIONS FOR CRM IN ACCUMULATORS

There are many material options for both anode and cathode side of the Li-ion batteries, enabling various battery designs. The same applies to the cathode side of NiMH batteries. However, the currently used material combinations almost exclusively employ CRMs at least on either electrode. The use of CRMs in Li-ion and NiMH batteries is summarised in the following table.

Table 3. Summary of the CRMs found in currently used Li-ion and NiMH battery designs.

	Anode side	Cathode side
Li-ion	Graphite	Cobalt
NiMH	Cobalt	Vanadium / REEs

3.2.1 SUBSTITUTIVE ELEMENTS

IN LI-ION BATTERIES

In the case of Li-ion batteries, substitution of CRMs is not the only driver for seeking alternative materials, but also the insufficient capacity, high cost, and toxicity of current commercial electrode materials. [9]

As for the **anode**, graphite-based carbons are the dominant active materials in EV applications. When high power is needed, lithium titanate $Li_4Ti_5O_{12}$ (LTO) is used as the anode material. Another possible substitution solution for graphite is the use of tin-based oxides (SnO and SnO_2). Promising results regarding high-power applications have been achieved especially by the combination of tin oxides with various carbon nanostructures. [9], [14] So far commercial examples of tin-based anode materials exist in portable applications [14].

Silicon (Si) has been considered as one of the most attractive anode materials for lithium-ion batteries because it has the highest gravimetric capacity among anodes. However, it has to be noted that silicon metal is on the EU's list of CRMs, although elsewhere in the world silicon is considered abundant. [9], [11] The drawback of the material is that it more than triples its volume when lithium ions are intercalated to form the alloy on the anode. This causes dramatic mechanical stress and a capacity fading during the discharge-charge process. To overcome this issue, many approaches have been applied to develop novel Si electrodes with high electrochemical performance, such as by designing the morphology of Si in the nanoscale or by surface coating. [9], [14] The use of silicon or carbon-silicon anodes are expected to characterise the future generation battery designs [1], [15].

Complex transition metal oxides and phosphates are currently the main **cathode** active materials used in Li-ion battery cells. These include: lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), lithium

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nickel cobalt aluminium oxide (NCA), lithium manganese oxide (LMO) and lithium iron phosphate (LFP). [1] There are four principal cathode materials used today for automotive applications: all of the above-mentioned except for LCO, which is more suitable for low-power applications [9]. Some state-of-the art Li-ion cells and their electrode material combinations used in EVs on the market in 2018 are presented in the next table.

Table 2. Manufacturers and users of Li-ion batteries employed in EVs [9].

Cell maker	Anode	Cathode	User company	Vehicle model
AESC	Graphite	LMO-NCA	Nissan	Leaf
LG Chem	Graphite	LMO-NMC	GM	Volt
Li-Tec	Graphite	NMC	Daimler	Smart
Li Energy Japan	Graphite	LMO-NMC	Mitsubishi	i-MiEV
Samsung	Graphite	NMC-LMO	Fiat	500
Lishen Tianjin	Graphite	LFP	Coda	EV
Toshiba	Graphite	NMC	Honda	Fit
Panasonic	Graphite	NCA	Tesla	Model S

One of the most promising lithium-ion battery cathode materials is LFP ($LiFePO_4$), as a substitute to LCO [14], especially for large-scale Li-ion batteries, such as for electric and hybrid vehicles and stationary ESS. The substitutive material combination is based on environmentally friendly, low cost, abundant raw materials. The drawback of the material is its very low electronic conductivity at room temperature, which means it can only achieve its theoretical capacity at a very low current density or at elevated temperatures. Various approaches to improve the poor conductivity have been used, such as coating $LiFePO_4$ with different conducting materials. [9] Several companies have commercialized lithium-ion batteries based on $LiFePO_4$ cathode [14], thus the solution is already on the market.

The replacement of cobalt has also succeeded on a laboratory scale by a lithium-rich cathode design, Li_5FeO_4. The design is advantageous not only because of cobalt substitution, but because oxygen also participates in the electrochemical reaction, increasing the capacity of the cell significantly. [16], [17]

IN NI-MH BATTERIES

A small amount of cobalt may be used on the anode of a NiMH battery, but the criticality studies usually concentrate on the use of REEs on the cathode side. For instance, the $LaNi_5$ alloy in NiMH batteries could be replaced by a REE-free titanium-iron alloy. However, currently there is no price incentive to do this because cerium and lanthanum, which form the largest part of the material combination, are inexpensive materials. [3], [18]

3.2.2 SUBSTITUTIVE TECHNOLOGIES

With the energy density of the Li-ion technology approaching its maximum, the research has proceeded to post-Li-ion systems [19]. It is assumed that in the short term, sodium-ion and lithium-sulphur battery technologies are the best candidates to reach sufficient technology maturity for wider commercial deployment. [20]

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SODIUM-ION BATTERIES

Compared with lithium, sodium (Na) has similar physical and chemical properties. However, Na is very abundant and low cost. However, the gravimetric and volumetric densities of Na-ion battery would not exceed those of its Li analogue because of the relatively heavier and larger Na atom and less-reducing potential of Na. On the other hand, as energy density is not a critical issue for stationary energy storage systems, developing room-temperature Na-ion batteries for this application is still a reasonable alternative. [21]

The electrode materials for Na-ion batteries are not yet established and there is a lot of variety on the researched materials. On the cathode side, layered transition metal oxides, tunnel-type oxides and phosphates have gained attraction, whereas on the anode side, carbon-based compounds, oxides and sulphides have been examined, to name a few. [21] Some of these alternatives employ cobalt.

The technology has already reached early commercialization stage, with a few efforts led by Aquion and Sumitomo Electric for stationary grid storage [20].

LI-AIR BATTERIES

Lithium-air systems, more precisely lithium-oxygen systems, are the most promising lithium batteries in terms of energy density, since the cathode active mass is not included in the battery system. Li-air batteries have the potential to achieve over an order of magnitude higher energy density than that of Li-ion batteries. Moreover, if the oxygen supplied is not included in the calculation, Li-air cells offer an energy density of about 11,000 Wh/kg. This value is approaching to the value for gasoline (octane) at 13,000 Wh/kg if the external oxygen supply is also neglected. Therefore, unlike other battery technologies, Li-air is competitive with liquid fuels. [9]

There are two types of Li-air batteries: aqueous and non-aqueous, and both types involve the reduction of O_2. In non-aqueous Li-air battery, the solid Li_2O_2 accumulates in the pores of the porous substrate cathode on discharge. Various catalysts have been utilized in order to reduce the voltage separation in this Li-air battery type, but, if a catalyst is used, controlling its size, morphology, and distribution within the pores is a challenge. Some of the tested catalysts employ cobalt, but it can be assumed that the needed amounts of cobalt in the catalyst would be significantly smaller than the amounts used in Li-ion battery cathodes. Moreover, there is a number of potential non-CRM based catalysts available, such as manganese oxides. Another challenge in non-aqueous Li-air batteries is to identify electrolyte materials that satisfy all the requirements of solubility, wettability, and stability. In addition, if the cell is to operate in ambient air, the penetration of CO_2 and H_2O must be avoided, allowing only O_2 to enter the cell. [9]

For aqueous Li-air battery, the system can only function with a solid electrolyte layer, which should be an ionic conductor, covering the lithium anode, since lithium reacts violently with water. Although the benefit of the aqueous system is that H_2O does not have to be excluded from the cathode, it is necessary to exclude CO_2 to avoid formation of Li_2CO_3 instead of LiOH. Therefore, aqueous Li-air battery faces many challenges similar to the non-aqueous Li-air battery for practical implementation. [9]

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LITHIUM-SULPHUR BATTERIES

Due to the abundance and low cost of elemental sulphur, lithium-sulphur (Li-S) battery has been considered as an advantageous choice for post-Li-ion systems. Sulphur is expected to deliver a specific capacity of 1675 Ah/kg and an energy density of 2600 Wh/kg, which are 3–5 folds higher than those of state-of-art Li-ion batteries. [19] Li-S batteries are also environmentally safe when compared to toxic cobalt oxide cathodes, which are currently used in Li-ion batteries [20]. In this battery construction, lithium forms the anode, whereas sulphur and carbon are used on the cathode side. [19]

Key applications of Li-S are transportation, military and defense, and stationary grid batteries. Current market for Li-S is in the pilot stage: a few pilot tests have already been done or planned (Sion, Oxis), and a pilot-scale manufacturing process designed (Polyplus). [20] Li-S technology is assumed to gain momentum by 2025 due to the high energy density and cycle life it can provide. The lack of technical know-how and sophistication related to the technology likely prevents its earlier adoption. [12]

It is estimated that both Li-air and Li-sulphur batteries will be commercially available after 2030 [20].

LIQUID ORGANIC HYDROGEN CARRIERS

With the transition of the energy system toward a higher share of renewable energy, hydrogen is often considered a very capable future energy storage and transport medium as it can be produced with renewable energy via electrolysis. However, due to the limitations related to the storage of hydrogen and the considerable investment costs that are necessary to establish a sufficient distribution infrastructure for hydrogen, researchers work on future concepts for the storage and transport of hydrogen in chemically bound forms, referred to as energy carrying compounds. [22]

One example of energy carrying compounds is liquid organic hydrogen carrier (LOHC), where hydrogen is covalently bound to a liquid carrier substance via hydrogenation. When needed, hydrogen can be released for energy use via dehydrogenation. The storage medium itself is not consumed but can be reloaded with hydrogen in further cycles. Various substances have been studied as potential hydrogen carrier media. Among the best understood LOHC systems with convenient material properties for the application as an energy carrier are heterocyclic aromatic hydrocarbons. [22]

LOHC is so far rather unrecognised technology in wider perspective, but in various scenarios LOHC could be used in long-distance transport of energy or for stationary energy storage, and therefore it could replace Li-ion batteries. It could also be used as energy storage in fuel cell vehicles using hydrogen, similarly as batteries are used for storing electrical energy in EVs. [23]

3.3 SUMMARY OF THE ACCUMULATOR VALUE CHAIN

The value chain of Li-ion batteries is quite heavily concentrated in Asia, namely in China, Japan and South Korea. However, Umicore and Johnson Matthey are strong players in the field of cathode material manufacture, and

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there are some active European companies also in the assembly of battery packs. Recycling sector of batteries is rather diversely spread out between Europe, North America and Asia.

Cobalt, used in the cathode material of Li-ion batteries, is identified as the most critical material to be substituted, and there is also commercial incentive for this because of cobalt's high price. There are already cobalt-free cathode material options on the market, but the best functionality is so far achieved with cobalt-bearing options, especially with nickel cobalt manganese complexes (NCM). This material is however continuously being developed to contain less cobalt. [12] There is less motivation to substitute (natural) graphite on the anode side, as there is no similar price incentive.

The substitutive solutions on the element and technology level (technologies beyond Li-ion) attached to a timeline of expected commercialisation are summarised in Figure 8.

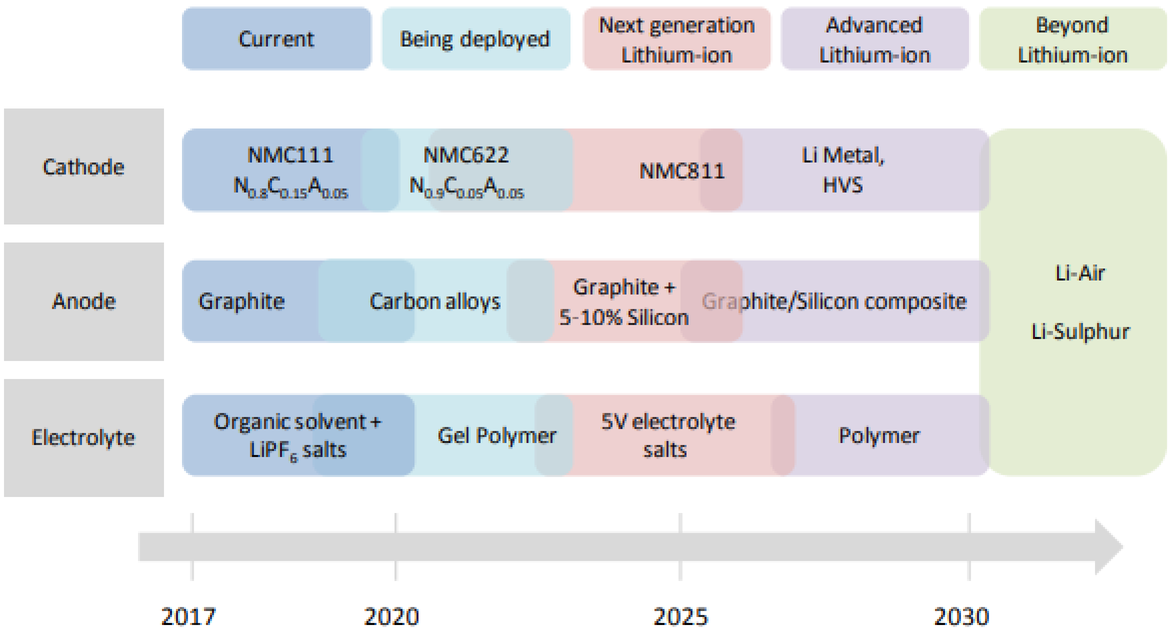

Figure 8. The estimated beginning of commercialisation for cathode, anode and electrolyte materials in current-type Li-ion batteries and post Li-ion technologies. Adopted from [24].

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4 ALLOYS

This chapter will concentrate on the economic assessment of substitution trajectories for CRMs used in metal alloys in transportation sector in two applications: automobiles and aircrafts.

Transportation is defined by the movement of people and goods over distances by vehicles travelling in land, water and air [1]. The transport sector provides products, i.e., vehicles, and services, e.g., transportation services or mobility-as-a-service gateways. As the focus of the research is on materials, particularly critical raw materials (CRMs) included in alloys, this study will concentrate on the products in transportation sector: the vehicles, especially on the alloys included in them. Additionally, given that the whole value chain of the CRMs and their substitution will be covered in this research, the attention will be put on two key categories of vehicles: automobile and aircraft. Indeed, substitution of CRMs in the transportation sector is an urgent demand due the extreme conditions of temperature, wear and corrosion that are frequent in transportation application [2].

Table 1 summarises the most important alloy categories with CRMs used in the selected two transportation applications: automobile and aircraft.

Table 1. The main alloy categories with CRMs included in automobile and aircraft.

Vehicle	Alloy category	Alloy type	Use, estimated amount	CRM included	Importance/ amount
Automobile	Ferrous alloys	Advanced high-strength steels (AHSS, HSLA)	Body, drivetrain	Nb, V	Nb ~ 100 g/car
	Stainless steels	Stainless steels	Exthaust system	Nb	Nominal
	Aluminium alloys	2000 series (Cu+Mg) 5000 series (Mg+Mn), 6000 series (Mg+Si) 7000 series (Zn+Mg)	Drivetrain, heat exchangers	Mg	Mg ~ 3 kg/car, ~3/4 of this amount is included in aluminium alloys
	Magnesium alloys	Wrought and cast alloys	Suspension [3]	Mg	Mg ~ 3 kg/car, ~1/4 in magnesium alloys
	Cobalt based alloys	Stellite	Exhaust valves of internal combustion engine, valve seats, valves	Co, (W)	Co ~42 g/car
	Lead alloys, tin alloys	White metal, PbSnSb	Bearings in the motor	Sb	Nominal

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	Copper alloys	Copper beryllium alloys	Wire harnesses and connectors	Be	Nominal
	Nickel alloys	Ni-P	Plating	P	Nominal
Aircraft	Nickel-based superalloys		Engines, turbine blades	Co, Nb, V, Ta, …	Significant
	Titanium alloys	Ti-Nb, Ti-Nb-Zr, Ti-Nb-Zr-Ta, Ti-Al-Nb, Ti-Al-V	Airframe, engine parts	V (Nb, Ta)	Significant
	Aluminium alloys	2000 series (Cu+Mg) 5000 series (Mg+Mn), 6000 series (Mg+Si) 7000 series (Zn+Mg)	Fuselage, lower wing and upper wing skins	Mg, Sc	Significant

Magnesium is included in *automobiles* both as an base alloy and as an alloying element included in aluminium alloys. On average, automobiles involve 3 kg of magnesium [3]. Most of the magnesium in automobiles falls within the *suspension* subsystem, while also *drivetrain*, *closures* and *body* contain some of the magnesium [3]. In general, the most common magnesium alloy applications in automobiles include gearboxes, steering column and driver's airbag housing, steering wheels, seat frames and fuel tank covers. Most of the magnesium alloy components in the automobiles are manufactured by die casting [4]. In aerospace applications, magnesium is included in aluminium alloys as an alloying element, but according to Grilli et al. [2], this is one of the most significant applications of magnesium in engineering field.

Magnesium is a critical raw material with the second highest economic importance to EU and with a high risk of supply. Magnesium has been listed as a critical raw material for the EU since the original assessment in 2010 [5]. Magnesium is a relatively common element: eight most abundant element in the Earth's crust and the third most abundant element in solution in seawater. Magnesium exists in different minerals, such as dolomite, $CaMg(CO_3)_2$, magnesite, $MgCO_3$, and carnalite, $KCl{\cdot}MgCl_2{\cdot}6H_2O$, which are primarily (by 87%) supplied by China. There is no production of pure magnesium in EU, thus EU relies 100% in import. However, semi-finished products of magnesium, particularly magnesium alloys and aluminium alloys involving magnesium, are manufactured in Europe, followed by their utilisation in various end uses, Figure. 1. In EU, transportation covers 58% of the magnesium end use. The substitution index of magnesium is 0.91 (the substitution index varies between 0..1, with 1 being the least substitutable) [5]. Magnesium in cast alloys and alloying elements in aluminium alloys can be partially substituted, mainly by composite materials, e.g., carbon-fibre reinforced plastics, titanium alloys and steel, but the substitution is then comprimised by higher costs and/or weight. In aerospace applications, where the strength-to-density ratio is of key importance, the Al-Mg-Zn alloys can be substituted by, e.g., Al-Li alloys (called also the third generation of Al-Li alloys) yet these often contain some Mg, up to 0.8 wt.% [2].

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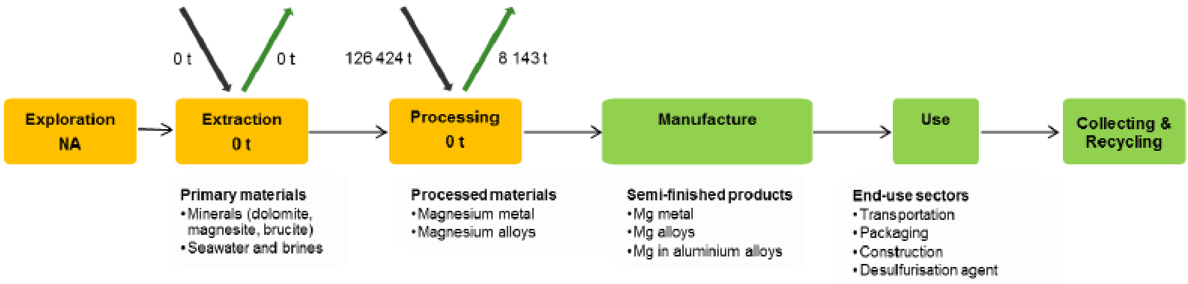

Figure 1. Simplified European value chain for magnesium [5].

Niobium is used in automobiles in small quantities in a large number of alloying applications. The more concentrated masses are however mainly found in certain high-strength steel applications, although to in varying amounts depending on the car model and specification. The conventional low-specified midsize car (CML): the largest mass of critical materials is represented by niobium (63.39 g). The high niobium content is mostly due to the its use as an alloying agent in high-strength steel and nickel alloys used in *Body Structure*, *Engine System* and in structural components of the seats in the subsystem *Seating*. The conventional high-specified midsize car (CMH), the second largest mass of critical materials is represented by niobium (81.42 g) used in nickel and high-strength steel alloys. The largest portions of the mass can be found in the subsystem *Engine System* where metallurgical use in the exhaust treatment system contributes the most. The subsystems *Seating* and *Body Structure* also contain substantial amounts of niobium alloyed high-strength steel. The midsized hybrid car (HMM) studied has a powertrain with a combination of a diesel engine and an electric motor with Li-ion battery. The largest concentrations of niobium are found in high-strength steel alloys in the subsystems *Exhaust Cold End* and *Body Structure*, similar to the use in CML and CMH but with additional mass found in alloying applications in the exhaust system. The large conventional medium specified car (CLM) has an automatic gearbox, a diesel engine and FWD. The largest mass of the materials studied is represented by niobium (89.81g), mainly used as high-strength steel and nickel alloys in *Seating* and *Engine System*.[1] In aircraft application, niobium is icluded as an alloying element included in nickel-based superalloys primarily employed in gas turbines.

Niobium has been listed as a critical raw material for the EU since the original assessment in 2010 (European Commission 2010, 2014c, 2017b). Most of the World's niobium resources are located in Brazil, with 95% of World's niobium production. Niobium is mostly mined as a primary product of carbonatite- and/or granite-hosted deposits. The British Geological Survey listed niobium as one of the materials that will most likely be in short supply globally in the future (BGS 2015). The substitutability of niobium has been assessed by the substitution index of 0.94 for supply risk and 0.91 for economic importance.

Niobium is principally imported into the EU in the form of ferroniobium and niobium unwrought metal, alloy, and powder, thus EU does not contribute to the processing of niobium ore in the value chain, Figure. 2. Globally, 90% of the niobium production is used to produce ferro-niobium, which is used in the production of high-strength low-alloy (HSLA) and advanced high-strength steels (AHSS). Indeed, EU holds plenty of steel production, directed both to automotive and other end use sectors of HSLA and AHSS. Through the use of HSLA and AHSS in automobiles and other vehicles, roughly 30 % of the niobium ends up in automotive industry.

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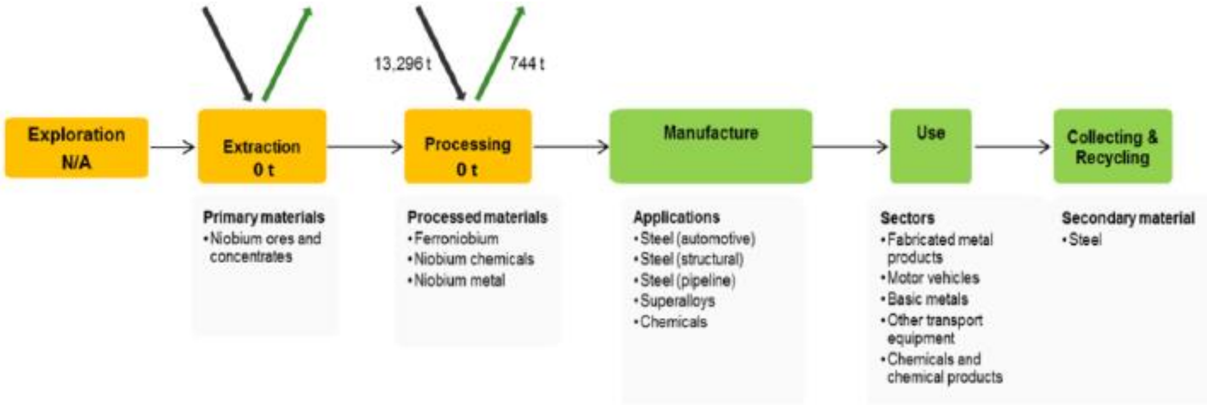

Figure 2. Simplified European value chain for niobium [5].

Cobalt is included in the automobiles in small amounts, with estimates of 42 g per car [3]. Most of the cobalt, more than 75% by mass, is included in drivetrain, with minor contribution by suspension, heating, ventilation and air conditioning (HVAC) and electrical systems. In aircraft applications, cobalt is included as an alloying element associated with nickel-based superalloys, which find use primarily in gas turbines.

Cobalt exists at relatively low quantities in Earth's crust, approximately 27 parts per million. It appears as mineral deposits, included in cobaltite, CoAsS, skutterudite, $(Co,Ni)As_{3-x}$, and erythrite, $Co_3(AsO_4)2{\cdot}8H_2O$. Cobalt may be found at economic concentrations in sediment-hosted deposits (e.g., in Democratic Republic of Congo), hydrothermal and volcanogenic deposits (e.g., Finland, Sweden, Norway) and magmatic sulphide deposits (e.g., Russia, Canada, Australia). Cobalt is mainly extracted as a by-product of co-product of nickel or copper production and, therefore, the cobalt beneficiation is dependent on the exploitation of nickel and cobalt base metals [5]. Cobalt is characterized by the substition index of 1.0, which means it is not really substitutable. According to U.S. Geological Survey, substitution for cobalt would results in a loss in product performance [6]. Such substitutes as iron, iron-cobalt-nickel, nickel, cermets or ceramics (cutting and wear-resistant materials) and nickel-based alloys or ceramics (elevated-temperature applications) are proposed [6].

Small quantities of cobalt are mined in the EU, more precicely in Finland, corresponding roughly to 1 % of global cobalt mine production. However, concerning refined cobalt, EU covers 18%, with 13% contribution by Finland and 5% by Belgium. Thus, the EU value chain covers all steps in cobalt utilization, Figure. 3. Worldwide, about 40% of cobalt is used in metal applications, with chemicals corresponding to 60% and battery chemicals being the most important end use.

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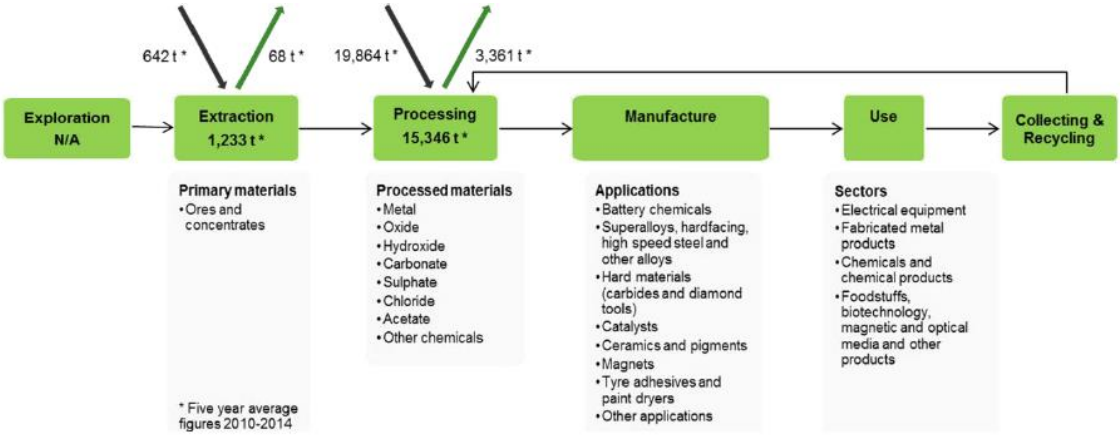

Figure 3. Simplified European value chain for cobalt [5].

Vanadium has been included in the EU critical raw materials list since 2017. Vanadium is typically obtained as a by-product in steel production. The most common vanadium.-bearing minerals include patronite, VS_4, vanadinite, $Pb_5(VO_4)_3Cl$, and carnotite, $K_2(UO_2)_2(VO_4)_2{\cdot}3H_2O$, but vanadium may also found in phosphate, bauxite and iron ores. When bound to iron ores, vanadium may be enriched in vanadium slag, from which V_2O_5 and V_2O_3 may be produced and further refined into metallic V [5].

Most of the vanadium (about 80%) produced worldwide is used as ferrovanadium or as a steel additive in high-strength low-alloy steels (HSLA, AHSS). Mixed with aluminium in titanium alloys is used in jet engines and high speed air-frames, and steel alloys are used in axles, crankshafts, gears and other critical components. In 2003, the contribution of other alloys than steels, cast irons and superalloys to the end use of vanadium was approximately 6%. Vanadium alloys are also used in nuclear reactors because vanadium has low neutron-adsorption abilities and it does not deform in creeping under high temperatures. No acceptable substitute for vanadium is currently available in aerospace titanium alloys [6], with substitution indexes of 0.94 (supply risk) and 0.91 (economic importance).

Global vanadium production between 2010 and 2014 amounted annually to 71 kt. The only reported producers of vanadium in the form of vanadium oxides are China (53%), South Africa (25%), Russia (20%) and Kazakhstan. Thus EU is fully reliant on the vanadium ore import, Figure. 4, but later steps in the value chain are efficiently covered.

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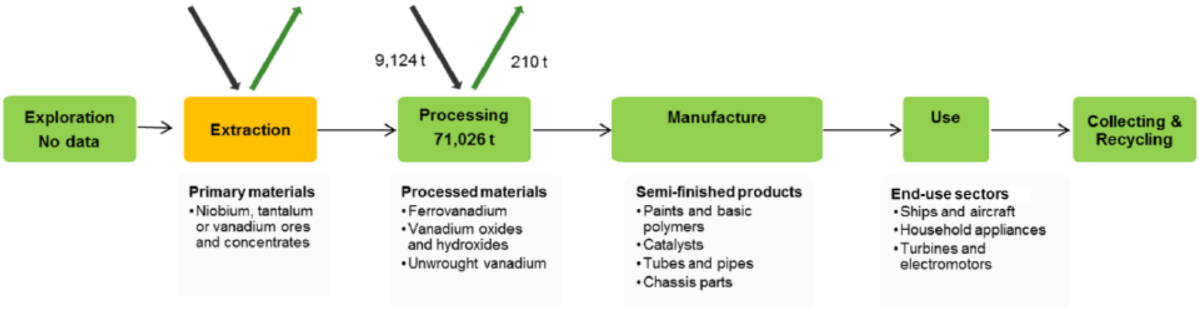

Figure 4. Simplified European value chain for vanadium [5].

Tantalum is the key alloying element in nickel-based superalloys used for the most critical, high-temperature rotor-blase applications in aircraft turbine engines [7]. Among the World consumption of tantalum by application, 22% was consumed to superalloys. The annual production of tantalum in 2017 was 1300 tonnes [6]. Most tantalum occurs in the ores of niobium, tin or lithium, and it is systematically obtained as a co-product from the extraction of these elements ([5].

Tantalum has been included as a EU Critical Raw Materials list in 2011 and 2017, with a substitution index of 0.95. It is stated that the following materials can be substituted for tantalum in high-temperature applications, but usually with less effectiveness: hafnium, iridium, molybdenum, niobium, rhenium and tungsten [6]. However, among these suggested substitutes, most are CRMs (hafnium, iridium, niobium, tungsten) similarly to tantalum.

There is no tantalum mining in Europe. World annual production of tantalum is about 1 800 tonnes, of which Rwanda accounts for 31%, Congo for 19% and Brazil for 14%. However, majority (81%) of tantalite concentrates is traded to EU from Nigeria. Nevertheless, EU has plenty of manufacturing employing tantalum, Figure. 5. Overall, 22% of the end use of tantalum falls into the realm of superalloys.

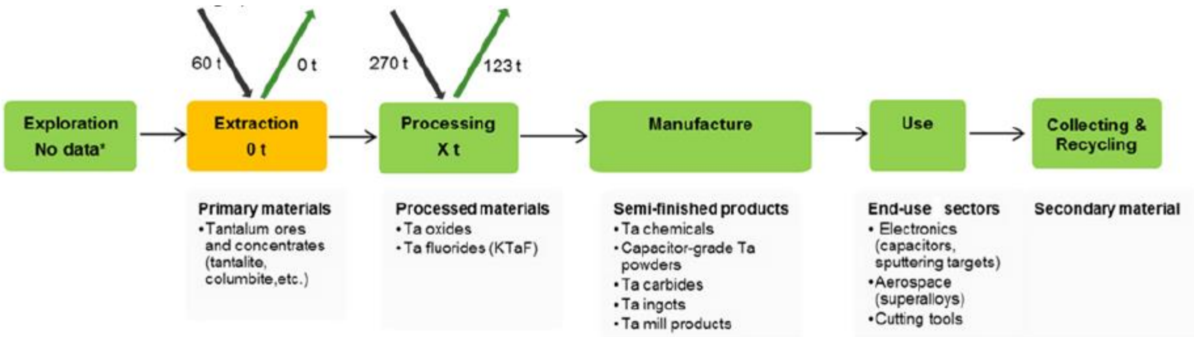

Figure 5. Simplified European value chain for tantalum [5].

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4.1 ECONOMIC ANALYSIS OF ALLOYS VALUE CHAIN

STATISTICAL DATA

For the economic analysis based on statistics (Eurostat, PRODCOM-data base) of the alloy value chain, the analysis has been divided to automobile and aeroplane value chain separately. There are some similar elements and product groups used in both chains which means that the graphs are partly similar since the value of a product/application specific component or material cannot be differentiated. However, this is not seen as a restriction since the relevance of a value chain phase for European manufacturing (industry) is the key outcome of the analysis. For the analysis, the structural composition of both applications has been produced in the tables below. Based on these divisions, the schematic economic value chain description has been produced and presented separately in the next two sections.

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Table 2. Structural composition of automobile with PRODCOM codes and names.

Application	*Component*	*Sub component*	*Materials*	*PRODCOM code and name*
Automobile				*29103000 Motor vehicles for the transport of <= 10 persons* *29102100 Vehicles with only spark-ignition engine of a cylinder capacity <= 1 500 cm³* *29102230 Motor vehicles with only petrol engine > 1 500 cm³ (including motor caravans of a capacity > 3 000 cm³) (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)* *29102230 Motor vehicles with only petrol engine > 1 500 cm³ (including motor caravans of a capacity > 3 000 cm³) (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)* *29102330 Motor vehicles with only diesel or semi-diesel engine > 1 500 cm³ but <= 2 500 cm³ (excluding vehicles for transporting >= 10 persons, motor caravans, snowmobiles, golf cars and similar vehicles)*
	Bodies			*29201030 Bodies for motor cars and other motor vehicles principally designed for the transport of persons (including for golf cars and similar vehicles) (excluding those for transporting >= 10 persons)* *29201050 Bodies for lorries, vans, buses, coaches, tractors, dumpers and special purpose motor vehicles including completely equipped and incomplete bodies, vehicles for the transport of >= 10 persons*
	Chassies			*29104400 Chassis fitted with engines, for tractors, motor cars and othermotor vehicles principally designed for carrying people, goods vehicles and special purpose vehicles including for racing cars*
	Gear boxes			*29323033 Gear boxes and their parts*
	Drive axels			*29323036 Drive-axles with differential, non-driving axles and their parts*
		HSLA steels		*24312050 Sections, of alloy steel other than stainless, cold finished or cold formed (e.g. by cold-drawing)*
		Light metal casting		*24531010 Light metal castings for land vehicles excluding for locomotives or rolling stock, construction industry vehicles* *24531020 Light metal castings for transmission shafts, crankshafts, camshafts, cranks, bearing housings and plain shaft bearings (excluding for bearing housings incorporating ball or roller bearings)*

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		Al alloy		*24421153 Unwrought aluminium alloys in primary form (excluding aluminium powders and flakes)* *24421154 Unwrought aluminium alloys (excluding aluminium powders and flakes)* *24421155 Unwrought aluminium alloys in secondary form (excluding aluminium powders and flakes)*
			Mg	*24453025 Magnesium and articles thereof (excluding waste and scrap), n.e.c.*
			Ta	*24453023 Tantalum and articles thereof (excluding waste and scrap), n.e.c.*
			Nb	*24453055 Beryllium, chromium, germanium, vanadium, gallium, hafnium ("celtium"), indium, niobium ("columbium"), rhenium and thallium, and articles of these metals, n.e.c.; waste and scrap of these metals (excluding of beryllium, chromium and thallium)*

Table 3. Structural composition of aeroplane with PRODCOM codes and names.

Application	***Component***	***Sub component***	***Materials***	***PRODCOM code and name***
Aeroplane				*30303200 Aeroplanes and other aircraft of an unladen weight <= 2000 kg, for civil use* *30303300 Aeroplanes and other aircraft of an unladen weight > 2000 kg, but <= 15000 kg, for civil use* *30303400 Aeroplanes and other aircraft of an unladen weight > 15 000 kg, for civil use*
	Aircraft engines			*30301100 Aircraft spark-ignition internal combustion piston engines, for civil use* *30301200 Turbo-jets and turbo-propellers, for civil use* *30301300 Reaction engines, for civil use (including ramjets, pulse jets and rocket engines) (excluding turbojets, guided missiles incorporating power units)*
	Parts of aircraft engines			*30301500 Parts for aircraft spark-ignition reciprocating or rotary internal combustion piston engines, for use in civil aircraft* *30301600 Parts of turbo-jets or turbo-propellers, for use in civil aircraft* *30305090 Parts for all types of aircraft excluding propellers, rotors, under carriages, for civil use*
		Ferro alloys		*24101290 Other ferro alloys n.e.c.*

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		Light metal casting		*24531010 Light metal castings for land vehicles excluding for locomotives or rolling stock, construction industry vehicles* *24531020 Light metal castings for transmission shafts, crankshafts, camshafts, cranks, bearing housings and plain shaft bearings (excluding for bearing housings incorporating ball or roller bearings)*
		Al alloy		*24421153 Unwrought aluminium alloys in primary form (excluding aluminium powders and flakes)* *24421154 Unwrought aluminium alloys (excluding aluminium powders and flakes)* *24421155 Unwrought aluminium alloys in secondary form (excluding aluminium powders and flakes)*
			Mg	*24453025 Magnesium and articles thereof (excluding waste and scrap), n.e.c.*
			Ta	*24453023 Tantalum and articles thereof (excluding waste and scrap), n.e.c.*
			Nb, V	*24453055 Beryllium, chromium, germanium, vanadium, gallium, hafnium ("celtium"), indium, niobium ("columbium"), rhenium and thallium, and articles of these metals, n.e.c.; waste and scrap of these metals (excluding of beryllium, chromium and thallium)*
			W	*24453013 Tungsten (wolfram) and articles thereof (excluding waste and scrap), n.e.c.*

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The automobile value chain composed of 12 groups which can be divided roughly to four stages which are materials, sub-components, components/parts and end applications. More detailed division together with PRODCOM codes and names can be seen in Table 2. In Figure 6 the relationship between production, import and export based on the statistical data has been presented. The positive values present how much value has been either generated and imported to Europe while the negative value present how much leaves as export from Europe.

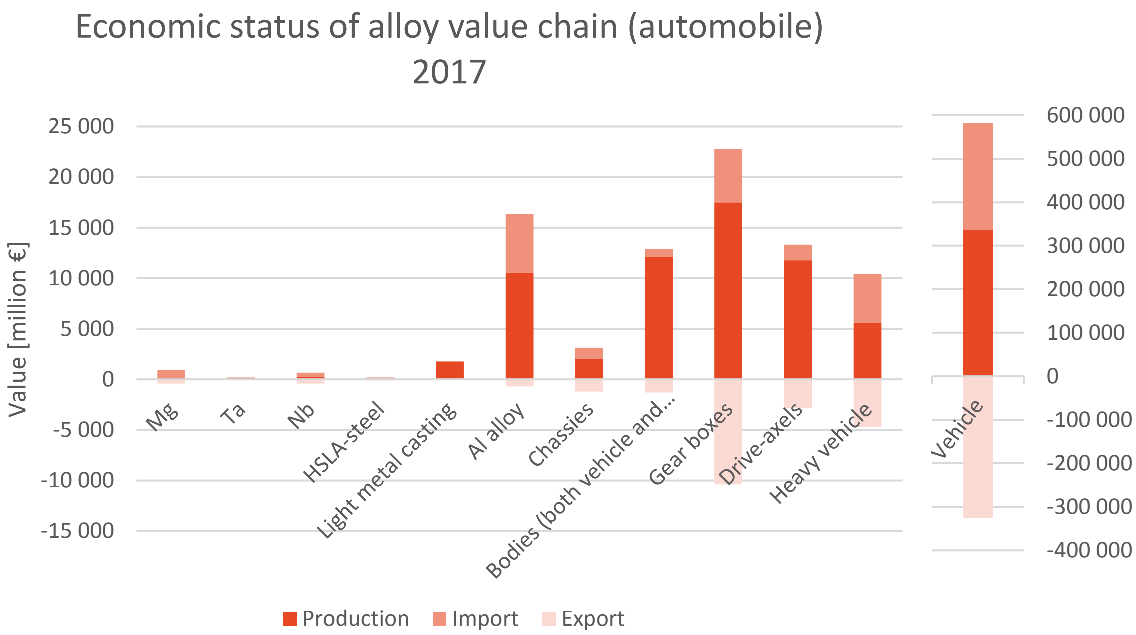

Figure 6. Relationship between production, import and export values for automobiles, components and materials in Europe 2017. Note that the values present the whole industry volume not specific to automobiles. [8]

The overview of automobile alloy value chain describes that large production exists especially in the component/part and end application stages. It should be noted that the scale for passenger vehicles on the right is different than for the other groups. The vehicle manufacturing industry is very significant industry which seems to generate also notable manufacturing upstream in the value chain. Beside the high manufacturing value, significant share of vehicles are also exported from Europe. On the other hand vehicle markets are global which makes the import values substantial. It should be noticed, that not all manufactured vehicles are exported, but re-export of imported vehicles may occur which explains the large value of export. In addition, exported figure may contain also older vehicles which are sold outside Europe as second-hand car.

As for the component/part stage manufacturing generates significant value for Europe. In this stage, there is some export but not as much as in the end application stage. It seems to be that a great share of manufactured components and parts are utilized within Europe, which is logical due to the massive end application industry. In addition, service market may also consume components and parts.

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The results for sub-component stage shows discrepancy between the groups. For Aluminium alloys there is rather significant manufacturing but for HSLA-steels and Light metal casting the manufacturing is remarkable lower.

For the materials, the values are substantially lower compared to other groups downwards on the value chain. This rather logical since the margin and value of a product within a value chain increases when moving towards the end application.

The relation between production and import in Figure 7 expresses how dependent Europe is of import compared to the production. If the production is larger than import the indicator gets positive bar in Figure . For Automobile alloy value chain it can be noticed that in overall reliance on import decreases when moving downwards on the value chain. Especially component and part stage has strong production within Europe providing parts to the end application industry. Since the markets of end applications are global, consumers are aware of high-end products and competing markets which may increase the import in relation to production. Even though the share of import increases when moving upward to the materials in the value chain, it can be noticed that there is still some production in Europe.

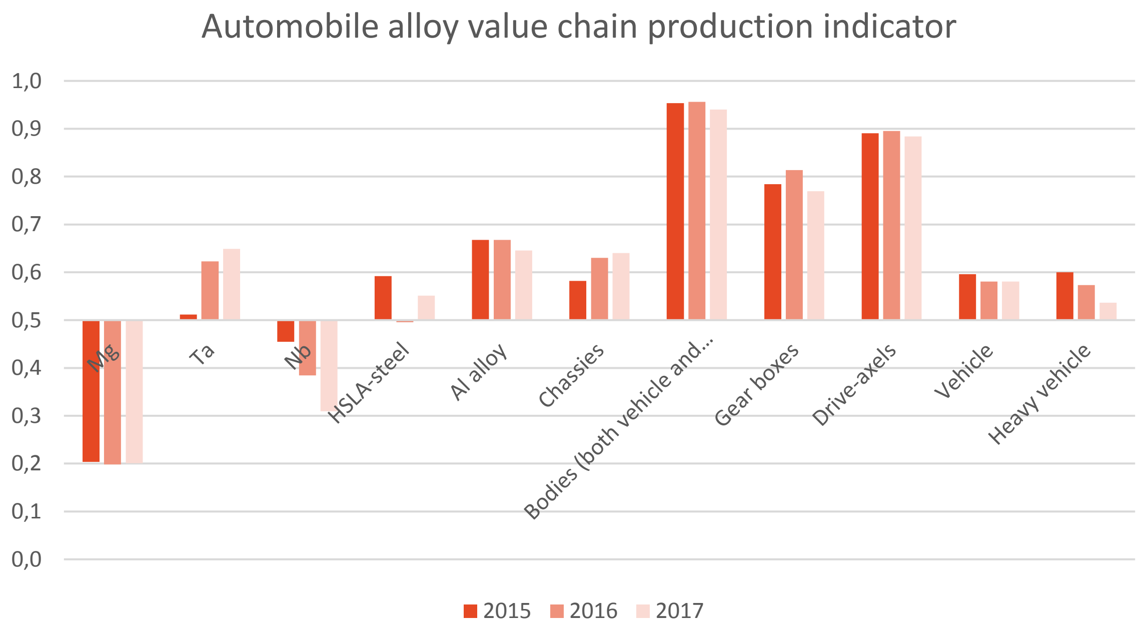

Figure 7. Production indicator (prod / imp + prod) for automobile alloy value chain in 2015, 2016 and 2017. [8]

When observing the time variations in the production indicator, no enormous changes has occurred. However, some indications such as increase in production and at the same time decrease in the import of tantalum has taken place. It should be noticed that tantalum PRODCOM group compose of tantalum and articles thereof (excl. waste and scrap), not of ore or concentrate which has been presented in the recent CRM-list 2017 to be totally reliant on import. The production of tantalum is most likely originated from manufacturing industry which utilizes

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goods containing tantalum and produces so called “pre-consume” scrap [5]. In addition, the total values and quantities for tantalum in PRODCOM data base are low at which time changes may have larger effect. Another some what considerable change has occurred for niobium which production has decreased while import increased. It should be noticed that PRODCOM group for niobium contains also other elements such as beryllium, chromium, germanium, vanadium at which time the indicator doesn’t tell solely the situation for niobium. According to CRM-list 2017, there has been increase in ferroniobium export from Canada to EU which could partly explain the changes [5].

The aeroplane value chain composed of 11 groups which can be divided roughly to four stages which are materials, sub-components, components/parts and end applications. More detailed division together with PRODCOM codes and names can be seen in Table 5. In **Figure** Figure 8 the relationship between production, import and export based on the statistical data has been presented. The positive values present how much value has been either generated and imported to Europe while the negative value present how much leaves as export from Europe.

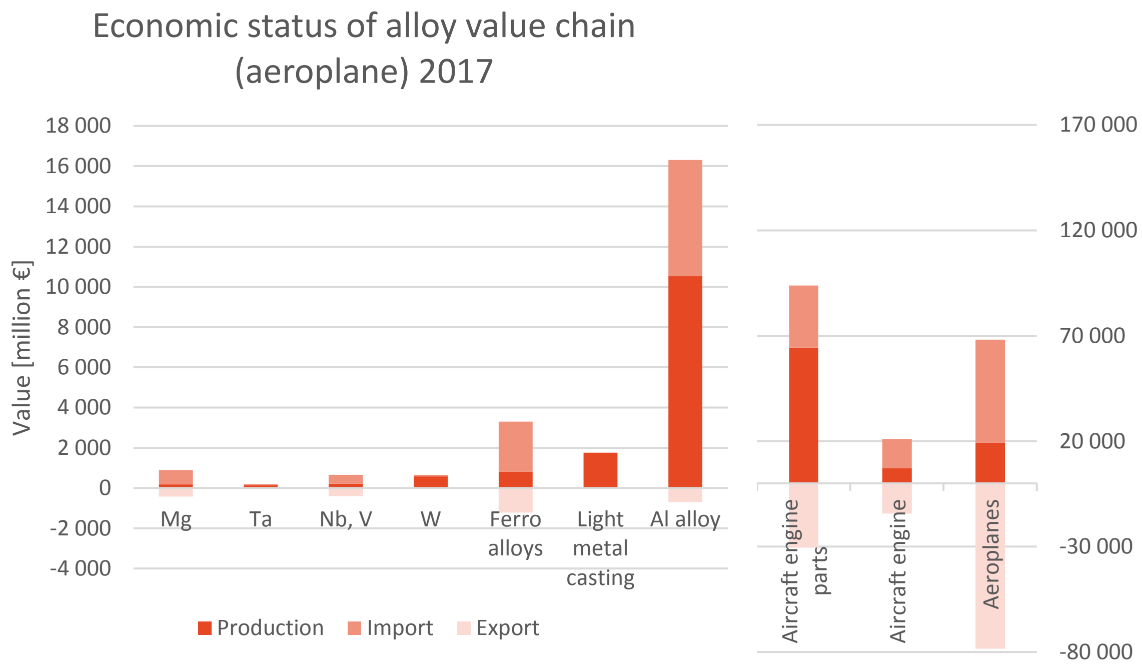

Figure 8. Relationship between production, import and export values for aeroplanes, components and materials in Europe 2017. Note that the values present the whole industry volume not specific to aeroplanes. [8]

The overall value chain figure resembles rather well automobile value chain where positive value through import and production increase towards the end of value chain. However, it seems to be that especially in the aeroplane value chain the aircraft engine parts group produces significant value. As for the end application, remarkable amount of aeroplanes are exported even though production is low. This can be partly explained through the export of used aeroplanes. For example, Finland has export of large aeroplanes even though there is no

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production. Airliners sell their old fleet which generates export without production. As for the materials stage the values are remarkable lover than for the groups at the end of the value chain.

The relation between production and import in **Figur**Figure 9 expresses how dependent Europe is of import compared to the production. If the production is larger than import the indicator gets positive bar in Figure 9. For Aeroplane alloy value chain it can be noticed that fluctuation on the import dependency exists throughout the value chain. It seems to be that even though the aeroplane manufacturing industry is significant in Europe producing notable amount (12-19 billion €) of value, there is also considerable amount of import. Aeroplanes are large investments which makes the markets very competitive and global.

In component and part stage high demand of engine parts by the manufacturers and service work seems to generate "local" demand in the form of European production. As for alloys Europe is more dependent import on ferrous alloys in which Asian actors are strong especially on the bulk side.

For the materials stage, similar elements are in relevance for aeroplanes as for automobiles. One difference is tungsten for which rather high production indicator can be identified. According to the CRM-list 2017 material fact sheet, there may be some uncertainties in the origin data entries within statistics [5], which may reflect as a positive indicator value.

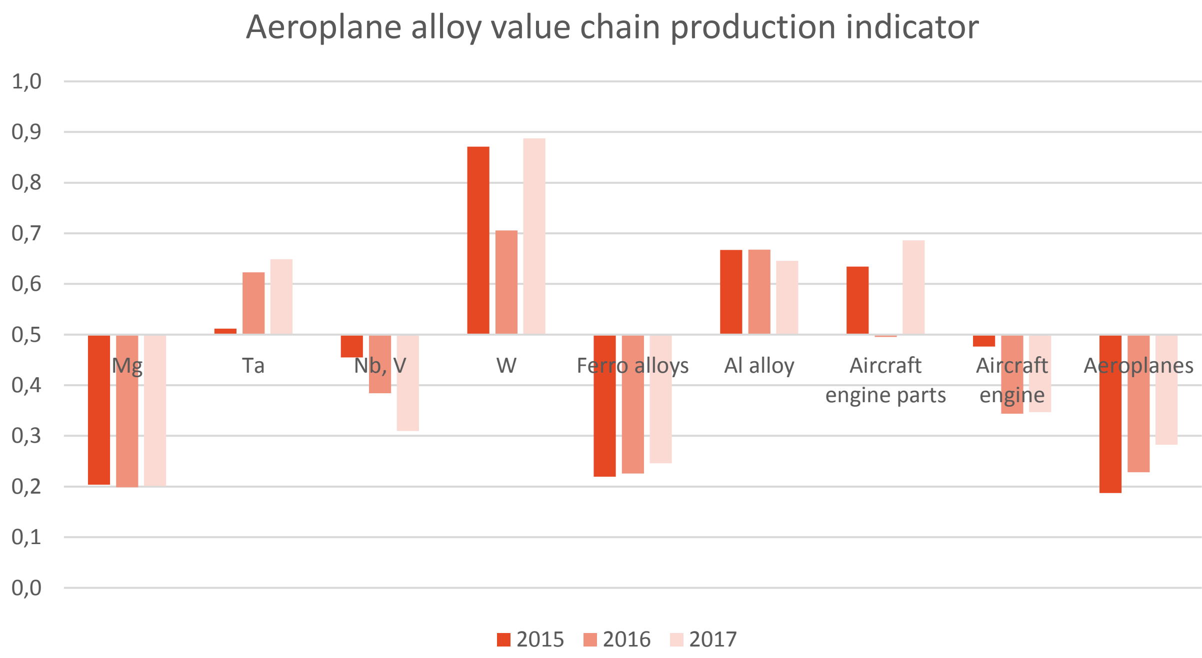

Figure 9. Production indicator (prod / imp + prod) for aeroplane alloy value chain in 2015, 2016 and 2017. [8]

Beside variations in the time series discussed for tantalum and niobium in previous section, also tungsten has fluctuation without a trend. This might originate from statistical uncertainties which was discussed previously. As for the groups at the end of value chain, fluctuation seems to exist for the aircraft engine and its part. For the

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engine parts there is a sudden increase in the import and export values in 2016 while the production value has stayed or increased slightly on steady base. This might indicate of statistical issue with data entries and therefore the fluctuation should be viewed rather critically. For aircraft engines the production has started to decrease during the recent two years while for import and export the decrease has not been as intense. As for the aeroplanes the trend of increasing production share originates from an increase in the production value after it had dropped in 2015 as well as fluctuation in import.

ACTORS IN THE VALUE CHAIN - AUTOMOBILE

The main industrial actors in the automobile value chain are compiled in Table 4. The information concerning the actors of the value chain and their geographical presence is gathered from [9] [10] and from the websites of the companies.

Magnesium and Niobium show highest contents of CRMs in automobiles as shown in Table 1. There is no production of pure magnesium in EU, thus EU relies 100% in import. However, semi-finished products of magnesium, particularly magnesium alloys and aluminium alloys involving magnesium, are manufactured in Europe, followed by their utilisation in various end uses. In EU, transportation covers 58% of the magnesium end use. Niobium is principally imported into the EU in the form of ferroniobium and niobium unwrought metal, alloy, and powder, Globally, 90% of the niobium production is used to produce ferro-niobium, which is used in the production of high-strength low-alloy (HSLA) and advanced high-strength steels (AHSS). World largest ferroniobium producers are from Brazil and Canada. Indeed, EU holds plenty of steel production, directed both to automotive and other end use sectors of HSLA and AHSS. Through the use of HSLA and AHSS in automobiles and other vehicles, roughly 30 % of the niobium ends up in automotive industry.

Frost & Sullivan forecast [9] that exterior and body-in-white (BIW) components are likely to witness more of metal-metal substitution in automobiles in the future. Aluminium remains the leading material of choice for exterior body panels, whereas for BIW structures, AHSS is expected to replace lower grade steels. Automotive metals market is mainly dominated by global conglomerates such as Arcelor-Mittal; POSCO; US Steel; Alcoa; Alcan; US Magnesium; and Dead Sea Magnesium. However, besides providing the basic raw material, some companies also process and mold these materials for the end users, which comprises tier-I suppliers and automotive OEMs. Automotive metals markets are also populated by alloy makers, die-casters and molders, which function as a conduit between the raw material supplier and the tier-I manufacturer/OEM. In terms of number of competitors, the automotive metals market has approximately 55 to 100 key suppliers (including both manufacturers and die-casters.

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Table 4. Main actors in the value chain of automobiles - Mg and Nb perspective. Country in parentheses represents the headquarters of the company.

Part of the value chain	Europe	Asia and North America
Sub-component production		
Aluminium alloys: 2000, 5000, 6000,7000-series	AMAG Austria Metall AG (Austria), Constellium (Holland), Norsk Hydro (Norway), Trimet Aluminium (Germany), Raffmetal (Italy)	Alcoa (USA), Alcan (Canada), Aleris (USA), Arconic (USA), RUSAL (Russia), Balexco (Kingdom of Bahrain), ARSLAN ALÜMİNYUM (Turkey), Zahit (Turkey), AL JABER (UAE)
Mg alloys: Wrought and cast alloys	Luxfer MEL Technologies	US Magnesium (USA), Dead sea Magnesium (Israel)
AHSS/HSLA steels	Arcelor-Mittal (Luxembourg),SSAB, (SWE) , Ovako (SWE)	POSCO (South Korea), U.S. STEEL (USA), Tata Steel (India), Leeco Steel
Component production		
Drivetrain	Robert Bosch GmbH (Germany), Continental AG (Germany), ZF Friedrichshafen AG (Germany), BASF SE (Germany), Valeo SA (France)	Magna International Inc (Canada), Aisin Seiki Co. (Japan), Hyundai Mobis (Korea)
Bodystructure, chassis	Robert Bosch GmbH (Germany) Continental AG (Germany), Friedrichshafen AG (Germany), BASF SE (germany), Valeo SA (France)	Magna International Inc (Canada), Aisin Seiki Co. (Japan), Hyundai Mobis (Korea)
Application manufacturing (Automobile)	Volkswagen (Germany), Renault (France), BMW (Germany), Peugeot (France), Fiat, Daimler AG	GM (USA), Ford (USA), Nissan, Honda (Japan), Toyota (Japan)

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4.2 SUBSTITUTION SOLUTIONS FOR CRMS IN ALLOYS

SUBSTITITES IN AUTOMOBILE APPLICATIONS

Overall use of materials in automobiles is presented in Figure 1, based on analyses conducted for three year 2013 car models (Ford Fiesta, Ford Focus, Ford Fusion) and covering all vehicle components. Concerning alloys, iron and steel corresponded to the dominant materials included in passenger cars, on average 800 kg per car, followed by aluminium (125 kg) and copper (31 kg). Among CRMs, magnesium was included at the amount of 3 kg per passenger car, niobium was present at 100 g/car and Co at 42 g/car. Light REEs include lanthanum, cerium, praseodymium, neodymium, promethium and samarium, the total average content of which was 76 g/car. However, these light REEs are treated separately in the Chapter dealing with Magnets, as magnets are their primary end use application. Additionally, tantalum is a CRM, which is used in passenger cars, on average, at the amounts of 6 g/car.

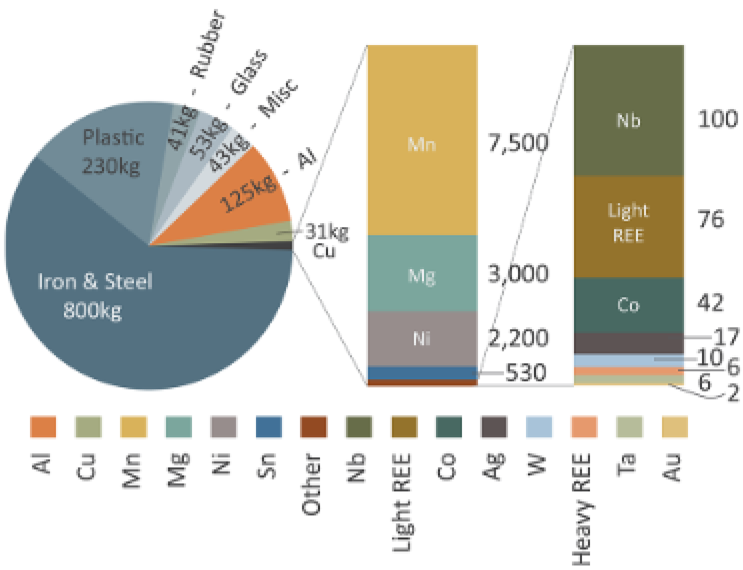

Figure 10. Overall materials content in cars. Values for all listed elements are expressed in grams [3].

Steels that are extensively used in automotive sector are high-strength low alloy (HSLA) steels, relying on high strength and lightweight (high strength-to-weigh ratio). The recent development versions of HSLA are called as advanced high-strength steels (AHSS), with the definition of yield strength > 300 MPa and tensile strength > 600 MPa. Additionally, the special feature of the AHSS is that they combine high strength and high ductility [11]. Due to the high strength of these steels, thinner steel structures allow for reduction in car weight, simultaneously decreasing the fuel consumption. HSLA and AHSS derive their strength from complex microstructure, which may be dual phase, *DP steels* (martensite or martensite-austenite areas in ferrite matrix), transformation-induced plasticity, *TRIP steels* (ferrite, bainite, retained austenite which then transforms into martensite in deformation, and possibly martensite), complex phase, *CP steels* (ferrite, martensite and bainite phases) and martensitic steels. These microstructures and, subsequently, the properties are brought about by the careful selection of alloying

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elements. Typically, CRMs vanadium and niobium are included, with the role of stabilizing austenite, refining of grain structure and precipitation strengthening. Although these elements typically exists at low concentrations (microalloying, up to some hundredth parts of %), they are crucial for reaching the high strength levels in the steels. HSLA and AHSS find use especially in vehicle body structure. Figure 11 shows example of the use of HSLA and AHSS in automobiles.

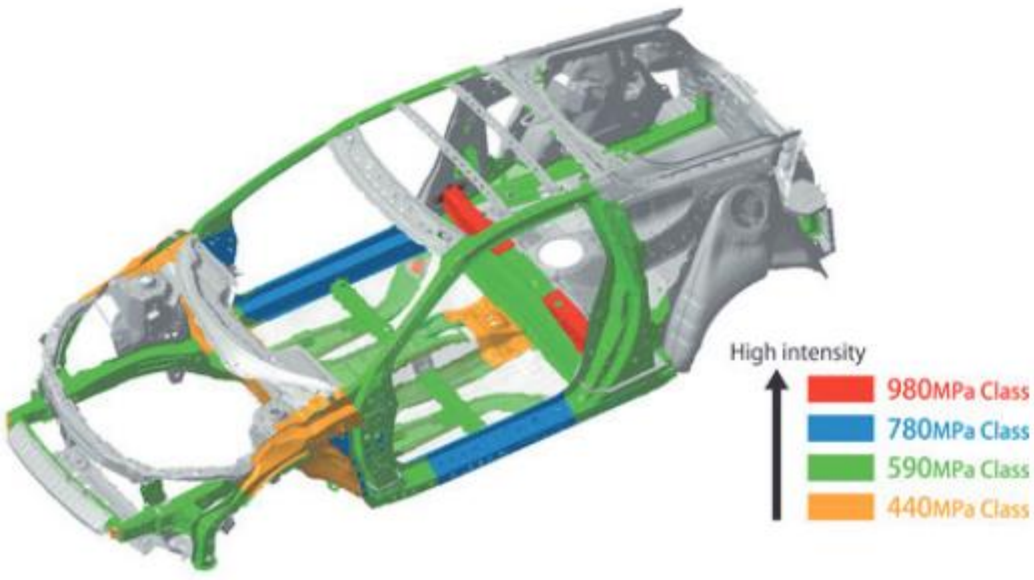

Figure 11. Example of the use of advanced high-strength steels in automobiles, case: Honda CR-Z 2011 [12]. The steel grades of various strength classes are shown in different colours, with red and blue colours referring to AHSS.

Aluminium alloys are increasingly used in automobiles in order to reduce the weight of structural parts conventionally manufactured of steel. One of the major advantages of aluminium alloys is that the stock material can be made by hot extrusion, in addition to the conventional steel production route involving casting, forging and rolling. Wrought aluminium alloys can be hot-extruded into strips and bars of complex cross sections, and such extrusions are increasingly being used for bumper systems, frame members and other passenger car components. CRM Magnesium as an alloying element is included particularly in 7000 series (Al-Zn-Mg), 6000 series (Al-Mg-Si) and 5000 series (Al-Mg-Mn) aluminium alloys. According to Hashimoto [13] , these alloys as extrusions have been widely adopted in passenger cars during the last 15 years, due to their light weight, high strength and rigidity. Examples of the automotive parts made of such aluminium alloy extrusions are given in Table5. Additionally, cast aluminium alloys are employed in passenger cars. Most of these alloys also contain magnesium as an alloying element: 7000, 6000, 5000 and 2000 series aluminium alloys. The application of cast aluminium alloys in automobiles is shown in Figure 12.

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Table 5. Examples of the use of Mg-bearing aluminium alloy extrusions in passenger cars [13].

Alloy	Part name	Required characteristics	Adoption
7000 series	Door beam	Bending strength, energy absorption	1993 →
	Instrument panel reinforce	Rigidity, bending strength	2003 →
	IPU guard	Bending strength	2012 →
	Seat back bar	Axial strength	2015 →
	Front side rail	Axial compressibility	2016 →
	Locker	Bending strength	2016 →
	Bumper system	Bending strength, energy absorption	1992 →
6000 series	Side step	Rigidity	2007 →
	Back step	Rigidity	2014 →
	Knee bolster	Compressibility in cross section	2005 →
5000 series	Sub flame	Rigidity	2005 →

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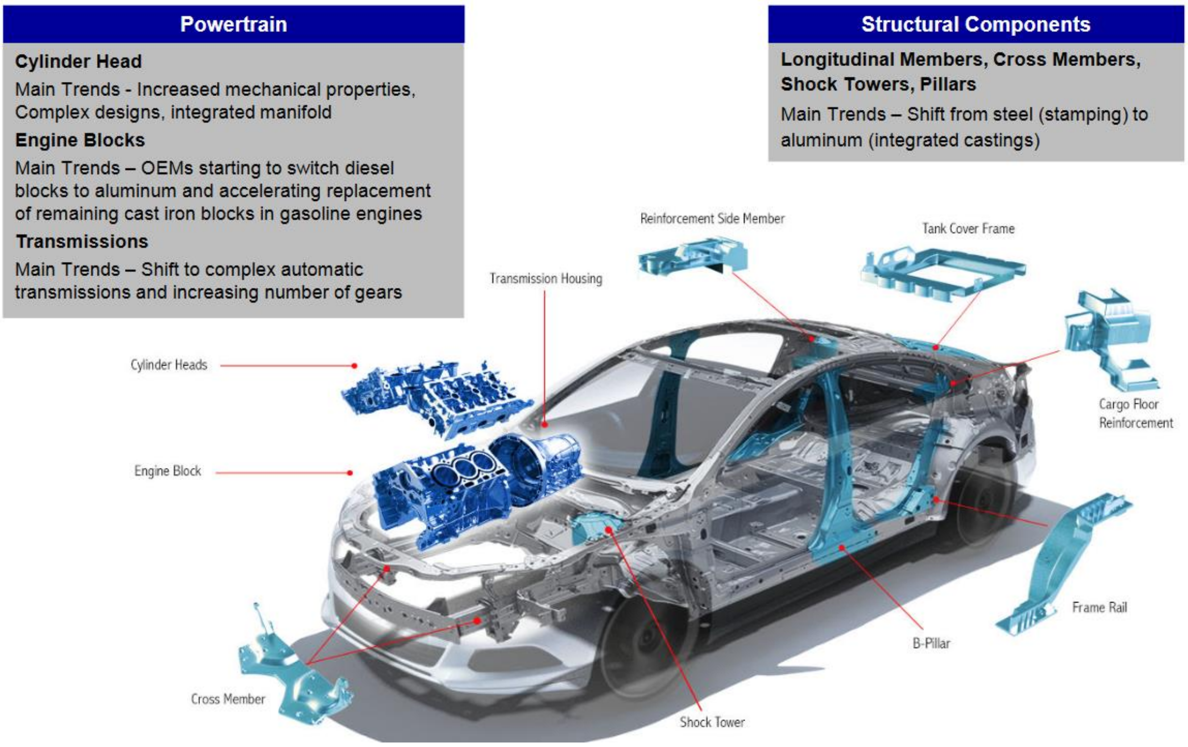

Figure 12. Example of application of cast aluminium alloys in passenger cars [14]. Majority of these applications rely on aluminium alloys with magnesium as an alloying element.

In contrast to HSLA and AHSS steels and aluminium alloys, both of which have experienced a tremendous growth in application in automotive sector, magnesium alloys remain minimally utilised despite significant weight saving potential. It has been estimated that magnesium alloys make up less than 0.5% of the weight of an average [15] vehicle, which based on analysis shown in Figure 12 would contribute to less than 700 g per a passenger car. This means that majority of magnesium included in passenger car is in aluminium alloys as an alloying element. Nevertheless, magnesium has been used in a wide variety of automobile applications: body, chassis, and interior components. Some other examples of Mg alloy applications in passenger cars include instrument panels, steering wheels, engine cradles, seats, transfer cases, and many different housings. Most of these parts and components have been manufactured by casting. However, the major challenges for the more widespread use of Mg alloy components in passenger car applications are the high and unstable prices of Mg and the poor corrosion performance of the material, putting significant pressures for efficient and often expensive corrosion protection. In passenger car applications, the key substitutes for Mg alloys are HSLA and AHSS steels as well as aluminium alloys, i.e., other key high-strength low-weigh alloys.

In automobiles with internal combustion engine, the engine valves and valve seats are typically manufactured of Co alloys [16], such as Stellites or Triballoys. These components are often manufactured via powder metallurgy

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route to produce the bulk components. Alternatively, Co alloys may be employed as thick coatings. Their use generally relies on excellent high-temperature resistance and corrosion performance, and with WC particles on good wear resistance. Nevertheless, in the future, the use of Co in passenger cars is expected to face a radical increase (although not as an alloy material), as Co is one of the materials needed for Li-ion batteries [17].

Table 6 lists the key substitutes that have been proposed for CRMs as alloying elements or base alloys included in alloys used in passenger car applications. Also the alloys with nominal use in this end application are included, e.g., lead/tin alloys, copper alloys and nickel alloys.

Table 6. Proposed substitution solutions for the alloying elements or alloys in passenger car applications.

Alloy type	CRM included	Role of alloying element	Alloying elements/Alloys giving parallel effect	Reference
HSLA, AHSS	Nb	Microalloying element for dispersion strengthening (NbC or Nb(C,N) precipitates), grain refinement, reduces M_s temperature	Ti, V High-N stainless steels	Steels [18]
	V	Austenite stabiliser, increases hardenability, strengthening (precipitation, refines microstructure)	Mn, Cr, Mo, Ni, B	Steels
Stainless steels	Nb	Microlloying element for stabilizing	Ti, Ta, Mo	[2]
Aluminium alloys	Mg	Hardener	Mn, Li, Cu	[2]
Magnesium alloys	Mg		Aluminium alloys, HSLA/AHSS	
Co alloys	Co		Nickel-base alloys	[][19]
Lead alloys, tin alloys	Sb	Hardener		
Copper alloys	Be	Hardener (age hardening, precipitation hardening), high conductivity	Ni, Si, Sn, Ti [20]	
Nickel alloys	P	Increases hardness (wear resistance), stable low friction coefficient	B, diamond nanoparticles	

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SUBSTITUTES IN AIRCRAFT APPLICATIONS

In automobile applications, the most important criteria for the materials are the weight and mechanical properties of the alloys, e.g., strength. These characteristics play a central role also in aircraft applications, but here the conditions are often so harsh that also some other special properties are required, e.g., thermal and corrosion resistance. Indeed, in aircrafts, one of the most critical application of CRM-bearing alloys is gas turbines. The gas turbine inlet temperature may exceed 1300°C and the materials see varying mechanical and environmental loads [21]. In such conditions, the alloy choices are limited to nickel- and cobalt-based superalloys (so that the latter may withstand somewhat lower loads and less corrosive environments than the former ones). In general, superalloys contain plenty of alloying elements: controlled alloying elements could be as many as 14, many of which are CRMs (e.g., Co, W, Nb, V, Hf), Ta, Ru) [22]. Indeed, Co- and/or Ni-based superalloys represent jointly one of the largest Co markets. In Ni-based superalloys, Co is an alloying element with the role of stabilizing and solution strengthening the γ phase, together with other alloying elements (Cr, Mo, Fe and W). Co alloying enhances the yield strength and the strain hardening capacity up to certain level. The essential solutes in Ni-based superalloys are Al and/or Ti required to form the characteristic γ' phase, an intermetallic compound of the formula $Ni_3(Al,Ti)$. Additional strengthening at low temperatures may be achieved by the γ'' phase with the composition Ni_3Nb or Ni_3V, and by oxide dispersion strengthening (ODS). It has proved a challenging task to find a substitute to Co by a less critical element which also enhances the yield strength and the strain hardening capacity. In some applications, Ni-based superalloys containing Nb and/or V may be substituted by Ni-based ODS superalloys. However, at present, ODS limited use in aircraft turbines is due to manufacturing complexity, and these alloys still contain CRMs, such as Y for ODS. In some applications, NI-based superalloys are successfully substituted by intermetallic TiAl materials or even by iron aluminides (FeAl, Fe_3Al). [2]

In aircraft, airframes represent a large-volume applications for titanium. Figure 4 shows a steady increase in the use of titanium alloys for airframes through the latter decades of the twentieth century. Figure revealed that titanium alloy airframes contributed at best to roughly 5% of the aircraft weight. However, the military aircraft applications are responsible for the largest overall application of titanium alloys. For example, in an advanced fighter airframe, some 42% of the structural weight may be of titanium alloys. In addition to airframe structures, gas turbine engines are typically of titanium alloys, Figure 5. The most common titanium alloys used in aircraft include CRM-bearing alloys Ti-6V-4Al (airframe and engine parts, cockpit window frames, wing box, fasteners), Ti-3Al-2.5V (hydraulic pipes), Ti-10V-2Fe-3Al (landing gear, track beam), Ti-15V-3Cr-3Sn-3Al (airframes, welded pipes, duct), thus these all involve V as the key alloying element. [23]

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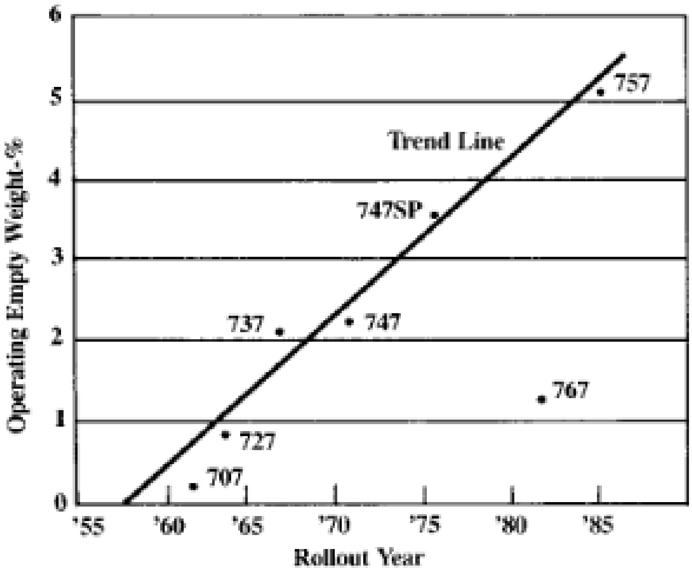

Figure 13. Titanium alloy use in Boeing aircraft from the first commercial jet to the Boeing 757 [24].

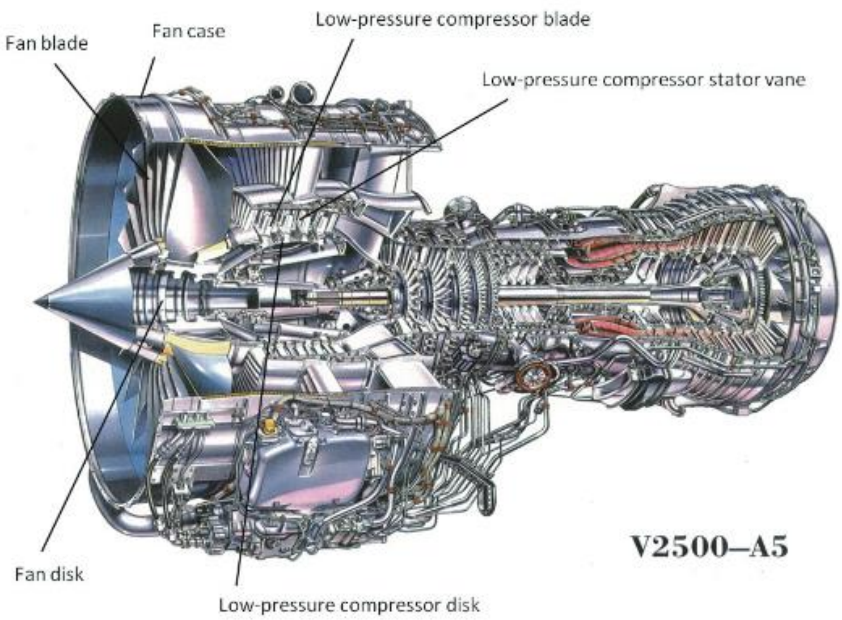

Figure 14. Example of application of titanium alloys for aero engine. [23]

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One of the most significant applications of Mg in engineering is as an alloying element in aluminium alloys used in aircraft. They play a central role in many key airfcraft components, such as upper wing structure and fuselage skin. Although the amount of Mg included in these 7000 series alloys is relatively small (~2-5 mass-%) [25], the annual demand of such alloys is large. The most significant property of these 7000 series aluminium alloys is their relatively high strength compared to other aluminium alloys, with other benefits covering high strength-to-weight ratio, ease of machining and relatively low cost. Mg included in these alloys is vital for age hardening through the precipitation hardening of coherent Guinier-Preston zones [2] [26]. An alternative to Al-Mg alloys is suggested by the new generation of alloys containing Cu and Li. Indeed, Al-Mg-Zn alloys of the 7000 series were originally developed to partially substitute 2000 series of Al-Cu. Now the new Al-Cu alloys with the additions of Li are considered as promising alternatives to them. The new Al-Cu alloys are often referred to as the third generation of Al-Li alloys, despite the fact that the Cu content is higher than that of Li and the alloys still contain some Mg (yet the Mg amount is significantly lowered, systematically below 0.8 %). The alloys behave in a similar way to Al-Mg-Zn alloys in that they are age hardenable, but they have improved strength, toughness and corrosion resistance as compared to 7000 series counterparts, and feature a lower density. Therefore, e.g., 2050 and 2060-T8 alloys are likely substitutes for 7000 series alloys for the fabrication of fuselage, lower wing and upper wing skins of aircraft. Another possible alternative to Mg-bearing Al alloys is composite materials reinforced with carbon fibers. However, their fabrication and certification costs are significantly higher than those for Al alloys, and their mechanical properties may vary depending on the environmental conditions (cold/hot, moisture absorption).[2] The most important CRM-bearing alloys in aircraft applications are listed in Table 7, together with the proposed substitutive alloying elements or alternative material candidates.

Table 7. Proposed substitution solutions for the alloying elements or alloys in aircraft applications.

	CRM included	Role of alloying element	Alloying elements giving parallel effect/Alternative materials	Reference
Ni-based superalloys	Co, Ta	Stabilisation of the γ' phase, strengthening	Cr, Mo, Fe and W	[2]
	Nb, V	Strengthening at low temperatures	ODS, e.g., Y	
			TiAl, FeAl, Fe_3Al	
Aluminium alloys	Mg	Strengthening,	Li-Cu	[2]
			Carbon-fiber reinforced composites	
Titanium alloys	V	β-stabiliser	Mo, Cu, Co, Cr, Ni [27]	
	V	Hampers the ductility of metastable β-alloys at high strength levels		[28]

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5 CATALYTIC CONVERTERS

A catalytic converter, or an autocatalyst, is an emission control solution for removing exhaust gases emitted by vehicle's internal combustion engine [27]. The type of the catalytic converter varies to some extent depending on the type of the combustion engine (i.e. gasoline-powered or diesel engine), but the principle and most of the used CRMs are same in both cases [28]. The exhaust gases to be removed include CO, unburned fuel, partially oxidised fuel, particulate matter, and nitrogen oxides (NO, N_2O, and NO_2, which are collectively termed NO_x). In the converter, platinum (Pt) and palladium (Pd) act as oxidation catalysts, whereas rhodium (Rh) catalyses the reduction reactions of NO. [27]

The structure of a catalytic converter is presented in Figure 1. The catalytic converter is based on a monolith support, which is a honeycomb structure of 1 mm^2 channels, made of ceramic or stainless steel. Since the monolith is non-porous, it is first wash-coated with a 20-60 µm layer of aluminium oxide to provide a higher surface area for the catalyst, which is then impregnated with a solution of Pt, Rh, and Pd salt precursors, together with a CeO_2 layer that acts as an oxygen reservoir. [27]

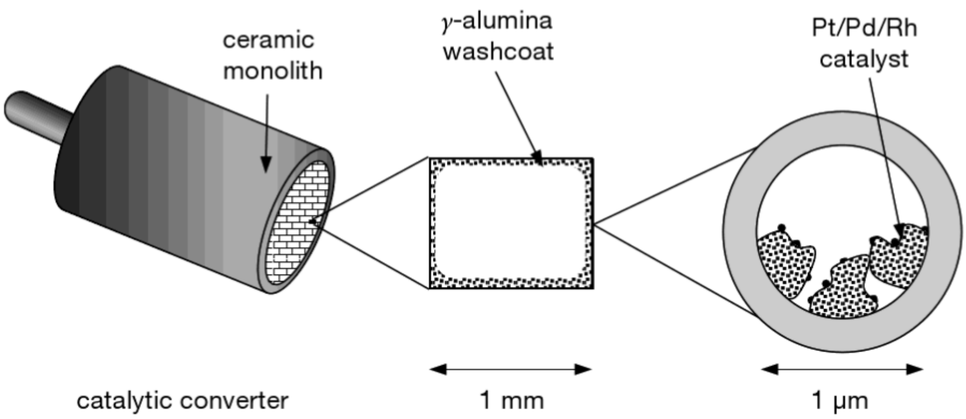

Figure 1. Structure of a catalytic converter: the converter is based on a ceramic honeycomb monolith, which is coated by a porous alumina layer. The alumina functions as a carrier for the Pt/Pd/Rh catalyst. Figure adopted from [27].

The total mass loading of noble metals in a catalytic converter is about 0.25%, most of which is Pt. The final catalyst is called a three-way catalyst (TWC) in the case of gasoline-powered engines, because it converts the three main pollutants, namely CO, hydrocarbons (unburned fuel) and NO, into non-toxic products: CO_2, H_2O and N_2. [27]

The catalytic converter for diesel engines, on the other hand, cannot employ a direct NO_x reduction because of excess oxygen present in the exhaust gas. Therefore, the reduction of NO_x has to be implemented by other techniques. In addition, all diesel engine systems need a particulate filter, which may be modified for either oxidation of CO and hydrocarbons, or for selective reduction of NO_x. [28] Particulate filters for gasoline engines are also becoming more common [29]. As an outcome, the emission control solutions for both diesel and gasoline engine systems can be composed of various combinations of catalytic converter techniques depending on the

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size and type of the vehicle (on/off-road). However, so far all combinations include at least one converter technique that employs precious metals Pt, Pd and Rh. [28] The emission control technologies and their PGM usage are further discussed in Section 5.2.

As a summary, the composition of CRMs in different catalytic converter solutions either include only Pt, or various ratios of Pt-Pd-Rh, Pt-Rh, and Pd-Rh depending on the combusted fuel. In 2016, catalytic converters accounted for approximately 84% of global Rh consumption, 67% of Pd consumption, and 46% of Pt consumption. Per vehicle the consumption of PGMs translates as amounts ranging from 1-2 g for a small passenger car to 12-15 g for a big truck. [30], [31]

The PGM-related value chain of catalytic converters is presented in Figure 2. PGM refiner companies refine PGMs from virgin PGM-bearing ores or from secondary sources, of which catalytic converters provide the largest supply source [32]. Next, the companies involved in catalytic material development produce Pt, Pd and Rh catalyst precursors, mainly PGM salts, to be applied in the manufacture of actual catalytic converters. The catalytic converters are then used by the original equipment manufacturers (OEMs) that automotive companies use as subcontractors. In some cases, the companies producing catalytic converters are also OEMs themselves. The companies that are not OEMs may also manufacture catalytic converters for the aftermarket in addition to being subcontractors for OEMs. The final products - passenger cars, trucks or off-road vehicles - are assembled by automotive companies. The final ring of the value chain is the recycling sector, which is actually composed of two parts: companies dismantling or wrecking ELVs and those that actually treat the catalytic converters and recover PGMs from them. This report takes into account only the companies recovering PGMs, as ELV dismantling business is highly dispersed: there are 1200 operators only in Germany [33].

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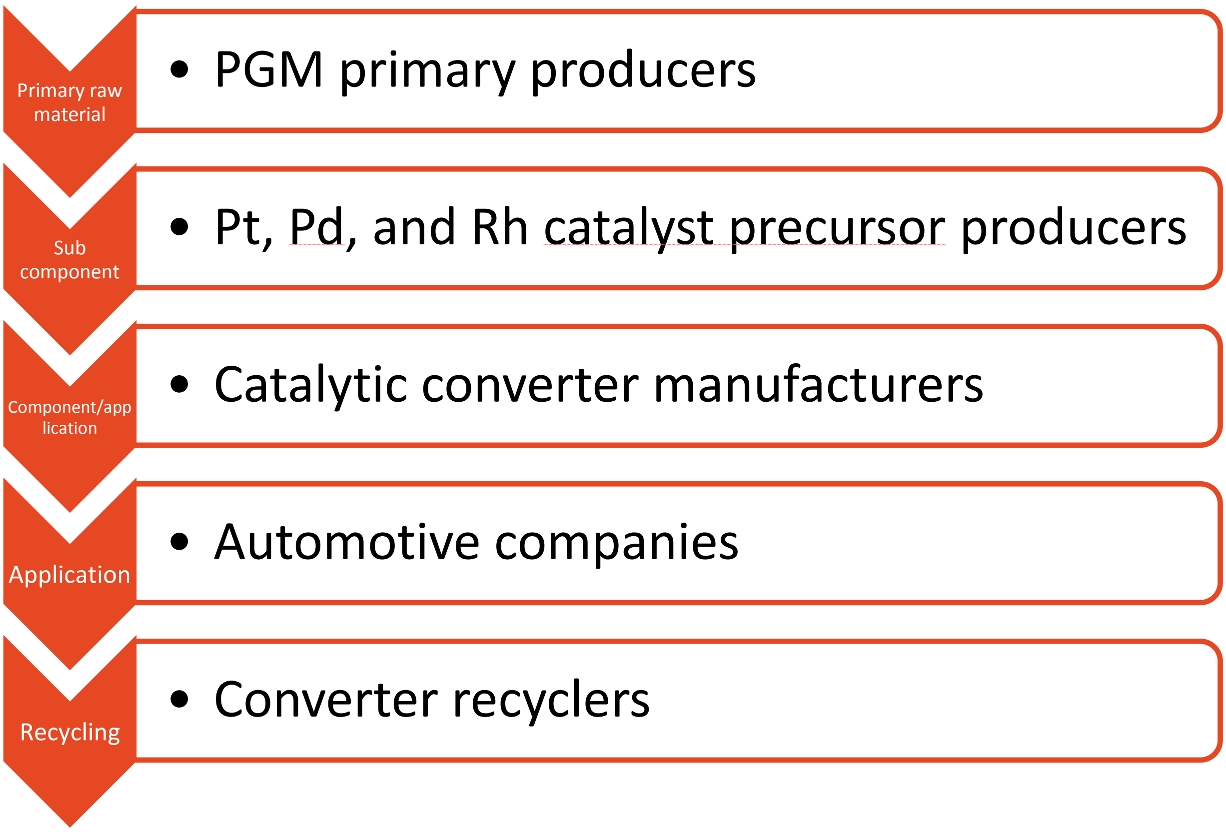

Figure 2. Operators in the PGM-related value chain of catalytic converters.

5.1 ECONOMIC ANALYSIS OF CATALYTIC CONVERTER VALUE CHAIN

STATISTICAL DATA

The economic analysis based on statistics (Eurostat, PRODCOM-data base) of the catalytic converter value chain is presented next. For the analysis, the structural composition of the application has been produced in the table below. Based on these divisions, the schematic economic value chain description has been produced and presented separately in the next section.

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Table 1. Structural composition of catalytic converter with PRODCOM codes and names

Application	*Component*	*Sub component*	*Materials*	*Prodcom code and name*
Automobile				*29103000 Motor vehicles for the transport of <= 10 persons* *29102100 Vehicles with only spark-ignition engine of a cylinder capacity <= 1 500 cm³* *29102230 Motor vehicles with only petrol engine > 1 500 cm³ (including motor caravans of a capacity > 3 000 cm³) (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)* *29102230 Motor vehicles with only petrol engine > 1 500 cm³ (including motor caravans of a capacity > 3 000 cm³) (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)* *29102330 Motor vehicles with only diesel or semi-diesel engine > 1 500 cm³ but <= 2 500 cm³ (excluding vehicles for transporting >= 10 persons, motor caravans, snowmobiles, golf cars and similar vehicles)*
	Exhaust silencer			*29323063 Silencers and exhaust pipes; parts thereof*
		Platinum catalyst		*24413070 Platinum catalysts in the form of wire cloth or grill*
			PGM	*24413030 Platinum, palladium, rhodium, iridium, osmium and ruthenium, unwrought or in powder form* *24413050 Platinum, palladium, rhodium, iridium, osmium and ruthenium, in semimanufactured forms (excluding unwrought or in powder form)*

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The catalytic converters value chain composed of five groups which can be divided roughly to four stages which are materials, sub-components, components/parts and end applications. More detailed division together with PRODCOM codes and names can be seen in Table 1. In Figure3 the relationship between production, import and export based on the statistical data has been presented. The positive values present how much value has been either generated and imported to Europe while the negative value present how much leaves as export from Europe.

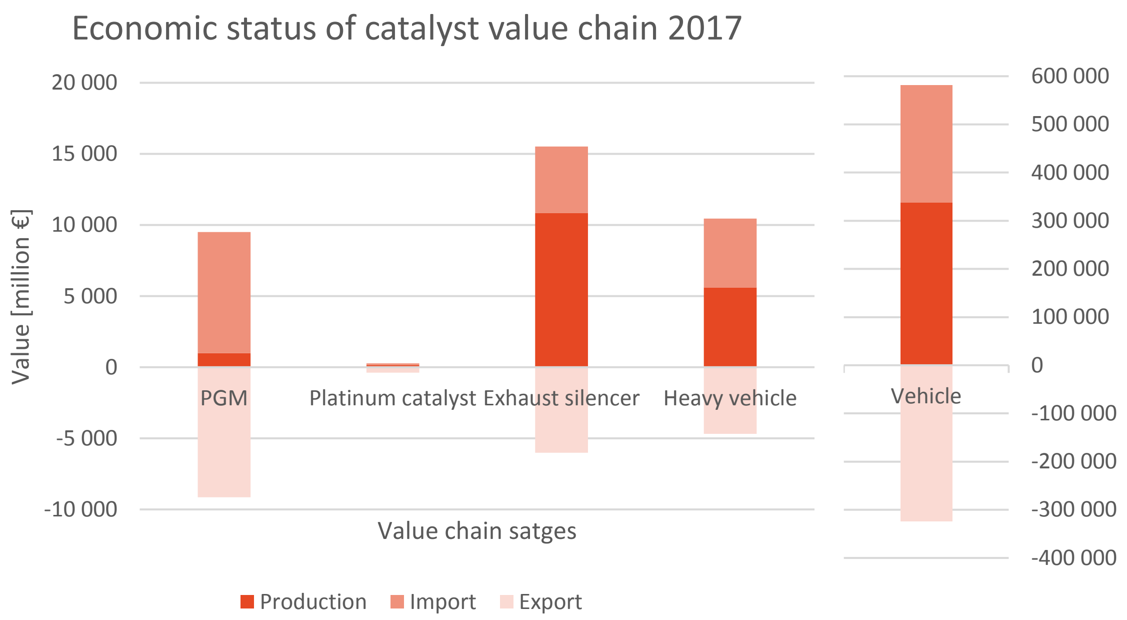

Figure 3. Relationship between production, import and export values for automobiles, components, catalysts and materials in Europe 2017. Note that the values present the whole industry volume not specific to automobiles. [1]

When observing the overview of the catalytic converter value chain in Figure 3 it can be noticed that rather significant variations both in overall value but also in the distribution between import, production and export exists. Total as well as production value tends to increase toward downstream whereas import and export seem to have larger importance upstream.

For materials stage the import and export values are significant. The high export value can be to some extent be explained by re-export but not all. A clear reason for the high export amount do not exist. As for the sub-component stage the values are low compared to the other groups in the value chain. In addition, the export value exceeds the production and import values which makes the figures questionable.

The component stage has rather notable production value which can be explained partly by the massive end application industry as well as the service markets. The production, import and export values for vehicles is over tenfold compared to the other groups. Beside the high production value, significant share of vehicles is also exported from Europe. On the other hand, vehicle markets are global which makes the import values substantial. It should be noticed, that not all manufactured vehicles are exported, but re-export of imported vehicles may occur which explains the large value of export. In addition, exported figure may contain also older vehicles which are sold outside Europe as second-hand car.

The relation between production and import in Figure 4 expresses how dependent Europe is of import compared to the production. If the production is larger than import the indicator gets positive bar in Figure4. For the catalytic converter value chain it can be noticed that for components/parts and end applications the production is higher than import. Especially for the component stage (Exhaust silencer) the production within Europe is rather significant. The massive end application industry and service market with repair work may explain to some extent the high share. For material stage, PGM's are highly import dependent.

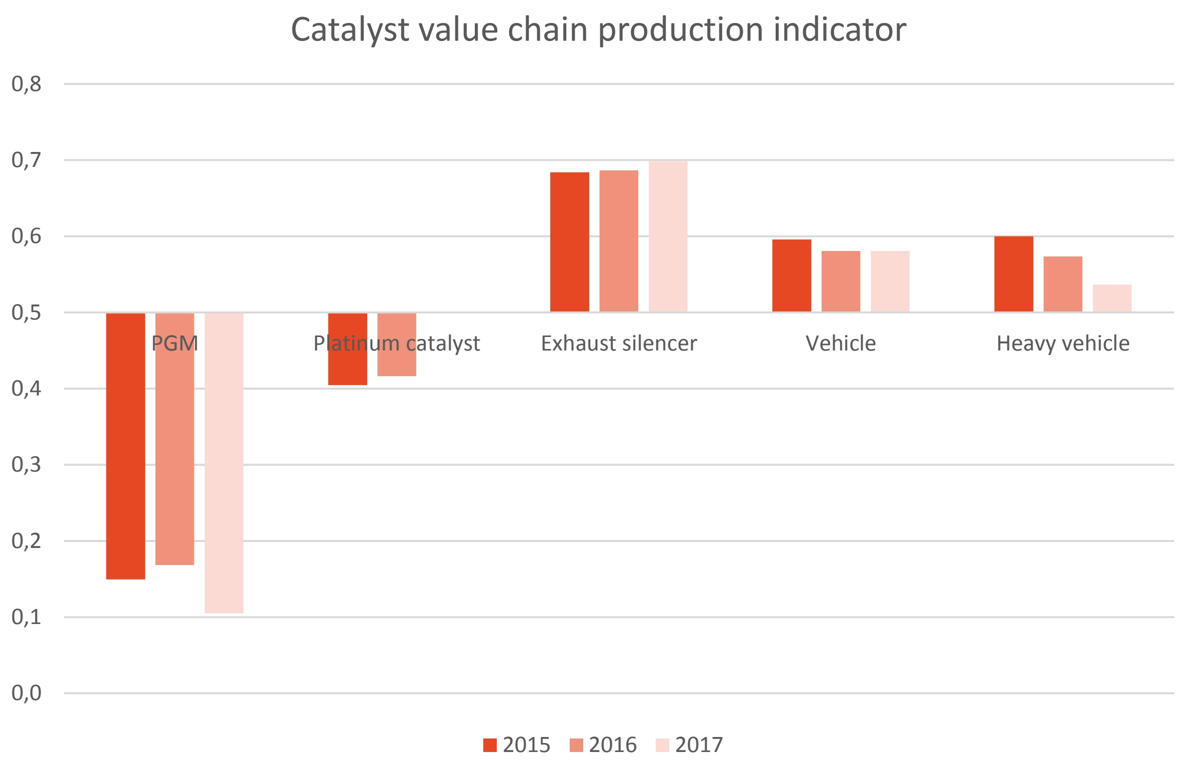

Figure 4. Production indicator (prod / imp + prod) for catalytic converter value chain in 2015, 2016 and 2017. [1]

The production/import share has for PGM's, exhaust silencers and vehicles remained to some extent on same level during the three years. When looking further back in time for PGM's there seem to be some fluctuation between import and production which may originate among other things from price fluctuations. As for heavy vehicle the production has stayed somewhat on the same level while the import has slightly increased which can be seen in Figure 4. However, this change is still rather low. For platinum catalysts, the statistical data has some uncertainty which may reflect to figure. While the production value has steadily increased the values for import has fluctuated during the last three years.

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FUTURE PERSPECTIVES ON THE MARKET

Emission legislation concerning combustion engines has a fundamental effect on the PGM use in autocatalysts, which in turn instantly affects primary production market, and also secondary production after these vehicles reach their end of life, as autocatalysts are one of the most important applications for PGMs.

During the phase-in period between Euro 6b and Euro 6d-TEMP emission legislations from September 2017 to September 2020, it is expected that a progressive shift away from the use of PGM-containing lean NO_x traps (LNTs) for NO_x control occurs, and a PGM-free selective catalytic reduction (SCR) technology becomes more popular. (LNT and SCR technologies are discussed in section 5.2.) SCR will continue to be used alongside PGM-bearing technologies, but on average Euro 6d-TEMP exhaust control systems are expected to contain less platinum than their Euro 6b predecessors. [32]

The next stage of European legislation, Euro 6d, will begin to take effect in January 2020, further limiting permitted NO_x emissions. These standards will be very challenging to comply, which means potential for some additional use of PGM-bearing NOx traps alongside PGM-free SCR, which would increase platinum use. However, further adoption of a technology that combines the functions of SCR and a particulate filter is also expected, permitting some reduction of PGM-loading in the system. [32]

At the other end of the value chain, in the autocatalyst recycling business, the dramatic increase in platinum loadings in diesel vehicles occurred in 2000-2007 gives grounds to assume future gains from the catalyst scrap in Europe when these vehicles reach their end of life. However, based on platinum assays at present, there is no evidence of this yet. [32]

ACTORS IN THE VALUE CHAIN

The main actors in the value chain are compiled in Table 2. The information concerning the actors of the value chain and their geographical presence is gathered from [29], [32] and from the websites of the companies. First of all, the raw material production in its entirety is located outside Europe, mainly in South Africa. Of the largest primary producers of PGMs, only one, Lonmin, is headquartered in Europe. On the other hand, it can be noticed that the next part of the value chain is dominated by EU-headquartered companies, namely Johnson Matthey, Umicore and BASF, which all have production facilities outside Europe as well. These companies are strong players also in the other end of the value chain, recycling. However, more diversity can be found among the catalytic converter manufacturers, of which some are also OEMs of complete exhaust systems for automotive companies. The ones that are not OEMs themselves, are subcontractors for OEMs or serve the aftermarket, or both. The automotive companies listed on the next row of the table are only listed by their headquarters and not by their production facilities due to the global presence of production of most of the companies. The recycling part of the value chain in Europe is mostly dominated by the same companies that also supply the raw materials, but in Asia and North America there are also recycling companies that are not identified as PGM suppliers.

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Table 2. Main actors in the value chain of catalytic converters - PGM perspective. Country code in parentheses represents the country of the headquarters of the company. The columns titled Europe or Asia and North America refer to a significant presence of production facilities in these geographical regions.

Part of the value chain	Europe	Asia and North America
Raw material production	Lonmin (GB)	Anglo American Platinum (ZA), Impala Platinum (ZA), Lonmin (GB), Norilsk Nickel (RU), Northam Platinum (ZA), Sibanye-Stillwater (ZA), Vale (BR)
Sub component production (catalyst precursor)	Johnson Matthey (GB), Umicore (BE), BASF (DE), Safina Materials (US)	Johnson Matthey (GB), Umicore (BE), BASF (DE), Safina Materials (US), CDTi (US)
Component/application manufacture (catalytic converter)	BM Catalysts (GB), European Exhaust and Catalyst (GB), Faurecia* (FR), Magneti Marelli (IT), Friedrich Boysen* (DE), Benteler* (DE), Eberspächer* (DE), Bosal* (NL)	Tenneco* (US), Yutaka Giken (JP), DCL International (CA), CDTi (US), Bosal* (NL), Benteler* (NL)
Application manufacture (vehicle)	VW Group (DE), PSA Group (FR), Renault Group (FR), FCA Group (NL), Jaguar Land Rover Group (GB), BMW Group (DE), Daimler AG (DE), Volvo Group (SE), Man Group (GB), Scania Group (SE)	Ford (US), Toyota Group (JP), GM (US), Nissan (JP), Hyundai (KR), KIA (KR), Suzuki (JP), Mazda (JP), Honda (JP), Mitsubishi Motors (JP), Tata Motors (IN), Paccar Inc. (US)
Recycling (converter recycling)	Johnson Matthey (GB), Umicore (BE), BASF (DE), Safina Materials (US), Vale (BR), Hensel Recycling (DE)	Johnson Matthey (GB), BASF (DE), Techemet (US), Alpha Recycling (US), PGM of Texas (US), Global Refining Group (US), Sibanye-Stillwater (ZA), Nippon PGM (JP)

*) Also an OEM of exhaust systems.

5.2 SUBSTITUTION SOLUTIONS FOR CRM IN CATALYTIC CONVERTERS

As mentioned earlier, catalytic converters can be based on several different combinations of emission control technologies. These technologies can be grouped in three categories depending on the emission they control: particulate emissions, carbon compound emissions or NO_x emissions. Technologies controlling only particulate emissions are essentially filters not employing PGMs (or any other active materials), and therefore they are out of the scope of this discussion. However, there is a trend to combine catalysts with particulate filters, producing multi-purpose but single-component emission control systems referred to as catalysed particulate filters. However, technologies controlling carbon compounds and NO_x emissions both include emission control methods based on PGMs, despite of being separate components or combined with particulate filters. [29] The

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technologies controlling carbon compound and NO_x emissions and their PGM usage are summarised by the following tables.

Table 3. PGM use of technologies controlling carbon compound emissions. The emission control performance is estimated on a scale: poor - tolerable - average - good - very good. Adapted from [29].

Carbon compound control technology	Used for		PGM usage			Emission control performance
	Gasoline	Diesel	Pt	Pd	Rh	
Three-way catalyst (TWC)	x		x	x	x	Average
Diesel oxidation catalyst (DOC)		x	x	x		Average

Table 4. PGM use of technologies controlling NO_x emissions. The emission control performance is estimated on a scale: poor - tolerable - average - good - very good. Adapted from [29].

NO_x emission control technology	Used for		PGM usage			Emission control performance
	Gasoline	Diesel	Pt	Pd	Rh	
Lean NO_x trap (LNT)	x	x	x	x	x	Poor
Exhaust gas recirculation (EGR)	x (except turbo engines)	x				Tolerable
Selective catalytic reduction (SCR)		x				Very good

As can be seen by the tables, the commercial emission control technologies for carbonaceous compounds currently do not include PGM-free options for either gasoline or diesel engines. On the other hand, the NOx emission control can be achieved without PGMs at least for diesel engines due to the SCR technology that provides a very good emission control performance. The SCR utilises iron, copper and vanadium to catalyse a reaction where ammonia selectively reacts with NO_x to produce nitrogen and water [34]. The Euro VI emission requirements already demand that heavy-duty vehicles are equipped with an SCR system [29], and consequently the technology is already provided by the largest autocatalyst suppliers such as Umicore, BASF, Johnson Matthey and CDTi.

SUBSTITUTIVE ELEMENTS

Obviously, there is will to replace PGMs in catalytic converters in order to reduce their cost and this is why catalyst researchers are trying to find alternative catalyst materials such as oxides of inexpensive metals or their combinations. However, recent studies show that not much progress has been made in this field. [29]. As PGMs are extremely effective and durable catalysts, replacing them entirely while maintaining the excellent catalytic ability is a very difficult task. For this reason, enhancing the activity of PGM catalysts, rather than increasing their

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loading while exhaust regulations tighten, is a viable alternative. Actually, the current use of CeO_2 as an oxygen reservoir in the catalytic converter is an example of a method to boost the activity of the catalyst. [35]

There are some successful attempts to reduce PGM loading in autocatalysts [36], but the most widely recognised example of an attempt to replace PGMs by non-precious elements is a patent claimed by CDTi (US). The patented solution is a catalyst technology Spinel™ which aims at replacing PGMs in catalytic converters in both gasoline and diesel vehicles. Spinel™ technology is based on various base metals which are combined together in a common structure resulting in unusual and very effective catalytic properties. The catalyst technology is also claimed to be highly versatile and durable. CTDi's interim target is to use low amounts of PGMs before realising the final target of PGM-free autocatalysts. [29], [37] In testing, CDTi was able to meet emissions standards on a turbocharged and a non-turbocharged car by reducing the amount of PGMs by 96% and 90%, respectively, but it has proved to be challenging to convince the original equipment manufacturers about the reliability of a new catalyst, because PGM-based catalysts have been in use as long as catalytic converters have been on the market. [38]

SUBSTITUTIVE APPLICATIONS

The most disruptive change for the catalytic converter market is however the electrification of transport, as electric vehicles (EVs) do not need catalytic converters. Vehicles based on fuel cell technology can also be considered as EVs, but so far the use of fuel cell technology is not a step away from PGMs, as many fuel cell technologies rely on PGMs as electrocatalysts. To separate fuel cell vehicles (FCVs) from electric vehicles deriving energy from batteries, a term battery electric vehicle (BEV) is used. Hybrid cars are also becoming more common, but as these vehicles usually rely on the internal combustion engine as one of the energy conversion methods, they are still dependent on the catalytic converter technologies. [29]

The rise of (B)EVs touches all parts of the catalytic converter value chain, however for some parts of the chain the impacts are more fundamental than for the other parts. As a large share of the PGMs produced globally is used in catalytic converters [30], the shift towards EVs means that a large part of the PGM demand will cease to exist, unless other PGM bearing applications, such as FCVs start to become more common. The decrease in demand will have a negative long-term effect on PGM prices, but on the supply-side, the continuing disruptions of palladium and platinum supply among major producers, with no more than a few new platinum and palladium projects in the pipeline, will on the other hand allow only minor production growth during the next decade, balancing the drop in demand. [39] The likely decrease in PGM prices will have an effect on both ends of the value chain: PGM refiners and PGM recyclers, which are in most cases the same companies.

The companies currently producing catalyst precursors for the catalytic converters, namely BASF, Umicore and Johnson Matthey, are also facing the effects of the EV transition. However, their strategy has been to switch the focus from catalyst materials to battery materials, adapting that way to the new market situation. [40]

The automotive sector is naturally in a steering position of the catalytic converter value chain in the EV transition. Some European automotive companies have either started to produce EVs or announced their EV release dates [41], but the global production of EVs is concentrated in China, which is attracting investments by its clean vehicle

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policy requiring automotive companies to obtain credits for the production of EVs [42]. The effect of EV transition on EU jobs in the automotive sector has already been examined in a briefing by Transport & Environment [43].

The banning of gasoline and diesel cars in the near future [44] will also affect the PGM recycling industry, as mentioned above. In 2016, the global number of vehicles on the roads was 1.32 billion, meaning about as many catalytic converters currently in use and eventually returning to PGM recyclers for recovery. However, if the planned bans of fossil fuel vehicles come into force, and unless the decreasing PGM demand is offset by new applications like fuel cells, there will be an excess supply of PGMs, which will have a negative impact on PGM prices in the next 10 to 15 years. As PGM smelters need to process and sell large volumes of PGMs in order to cover the high operating costs, a significant decrease in PGM demand could compel some of the refineries to go out of business. However, what is seen as a redeeming feature of the situation is that the bans have been announced years or decades ahead of time, leaving catalytic converter collectors and PGM refiners time to adjust to new market conditions, such as to start recycling other types of PGM bearing waste. [45]

5.3 SUMMARY OF THE CATALYTIC CONVERTER VALUE CHAIN

Catalytic converters, or autocatalysts are one of the most important applications for platinum group metals. The value chain of catalytic converters is globally spread so that the primary production of PGMs is located outside Europe, but all other steps involve EU-headquartered operators. Both catalyst precursor production and autocatalyst recycling are globally dominated by the EU-based companies Umicore, Johnson Matthey and BASF, although on the recycling side some US-based companies have a strong presence in the North America. EU has a strong competence in catalytic converter manufacture and exhaust system assembly through numerous large companies, but there are also a couple of strong US-based players on the sector. Finally, automotive industry, the end-user of catalytic converters, has important EU-based companies in both passenger car and heavy-duty vehicle sector accompanied by the other well-known companies mainly from Japan and the US.

The possible substitutive solutions for currently used PGM-bearing catalytic converters and the effects of these substitutions on different parts of the value chain are summarised in Table 5. Some of the effects have already partly taken place, such as catalyst precursor producers' adaptation to produce battery materials for electric vehicles.

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Table 5. Substitutive solutions for PGM-containing autocatalysts, their substitution mechanism, development stage and parts of the value chain that would be affected by the substitutive solution. The parts of the value chain are divided on the basis of estimated significance of the effect in a scenario where the substitution would occur in full: those sectors that would be required to make significant changes in their competence and product portfolio and those sectors that would have to change nothing or would only need to refine their core business.

Substitutive solution	Substitution mechanism	Development stage	Parts of value chain affected	
			Fundamental effect	Less fundamental effect
Spinel™ (PGM-free catalyst)	Element	Laboratory	PGM producers, catalyst precursor producers, PGM recyclers	Converter manufacturers, automotive companies
Battery electric vehicles (no need for catalytic converter)	Application	On market	PGM producers, catalyst precursor producers, converter manufacturers, automotive companies, PGM recyclers	
Fuel cell vehicles (as above, but PGMs used as fuel cell catalysts)	Application	On/Near market	Converter manufacturers, automotive companies	PGM producers, catalyst precursor producers, PGM recyclers

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6 ELECTRONIC COMPONENTS

Printed Circuit Boards (PCBs) are key components in most electrical and electronic equipment (EEE) used in a wide range of applications: consumer electronics, medical devices, industrial applications, automotive industry, aerospace sector and lightning applications. This chapter will concentrate on the economic assessment of substitution trajectories for CRMs used in electronic components, with the focus on PCBs with components.

PCBs form the base of electronics and are the essential part of almost all of the electronic products. PCBs are used to mechanically support and electrically connect electronic components (EC) using conductive pathways, tracks or signal traces (typically Cu sheets) laminated onto a non-conductive substrate. The actual PCBs are a mixture of woven glass fiber and epoxy resins (green and high grade) or phenolic/cellulose paper (yellow and low grade), thus typically with either green or yellow background colour. Cu sheets are claddings are laminated in them to allow for electricity flow between ECs, with metal connections (Sn, Pb) [1] . The common ECs in the PCBs include resistors (control the electric current that passes through them), Light Emitting Diodes (LEDs; emit visible light when electric current passes through them), transistors (amplify charge), capacitors (harbour electrical charge), inductors (store charge, stop and change in current), diodes (allow current to pass in one direction only), switches (allow or block the current) and integrated circuits (chips with multiple functions: amplifier, oscillator, timer, microprocessor, or even computer memory). Additionally, battery is the common component that provides voltage to the circuit).

Printed circuit board assemblies, i.e., PCBs with ECs, vary in composition between individual cases, but on average, contain 30% (by weight) plastics, 30% ceramics and 40% metals. Most of the materials are of commonly available and abundant raw materials, such as epoxy, polyethylene (PE), polypropylene (PP), silica (SiO_2), alumina (Al_2O_3), copper (Cu) and iron (Fe). However, there are also precious metals (gold, Au; silver, Ag) and Critical Raw Materials (CRMs; palladium, Pd; platinum, Pt), often at low concentrations but playing a vital role with respect to performance. [2] The electronic components typically contain majority of the CRMs included in the PCBs [1]. Indeed, the critical raw materials (CRMs) typically encountered in electronic components and materials are: iridium, palladium, platinum (all being platinum-group metals, PGM), indium, gallium, germanium, tantalum, yttrium (included in heavy rare-earth elements, HREE), silicon metal, baryte and beryllium. In the following, a short overview is presented about the uses of each of these elements.

Approximately half of **Iridium** consumed in Europe is consumed for electronic applications (43%). However, here it is primarily the high melting point (2446°C) and the chemical stability (corrosion resistance) that are of importance, as the key end use is crucibles for growing single-crystal sapphire. The sapphire provides a substrate for the production of gallium nitride (GaN) in EEE. Thus, although much of iridium is directed to electronic applications, it is rarely an essential material in electronic components. [3]

According to analyses, **palladium** is the most frequently found critical raw material (CRM) in waste electrical and electronic equipment (WEEE) [2] [4] []. The largest area of palladium use in the electronics sector is in multi-layer ceramic capacitors. Smaller amounts of palladium are used in conductive tracks in hybrid integrated circuits and for plating connectors and lead frames [5] [6]. Majority of the produced palladium is consumed in catalysts for automotive industry (~92% in EU, ~75% worldwide), followed by electrical applications (~6% in EU, ~10

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worldwide) [3]. However, although the relative share of palladium used in the electronic sector is quite small, it is in a key role enabling the miniaturisation of electronics (e.g., multi-layer ceramic capacitors). Additionally, palladium is used for electronic contacts.

The share of produced **platinum** that ends up in electronic sector is small, only ~1% in EU and ~ worldwide. [3][] However, despite the small share in consumption, the contribution of value added in electrical applications by platinum is third after autocatalyst and chemical applications. In electronic components, the major uses are platings in electronic connections and ceramic capacitors. [7] [5]

Concerning **indium**, the production of indium tin oxide (ITO) accounts for most of global indium consumption. ITO thin films were primarily used for electrical conductivity purposes in flat-panel displays, most commonly liquid crystal displays (LCDs). Flat panel displays is reported to correspond to 56% of end uses of indium. Other applications include alloys and solders, thin film solar panels, thermal interface materials, light emitting diodes (LEDs) and laser diodes. Altogether semiconductor and LED applications cover 3% of the total indium production. [3] [5]

In the case of **gallium**, EEE sector consumes approximately 90% of the total production. Almost 99% of the produced gallium is applied in the form of GaAs and GaN, with the majority (68%) being used for integrated circuits (IC). [8] Within EU, the figures are quite equal to those worldwide, IC end-use covering 70% of all gallium consumption, followed by LED applications (25%) [3].

Within EU, the end uses of **germanium** include infrared optics (47%), optical fibers (40%) and satellite solar cells (13%). Infrared optics makes use of germanium both as metal and as its oxide glass form. In fiber optics, germanium oxide is the preferential form of use. In space applications, solar cells employ germanium substrates. Outside of EU, germanium is also used in electronic components, e.g., in LEDs and transistors (SiGe). [3]

The manufacturing of capacitors is the largest single use of **tantalum** worldwide, accounting for the use of 33% of the produced raw material. It represents 500-600 tonnes of contained Ta used annually. It is a vital element for the electronic sector, as all electronic devices contain capacitors: they store an electrical charge for later use. The other important end uses are superalloys (alloying element) and sputtering targets [3].

In Europe, **yttrium** is mainly used for lighting (46%) and ceramics (35%) applications [3] . Elsewhere in the world, yttrium is also used in electronics applications, e.g., in microwave radar to control high-frequency signals [9].

Silicon metal exists in two grades: metallurgical grade silicon, representing the majority of produced silicon metal, and polysilicon, which is a high-purity polycrystalline form of silicon. The former is applied in metallurgy and in the chemical industry in the production of silicones and silanes, whereas the latter is used as a semiconductor in photovoltaic applications or in microelectronics. Despite the overall low share of electronic applications in the silicon consumption, 2%, ultra-high purity grade silicon is used extensively in silicon semiconductors, transistors, printed circuit boards and integrated circuits.[3]

Baryte (barite) is a barium sulphate mineral, $BaSO_4$. It is the raw material for barium compounds, notably barium carbonate ($BaCO_3$). $BaCO_3$ is increasingly used in electronic components, such as electronics ceramics and

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capacitors. In the overall end uses of baryte, the chemical industry that yields a variety of barium compounds accounts for 10% of the produced baryte, with special glass applications being the primary baryte consumer. [3]

Beryllium is used in the solder alloy for electronic components, typically as an alloying element in copper. Various electronic applications account for the consumption of more than half of the produced beryllium, although beryllium is not included in the electronic components but in their contacts.[3][5]

Table 1 summarises the CRMs included in the PCBs.

Table 1. The main electric components of PCBs, the CRMs included and the relative importance.

	Component	CRMs included	Form	Importance
Printed circuit boards	LEDs	Indium Gallium Germanium Iridium Yttrium	Ga in Gallium arsenide (GaAs), gallium nitride (GaN)	Indium: Minor (semiconductor + LED applications altogether 3% of Indium production) [3]. Ga: approx. 22% of gallium is used for opto-electronic components, such as LEDs and laser diodes [8] Ge, I, Y: Minor
	Transistors	Germanium Silicon Bismuth	Silicon germanium	
	Capacitors	Palladium Tantalum Baryte	Baryte: $BaCO_3$	Pd: ~6% produced palladium, but it is in a key role enabling the miniaturisation of electronics (e.g., multi-layer ceramic capacitors). Tantalum: 33% produced Ta used in capacitors Baryte: minor
	Diodes	Gallium Indium Bismuth		Ga: approx. 22% of gallium is used for opto-electronic components, such as LEDs and laser diodes Indium: minor
	Integrated circuit (IC)	Gallium	GaAs, GaN	68% of produced gallium used in ICs for high-frequency wireless

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		Silicon		communication (mobile phones, wireless local area network)[8]
	Connections, connectors	Palladium Platinum Indium Beryllium	Metallic, In and Be as alloys	>50% of Be consumed in electronic applications

Based on Table 1, the most important CRMs in electrical components are palladium, gallium, tantalum and beryllium. A short overview of these elements is given below.

Palladium is an element that belongs to the platinum group metals (PGM) and is obtained as a co-product in Ni, Cu and Zn production. It is a shiny, silvery-white metal that resists corrosion. Finely divided palladium is a good catalyst and is used for hydrogenation and dehydrogenation reactions. Hydrogen easily diffuses through heated palladium and this provides a way of separating and purifying the gas. Major palladium producers are Russia, South Africa and Canada. Figure 1 shows that In Europe, there are manufacturing activities related to catalysts, electrical components and dental restorations.

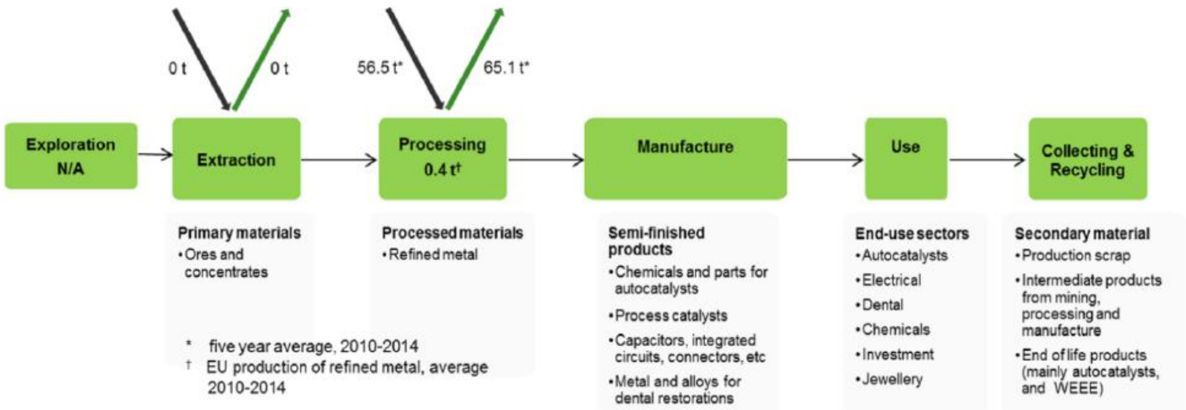

Figure 1. Simplified value chain for palladium [3].

Gallium is a soft, silvery metal with an extremely low melting point, 30°C, but a high boiling point, 2229°C [10]. It is an excellent conductor of both heat and electricity, and its compounds: gallium arsenide, GaAs, and gallium nitride, GaN, show exceptional semiconducting properties [10][3]. Gallium is exclusively obtained as a by-product during the processing of other metals, e.g. aluminium (bauxite) and zinc (sphalerite). The total production of gallium is of the order of a few hundred tonnes per year. China accounted for the majority of world's gallium production (production capacity 400-500 tonnes annually), followed by Germany (25-40 t/a) and Kazakhstan (25 t/a). In terms of final end-uses (on average during 2010-2014), about 70% of gallium is used for Integrated Circuits

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(ICs) while 25% is consumed for lighting applications (mostly LED technology). Figure 2 shows that in Europe, there are manufacturing activities in the areas of GaAs and GaN wafers and well as Ga compounds.

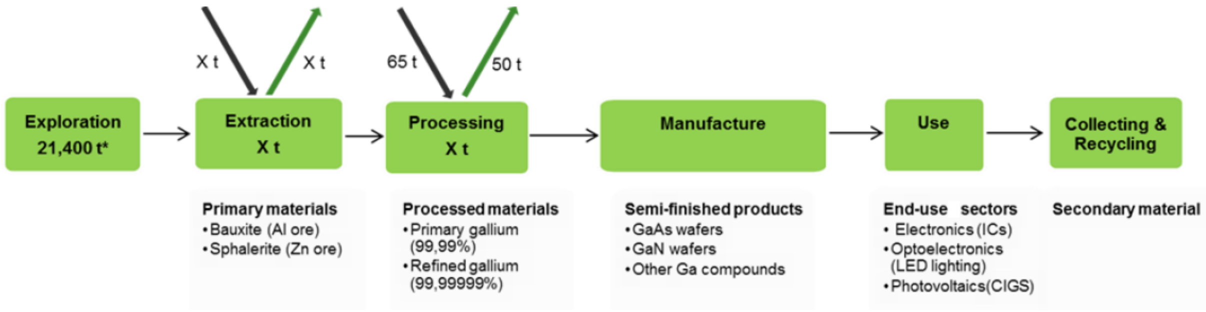

Figure 2. Simplified value chain for gallium [3].

Tantalum is a silvery transition metal that is very resistant to corrosion and exhibits excellent thermal resistance (melting point 3017°C, boiling point 5455°C). An oxide layer which forms on the surface of tantalum can act as an insulating (dielectric) layer. Because tantalum can be used to coat other metals with a very thin layer, a high capacitance can be achieved in a small volume. Indeed, one of the main uses of tantalum is in the production of electronic components, with capacitors corresponding to the primary end use of tantalum (33%). Most tantalum is produced as a co-product as it occurs in complex mineral form, often associated in ore bodies with niobium, tin or lithium. In Europe, there are some activities related to the manufacturing of tantalum chemicals, powders, carbides, ingots and mill products, Fig. 3.

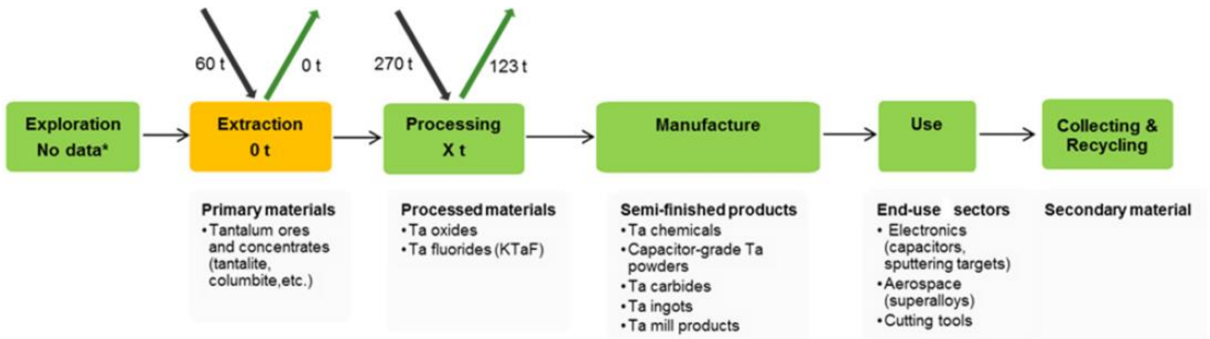

Figure 3. Simplified value chain for tantalum[3].

Beryllium is a silvery-white metal. It is relatively soft and has a low density. Beryllium is used in alloys with copper or nickel to make gyroscopes, springs, electrical contacts, spot-welding electrodes and non-sparking tools. Mixing beryllium with these metals increases their electrical and thermal conductivity [11]. Particularly copper beryllium is widely used in electrical connectors in a wide range of sectors, e.g., transportation. USA accounts for 90% of global beryllium production, followed by China. Europe has manufacturing activities in the manufacturing of products made of beryllium ceramics, beryllium alloys and beryllium metal, Figure 4.

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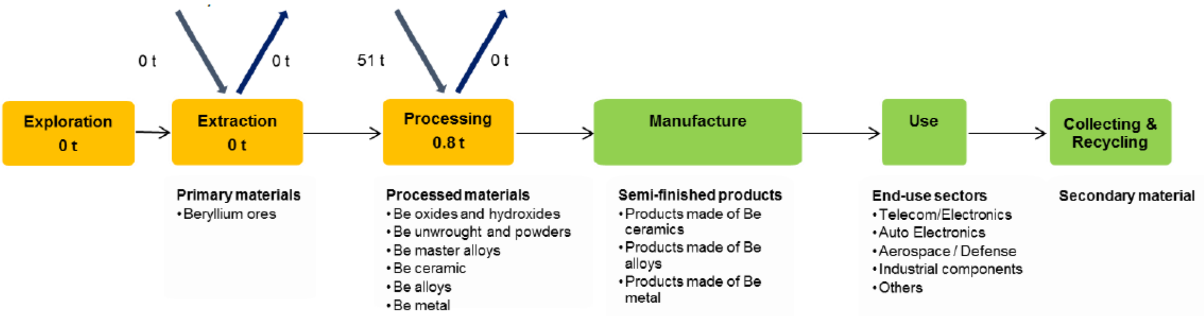

Figure 4. Simplified value chain for beryllium [3].

6.1 ECONOMIC ANALYSIS OF ELECTRONIC COMPONENT VALUE CHAIN

STATISTICAL DATA

For the economic analysis based on statistics (Eurostat, PRODCOM-data base) of the electronics value chain. For the analysis, the structural composition of the application has been produced in the table below. Based on these divisions, the schematic economic value chain description has been produced and presented separately in the next section.

The electronics value chain composes of 13 groups which can be divided roughly to three stages which are materials, sub-components, components/parts. More detailed division together with PRODCOM codes and names can be seen in Table 2. It should be noted that in the electronics value chain analysis, the focus is on only materials, sub-components and component/parts, since electronics are utilized in so many different end applications crossing several industries which makes their mapping very complex.

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Table 2. Structural composition of electronics with PRODCOM codes and names.

Component	*Sub component*	*Materials*	*Prodcom code and name*
Printed circuit board			*26115020 Multilayer printed circuits, consisting only of conductor elements and contacts* *26115050 Printed circuits consisting only of conductor elements and contacts (excl. multiple printed circuits)* *26121020 Bare multilayer printed circuit boards* *26121050 Bare printed circuit boards other than multilayer*
Integrated circuits			*26113003 Multichip integrated circuits: processors and controllers, whether or not combined with memories, converters, logic circuits, amplifiers, clock and timing circuits, or other circuits* *26113006 Electronic integrated circuits (excluding multichip circuits): processors and controllers, whether or not combined with memories, converters, logic circuits, amplifiers, clock and timing circuits, or other circuits* *26113023 Multichip integrated circuits: memories* *26113027 Electronic integrated circuits (excluding multichip circuits): dynamic random–access memories (D–RAMs)* *26113034 (cache–RAMs)Electronic integrated circuits (excluding multichip circuits): static random–access memories (S–RAMs), including cache random–access memories* *26113054 programmable, read only memories (EPROMs)Electronic integrated circuits (excluding multichip circuits): UV erasable,* *26113065 Electronic integrated circuits (excluding multichip circuits): electrically erasable, programmable, read only memories (E²PROMs), including flash E²PROMs* *26113067 Electronic integrated circuits (excluding multichip circuits): other memories* *26113091 Other multichip integrated circuits n.e.c.* *26113094 Other electronic integrated circuits n.e.c.*
	Transistors		*26112150 Transistors, other than photosensitive transistors*
	Capacitors		*27905220 Fixed electrical capacitors, tantalum or aluminium electrolytic (excluding power capacitors)* *27905240 Other fixed electrical capacitors n.e.c.* *27905300 Variable capacitors (including pre-sets)*

	Resistors		*27906037 Fixed electrical resistors for a power handling capacity > 20 W (excluding heating resistors and fixed carbon resistors, composition or film types)* *27906035 Fixed electrical resistors for a power handling capacity <= 20 W (excluding heating resistors and fixed carbon resistors, composition or film types)*
	Semiconductors		*26112260 Semiconductor devices (excluding photosensitive semiconductor devices, photovoltaic cells, thyristors, diacs and triacs, transistors, diodes, and lightemitting diodes)* *26112120 Semiconductor diodes* *26112180 Semiconductor thyristors, diacs and triacs*
	Connectors		*27331360 Prefabricated elements for electrical circuits for a voltage <=1kV* *27331370 Connections and contact elements for wires and cables for a voltage <=1 kV* *27331380 Other apparatus for connections to or in electrical circuit, voltage <=1000 V*
		Si	*20132150 Silicon* *20132475 Silicon dioxide*
		Sb	*20121975 Antimony oxides* *24453047 Zirconium and articles thereof (excluding waste and scrap), n.e.c.; antimony and articles thereof (excluding waste and scrap), n.e.c.*
		REE	*20132300 Alkali or alkaline-earth metals; rare-earth metals, scandium and yttrium; mercury* *20136500 Compounds of rare-earth metals, of yttrium or of scandium or mixtures of these metals*
		PGM	*24413030 Platinum, palladium, rhodium, iridium, osmium and ruthenium, unwrought or in powder form* *24413050 Platinum, palladium, rhodium, iridium, osmium and ruthenium, in semimanufactured forms (excluding unwrought or in powder form)*

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		Ga, Ge	*24453055 Beryllium, chromium, germanium, vanadium, gallium, hafnium ("celtium"), indium, niobium ("columbium"), rhenium and thallium, and articles of these metals, n.e.c.; waste and scrap of these metals (excluding of beryllium, chromium and thallium)* *20121950 Lithium oxide and hydroxide; vanadium oxides and hydroxides; nickel oxides and hydroxides; germanium oxides and zirconium dioxide*
		Ta	*24453023 Tantalum and articles thereof (excluding waste and scrap), n.e.c.*

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In Figure 5 the relationship between production, import and export based on the statistical data has been presented. The positive values present how much value has been either generated and imported to Europe while the negative value present how much leaves as export from Europe.

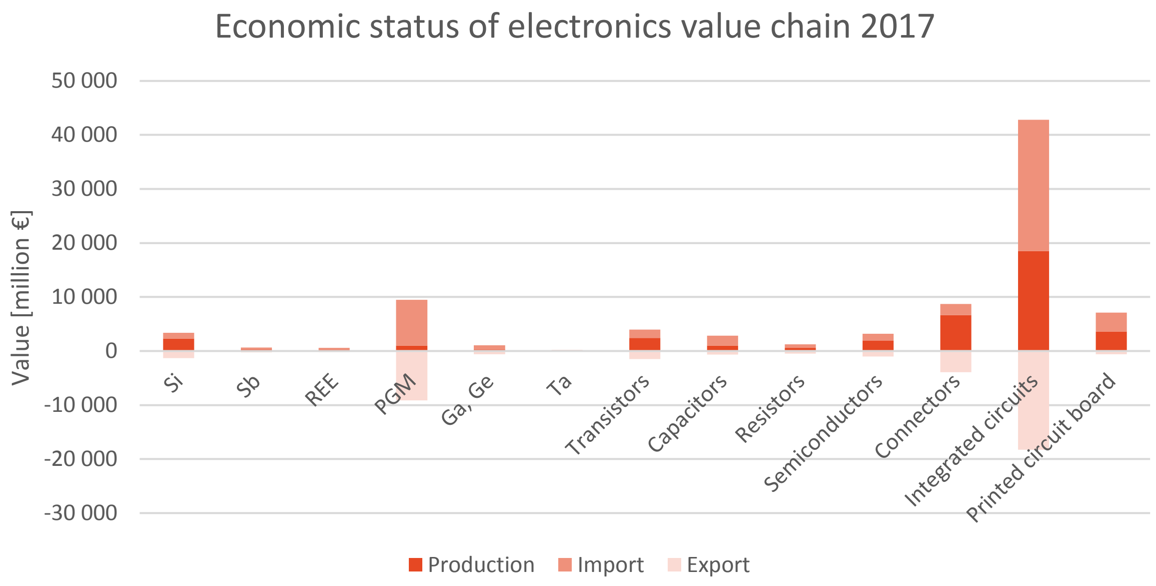

Figure 5. Relationship between production, import and export values for electronics, components, and materials in Europe 2017. Note that the values present the whole industry volume not specific to end application. [12]

From Figure 5 it can be noticed as the overall impression of the electronics value chain that the value which is produced, imported and exported is on a higher level in the component/part stage compared on raw materials with exception of PGMs even though the electronic component manufacturing industry is heavily competed and global. For integrated circuits which generates the highest values (both positive and negative) in the value chain, rather same value is produced as exported where as the import value is larger. This indicate rather great demand for higher grade components in Europe even though export exists. To one extent the strong industrial and automotive industry drives the demand [13][14]. As for other sub-components the strong demand of components/parts as well as automotive industry generate somewhat notable demand for the sub-components.

For materials stage the values are significantly lower compared to components with the exception of PGMs and silicon. For PGMs, especially palladium is used in electronics for example in multi-layered ceramic capacitors, while platinum in lower quantities [3]. In terms of trade, the high export, tenfold compared to production, indicate uncertainty in the data even though some re-export of imported goods may occur. For silicon ultra-high purity grade silicon is used extensively in electronic devices such as silicon semiconductors, transistors, printed circuit boards and integrated circuits [3]. The trade balance indicate that significant share of value stays in Europe due to the lower export compared to the import and production. This would be logical since component manufacturing e.g integrated circuits exists in Europe. Certainly not all silicon is utilized in electronics manufacturing. According to CRM list 2017 the major share of imported silicon compose of lover purity (< 4 N, silicon containing < 99.99% by weight of silicon) silicon while only few percent is so called polysilicon (<6 N, 'silicon containing >= 99.99% by weight of silicon) which is utilized in the generation of ultra high purity silicon for semiconductor and integrated circuit industry [3] [15]. As for other materials much lover trade values can be noticed.The relation between production and import in Figure 6 expresses how dependent Europe is of import compared to the production. If the production is larger than import the indicator gets positive bar in Figure 6. It can be noticed that there is rather much fluctuation in the production-import relation through the entire value chain. Already in the subcomponent and component stages rather great differences occur for example capacitors have significantly lover indicator value compared to semiconductors or connectors. However, it should be noticed that connectors group compose of several PRODOM groups which may mix the situation. As for integrated circuits which have high trade values (Figure 5) the import and production values are somewhat the same for the last three years indicating strong demand in Europe. In material stage Europe tend to be more reliant on the import with the exception of silicon and tantalum. As has been already discussed in the alloys section the tantalum PRODCOM group compose of tantalum and articles thereof (excl. waste and scrap), not of ore or concentrate which has been presented in the recent CRM-list 2017 to be totally reliant on import. The production of tantalum is most likely originated from manufacturing industry which utilizes goods containing tantalum and produces so called “pre-consume” scrap [3]. In addition, the total values and quantities for tantalum in PRODCOM data base are low at which time changes may have larger effect. As for silicon, the production value is notable larger than the value for import which results in a positive bar in Figure 6. Compared with the outcomes in CRM-list 2017 which report on a higher import reliance, the results are divergent. However, this may be explained partly with Norway’s production data which is included in the PRODCOM data analysis where as in CRM-list 2017 assessment it is regarded as an importer to Europe. In addition, PRODCOM data do not specify the type or grade of silicon that is compiled in the statistics which generates some unclarity and should be regarded with a critical viewpoint. For other materials the production indicator shows higher dependency on import. Especially on PGMs the import dependency is significant. However as was discussed earlier for PGMs some uncertainties in the trade data may exist.

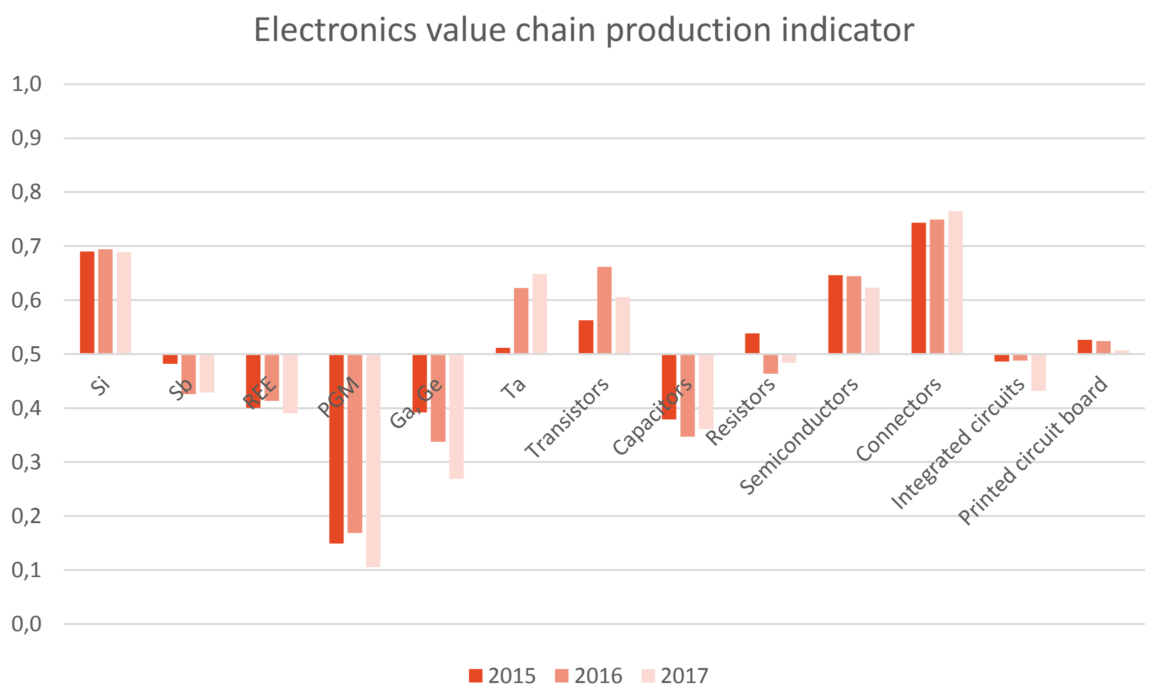

Figure 6. Production indicator (prod / imp + prod) for electronics value chain in 2015, 2016 and 2017. [12]

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When looking at the indicator values of the materials, sub-components and components/parts for the past three years, some variations exist. Especially for gallium/germanium, tantalum, PGMs, transistors and resistors fluctuation in the indicator exists. For gallium/germanium the import has remained on the same level or increased whereas the production has decreased annually which explains the decrease in the production indicator. According to the CRM material datasheets 2017, two European gallium producers (Hungary and Germany) has stopped their operation in 2013 and 2016 i.a. high operating costs and cheap Chinese material availability which has resulted in higher import dependency [3]. As for tantalum the production has in turn increased while import decreased. As was earlier discussed there is some uncertainties in the statistical data and in rather delicate change factor due to the low original values. In sub-component stage both transistors and resistors have fluctuation. For resistors the production has first decreased and then increased while the import has increased constantly where as for transistors the production has behaved the opposite while similar constant increase in the import. Fluctuations may origin from several reasons which individual causes are not clear.

ACTORS IN THE VALUE CHAIN

Table 3. Main actors in the value chain of Printed Circuit Boards with components. Country in parentheses presents the headquarters of the company.

Part of the value chain	Europe	Asia and North America
Precursor manufacturing		
TMGa (Trimethylgallium) and TEGa (Triethylgallium)	Umicore (Belgium)	Nouryon (USA)
Tantalum powder		Inframat Advanced Materials (USA), JX Nippon mining & Metals Group (Japan), Showa Cabot Supermetals K.K. (Japan), Stanford Advanced Materials (USA), American Elements (USA), Ningxia Nonferrous Metals Import & Export Corporation (China)
Pd powder, Pd-powder-based ink	Heraeus (Germany), Metalor (Switzerland)	Ferro Corporation (USA), Cermet Materials, Inc. (USA)
Copper-beryllium connector alloy	Lamineries Matthey (Switzerland)	
Component production		
GaAs wafer[16] , GaN wafer	Freiberger Compound Materials (Germany), United Monolothic Semicondiuctors, UMS (Germany), EpiGaN (Belgium)	Sumitomo Electric (Japan), Americal Xtal Technology, AXT (USA), Xinxiang Shenzhou Crystal Technology Co., Ltd

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		(China), RF Micro Devices (USA), Xiamen San'an Integrated Circuit Co (China)
Tantalum capacitors		AVX Corporation (USA), NEC (Taiwan), ROHM semiconductor (Japan), NTE Electronics (USA), United Chemi-Con (USA)
Palladium-containing multi-layer ceramic capacitors	Johnson Matthey Plc (UK)	Taiyo-Yoden (Japan), Kyocera (Japan), Murata (Japan), TDK (Japan)
Beryllium-containing connectors		Materion (USA), PMX Industries (USA)
Application manufacturing		
Led and photonic applications of GaAs [16], GaN	Osram (Germany), AMS Technologies (Germany)	Xiamen San'an Integrated Circuit Co (China), II-VI (USA), Lumentum (USA), Finisar (USA)

6.2 SUBSTITUTION SOLUTIONS FOR CRM IN ELECTRONIC COMPONENTS

Most of the CRMs included in electronic components are difficult to substitute without loss in performance. Indeed, among the four most important CRMs in the electronic component sector: palladium, gallium, tantalum and beryllium, either losses in performance or price are expected in the case of substitution. For example, for palladium the potential substitutes are other PGMs (e.g., platinum), gold or base metals, but this may results in increase in price or compromise in performance. For gallium, silicon or silicon-based substrates, such as SiGe, are usually the main substitutes for GaAs or GaN substrates in semi-conductors. However, silicon has a lower electron mobility and is therefore significantly less efficient. GaAs-based semiconductors also operate at higher breakdown voltages and generate less noise at high frequencies (>250 MHz). In capacitors, the substitution of tantalum typically means a change in capasitor technology. Even at present, the vast majority of capacitors in electronic devices do not contain tantalum, but such capacitors (based on, e.g, niobium) are usually larger and have a shorter life-span or have larger size, reduced capacitance and are more sensitive to harsh and hot operating conditions (ceramic capacitors, aluminium capacitors). The superior performance and robustness of tantalum capacitors thus remains the only reliable choice in applications where long term reliability, size and/or security matters (e.g. automobile anti-lock brake systems, airbag activation systems, satellites, etc.). Substitution of beryllium always leads to a loss of performance [3]. Silicon can be a less-expensive substitute for germanium in certain electronic applications, such as transistors. [9][3]. However, there has recently been a shift back to the use of germanium, as this will allow the miniaturization of electronics [3]. Nickel and copper have been substituted for palladium in certain electronic applications (e.g., platings) , albeit with some reduction in performance. Consequently for many high-tech electronics applications palladium remains the material of choice, i.e., is practically impossible to substitute.[3]

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Table 4. Possible substitutes for CRMs in printed circuit boards.

	Component	CRM	Form	Substitutes
Printed circuit boards	LEDs	Indium Gallium Germanium Iridium Yttrium	Gallium arsenide (GaAs), gallium nitride (GaN)	Ga: Liquid crystals made from organic compounds [9] GaAs, GaN: silicon or silicon based substrates sich as SiGe
	Transistors	Germanium Silicon Bismuth	Silicon germanium	Ge: Si
	Capacitors	Palladium Baryte Tantalum		Pd: other PGMs (e.g., platinum), gold or base metals Ta : Nb-based capacitors, ceramic capacitors, aluminium capacitors
	Diodes	Gallium Indium Bismuth	GaAs	Ga: Indium phosphide components (laser diodes, specific wavelengths) [9]
	Integrated circuit	Gallium Silicon		Ga: No effective substitutes [9]
	Connections	Palladium Platinum	Metal	Gold, nickel, copper, silver [5]

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7 PERMANENT MAGNETS. ENERGY SECTOR – APPLICATION: WIND TURBINE

In the last decade, wind power has exhibited an enormous growth thanks to its competitiveness with fossil fuel-fired electricity generation, unlike other renewable energy technologies, and positive life-cycle assessment on air, water and land. Wind turbines can be classified according to the driven force (aerodynamic drag or lift), spin axis orientation (horizontal or vertical), rotational speed (constant or variable) and generator type (asynchronous or synchronous) [1]. Nowadays, the wind turbines with aerodynamic lift, horizontal spin axis type and variable rotational speed are the most widely used due to their performance. There are two types of wind turbine with variable rotational speed: doubly-fed asynchronous and synchronous generators. Synchronous generators can further be subdivided according to their use of electromagnets (predominantly made of copper) or permanent magnets (mostly $Nd_2Fe_{14}B$), that are called separately excited synchronous generators and permanently excited synchronous generators, respectively. Only permanently excited synchronous generators require expensive rare earths like Nd (CRM), that are monopolized by China's market. Permanently excited synchronous generators have many advantages, e.g. very high efficiency (96-98%, which is greater than the separately excited synchronous generators with 94% and the doubly-fed asynchronous generators with 94-95.5%), robustness (saving about 25% weight) and reduced maintenance (no rotor with slip ring brushes). However, production of wind power plants driven by a permanent-magnet generator is more expensive due to the use of CRM, thus inducing a trade-off from the perspective of manufacturers and clients, especially in Europe. In 2015 the supply risk for Rare Earth chemical elements was evaluated as 9.5 over 10 by the British Geological Survey [2]. Fig. 1 shows a list of materials and components frequently used in wind turbines. We see that the most critical material in this application is the high-performance permanent magnet employed in permanently excited synchronous generators.

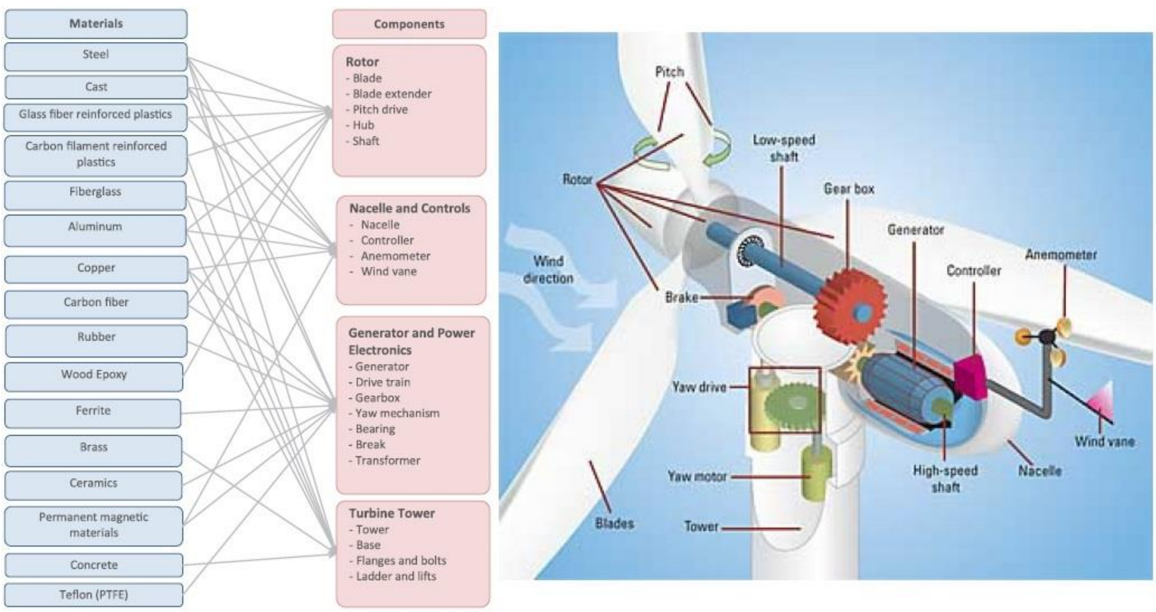

Figure 1. Materials and components in wind turbines [10,11].

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The wind turbine value chain starts with the supply of raw materials like steel, carbon fiber, permanent magnets, etc, and machinery suppliers followed by design and development services, component suppliers of generators, gearbox, blades for wind turbine companies that supply construction companies to fulfil the requests of wind farm developers, see Fig. 2 [10,11]. The enormous growth of wind power in the last years jointly with a small amount of suppliers, that had the right capabilities, have motivated the vertical integration of the supply chain where large wind companies buy out suppliers of critical components such as blades, generators, and gearboxes in order to get the products on time, and at an acceptable price [10]. Table I shows some of the current main actors of the wind turbine's value chain [27,28].

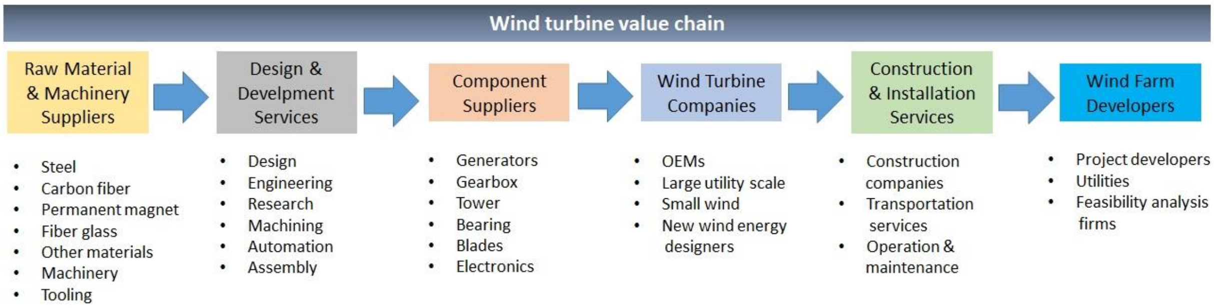

Figure 2. Value chain of wind turbine [10,11].

7.1 ECONOMIC ANALYSIS OF WIND TURBINE VALUE CHAIN

STATISTICAL DATA

The economic analysis based on statistics (Eurostat, PRODCOM-data base) of the wind turbine value chain is presented next. For the analysis, the structural composition of the application has been produced in the table below (Table 1.). Based on these divisions, the schematic economic value chain description has been produced and presented separately in the next section.

Table 1. Structural composition of wind generator/turbine with PRODCOM codes and names.

Application	*Component*	*Sub component*	*Materials*	*Prodcom code and name*
Wind power				*28112400 Generating sets, wind-powered*
	Wind turbine generator			*27112540 Multi-phase AC motors of an output > 75 kW but <= 375 kW (excluding traction motors)*

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		Magnet		*25992995 Permanent magnets and articles intended to become permanent magnets, of metal* *23441230 Permanent magnets and articles intended to become permanent magnets (excluding of metal)*
			Nd, Dy	*20132300 Alkali or alkaline-earth metals; rare-earth metals, scandium and yttrium; mercury* *20136500 Compounds of rare-earth metals, of yttrium or of scandium or mixtures of these metals*

The wind generator/turbine value chain composed of 4 groups which can be divided roughly to four stages which are materials, sub-components, components/parts and end applications. More detailed division together with PRODCOM codes and names can be seen in Table 1. In Figure 3 the relationship between production, import and export based on the statistical data has been presented. The positive values present how much value has been either generated and imported to Europe while the negative value present how much leaves as export from Europe.

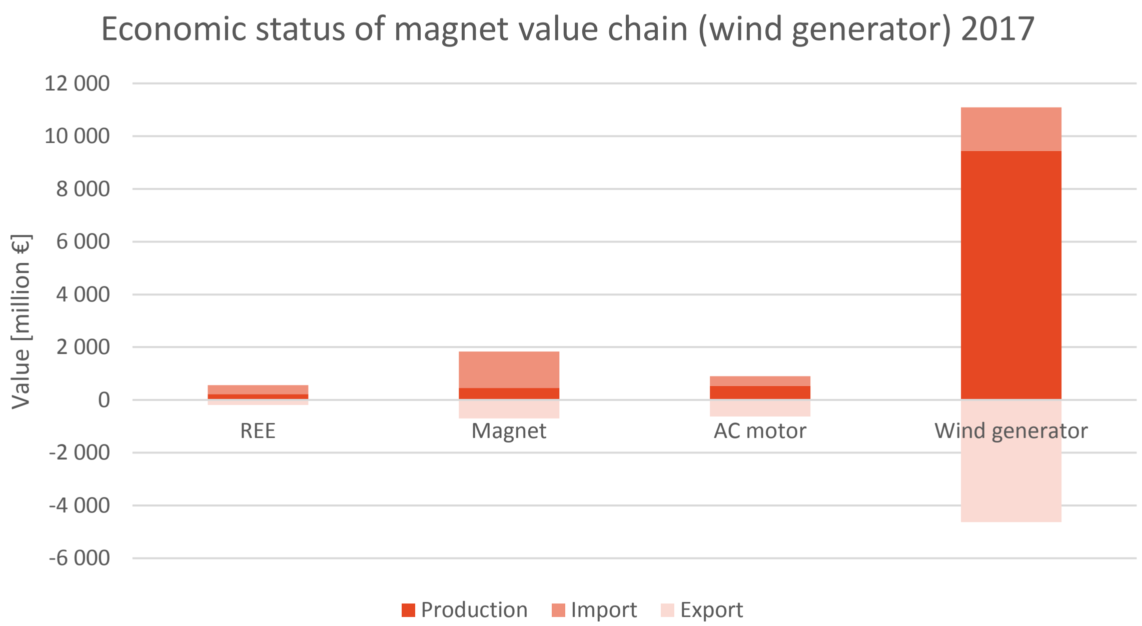

Figure 3. Relationship between production, import and export values for wind generator, components and materials in Europe 2017. Note that the values present the whole industry volume not specific to wind generator. [32]

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The value which is produced, imported and exported in wind generator/turbine value chain is heavily focused on end application. Especially production value is multifold compared to the other groups and stages in the value chain. The European wind turbine/generator manufacturers have strong position in the European market when considering the low import value. In addition, the some what low export value compared to production value indicates that the wind turbines/generators are utilized within Europe.

For the other stages in the value chain the figures are significantly lower. Production values vary from ~200 million euros for REE production to ~500 million euro for AC motor production. Especially for magnets there is rather significant import as well compared to its production which increase the positive value meaning the value that is either imported or produced in Europe. The massive end application production value compared to the other stages seems to indicate that significant value addition is generated in the turbine production.

The relation between production and import in Figure 4 expresses how dependent Europe is of import compared to the production. If the production is larger than import the indicator gets positive bar in Figure 4.

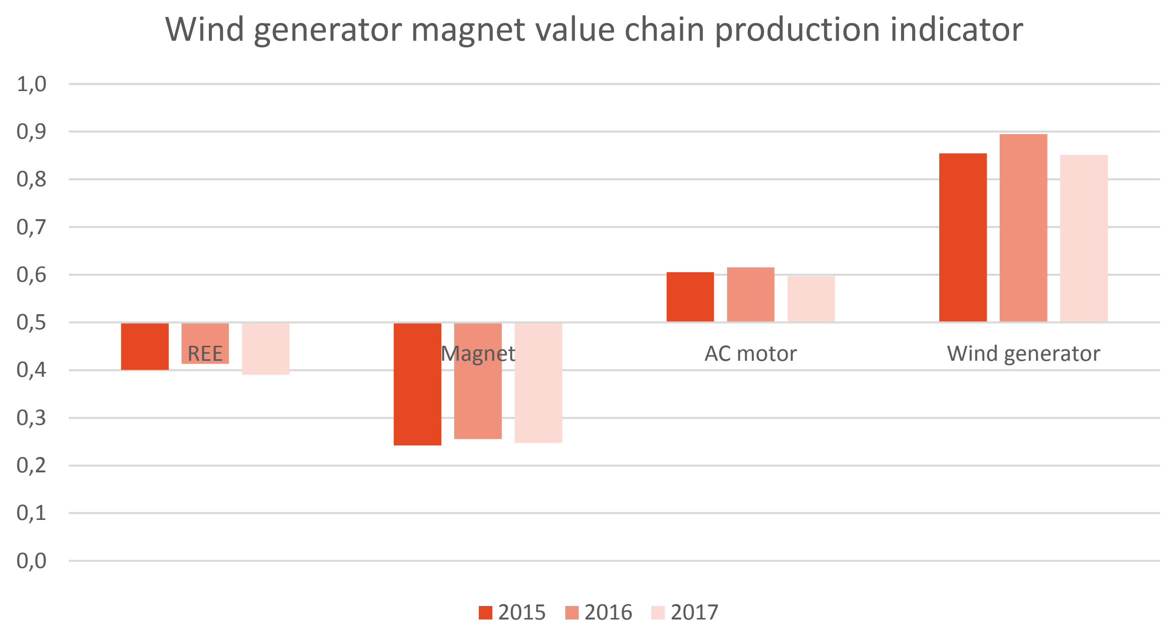

Figure 4. Production indicator (prod / imp + prod) for wind generator magnet value chain in 2015, 2016 and 2017. [1]

For Wind turbine/generator value chain it can be noticed that in overall reliance on import decreases when moving downwards on the value chain. Especially end application has strong production within Europe which has stayed as such for the last three years. For components AC motors, the production has been rather strong and sable for the last three years.

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For sub-components (magnets) and materials (REE) Europe has been dependent on import the last three years and no significant changes in the indicator can be seen. In both stages (material and sub-component) the production and import has more or less increased in the same relation which results in a relatively even bar in the Figure 4.

ACTORS IN THE VALUE CHAIN - WIND TURBINE

Table 2. Some main actors in the wind turbine's value chain [27,28].

Value chain	Main actors (Europe)	Main actors (USA & Asia)
Raw Material	ArcelorMittal (LU), Exel Composites (FI)	Hangseng(Ningbo) Magnetech (CN), Risheng magnets (CN), Miles Fiberglass and Composites (US), Zoltek (US)
Design	Acciona (ES), Adwen Offshore (DE), Lagerwey (NL), Mervento (FI), Nordex SE (DE), Siemens (DE), Sway (NO), Turbowinds (BE) , ALXION (FR)	Sinovel (CN), Nanjing Willgain Power Equipment Co. (CN), Qingdao Greef New Energy Equipment Co. (CN)
Component suppliers	Acciona (ES), Adwen Offshore (DE), Alstom Wind (FR), Enercon GmbH (DE), Gamesa (ES), Leitwind (IT), LM Windpower (DK), MHI Vestas Offshore Wind (DK), Nordex SE (DE), PowerBlades GmbH (DE), Riablades (PO), Senvion SE (DE), Siemens (DE), Vestas (DK)	Sinovel (CN), Ameron (US), Trinity Structural Towers (US), DMI Industries (US), Broadwind Towers (US), Timken (US), Nanjing Willgain Power Equipment Co. (CN), Qingdao Greef New Energy Equipment Co. (CN)
Wind turbine companies	Acciona (ES), Adwen Offshore (DE), Alstom Wind (FR), Enercon GmbH (DE), Gamesa (ES), Leitwind (IT), LM Windpower (DK), MHI Vestas Offshore Wind (DK), Nordex SE (DE), Vestas (DK)	NextEra (US), Sinovel (CN), Goldwind (CN), United Power (CN), Envision (CN), Suzlon (IN)
Installation	Gamesa (ES), Vestas (DK), Iberdrola renewables (ES), Capture Energy Ltd. (UK), Absolute Solar and Wind Ltd. (UK), Total Wind A/S (DK),	NextEra (US), Mortenson (US), NextEra Energy Resources (US), China Datang Corporation renewable Power Co (CN), Invenergy (US), Goldwind (CN), United Power (CN), Envision (CN), Suzlon (IN)

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Wind farm developers	Acciona (ES), Iberdrola renewables (ES), Vattenfall (SW), WPD (DE), RES (UK), Enel GreenPower (IT), EDF renewables (FR), EDP Renovaveis (ES), Enercon (DE)	NextEra (US), Mortenson (US), NextEra Energy Resources (US), China Datang Corporation renewable Power Co (CN), Invenergy (US)

7.2 SUBSTITUTION SOLUTIONS FOR CRM IN WIND TURBINES

In this section, different substitution solutions and strategies for the problem of CRM in permanent magnets applied to wind turbines are discussed [3,21]. These solutions mainly affect the first stages of the wind turbine value chain, that is, raw material (element-element substitution) and design (product substitution), see Fig. 2. Additionally, other renewable energy sources, as alternatives to wind turbine, are analyzed (service substitution). Table III summarizes the main substitution solutions mentioned here.

ELEMENT-ELEMENT SUBSTITUTION

The most used permanent magnet in generators is Nd-Fe-B magnet because it gives the best performance (the largest output power). Fig. 5b presents the crystal structure of the Nd-Fe-B magnet ($Nd_2Fe_{14}B$). The addition of Dy (Nd-Dy-Fe-B) enhances its performance at high temperatures. For example, a modern low-speed direct drive generator for wind turbine have a Rare-Earth magnet content of around 650 kg/MW [29], with a cost of around $100/kg, see Fig. 5c. The figure of merit of a permanent magnet is the maximum energy product $(BH)_{max}$, which is related to the maximum magnetostatic energy stored in the magnet. Another important property is the coercivity H_C since it is a key to resisting thermal demagnetization. The Nd-Dy-Fe-B magnets exhibit $(BH)_{max}$ around 300 kJ/m^3 at maximum operating temperatures close to 60 ^oC, which are required for generators in wind turbines [21].

a. Reducing Rare-Earth (RE) content in RE-based permanent magnet (PM).

Recently, research in PM has focused on reducing the amount of RE elements in PM and especially on Dy in Nd-Fe-B magnets. To this end, in the last decade the following strategies have been used: i) large shape anisotropy, with non-spherical particles, to compensate for the loss in magnetocrystalline anisotropy when reducing RE content, ii) substitution of Dy by a more abundant and cheaper RE as Pr and Ce, iii) reducing Dy content, by diffusion of some Dy along the grain boundaries for its introduction only at places required for coercivity enhancement. The tetragonal 1:12 structure (the $ThMn_{12}$ type, space group I4/mmm) is the most rare-earth-lean structure known to form in the (RE,Fe)-based compounds; it features only 7.7 at.% RE compared to 11.8% in the $R_2Fe_{14}B$ [12]. The 1:12 alloys with R = Ce, Sm exhibit uniaxial anisotropies with $\mu_0H_a \approx 10$ T; for R = Nd, and anisotropies of $\mu_0H_a > 7$ T can be induced through interstitial modification with nitrogen atoms. Unfortunately, the RFe_{12} structures do not form in the equilibrium binary alloys (only observed in thin films with R = Sm and Nd); they must be stabilized by a third element M. These kind of solutions are still under development (lab stage, TRL

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4-6) and there are not clear indications when it will come to the market. On the other hand, Sm-Co magnets are considered as an alternative to Nd-Dy-Fe-B because they have a good performance at high-temperatures and slightly lower price, see Fig. 5c.

b. Advances in RE-free PM.

Alnico magnets are a family of heat-treated Fe-Co-Ni-Al alloys with possible additions of Cu, Ti, … which were developed over 30-year period from 1932 [13]. They have some interesting properties as high remanence and high Curie temperature (T_C). Unfortunately, its coercivity is very low due to an inefficient microstructure, which favors the magnetization reversal. As a result, it leads to a low maximum energy product ($(BH)_{max}$=80 kJ/m^3). At the present time, the research in this PM is focused on improving the coercivity by reducing the scale of the microstructure, which could improve anisotropy, and reducing the interaction strength between FeCo-rich precipitates and enhancing the domain wall pinning. Alnico are already used in some applications where not very high-performance PMs are required as instrument panels of cars or transformer (TRL 9).

Ferrites like $MFe_{12}O_{19}$, where M is Sr or Ba, are oxides which have high coercivity, high resistant to corrosion and low cost [13]. However, the antiferromagetic coupling between Fe atoms leads to a very low remanence and low maximum energy product ($(BH)_{max}$=30 kJ/m^3) [21]. Nowadays, some efforts are aimed at reducing the magnetization of one sublattice without changing to much T_C. Ferrites can be found in some low demanding applications as adorn refrigerator door, small motors, loudspeakers, etc (TRL 9). Fig. 5a presents the crystal structure of ferrite $BaFe_{12}O_{19}$. On the other hand, some non-oxide Fe-based magnets have high remanence and T_C but low coercivity. Since low symmetry crystal structures enhance magnetocrystalline anisotropy and thereby improve coercivity, research has focused on Fe-based magnets with tetragonal crystal structures like tetrateanite (FeNi) and iron nitride (α''-$Fe_{16}N_2$). Another interesting non-oxide Fe-based magnet is Fe_3Sn that exhibits high saturation mangetization and high Tc [14]. The main problem with this phase is its strong in-plane magnetocrystalline anisotropy, so the research in this magnet is focused on switching it to out-plane anisotropy by doping (TRL 3).

Mn-based magnets are promising cheap alternatives to RE-PM [15]. The low temperature phase (LTP) MnBi and τ-phase MnAl are characterized by having a high magnetocrystilline anisotropy, high T_C (~650 K), experimental moderate maximum energy product ($(BH)_{max}$=35-60 kJ/m^3) and low cost (<10 $/Kg). Unfortunately, these phases are quite unstable, therefore at the present time most efforts are destined to improve the synthesis, processing and phase stability of them (TRL 4). For example, the stability of the τ-phase MnAl can be increased adding C, MnAlC, but the coercivity and T_C decreases significantly.

Nanocomposites made of high magnetization soft ferromagnet with a high coercivity hard ferromagnet, called "exchange spring magnet", are now considered one of the most promising candidates for next-generation of PM [3]. Recently, high energy product ($(BH)_{max}$=130 kJ/m^3) has been achieved in Zr_2Co_{11}/FeCo nanocomposites. Moreover, some attention has been paid on $L1_0$-type MnAl(C)/∝-FeCo nanocomposite magnet, which could be an interesting exchange spring magnet with high coercivity and T_C. Main present unsolved problems in this approach are the synthesis, processing and stability of the appropriate nanostructure.

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Presently, a magnetic material needs to have quite demanding extrinsic properties in order to be considered as a high-performance PM. Desirable values might be $\mu_0 M_S$ >1T, $\mu_0 H_c$ >1T and $(BH)_{max}$ > 200 kJ/m^3, with cost <50$/Kg. Typically, the above mentioned RE-free magnets exhibit a maximum energy product $(BH)_{max}$ that is much lower than the RE-based PM, so presently they cannot be used in applications as wind turbine generators, where high-performance PM are required. The improvement of these RE-free solutions are still under development (lab stage, TRL 3-5) and there are not clear indications whether they will finally fulfil industry demand [3].

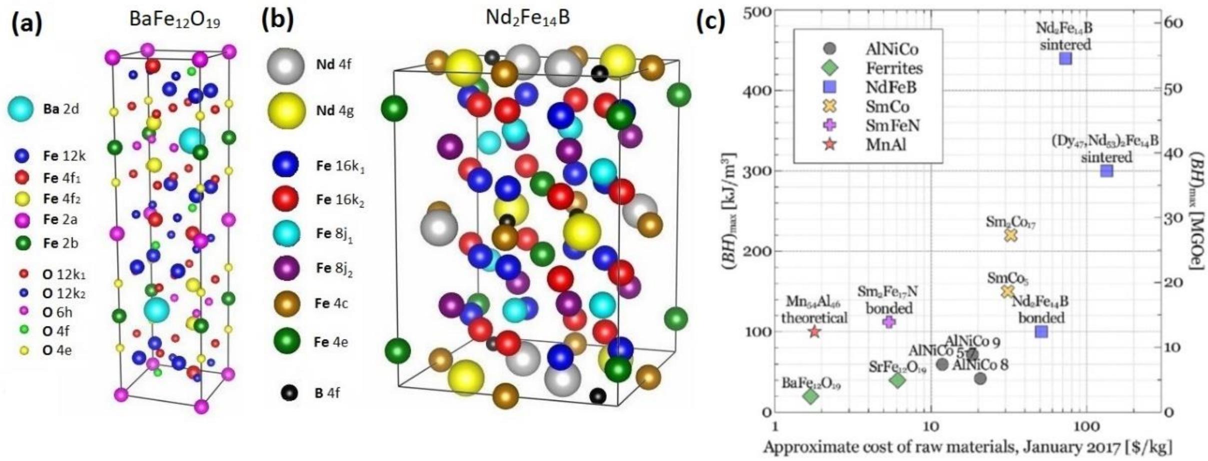

Figure 5. (a) Crystal structures of Ferrite $BaFe_{12}O_{19}$ and (b) $Nd_2Fe_{14}B$. (c) Room temperature $(BH)_{max}$ as a function of approximate raw material costs for a selection of common commercial permanent magnets. Figures taken from Refs. [30, 31].

c. Recycling RE-PM.

Both for economic and environmental reasons the recycling of RE-based magnets has gained increasing attention and importance in the PM industry. In our modern society, the number of obsolete devices which contain RE-PM is increasing very rapidly, which may provide a cheap source of RE-PM. For example, it was estimated [4,5] that the hard disk drive (HDD) industry could source around 57-64% of its NdFeB requirement from recycled HDD sources, which equates to approximately 3-11% of total NdFeB demand. Recently, it has been shown that hydrogen can be used as a very effective processing agent to decrepitate sintered NdFeB magnets from HDDs using a method called Hydrogen Processing of Magnetic Scrap (HPMS), this technique may also be applied to other devices such as electric motors, generators and actuators [6]. At the present time, Hitachi recycles RE-PM using a self-developed process that separates the RE magnets from HDD and air conditioner compressors [7] (TRL 9). Similarly, additional efforts are also being made to recycle Nd elements of NdFeB magnets from electric drive motors of (hybrid) electric vehicles [8]. Most recycling efforts of magnets currently focus on production scrap (so-called new scrap) [9].

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PRODUCT SUBSTITUTION

Permanently excited synchronous generators imply the usage of permanent magnets (mostly made of $Nd_2Fe_{14}B$). Electromagnets (Cooper-based) usage is an alternative to permanent magnets in wind power generators. Only permanently excited synchronous generators require expensive rare earths like Nd (CRM), which are monopolized by China's market. Wind turbines with PM-based generators account for 12 per cent of the global installed onshore wind capacity in 2016, while those with electrically excited generators are used by 9 per cent of the global onshore wind turbines (in terms of capacity) [22]. Fig. 6 shows the onshore drivetrain installed base by configuration of wind turbines.

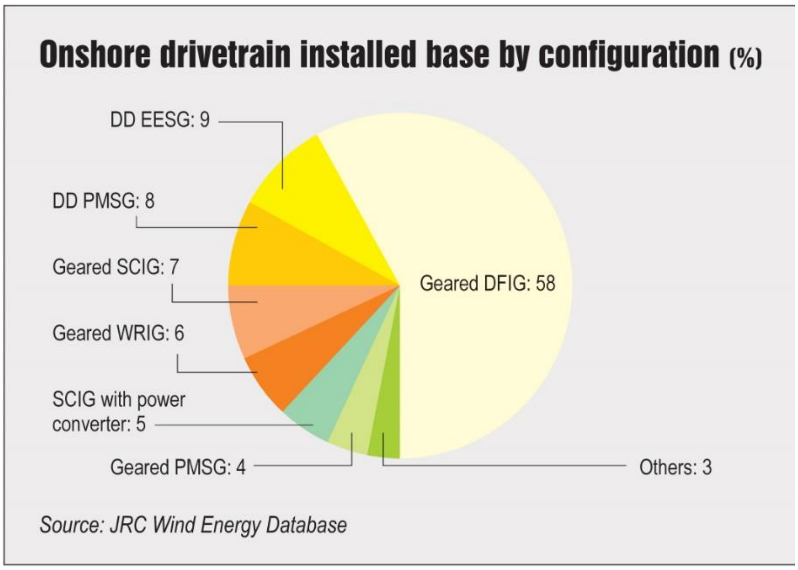

Figure 6. Onshore drivetrain installed base by configuration of wind turbines. Wind turbines with PM-based generators (DD PMSG and geared PMSG) account for 12 per cent of the global installed onshore wind capacity in 2016. Figure taken from Ref. [22].

Due to the cost-effectiveness and market independence of this alternative, production of wind power plants driven by electromagnetic generators has grown in the last years, although it has some disadvantages such the lower efficiency, more expensive maintenance and more robustness [1]. These alternatives are already in the market (TRL 9). In Ref. [23], one can find a more detailed analysis of substitution strategies for reducing the use of rare earths in wind turbines. Fig. 7 shows some possible component substitutions in wind turbines and their current technological status [23].

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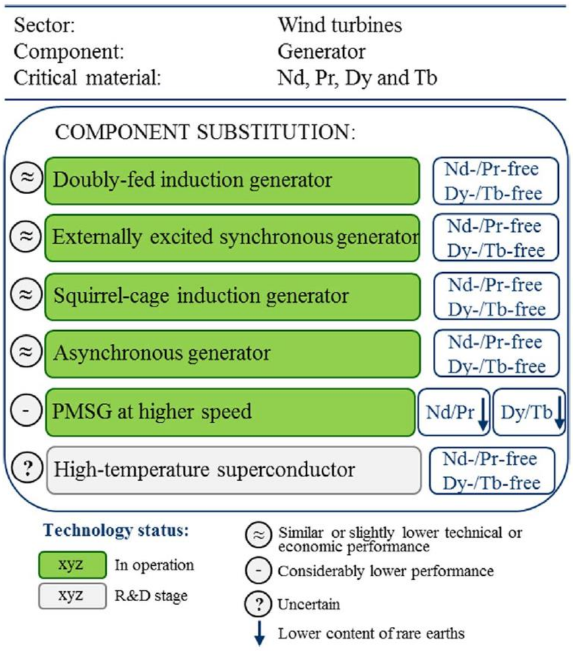

Figure 7. Possibilities for component substitution in wind turbines. Figure taken from Ref. [23].

SERVICE SUBSTITUTION

Wind power is a renewable energy resource widely distributed that is been implemented exponentially worldwide. For example, wind power energy production in peninsular Spain was the second primary energy source behind nuclear power in 2017 [16] and supplies 11.6% of the EU's electricity consumption. Wind power in Denmark provides 39% of Danish domestic electricity in 2015 [17], generates the 21.30% of consumed energy in Germany in 2017 [18] and it is the most important renewable energy source in Spain. The EU wind industry has had an average annual growth of 15.6% over the last 17 years (1995-2011). As of December 2017, the installed capacity of wind power in the European Union totaled 169.3 MW.

Other renewable sources are bioenergy, geothermal, concentrated solar power, hydraulic, wave power, photovoltaic solar power and hydrogen energy. The substitutive energy sources that do not imply the use of turbines in electric production are photovoltaic solar power and hydrogen fuel.

Hydrogen fuel has not got commercial application yet. Some current TRL values of Hydrogen fuel for mobility applications are: aviation (TRL 5-6), buses (TRL 7-8), cars (TRL 8) and aerospace (TRL 9) [20]. Solar power amounts to about 3.2% of the European Union's electricity production [19]. This share is logically higher in the countries most involved in photovoltaic technology, namely Germany (5.9%), Italy (7.9%) and Greece (7.4%) [19]. Photovoltaic panel does not need RE to work.

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Electricity production of photovoltaic technology in Spain only reaches 16.81% of the wind power production in the year 2017 [16]. Photovoltaic energy production also implies more landfield to produce the same amount of energy than wind power. Fig. 8 shows the average Levelized Cost of Electricity (LCOE) of renewable and non-renewable energy prices [24,25] across the 22 U.S. supply regions of the National Energy Modeling System electricity market module. We observe that the LCOE value of onshore wind turbine is slightly lower than the solar photovoltaic. In Fig. 9 we present the time evolution of global cumulative installations of wind and solar energies [26]. At present, the global installation of wind energy is larger than solar energy (photovoltaic), but it is expected that the global installation of solar energy will overcome the wind energy by 2020.

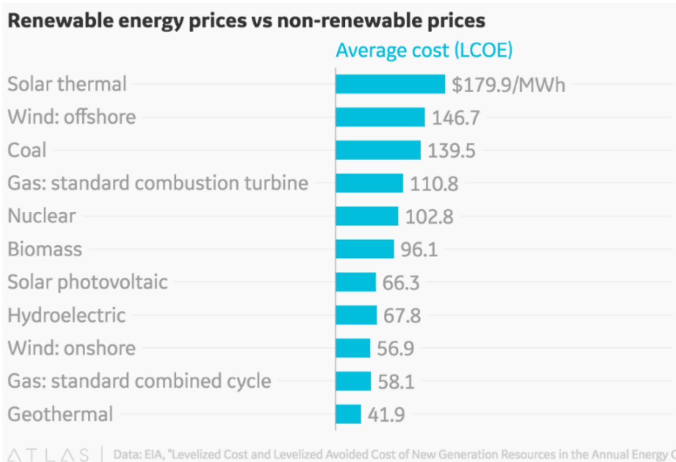

Figure 8. Levelized Cost of Electricity of renewable and non-renewable energy prices. Figure taken from Ref. [24].

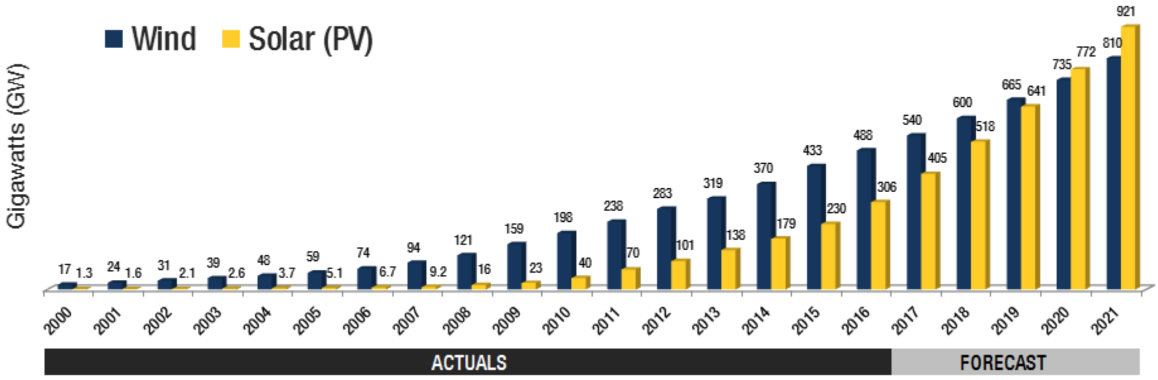

Figure 9. Global Cumulative Installations of wind and solar energies. Figure taken from Ref. [26].

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Table 3. Summary of substitution solutions for CRM in permanent magnets applied to wind turbine.

Value chain point	Potential substitute			Advantages	Drawbacks	Lab stage vs market (including TRL)
Element	Reducing RE content in RE-based permanent magnet	Replace Dy by Pr or Ce		More abundant and cheaper elements than Dy	Lower performance at high temperatures than using Dy	6
		Large shape anisotropy		low cost	Synthesis, processing and upscaling	4
		Improve microstructure design		Cheap, good performance	Grain boundary stability and complex phenomenology	5
		$NdFe_{12}$		Low content of Nd	Bulk is very unstable	4
	RE-free PM	Alnico		High remanence and high Tc	Low coercivity, low demanding applications	9
		Ferrites		High coercivity, high resistant to corrosion, low cost, coercivity increases with temperature	Very low remanence, low demanding applications	9
		Non-oxide Fe-based magnets	FeNi	Cheap, good performance	Bulk very unstable, problems with synthesis and upscaling	4
			Fe_3Sn	High saturation magnetization and Tc	Strong in-plane magnetocrystalline anisotropy	3

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		Mn-based magnets	High magnetocrystalline anisotropy, high Tc, low cost	Modest saturation magnetization, synthesis, thermal stability	4
		Exchange spring magnet	high energy product	Synthesis, processing and stability of the appropriate nanostructure	4
	Recycling RE-PM	Recovery Nd from scraps	cheap source of RE, large number of obsolete devices which contain RE-PM	Only few companies do it. There is not too much social conscience to recycle RE-PM.	9
Product	Doubly-fed asynchronous wind turbine		Cheaper, no CRM	Lower efficiency, more expensive maintenance	9
	Ecited synchronous generators		Cheaper, no CRM	Lower efficiency, more expensive maintenance	9
Service	Photovoltaics		No RE	Lower efficiency, landfield uses	9
	Hydrogen fuel		Diverse sources, abundant	Low TRL	Mobility applications: [20] Aviation 5-6 Buses 7-8 Cars 8 Aerospace 9

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8 PERMANENT MAGNETS. TRANSPORT SECTOR – APPLICATION: ELECTRIC VEHICLES

Nowadays, some problems related to the massive worldwide use of internal combustion engine vehicles (ICEVs), like fossil fuels resources, global greenhouse gas emission, high air pollution and disturbing noise levels in big cities, are forcing the development of greener transportation systems based on efficient electric vehicles (EVs). EVs make use of electric motors that contain high-performance permanent magnets (PMs) with Critical Raw Materials (CRMs), as Nd or Dy, in order to generate a high torque. PM-based motors have many advantages compared to ICEs including high efficiency, compact size, light weight, and high torque [2]. EVs can be classified according to the type(s) and combination (if any) of energy converters used. As it is shown in Fig. 1, this classification leads to two types of EVs: (i) Battery Electric Vehicle (BEV), which doesn't contain any kind of ICE, and (ii) Hybrid Electric Vehicle (HEV), which combines an electric motor and ICE. HEVs are further divided into four types depending on the architecture: series hybrid, parallel hybrid, series-parallel hybrid and complex hybrid [1]. More details of these types of EVs and other possible classifications are described in Ref. [1]. Fig. 2 shows the key components of the BEV and PM-based motor, while Table I gives the nominal range and price of some of the best EVs in 2018 [6,7].

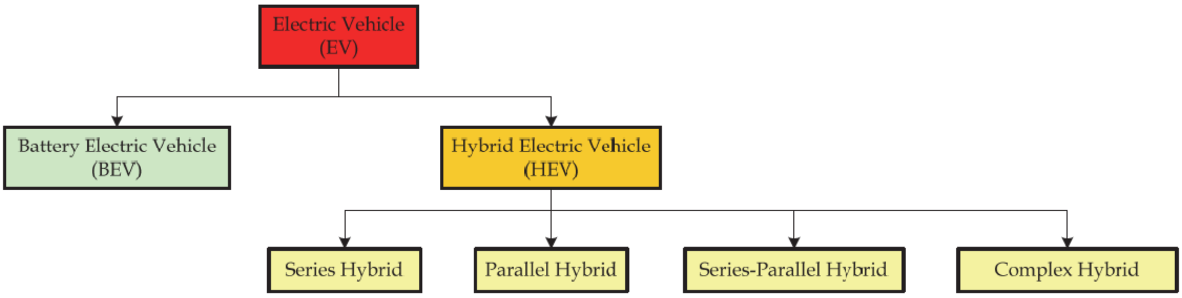

Figure 1. Classification of electric vehicles according to the type(s) and combination (if any) of energy converters used [1].

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Figure 2. (Left) Key Components of an All-Electric Car, and (right) a Permanent Magnetic Electric Motor [4,5].

Table 1. Some of the best EVs in 2018 [6,7].

Model	Range (Km)	Price (Euro)
Tesla Model 3	500	43.000
Chevrolet Bolt EV	383	26.200
2018 Nissan Leaf	240	26.200
BMW i3	180	39.000
Jaguar I-Pace	386	60.700

The EV value chain starts with the supply of raw materials like steel, aluminum, polymers, permanent magnets, rubber, copper, lithium, etc, that are used to make components as transmission, brakes, seats, batteries, electric motor, etc. Next, these components are assembled by automotive companies to make the final product, which is distributed and sold by transportation and marketing services, respectively. Finally, services like maintenance, charging, insurance or parking play an important role in the usage of EVs by customers (citizens, transportation companies, public transport, etc.) [3]. In particular, the current low number of charging stations in many countries is limiting the growth of the EV market. It is estimated that around one public charging station per 100 EVs would be sufficient to fulfill the user's demand [8]. Possible scenarios of the EV market influenced by governmental measures and other factors are analyzed in Ref. [3]. Fig. 3 shows a diagram of the EV value chain, while Table II provides some of its main actors (other companies involved in the EV value chain can be found in Ref. [9]).

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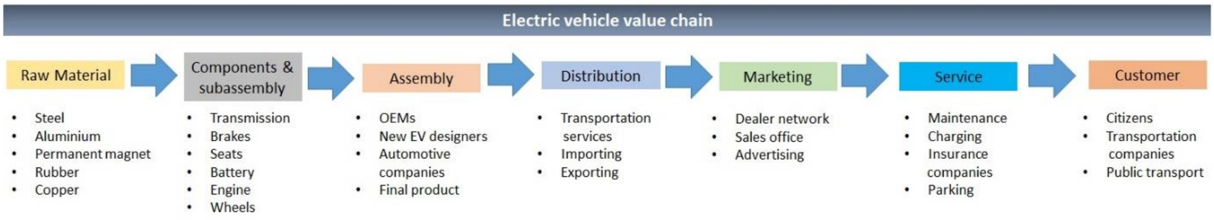

Figure 3. Structure of the electric vehicle supply chain.

8.1 ECONOMIC ANALYSIS OF ELECTRIC VEHICLE VALUE CHAIN

STATISTICAL DATA

The economic analysis based on statistics (Eurostat, PRODCOM-data base) of the electric vehicle value chain is presented next. For the analysis, the structural composition of the application has been produced in the table below (Table 2). Based on these divisions, the schematic economic value chain description has been produced and presented separately in the next section. There are some similar elements and product groups used in both chains for different applications of permanent magnets (wind generation/turbine and electric vehicle) which means that the graphs are partly similar since the value of a product/application specific component or material cannot be differentiated. However, this is not seen as a restriction since the relevance of a value chain phase for European manufacturing (industry) is the key outcome of the analysis. For the analysis, the structural composition of both applications has been produced in the table. Based on these divisions, the schematic economic value chain description has been produced and presented separately in the next two sections.

Table 2. Structural composition of Electric/hybrid vehicle with PRODCOM codes and names.

Application	*Component*	*Sub component*	*Materials*	*Prodcom code and name*
Electric/hybrid vehicle				*29102410 Motor vehicles, with both spark-ignition or compression-ignition internal combustion reciprocating piston engine and electric motor as motors for propulsion, other than those capable of being charged by plugging to external source of electric power* *29102430 Motor vehicles, with both spark-ignition or compression-ignition internal combustion reciprocating piston engine and electric motor as motors for propulsion, capable of being charged by plugging to external source of electric power*

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				29102450 Motor vehicles, with only electric motor for propulsion
	Electric motors			*27111050 DC motors and DC generators of an output > 750 W but <= 75 kW (excluding starter motors for internal combustion engines)* *27111070 DC motors and generators of an output > 75 kW but <= 375 kW (excluding starter motors for internal combustion engines)*
		Magnet		*25992995 Permanent magnets and articles intended to become permanent magnets, of metal* *23441230 Permanent magnets and articles intended to become permanent magnets (excluding of metal)*
			Nd, Dy	*20132300 Alkali or alkaline-earth metals; rare-earth metals, scandium and yttrium; mercury* *20136500 Compounds of rare-earth metals, of yttrium or of scandium or mixtures of these metals*

The electric vehicle value chain composed of 4 groups which can be divided roughly to four stages which are materials, sub-components, components/parts and end applications. More detailed division together with PRODCOM codes and names can be seen inTable2. In Figure 4 the relationship between production, import and export based on the statistical data has been presented. The positive values present how much value has been either generated and imported to Europe while the negative value present how much leaves as export from Europe.

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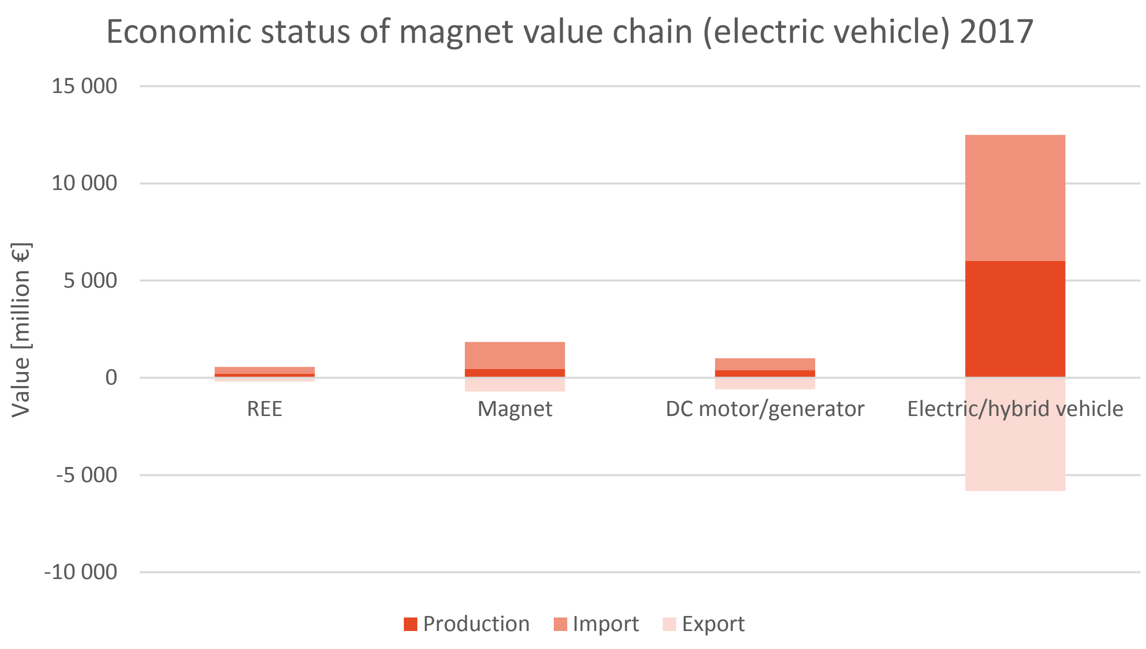

Figure 4. Relationship between production, import and export values for electric and hybrid vehicle, components and materials in Europe 2017. Note that the values present the whole industry volume not specific to electric vehicle.[15]

The value which is produced, imported and exported in electric vehicle value chain is heavily focused on end application similar to wind turban value chain. Values are multifold compared to the other groups and stages in the value chain. However, when looking the distribution of production, import and export in electric vehicle stage it can be noticed that rather significant share of positive value comes from import. Global and competitive industry with aware consumer might to some extent explain the rather significant import value. In addition, the electric vehicle manufacturing is first now starting to gain its momentum [14] in Europe which may reflect in the rather notable import. High export of electric vehicle may origin partly from re-export and second-hand vehicle export.

For the other stages in the value chain the figures are significantly lower in the similar way as in the wind turbine value chain which is logical since the PRODCOM groups for REE and magnets are same. As for the DC motor/generator the value amounts are rather same as for the AC generators in wind turbine value chain and it seems to be that a great link between the DC generator and electric vehicle can not be made. The slower start in electric vehicle manufacturing might also reflect in the component manufacturing values.

The relation between production and import in Figure 5 expresses how dependent Europe is of import compared to the production. If the production is larger than import the indicator gets positive bar in Figure 5.

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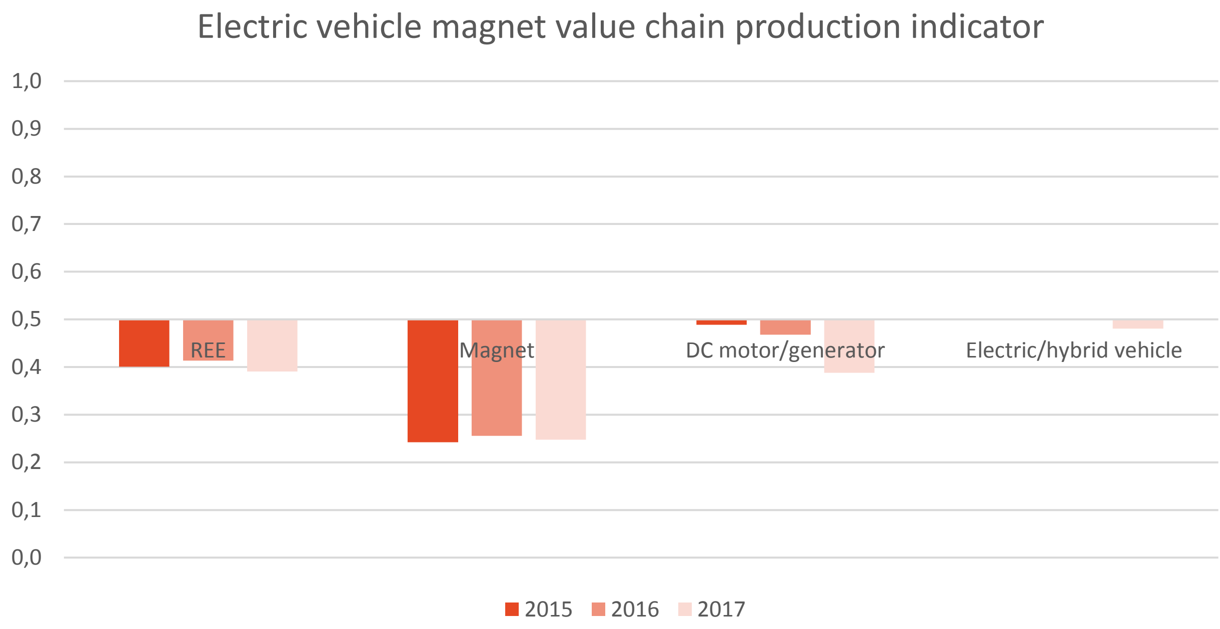

Figure 5. Production indicator (prod / imp + prod) for electric and hybrid vehicle magnet value chain in 2015, 2016 and 2017.[15]

The electric vehicle value chain is somewhat novel which results that for example statistical data on electric vehicle manufacturing, import and export do not exist prior 2017. Therefore, profound deduction and speculations based on statistical data cannot be made. It seems to be that the markets first now in terms of statistics start to take shape. For DC motors/generators there seem to be a slight decreasing trend which is caused by both an increase in the import and decrease in the production at the same time during the last three years. However, linkages between DC motor/generator and electric vehicle indicator cannot be made.

For sub-components (magnets) and materials (REE) the figures has been discussed already in the wind turbine value chain and therefore are not dealt here.

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ACTORS IN THE VALUE CHAIN - ELECTRIC VEHICLE

Table 3. Some main actors in the EV's value chain.

Value chain	Main actors (Europe)	Main actors (USA & Asia)
Raw Material	STEP-G (DE), thyssenkrupp Materials (UK), Albis (DE), Intertek (UK), Goudsmit (NL)	Hangseng(Ningbo) Magnetech (CN), Risheng magnets (CN), Novelis (US), Aleris (US), Magnequench (CN)
Components	Magtec (UK), Axeon (UK), Elaphe (SL), Magnax (BE), Bosch (DE)	Tesla (US), General Motors (US), A123 Systems (US), Panasonic (JP), BYD (CN), LG Chem (SK), Samsung (SK), AESC (JP), Ener1 (US)
Assembly	BMW (DE), Citroën (FR), Fiat (IT), Mercedes-Benz (DE), Peugeot (FR), Renault (FR), Volkswagen (DE)	Tesla (US), Chevrolet (US), Honda (JP), Hyundai (SK), Mitsubishi (JP), Nissan (JP)
Service	Schneider Electric (FR), Ecotricity (UK), Endesa (ES), Iberdrola (ES), KEBA (AT)	ChargePoint (US), EVgo (US), Volta (US), Evconnect (US)

8.2 SUBSTITUTION SOLUTIONS FOR CRM IN ELECTRIC VEHICLES

In this section, different substitution solutions and strategies for the problem of CRM in permanent magnets applied to EVs are discussed. These solutions mainly affect the first stages of the value chain, that is, raw material (element-element substitution) and components-assembly (product substitution), see Fig. 3. Additionally, possible alternatives to EVs are analyzed (service substitution). Table IV summarizes the main substitution solutions mentioned here.

ELEMENT-ELEMENT SUBSTITUTION

The most used permanent magnet in electric motors is Nd-Dy-Fe-B magnet because it gives the best performance (the highest torque). For example, the Toyota Prius uses around 1.3 Kg of Nd-Dy-Fe-B magnets [2]. In the case of electric motors, it is required slightly larger energy products (300 kJ/m^3), coercivity (30 kOe) and maximum operating temperature (180ºC) than for generators in wind turbine applications [2]. Main research lines and their development stage to solve the problem of CRM in permanent magnets applied to EVs are very similar as in the case of generators for wind turbines, which were previously analyzed in the section of substitution solutions for wind turbines.

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PRODUCT SUBSTITUTION

One possible strategy for minimizing the problem of CRM in PM applied to EVs is the improvement and optimization of the design of PM-based electric motors in order to reduce the amount of PMs needed for providing a good performance (torque). For example, it was found that the drive torque of the Toyota Hybrid System can be increased by around 15% (from 350 to 400 N*m) just by arranging the PMs in a V-shape rather than a flat-shape [2]. Recently, Magnax company designed a new generation of electric motors called Axial Flux PM motor (TRL 9) with a high power density resulting in much lower overall weight and size, while the efficiency is the highest in the market [11]. The required drive torque of PM-based motor in EVs can be partially reduced combining it with ICE as in HEV, or by totally replacing it by ICE as in ICEVs. However, PM-based motors have many advantages compared to ICEs including high efficiency, compact size, light weight, and high torque [2]. Moreover, the substitution of ICEVs by EVs can solve some of their problems like fossil fuels resources, global greenhouse gas emission, high air pollution and disturbing noise levels in big cities.

SERVICE SUBSTITUTION

In the near future, it is expected an enormous worldwide growth in new sales of EVs [10], with approximately 60 million cars sold per year by 2040, see Fig. 6a. In 2018, almost a third of new cars sold in Norway were pure electric, a new world record as the country strives to end sales of fossil-fueled vehicles by 2025, see Fig. 6b [12,13]. The transportation service given by private electric cars can be substituted by using public transport (bus, train, metro, etc.), bikes or other low cost EVs as electric bikes or electric scooter that make use of small PM-based motor with low content of PMs. These strategies might have some advantages, especially in big cities, like reducing the number of required charging stations, saving money and electricity consumption, or avoiding possible traffic jams.

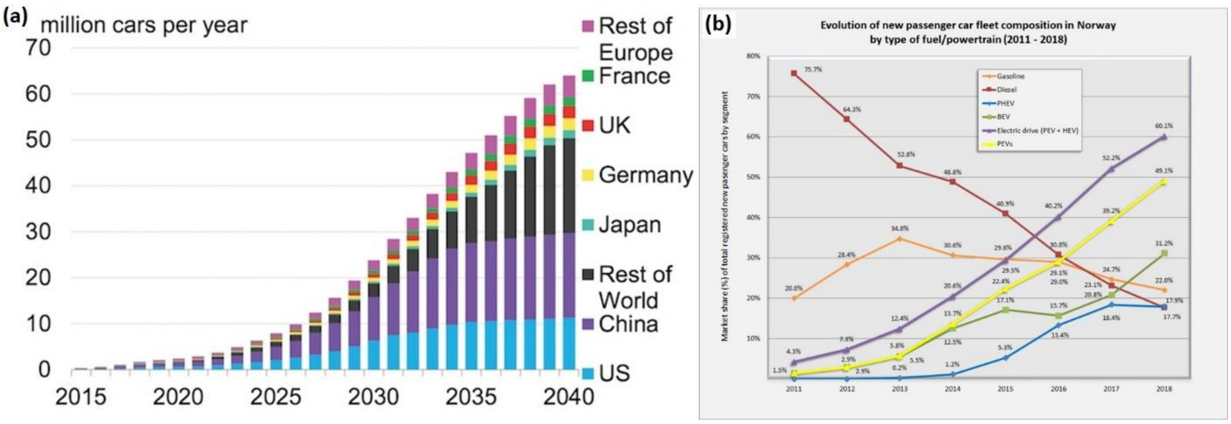

Figure 6. (a) Forecast for EVs shows explosive growth in new sales [10]. (b) Evolution of passenger car fleet market share in Norway by type of fuel or powertrain between 2011 and 2018 [13].

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Table 4. Summary of substitution solutions for CRM in permanent magnets applied to EVs.

Value chain point	Potential substitute	Advantages	Drawbacks	Lab stage vs market (including TRL)
Product	Optimizing the design of PM-based motor	Reduction of the amount of required PM, lower weight and size, high efficiency	It still needs expensive PMs	9
	Hybrid Electric Vehicles	high efficiency, compact size, light weight, and high torque	It still needs expensive PMs	9
	Internal Combustion Engine Vehicles	It doesn't used PM-based motors, long range, many gas stations available	Low fossil fuels resources, global greenhouse gas emission, high air pollution and disturbing noise levels	9
Service	Public transport	Cheap	Not very flexible schedule	9
	Low cost electric vehicles (electric bikes, electric scooter, …)	No traffic jam, PM-motor with low content of PMs	Only 1 passenger, only suitable for short trips	9

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