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CRM-Innonet Project

« Internal report summarising the results of energy sector analysis»

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Résumé

Le projet CRM-Innonet est une *Coordination & Support Action* du programme européen NMP 2012 sur la substitution des matériaux critiques. Il vise à :

- identifier les applications les plus à risques et prioritaires pour la substitution matériaux ;
- créer une communauté d'intérêt sur le thème de la substitution des matériaux critiques (CRM) ;
- enfin, développer des roadmaps de R&D pour la substitution des CRM ainsi que des préconisations auprès de l'Europe.

Le présent rapport s'inscrit dans le contexte de la première phase d'étude du projet, visant à caractériser d'un point du vue des risques et des impacts potentiels pour l'Europe les applications candidates à la substitution. En parallèle d'autres travaux sur les secteurs ICT et du Transport, il s'intéresse aux dépendances en CRM du *secteur européen de l'énergie*, et cherche à en identifier les applications prioritaires du point de vue du risque matériau et de l'impact économique potentiel.

Un filtrage a été effectué afin de réduire le périmètre d'étude à des applications représentant à la fois une dépendance matériau avérée (en lien avec la liste des 14 matériaux jugés critiques par l'Europe) et une importance économique notable (marché européen typiquement estimé supérieur à 1 b€). Ceci a permis d'identifier les technologies suivantes comme les plus à risques :

- éolien : Terres Rares pour les aimants permanents ;
- PV : Indium et Gallium dans les technologies CIGS ;
- batteries : utilisation de Cobalt, Graphite et Terres Rares pour les technologies Li-ion et NiMH.

D'autres applications comme le nucléaire (fission) et les nouvelles technologies de production hautes performances à base fossiles ont aussi été identifiées, mais non-approfondies.

Dans un deuxième temps, une analyse plus fine des chaines de valeur de l'Eolien, du PV et des Batteries a été effectuée afin de mieux quantifier le niveau de risque et l'importance économique de ces secteurs pour l'Europe :

- un risque notable est identifié pour l'Eolien, pour lequel le rôle d'intégrateur composants et système de l'Europe est mis à mal par de forts approvisionnements en aimants permanents venus d'Asie ;
- bien que d'une production européenne actuellement limitée, un risque *relatif* existe pour l'Europe sur les batteries, en lien en particulier avec les perspectives de développement de l'usage transport et le positionnement EU en R&D sur ces sujets ;
- concernant le PV CIGS par contre, l'importance de l'application pour l'Europe est jugée faible du fait d'un effondrement récent de l'industrie européenne du PV.

Globalement, l'étude montre également que l'impact économique potentiel pour l'Europe de la dépendance sur les CRM est à relativiser.

Mots clés

Matériaux critiques ; CRM ; Substitution ; Secteur de l'Energie ; Eolien ; PV ; CIGS ; Batteries ; Chaîne de Valeur

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CRM_InnoNet

Substitution of Critical Raw Materials

Deliverable report

D4.1 Internal report summarising the results of energy sector analysis

November 2013

SEVENTH FRAMEWORK PROGRAMME

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D4.1 Bottleneck analysis - Internal report summarising the results of the energy sector

Deliverable description

This report concludes the task of analysis of the energy sector, focussed on identifying CRM bottlenecks for specific applications and understanding the EU exposure to these risks through the characterisation of their value chains.

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Abbreviations

a-Si	Amorphous silicon (PV cell)
AZO	Aluminium doped zinc oxide
AIC	Ag-In-Cd compound
APAC	Asia-Pacific (region)
ATO	Antimony-doped tin oxyde
CEA	French Alternative Energy and Atomic Energy Commission
CAES	Compressed air energy storage
CAGR	Compound annual growth rate
CCGT	Combined cycle gas turbine
CCS	Carbon capture and sequestration
CHP	Combines heat and power
CIS / CIGS	Copper-Indium-(Gallium)-di-Selenide (PV cell)
CPV	Concentrated PV systems
CRM	Critical raw material
CRM-Innonet	Critical raw material innovation network
DMFC	Direct methanol fuel cells
DSSC	Dye-sensitized solar cells
EPIA	European Photovoltaic Industry Association
EPR	European pressurized reactor
EU	Europe / European
EU-14 CRM	List of 14 CRM identified by the EU in (European Commission, 2010)
EU ETS	EU Emission Trading System
EV	Electric vehicles
EVA	Ethylene-vinyl acetate
FTE	Full time employee
FTO	Fluorine doped tin oxide
GHG	Greenhouse gas
HEV	Hybrid electric vehicles
HRE	Heavy rare earth elements
ICT	Information and communication technologies
ITER	International thermonuclear experimental reactor
ITO	Indium-tin oxide
JET	Joint European torus (reactor)
L2ED	Lab. of Design, Assessment and Field Demonstration of Energy Processes
LCD	Liquid crystal display
LCO	Lithium-cobalt (batteries)
LED	Light-emitting diode
LFP	Lithium-iron-phosphate (batteries)
LMO	Lithium-manganese (batteries)
LMP	Lithium-metal-polymer (batteries)
LOI	Letter of intent
m-Si	multi-crystalline silicon (PV cell)
MOCVD	Metal organic chemical vapour deposition
NdFeB magnet	Neodymium-iron-boron magnet, permanent magnet
NCA	Nickel-cobalt-aluminium (batteries)
NiMH	Nickel-metal hydrides (batteries)
NiCd	Nickel-cadmium (batteries)

NMC	Nickel-manganese-cobalt (batteries)
OPV	Organic PV
PCB	Printed circuit board
PEM	Proton exchange membrane (fuel cell, electrolyser)
PGM	Platinum group metal
PHEV	Plug-In hybrid electric vehicle
PM	Permanent magnet
PMDD	Permanent magnet direct drive (wind turbine)
POE	Ethylene poly-oxide
PV	Photovoltaic
PWR	Pressurized water reactors
R&D	Research & development
RE	Rare earth
REE	Rare earth element
REO	Rare earth oxide
s-Si	Single-crystalline silicon (PV cell)
SET	Strategic energy technologies
SMES	Superconducting magnetic energy storage
SOFC	Solid oxide fuel cells
TCO	Transparent conducting oxide
TF	Thin film (photovoltaic)
TRL	Technology readiness level

1 Introduction and objectives of value chain analysis, definition of the perimeter studied

The objectives of this report is to identify specific Critical Raw Materials (CRM) dependence of the energy sector and through the analysis of specific application value chains *to better understand the exposure of European industry in terms of economic value and employment to a potential CRM supply risk*.

This analysis of the energy sector will be complemented by similar analysis for the ICT and Transportation sectors, with corresponding reports. These reports will participate to the background information required to later prioritize the applications for substitution roadmapping.

Analysing the energy sector in general is an extremely ambitious objective: the energy sector is very wide and may be considered as going from the extraction of energetic resources, through their transport, their transformation into intermediate energy vectors, the transport and/or storage of these vectors, their use at customer premises, including the efficiency of these use (e.g. boiler efficiency) or even the drivers for the customer energetic needs (e.g. thermal insulation of buildings…). Each of these areas covers several underlying technologies, e.g. different types of coal-fired power plant, each of them having potential dependence on CRM and their own specific value chains (i.e. chain of production, from materials to components to system in order to ultimately deliver the final “product”, such as a power plant).

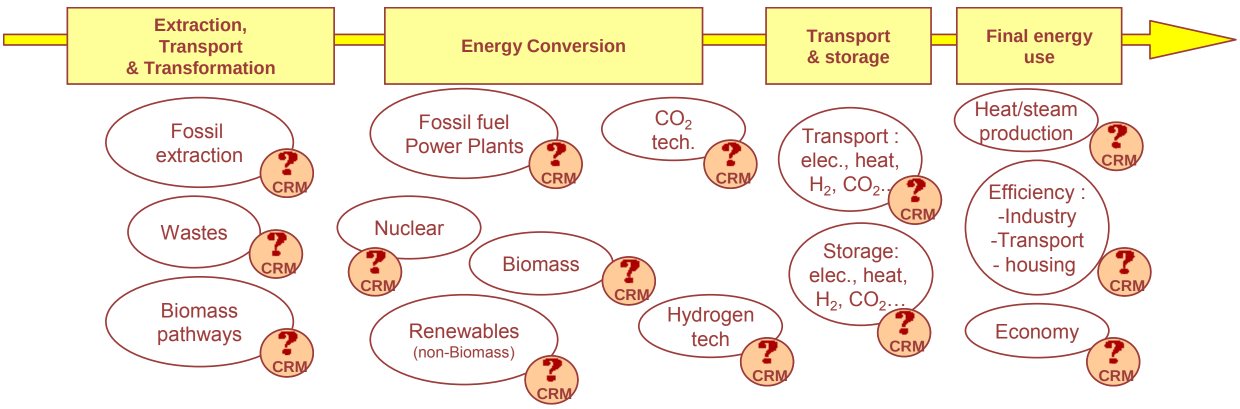

Figure 1: Energy sector – a wide perimeter

In link with the sizing of the efforts for this task, only a limited number of value chains can be analysed. A screening step is thus necessary to identify the few applications that should be the focus of this work.

2 Value chain & supply chain analysis methodology

In order to have a unified and transparent approach for the selection of applications for value chain analysis and to enable direct comparison of the applications chosen, a common methodology was developed and applied for the three sectors (energy, ICT, transport) studied. The process of application selection for value chain analysis is presented in Figure 2.

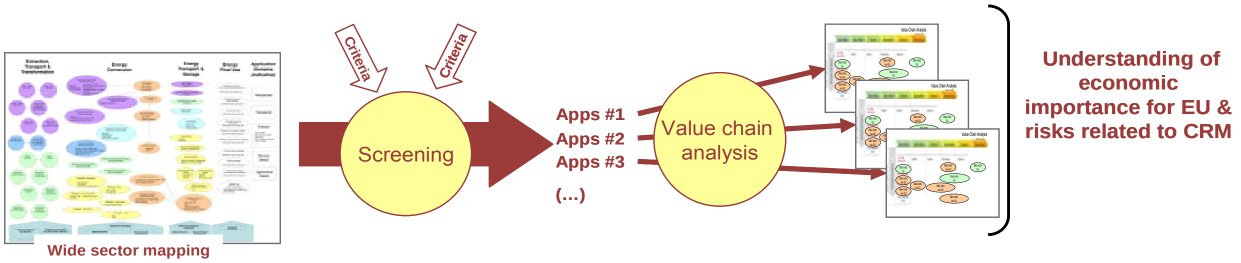

Figure 2. Approach to selection of applications for value chain analysis.

The process of selection of applications for value chain analysis is divided into two steps. In the first step, the quantity of applications was reduced by screening to approximately three to five applications. The second step comprised of value chain analysis including statistical analysis and examination of market and technical quantitative and qualitative data by experts. More detailed description of the methodology applied in value chain analysis is described in the summary report D4.4.

The main criteria for screening the key applications for considerations are described in D4.4 as:

- Risk exposure: which relates to the use within the application *of one of the EU-14 CRM* ;
- *Current* economic importance: based on production or market value, share of EU production and share of the application production in the sector. These metrics are estimated and based mostly on Eurostat data or market information.

In addition to these two criteria, the potentially very wide initial perimeter of the energy sector requires additional focus. To incorporate a more *strategic perspective* in this key sector, it was decided that the studied applications should be *both* economically important *now* and represent a *strategic importance* (future-looking) for EU. The perimeter used is the EU Strategic Energy Technologies Plan (SET-Plan) (European Commission, 2009). These technologies cover between 11 and 18 technologies (depending on how they are formulated) considered strategic for EU, the more detailed list of 18 technologies (JRC 2011b) being illustrated below.

European « Strategic Energy Technologies»

- **Wind power**
- **Solar PV**
- **Concentrated Solar Power**
- **Hydropower**
- **Geothermal**
- **Marine energy**
- **Cogeneration & CHP**
- **Carbon Capture & Storage**
- **Advanced Fossil Fuel power gen.**
- **Nuclear fission**
- **Nuclear fusion**
- **Smart grids**
- **Bioenergy – power & heat generation**
- **Biofuel for transport**
- **Fuel cells & Hydrogen**
- **Electricity storage**
- **Energy-efficient & CO_2 emission reduction**
- **Energy performances of buildings**

Figure 3: List of SET-Plan technologies (JRC 2011b)

The SET-Plan list is thus used as the initial basis for later analysis, with minor changes:

- "Biofuel for transport" is considered for the CRM_InnoNet project in the Transport sector and thus outside the scope of this report;
- "Electricity storage" along *all* its different form (stationary, portable, transport…) will be within the perimeter of this task;
- Bioenergy, for the production of power and heat, will be considered as a particular case of fossil-based co-generation and fossil-based power production, and not handled separately. The rationale is the strong historic link between biomass technologies and coal-based technologies;
- Some of the "strategic technologies" cover in practice a wide perimeter which is very context- or user-dependent. "Energy efficiency", "CO_2 emission reduction" and "Energy performances of buildings" are considered to have a too much diverse technological background to be covered: they have been removed from the list.

Value Chain vs. Supply Chain analysis

When starting the work, the objective was to make a value chain analysis of selected applications. However it was found that using the data sources available, it was not possible to get information required for a full value chain analysis. Therefore it was chosen to rather make an analysis of the supply chains as a way to get at least partial information on the value chain.

In the rest of this report, the notion of "supply chain" is thus substituted to the notion of "value chain", in order to be more consistent with the actual content of the analysis.

3 Screening of applications for supply chain analysis

3.1 Identification of CRM dependence

The adapted list of SET technologies (see previous paragraph) has been considered for further screening, based on a preliminary review of possible CRM dependence identified in the literature. It is considered that the generous amount of existing literature on the subject provides an appropriate picture for such a screening, and therefore no detailed analysis of each technology is required at this stage.

The analysis is thus based on a quick overview of the existing literature to identify potential dependence of SET technologies on the EU-14 CRM. Where such dependence is identified, the corresponding technology can proceed to the next screening step (economic preliminary analysis).

Table 1: CRM dependence of technologies

	Comments	Typical CRM
WIND POWER	Dependence of specific wind power technologies on permanent magnets, typically using rare-earth elements (CRM): neodymium, and dysprosium (JRC, 2011).	Nd Dy
PHOTOVOLTAIC POWER	Identified dependence of photovoltaics on several raw materials possibly problematic the future (e.g. (Fraunhofer & IZT, 2009), (JRC, 2011), (US DoE, 2011), (Tao, 2011)): gallium (CRM), indium (CRM), germanium (CRM), ruthenium (CRM), tellurium, and silver.	Ga Ge In (Ru)[1]
CONCENTRATED SOLAR POWER	No specific requirements with respect to CRM have been identified in the literature. Solely requirements on silver are identified (JRC, 2011), but the quantity of material involved is not considered significant (by 2020: <0.1% of 2010 world supply of Ag).	
HYDROPOWER	An assessment of CRM dependence for hydropower has been performed by Fraunhofer ISI and Oakdene Hollins in a report under review by JRC (FhG-OH, 2013). From the EU-14 CRM list, solely magnesium is identified, used for mostly reservoir plants (Vattenfall, 2011). However, further comparison with other references (e.g. (ELAQUA, 2011)) rather points towards the use of magnesite ($MgCO_3$ - currently considered a non-CRM material for Europe) related to upstream steel production process.	
GEOTHERMAL	Potential use of special alloys for parts of well pipes that are subjected to harsh environments (high temperature, acidity, salinity, etc.) are identified (FhG-OH, 2013). Such alloys (e.g. type X-56, type 625) may contain a few percent in weight of niobium, and/or tantalum content. X-56 (Nb content) can be encountered with binary and flash high temperature geothermal systems (Sullivan, 2010).	Nb Ta
MARINE ENERGY	Tidal barrage requires huge structural works (embankments, caissons) mainly made by rocks, concrete and reinforcing steel bars, and turbine components mostly made of steel and copper (Kelly, 2012). Wave energy set-ups like the Wave Dragon are mostly composed of steel, cast iron, copper, silicone product and synthetic rubber (FhG-OH, 2013) with no identified dependence on CRM.	

[1] Cases of CRM use that are possibly minor, or where consensus is not reached in the available literature, are identified between brackets ( ) in this list.

COGENERATION & CHP	Electric power generation is considered more demanding technically and material-wise than heat generation, in particular due to the need to maintain good mechanical properties of rotating components (turbines) in high-temperature environments. As a consequence, combined heat and power (CHP) key material requirement is estimated to be driven by electric power generation rather than heat generation. These material requirements for district-heating of medium-large scale CHP are thus considered similar, in a worst case scenario, to those of fossil-fuel-based power generation (see below). For Micro-CHP, a Life Cycle Assessment of a Stirling-engine based micro-CHP identifies the use of neodymium permanent magnets (Gazis, 2011).	(see fossil) Nd (micro-CHP)
CARBON CAPTURE & STORAGE	Due to limited carbon capture and storage (CCS) commercial and technical maturity, few material needs can be assessed. Assumptions encountered are the likely requirement for high-specifications steel upgrade to existing generators (JRC, 2011), leading to potential needs in vanadium, niobium (CRM), nickel and manganese, plus minor (with respect to production in 2010) requirements for cobalt (CRM), copper, molybdenum and chrome.	Nb (Co)
ADVANCED FOSSIL FUELS POWER	Pressure to increase efficiency is expected to drive increases in operating temperatures in the future, with new alloy requirements and CRM dependence as alloying elements (e.g. Ni-based superalloys with Co and Nb content). Current coal-based technology, e.g. based on T91, T92, NF616 alloys (FhG-OH, 2013), already use some niobium and sometimes tungsten (both CRM) as alloying elements (Klueh, 2004). Current best technologies for gas turbines are Ni-based alloys such as CMSX-4 which have some cobalt, tungsten and rhenium content. Other Ni-based alloys such as Haynes 230 are also used in the combustion chamber (Martinsson, 2006) and contain cobalt and yttrium. A Life Cycle Assessment of a Combined cycle gas plant (CCGT) also identified the use of cobalt (Ataei, 2012).	Co Nb W (Y)
NUCLEAR FISSION	Material requirements have been identified for fission nuclear reactors, both Westinghouse AP1000 or Areva EPR (European Pressurized Reactor), with notable use of hafnium, indium, silver, molybdenum and nickel (JRC, 2011). Indium (CRM) is typically used in the control rods of the reactors, for example as an Ag-In-Cd (AIC) material used in the lower part of the EPR control rods (AREVA, 2005). Some niobium (CRM) is also used in the jacket reactor (M5® alloy of Areva).	In Nb
NUCLEAR FUSION	Nuclear fusion is of highly limited technical maturity. Current experimental set-ups such as the Joint European Torus (JET) has however demonstrated the superior characteristics of beryllium as protective tiles for the reactor interior, and is planned for ITER experimental reactor. Other CRM use may also exist, for example in supra-conducting coils (niobium) or tungsten (CRM) for the test blanket modules.	Be Nb W (…)

SMART GRIDS	Smart grids are composed of two functional components: electricity transport (grid), and "smartness", which heavily relies on information technologies. Electricity transport uses commodity materials: copper (underground cables), steel (structures), aluminium (overground cables) and lead (submarine cables), with no identified CRM dependence. The ICT part is covered in a parallel report focussing on the ICT and electronics sectors.	
FUEL CELLS & HYDROGEN	Platinum (CRM) for proton exchange membrane (PEM) fuel cells has, for a long time, been a cost-issue slowing market penetration of the technology. Other fuel cells technologies cover : • high-temperature solid oxide fuel cells (SOFC) that typically rely on a ceramic cell (LSM/YSZ/Ni-based cermet) containing yttrium and lanthanum (both CRM); • Direct methanol fuel cells (DMFC) that rely on methanol conversion, and use platinum/ruthenium (FhG-OH, 2013). This however remains today a marginal technology. Matching electrolyser technologies (PEM & high-temperature vapour electrolysis) are based on the same materials as PEM and SOFC with the same drawbacks. Alkaline electrolysis, the main commercially mature technology for large-scale hydrogen production is based on commodity materials : NaOH or KOH electrolyte, asbestos or polymer separation membranes, and nickel-coated steel electrodes (IEA-HIA, 2013). On the hydrogen storage side, no critical material need has been identified for compressed hydrogen storage. However, technologies used to store hydrogen in a "solid" form may be based on a material such as MgH_2 (Mg being a CRM).	Pt Ru La Y Mg

<table>
<tr>
<td>ELECTRICITY STORAGE</td>
<td>Electricity storage is a vast subject with a lot of underlying technologies:
• Mechanical storage :
o Pumped hydro storage: same material requirements as hydropower (nil).
o Compressed air energy storage (CAES) has only commodity material requirements (steel, aluminium, copper) (FhG-OH, 2013), the gas turbine associated with current CAES design running at lower temperature than typical power-plant gas turbines.
o Flywheels can be made of different materials, depending on the choice of metal-based high-weight (low speed) or composite-based light-weight (high speed) design. Magnesium-based (CRM) alloys (e.g. Al-Mn-Mg-alloy) may be used (FhG-OH, 2013).
• Electrochemical storage
o Numerous battery technologies, with some material dependence: cobalt (CRM) for NiCd and NiMH, lanthanum and other REE for NiMH, cobalt and graphite for lithium-ion (BIO-IS 2011).
o Hydrogen for energy storage: see hydrogen technologies above.
• Electromagnetic storage
o Certain metal oxides may be used in super-capacitors, including ruthenium oxides (RuO_2) (FhG-OH, 2013).
o A broad spectrum of materials with high-temperature superconducting properties can be used for superconducting magnetic energy storage (SMES). Mainly niobium, yttrium compounds and MgB_2 are used (FhG-OH 2013).
• Thermal storage: this type of storage covers both sensitive and latent heat storage. No CRM dependence has been identified in the literature with respect to those.</td>
<td>Mg
Co
Graphite
Ru
Nb
Y
REE</td>
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3.2 Preliminary evaluation of European economic importance

The different applications with CRM dependence have been reviewed from an economic point of view. The purpose was to develop some understanding of the EU market/production size in order to later focus the analysis solely on applications that represented *today* a significant economic value (i.e. potential impact of the risk).

This approach may overlook some applications with small or no economic value today but with important potential tomorrow. It was however decided that more weight should be put on *today's economic* *importance*, more relevant in terms of *risk exposure,* than on predictions of possible development of specific technologies.

To cover the wide perimeter of the applications, *rough economic estimates* were performed on data coming from a variety of sources, some more reliable than others (e.g. possibly biased or non-reviewed sources were used in some applications for which data were scarce). **For this reason, the figures mentioned below should be considered as rough estimates (in some specific cases they may even be *orders of magnitude)* and with possibly significant margin of error.**

The general attempt was to estimate the market value of the new yearly installed capacity (investment on equipment), with a particular focus on domestic product/component producers. For wind energy, for example, this means the average value of the new wind turbines installed during a year. The rationale is:

- to focus the analysis on the product/component producers, directly exposed to potential material risks, while leaving aside other actors (e.g. energy developers: installing production capacity and then selling the electricity) which have a very different dependency on materials ;

- to assess the “need” that Europe has for a given application, despite the fact that some new capacities may have been manufactured abroad.

When available, information on EU production is obviously provided.

Table 2: Economic weight of technologies

WIND POWER	12.6 GW of new wind production facilities is reported in 2012, up from 9.4 GW installation in 2011, and representing between 12.8 and 17.2 b€ investment for 2012 (EWEA 2013b). In parallel, EWEA estimates that the strict contribution of EU wind turbine and component manufacturers to the 17.6 b€ total direct economic value of EU wind sector in 2010 was about 6.5 b€ (EWEA 2012). Eurostat production data for "Generating sets, wind-powered" is about 9.9 b€ for 2012, which represents 1.8% of the "Manufacture of machinery & equipment" sector. About 98% of the available goods (production + imports) come from EU production.
PHOTOVOLTAICS	16.5 GW of PV capacity was connected to the EU grid in 2012, out of which ~7.6 GW was in Germany (NPD Solarbuzz Marketbuzz, 2013), (EPIA, 2013). In its 2012 fact-sheet (EPIA 2012), EPIA estimates the total economic value of the EU photovoltaic market (including PV modules, other system parts and installation) at 58 b€, out of which about 58% (33.6 b€) is "produced" in the EU. Looking only at module manufacturing, the internal market need is estimated to about 26 b€ for EU production value of 6.6 b€. Eurostat production data for photosensitive semiconductors (including PV cells) gives a figure of 3.98 b€ for 2012 which represents 1.54% of the "Manufacturing of computer, electronic & optics" sector. About 28% of the EU available goods (production + import) come from EU production.
GEOTHERMAL	The focus is here on geothermal for electricity production. For the EU-27, an average estimate of 70 MWe/yr of new installation has been computed between 2012 and 2019. Current projects mostly use conventional/flash (66%) or binary technologies (26%) (EGEC, 2012), which are the ones reported by (Sullivan, 2010) to potentially use niobium in X-56 alloys. Capital cost for geothermal investments is being estimated between 4 k€/kWe installed (Flash technology) and 6 k€/kWe (Binary) (EGEC, 2013), an estimate of capital investment is thus about 300 M€/yr for EU-27. No relevant Eurostat/Prodcom product category was found to backup this estimate.
COGENERATION & CHP	Only medium/large size combined heat and power (CHP) markets are considered here, the micro-CHP market being in its infancy. CHP development in the EU was planned to have a significant boost during the 2005-2015 period, with a 2.6 GWe/yr to 2.9 GWe/yr penetration rate, followed by a stabilization period around 1.23 GWe/yr during the 2015-2025 period (European Commission, 2010b). Capital cost estimates for medium to large scale CHP unit vary between 1,900-2,400 €/kWe (coal), 800-1,200 €/kWe (gas) and 2,400-6,000 €/kWe (biomass) (SETIS, 2007). With a 1,500 €/kWe hypothesis (strong gas share), annual post-2015 capital expenditure for the EU would represent about 1.8 b€/yr.

CARBON CAPTURE & STORAGE	No commercial market has so far developed around CCS, due to the very low prices of the EU Emission Trading System (EU-ETS). Demonstrator projects exist, but with a lack of industrial demand for this technology.
ADVANCED FOSSIL FUELS POWER	Deployment of 72.7 GW of net new coal power plants and 73.8 GW of net new gas power plant during the 2010-2020 period was identified in 2007 (European Commission, 2007). Adapted figures integrating backup capacities (Mengede, 2011) presented ~96 GW (coal-power) and ~98 GW (gas power) for the 2010-2020 period, giving a yearly increase of about 9.6 GW/yr (coal) and 9.8 GW/yr (gas). Order of magnitude is similar with the need for 170 GW of fossil-fuel capacity by 2020 already identified in 2009 (VGB, 2009). These figures likely also cover some double-counting with CHP installations. Assuming average capital cost at 2,400 €/kW (coal) and 800 €/kW (gas) – inspired from (EIA, 2013) and with a 1.25$/1€ conversion - this leads to an estimated 31 b€/yr investment need in the EU. In Eurostat, “Fossil Fuel cells/gas turbine” product shows a 3.6 b€ EU production, with a 70% share of (production + import), and a 0.65% share of the “Manufacture of machinery and equipment segment”.
NUCLEAR FISSION	As of 2013, four nuclear reactors are under construction in EU-27: two 1,600 MWe EPR in France and Finland (due respectively in 2016 and 2014), and two PWR (Pressurized Water Reactors) in Slovakia for 880 MWe (due in 2014). This is without taking into account the units 3&4 of Cernavoda (Romania) which have a highly uncertain future. Based on construction time since the projects were launched (9 years for EPR, 29 years for PWR – of marginal influence on this computation) (WNR, 2012) , and average of 356 MWe/yr from EPR capacity and 30 MW/yr of PWR capacity are currently added. Considering only EPR, the latest cost estimate of 3,700 €/kWe (Cour des Comptes, 2012) gives an estimate of 1.3 b€/yr of average capital investment. These “market” figures are however highly sensitive and would arithmetically drop after 2014 (planned delivery of the Finnish EPR) if no decision for new nuclear facility commissioning is taken in EU-27 in the short term. Eurostat 2012 data provides a quite close figure with 1.5 b€ of production, 100% EU coverage of its use, for a 0.3% share of the “Manufacture of fabricated metal products” sector.
NUCLEAR FUSION	Nuclear fission is very far today from being a commercial technology, with the ITER demonstrator not being expected to function before 2027.

FUEL CELLS & HYDROGEN	Electrolyser technologies can be split between alkaline electrolysers (mature, widespread commercially and used for large hydrogen production in industrial applications), and PEM electrolysers (less maturity and currently a niche market for small productions). The share of electrolysis in hydrogen production technologies was estimated in 2007 ~4% of 65 million metric tons production of H_2 (IEA, 2007). Current growth of the electrolysis capacity is however unknown. Assuming it follows the general trend of the growth of the H_2 market for "on-purpose" applications, forecasted to grow 6.2% compound annual growth rate (CAGR) between 2011-2016 (ASDReports, 2012), this would lead to around 1.1 GW/yr of new electrolyser capacity and 800 M€/yr CAPEX *globally* (750 €/kW hypothesis for alkaline technology). European market share and PEM (CRM-dependent) share is expected to be much smaller. The fuel cell EU market remains today a relatively small market, estimated to 120 M€ in 2013 despite its projected growth to 490 M€ by 2018 (MarketandMarket, 2013). On the storage side, hydrogen storage by MgH_2 technology is considered as an emerging technology, brought to market by the McPhy start-up. Despite a few demonstrators of storage tanks sold up to now, this is currently a minor market.
ELECTRICITY STORAGE	Since rechargeable batteries are often embedded in other electronic devices (mobile phones, laptops…), estimating the market solely for the EU is difficult. The *global* rechargeable battery market was estimated to be about 12 b$ (~10 b€) by 2013 (Pillot, 2010), and hugely dominated by Li-ion batteries for portable electronics (electric and hybrid vehicles still being a niche market). This leads to likely >1 b€ total battery market in EU, integrating the fact that the specific "standby battery" market only is estimated for the EU-27 as 509 M€ (EUROBAT, 2013). For rechargeable batteries (NiMH, NiCd, Li-ion, etc.), Eurostat data records a 690 M€ EU production, a 30% coverage of (production + imports), and a 0.24% share of the "Manufacture of Electrical Equipment" sector. Flywheel energy storage is currently a commercial technology but has difficulties finding its market. Installed capacity *globally* was estimated in 2010 to be lower than 25 MW (EPRI, 2010). Its market value was estimated in 2005 to be ~80 M€ (100 M$) *globally* and projected to grow to ~180 M€ (225 M$) by 2010 (BCCR, 2005), which is consequently a limited EU market value. The capacitor market was also evaluated by (BCCResearch, 2005) to be about 90 M€ (110 M$) *globally* in 2005, with projected growth to ~240 M€ (300 M$) by 2010. Superconducting magnetic energy storage is not commercially deployed yet, and is more at the demonstrator stage (IRENA, 2012).

3.3 *Selection of applications for CRM supply chain analysis*

The table below summarizes the main findings about the CRM dependence and economic importance of EU strategic energy technologies, and the selection of applications for the next step of analysis (detailed supply chain analysis).

Table 3: Selection of applications for CRM supply chain analysis

Application	CRM-Use (EU-14 CRM)	EU economic importance			Supply chain analysis
		Value[2] (yearly)	Share of prod. >25 % (Eurostat)	Share of products in sector >0.2 % (Eurostat)	
Wind Power	Nd, Dy	12.6 GW 12.8-17.2 b€ market 6.5 b€ EU production 9.9 b€ prod. Eurostat	98%	1.8%	Candidate for supply chain analysis
Solar PV	Ga, Ge, In, (Ru)	16.5 GW 26 b€ market 6.6 b€ EU production 3.98 b€ prod. Eurostat	28%	1.54%	Candidate for supply chain analysis
Concentrated Solar Power					No CRM
Hydropower					No CRM
Geothermal	Nb, Ta	~70 MWe installation ~300 M€ market	No data	No data	Limited market. Not Pursued.
Marine energy					No CRM
Cogeneration & CHP	Medium/large : see fossil fuels power micro-CHP : Nd	~1.23 GW installation ~1.8 b€ market Micro-CHP: minor market.	No data	No data	Cf. advanced fossil fuels power
Carbon Capture & Storage	Nb, (Co)	No commercial market today			No market
Advanced Fossil Fuel power gen.	Nb, W, Co, (Re), (Y) alloys with potential alternatives	~9.6 GW (coal) ~9.8 GW (gas) ~31 b€ market 3.6 b€ prod. Eurostat	70%	0.65%	See discussion below
Nuclear fission	In, Nb	~386 MW ~1.3 b€ market highly variable 1.5 b€ prod. Eurostat	100%	0.33%	See discussion below
Nuclear fusion	Be, Nb, W, (…)	No commercial market today			No market
Smart grids					No CRM
Bioenergy-power & heat gen.	See fossil fuel & CHP				
Fuel Cells & Hydrogen	Alkaline elec: nil PEM elec: Pt Fuel cells :	~1.1 GW globally ~800 M€ globally PEM elec. : niche Fuel cells : 120 M€	No data	No data	Small market

[2] Strong hypothesis exist on some estimates that should be considered as rough estimate or even *orders of magnitude*, typically preceded by a ~ character.

	Pt, La, Y, Ru MgH_2 storage : Mg	(2013) MgH_2 storage: niche			
Electricity Storage	Batteries : Co, Graphite, La & REE Flywheels : Mg Supercapacitors : Ru SMES: Nb, Y, Mg	10 b€ *global* market >1 b€ EU market likely 509 M€ EU uptake batt. 690 M€ Eurostat prod. Flywheels : limited market Capacitors : limited market SMES : not commercial	30%	0.24%	Batteries candidate for supply chain analysis

<u>Additional considerations</u>

The screening process led to the identification of five potential applications of interest for supply chain analysis, with respect to their possible CRM dependence and market/economic value (typically >1 b€/yr for EU) : wind power, photovoltaics, battery technologies, nuclear (fission) and advanced fossil fuels power.

However, not all appear with the same level of priority. Wind and PV are obvious technologies of concern, with high market value and CRM dependence for active materials. Batteries have a clear CRM dependence but a more uncertain market value (yet very likely >1 b€). However, the huge potential of CRM-dependent Li-ion technologies for electric and hybrid vehicles make it an important application to study.

The risks for the case of nuclear (fission) and advanced fossil fuel power is more mitigated:

- Nuclear fission has today a significant market with average 1.3 b€/yr EU market, and indium (at least) dependence. Market estimate is however almost exclusively based on the current construction on two EPR reactors which are expected to be delivered in 2014 and 2016. Beyond this horizon, there is a relative uncertainty of the nuclear market in EU, as a consequence of the Fukushima event and the positioning of several EU countries to reduce the nuclear share in their electricity mix (e.g. Germany quite drastically);
- Advanced fossil fuels power (together with biomass-based power) still has a huge market in front of it, with potentially tens of billions € of annual investment. Its CRM dependence is however relative, as CRM are mainly used as alloying elements (few %wt to few 10s%wt for cobalt) of specific and limited pieces of the power plant e.g. turbine blades and high temperature combustion chambers. This relates to current technologies based for example on T92/T91/NF616 alloys. Moves towards higher temperatures for increased efficiency may affect material choices. Typical evolution towards Ni-based super-alloys is foreseen, with potentially increased dependence on cobalt (alloying element for Ni-based alloys) but sometimes not on other CRM like Nb or Ta (e.g. Nimonic 263, Inconel 617). Obviously, alloy choices are driven by technical requirements, but alternatives (other alloys or coatings) may exist. A much more detailed and technical analysis would be necessary *to better understand the real risk related to CRM-dependence on alloying elements for power stations*, in link with the possibility of alloy substitution. Information is thus not judged sufficient at this stage for efficiently moving towards supply chain analysis in this area.

As a result of the screening process, three applications will thus be analysed in terms of supply chain analysis:

- Wind power;
- Solar photovoltaics;
- Battery electricity storage.

General considerations about the inclusion of electronics & ICT in the energy technologies under study

Almost any system today contains a share of electric and electronic components. For e.g. wind turbine, these typically cover sensor systems, electronics for information treatment (command & control), actuators, and ICT components for communication with the rest of the system. Printed circuit boards and more generally electronic components often have dependences with CRM, that should not be overlooked. However, due to these electronic elements being everywhere nowadays, it was decided not to overload the picture of energy generation technologies with commodity-type electronic components dependence on CRM. Such dependence of electronics on CRM is addressed more specifically in another CRM_Innonet report on the electronic and ICT sector analysis (CRM_Innonet, 2013b).

4 Supply Chain analysis of applications

4.1 *Wind power*

4.1.1 Wind power technologies and CRM dependence

Wind energy is seen as a key renewable energy contributor in the short, medium and long-term energy mix, with about 15% of the 2030 average EU electricity mix potentially coming from wind (Baseline Scenario of (European Commission, 2010b)).

Wind turbines convert wind energy captured by blades into the rotation of a shaft. This rotation is then transformed into electricity through a generator. Two main markets exist, with different requirements on equipment: on-shore and off-shore wind turbines. The later obviously operates in a more demanding environment (weather conditions, saline and corrosive environment…) and is potentially more difficult to access. A general trend towards larger and more powerful wind turbines is observed, in particular for the off-shore market.

Wind turbines are typically made of a tower, supporting a nacelle, and a rotor. The nacelle and rotor are connected through a rotating shaft. Typical components of the nacelle are the gearbox (when necessary) to which the shaft is connected, the electric generator, and other systems components (shaft brake, controller, weather sensors, yaw control system, cooling system…). The tower also contains some electric components, in particular related to yaw control, and the connection to the electrical cable (Wilburn, 2011).

<u>Structural components and auxiliary systems</u>

On-shore turbines towers are typically set on concrete foundations. For off-shore turbines, a combination of underwater support structure and foundations are used. They can be either gravitary-based (mass of concrete) or fixed/sealed on the seabed for steel-made single-stake, tripod or jacket designs. The single-stake design, with a steel cylinder prolonging the tower which is hammered or sealed into the seabed is currently the most common design and minimizes the amount of steel required.

Buoyant off-shore wind turbines are a special case that enables tapping the wind potential in areas with deeper seabeds. This technology is under rapid development but typical concepts are based on buoyant single-stake, surface-buoyant structure, or immerged-buoyant structures. Hollow steel cylinders with a concrete mass at the bottom are typically used. Buoyant off-shore wind turbines need to be anchored on the seabed by cables (Ruer, 2013).

Towers are usually made of steel. Nacelles are made of steel, fibreglass and steel-reinforced plastics. Other system-related elements (command, controls, etc.) are common components in terms of sensors, electronics and actuators (Wilburn, 2011).

Undersea electric cables for electricity transport from off-shore turbines are made of copper or aluminium core, polymer insulation and steel-based reinforcement.

Drive-Train

Important differences in technologies exist for the drive-train used to convert the wind-shaft rotation, at a relatively slow 10-20 RPM, into electricity.

Four main conversion technologies can be differentiated (Li, 2007):

- Fixed-speed wind turbine systems, with a multiple-stage gearbox and a cage induction generator;
- Variable speed wind turbine system, with a multiple-stage gearbox and a doubly-fed induction generator;
- Variable speed wind turbine, without gearbox and using a direct-drive generator (low speed high-torque synchronous generator);
- Hybrid of the two previous solutions with a simple (e.g. single-stage) gearbox and a small low-speed synchronous generator.

Gearboxes are required to convert the 10-20 RPM of the rotor into the 700-1,500 RPM minimum speed required for induction generators. However, they are an important source of failure (Musia, 2007) and require frequent surveillance & maintenance which are costly at sea.

Direct-drive low speed synchronous generators do not require gear boxes due to their ability to produce current at much lower rotation speeds. Lower maintenance is necessary and higher performances are achieved (more flexibility with wind-speed, less friction). Permanent-magnets-based designs are preferred for such synchronous generators, due to significant weight gains (about 25%) over induction systems. Still, such systems require higher investments than induction-based systems, which are amortized through performance and maintenance gains, especially off-shore.

Rare-earth-based NdFeB magnets are generally used. About 600 kg/MW of permanent magnets are required for a direct-drive generator, with ~29%wt of neodymium and ~3%wt of dysprosium for temperature tolerance[3] ((JRC, 2011), (US Department of Energy, 2011)). Samarium-based magnets are a possibility, but have not been utilized industrially due to their high price and relatively lower performance (still much better than non-rare-earths based permanent magnets e.g. AlNiCo or ferrite) (Pyrhonen, 2010). Hybrid set-ups, with single-stage gearboxes, reduce the need for permanent magnets to a fraction of this quantity, depending on the design.

Induction generators, conversely, only typically require copper windings.

Rotor

The rotor represents 10-14% of the wind turbine weight. Rotor blades are made of fibreglass reinforced plastic mixed with epoxy adhesives and a light-weight core like polymer foam. The current trend is increased use of composite materials such as carbon-reinforced plastic fibres to enable longer, stiffer and lighter blades for increased efficiency. Steel and cast iron are used for other parts of the rotor (blade support, hub, pitch drive…) (Wilburn, 2011).

Despite not being a CRM, this trend towards carbon fibre use was identified as a potential material bottleneck for wind technologies (IEA-RETD, 2012).

[3] Additions of Dy are lower than those encountered in permanent magnets for automobile (4.5-6%), due to lower operating temperatures.

Selection of technologies for supply chain analysis

From the above-analysis, most materials used in wind turbines are commodity materials (steel, iron, concrete, copper, aluminium…). The main identified dependence on CRM is related to direct-drive (permanent magnet-based) generator technologies, and to a lesser extent hybrid generator technologies, both relying on NdFeB permanent magnets. Direct-drive technology will thus be the focus of the following supply chain analysis.

Table 4: CRM dependence of Wind power

Wind Power Plant	Typical material involved	CRM Content	Comments
Wind Power Plant		Nd, Dy	
Nacelle		Nd, Dy	
Drive-train - Gearless		Nd, Dy	
Permanent-magnet-based Direct-drive		Nd, Dy	
Permanent magnet generator (PMG)		Nd, Dy	
Permanent magnets		Nd, Dy	Nd (29%wt), Dy (2%wt) [EU 2011]
Nd, Fe, B & Dy powder, separate of in mixtures		Nd, Dy	Used typically in sintering of compression molding
Nd metal	Nd	Nd	
Dy metal	Dy	Dy	

4.1.2 Analysis of CRM-related Wind Power market and supply chain.

Economics

Wind turbine market in the World and in Europe

The wind power industry is growing worldwide, driven by the need for new sources of clean and affordable electricity. Global wind power installations increased to 44 GW in 2012, bringing the total cumulative installed capacity up to 281 MW worldwide, representing an increase of 18.7% over the previous year.

Europe with 12.6 GW newly installed capacity in 2012 positions itself third (29% of the total world installed capacity in 2012) after China and the USA (both with around 30%). Within Europe, Germany is the market leader with half of new capacity. However, the total cumulative wind power capacity of 109 GW in Europe in 2012 brings it to the top (39% from the total) before China (27%) and USA (21%). In 2012, Germany was the biggest wind power producer in Europe followed by Spain and the UK.

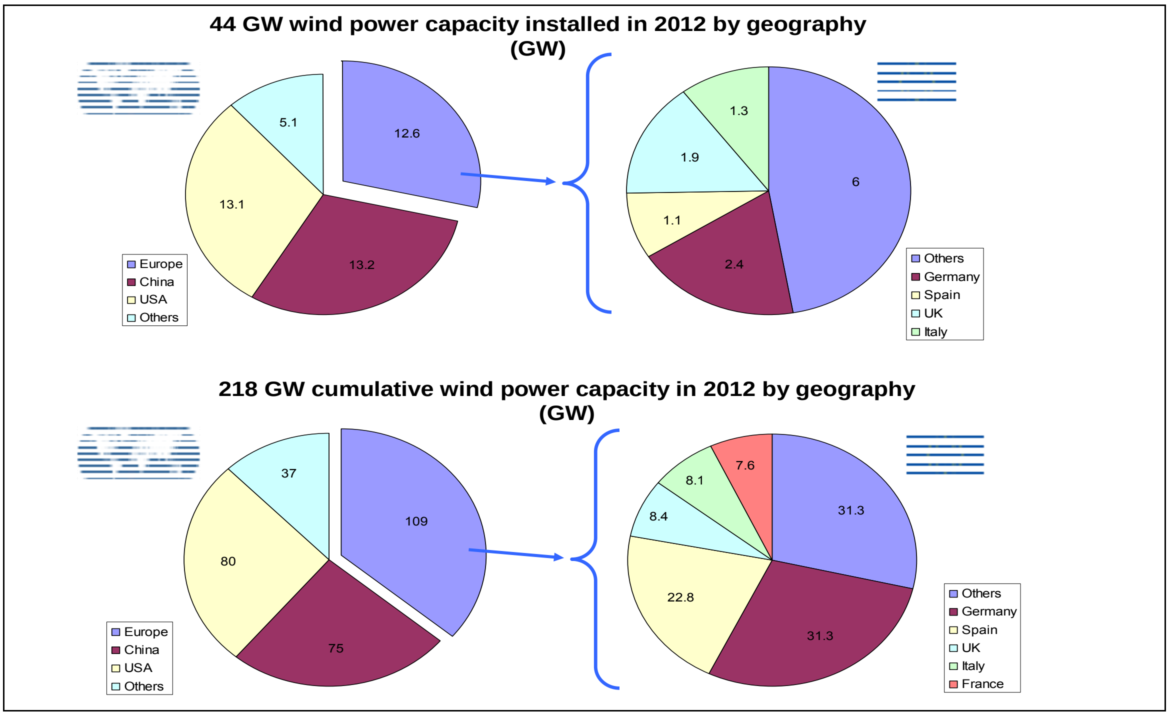

Figure 4: Wind power capacity installed and cumulative capacity in 2012 by geography (EurObserv, 2012)

Total new installations for the period 2012-2017 is estimated to about 255 GW and cumulative market growth averaging just under 16%. The Asian market is growing strongly. (GWEC, 2011)

According to the national governments of the European Union, wind energy will supply 14% of the EU's electricity consumption in 2020 (494.7 TWh of electricity from 213 GW wind power installed capacity). The European Commission, in its Energy Roadmap 2050, expects wind energy to be the key renewable energy technology by 2050, supplying more electricity than any other technology and meeting between 31.6% and 48.7% of Europe's electricity production (EWEA, 2012).

Off-shore wind turbine market in the World and in Europe

The off-shore wind new capacity worldwide in 2012 was 1,296 MW, 33% more than in 2011, bringing the global off-shore installed capacity to 5,415 MW.

In 2012, 90% of the installations were in Europe, with over 73% of all new capacity installed in the UK (854 MW). The second largest amount of installations is in Belgium (185 MW, 16%), followed by Germany (80 MW, 7%) and Denmark (46.8 MW, 4%). About 55 wind farms were operational in ten European countries in 2012. The average capacity of new wind turbines installed was 4 MW, 11% higher than in the previous year. (GWEC, 2012)

In 2013 new installations could be around 1,400 MW and in 2014, 1900 MW (EWEA 2013).

Offshore wind energy's share of total wind power capacity will increase gradually from 3.5% in 2010 to 9.9% in 2015 and 17.4% in 2020.

After 2020, wind energy development will be determined by the price and availability of fuel and the cost of emitting CO_2. By 2030 EWEA expects 400 GW of global cumulative capacity to be operating in Europe – 250 GW on land and 150 GW off-shore (38%).

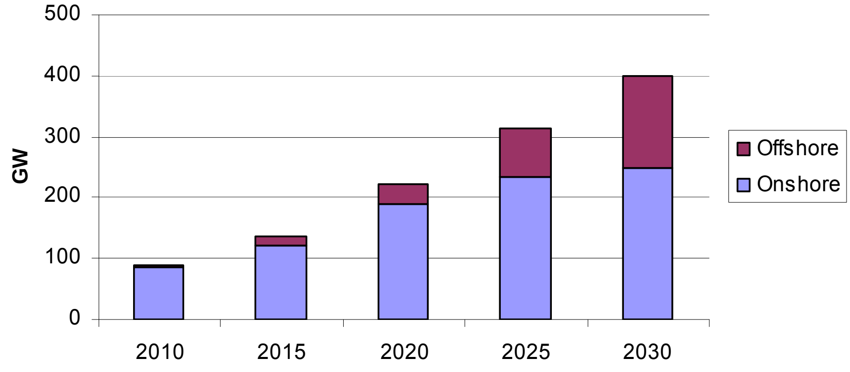

Figure 5: Cumulative on-shore and off-shore wind power in the EU 2010-2030 (EWEA, 2011)

Permanent Magnet Direct Drive (PMDD) wind turbine market in the World and in Europe

Direct drive technology is favored for large off-shore turbines. Compared to geared turbine, direct drive turbines containing permanent magnet rotors (relying on large quantities of NdFeB magnets) have two main advantages: a simpler design and a reduced maintenance cost. For these reasons the PMDD system is particularly suitable for off-shore applications even if they have a higher production cost. PMDD technology makes it easier to scale up the turbine to large scale, the lifetime of the turbine is longer and less maintenance is needed. In the end, only new design, Generation-4, large-size direct drive or hybrid turbines (half-speed hybrid generators incorporating PM in geared turbine) rely on large quantities of NdFeB magnets. For more details on Wind turbine technologies please refer to section 4.1.1.
The share of direct drive turbine installations worldwide accounted for 18% of the global wind turbine installations in 2006, 22% in 2011 and is projected to grow to 29% in 2020 according to Research and Market optimistic forecasts (Research & Market, 2012). Conversely, the EU JRC predicts that the penetration of permanent magnet direct drive turbine will be lower in Europe than in the rest of the world. It forecasts 15% of market share by 2020 of global wind turbines and possibly 20% by 2030 (estimated at 10% in 2012). An intermediate scenario, used as an estimate of current penetration, seems to be more realistic leading to a 15% PMDD turbines market share in Europe in 2012, and about 20% in 2020.

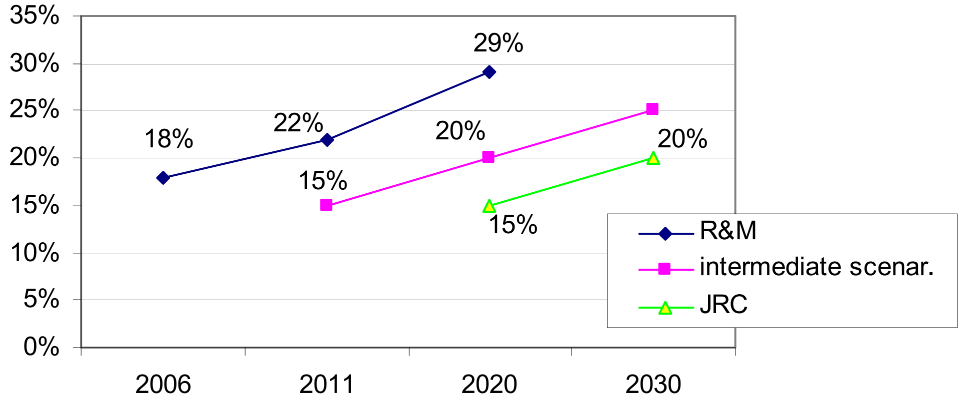

Figure 6: Direct drive turbine market share 2006-2030, globally (Research & Market estimations) and in EU (JRC estimations)

Economic value of application for EU

Within the EU, the wind energy market value was about 17 billion € in 2012, it is forecasted to reach 32 billion € by 2017. The revenue growth rate 2010-2017 is medium with a CAGR of 12%. High growth rates between 2012 and 2015 are expected due to offshore wind developments.

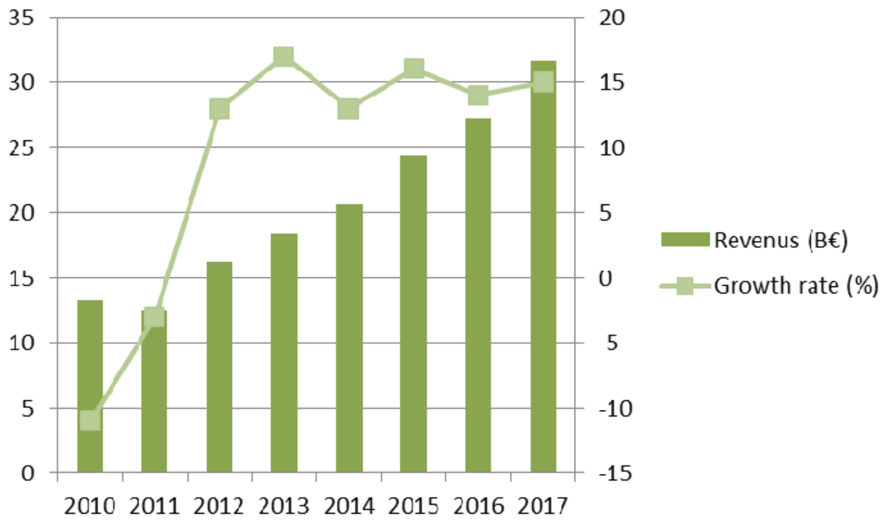

Figure 7: Wind energy market: revenue Forecast in Europe 2012-2017 (Frost & Sullivan, 2011)

Assuming that the value ratio and the market share are the same (15% in 2012 for PMDD) and that 40% of the market value is captured by wind energy developers and 60% by wind turbines and components manufacturers, the European permanent magnet direct drive turbines market value is estimated to be about 1,400 – 2,200 million € in 2012.

Position of EU on the supply chain

The wind energy supply chain consists of a number of specific and distinct steps – from the supply of raw materials to the transmission of electricity. Some actors might be vertically integrated. For example, wind turbine companies are usually both components and wind turbines manufacturers and some mining companies are also producing permanent magnets ("from mine to magnet" strategy).

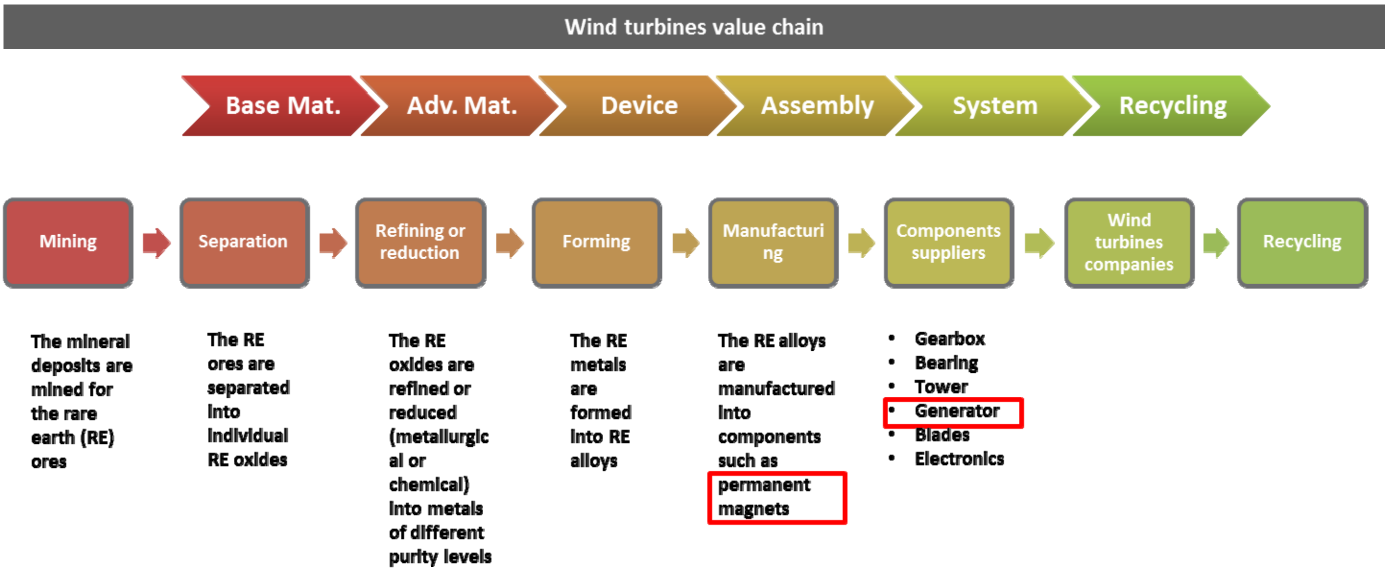

Figure 8: Permanent magnet direct drive wind turbine supply chain

The presence of Europe in the wind energy supply chain is represented mostly by the wind turbine companies. Europe has 4 companies in top 10 with 38% market share, mainly using hybrid or PMDD (Enercon only) or both technologies and are vertically integrated turbine manufacturers. Chinese wind turbine manufacturers are small companies compared to those from Europe and are mainly focused on permanent magnet direct drive technology.

The upstream part of the supply chain (REE production and permanent magnets manufacturing) is dominated by Asia and/or the USA.

Europe is poor in REE reserves and mining. China possesses more than 95% of the world REE production capacity.

But some emerging European mining companies (e.g. Frontier Rare Earths) or wind turbine manufacturers (Siemens Drive Technologies) form joint ventures to exploit mineral reserves in Africa or Malaysia.

In terms of PM manufacturing, ten companies are estimated to cover 55% of the total market share in terms of volume, dominated mainly by permanent magnets manufacturers from China and Japan (China with 6 companies and Japan with 2 companies in the top 10). One of the European permanent magnet manufacturers (German VAC - Vacuumschmelze GmbH) has been bought by OM Group Inc (USA). Interesting illustration of the global nature of permanent magnets manufacturing, VAC's manufacturing facilities are located in Germany (its home country), Slovakia, but also China & Malaysia. The USA is represented by 2 main companies: Arnold Magnetic Technologies, with production assets in the US but also Europe and China, and OM group, which main magnetic activities are now represented by VAC.

The rest of the total market of permanent magnet manufacturers is highly fragmented and shared again between China and Japan.

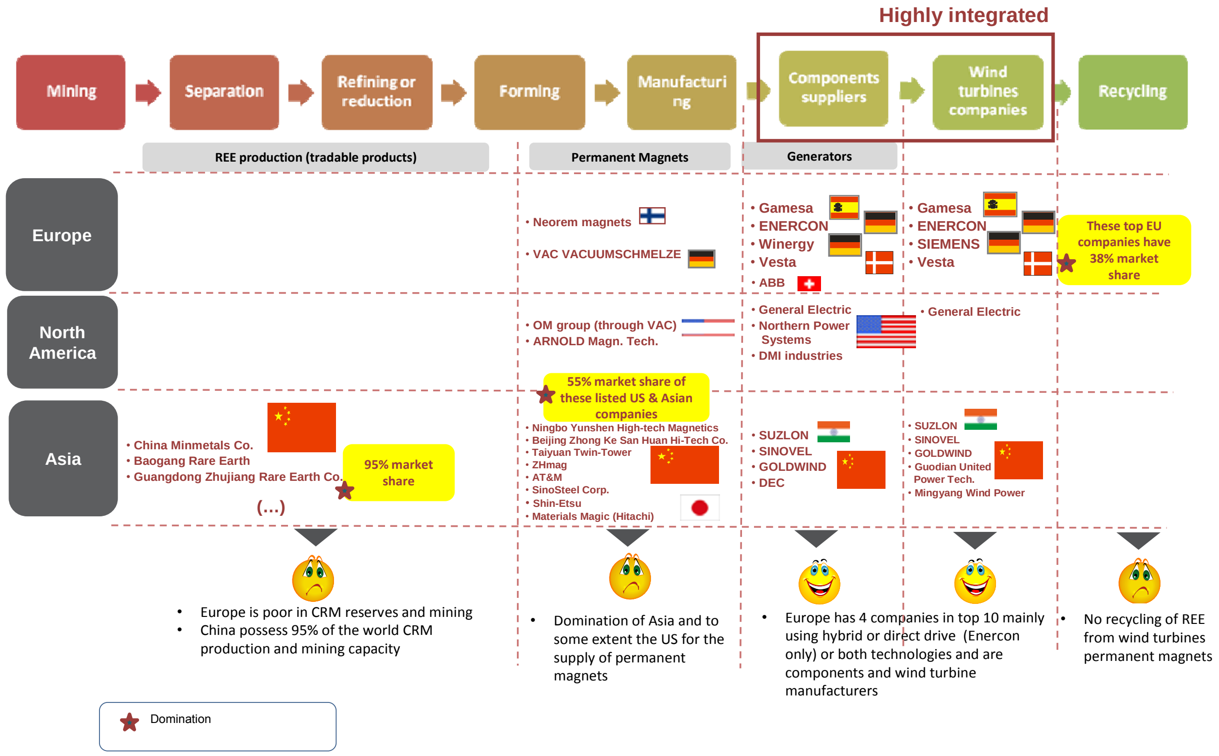

Figure 9: Position of European companies in the permanent magnet direct drive wind turbine supply chain

<u>Supply chain analysis based in Eurostat/PRODCOM data</u>

Eurostat (Prodcom) data have been extracted for 2012 in order to provide a quantitative view based on formal statistical data in Europe. Three indicators have been used: Production value (€), Imports (€) and Exports (€).

Products selected in Eurostat were chosen due to **an identified relationship with the studied supply chain (here: Wind Power)**, whether they are directly part of the supply chain (e.g. "Permanent magnets" are clearly an input component for "Generating set- wind powered"), or because database documentation stated a direct or indirect relationship with wind power. *The objective was to identify, within a reasonable range, the products that may be impacted by a CRM supply issue in link with the final application*. It was also of interest to understand to which extent Eurostat data could be used to assess the supply chain of the applications.

A list of selected Eurostat products is provided in appendix 1-2-3. Simplified naming is used in the graphics below.

Some caution should be applied when interpreting these data:

- Eurostat (Prodcom) groups do not provide a perfect match with the actual products or components we are interested in. For example, "Generating set – wind-powered" are not all based on the hybrid or direct-drive generator technologies of interest;

- Intermediate products are usually not *specific* to the considered supply chain (i.e. up-stream products, and down-stream products): not all “Permanent magnets, of metals” product goes to wind power, nor do they all use upstream rare earths;

- Production statistics do not represent value-addition but actual production value. As a result, some double-counting may occur when several steps of transformation may be reported by different companies within a same Eurostat “product”. Imports value may also be accounted as part of Production in case of minor transformation (e.g. repackaging of imported goods). For this reason, import vs. production or export vs. production should be considered with caution.

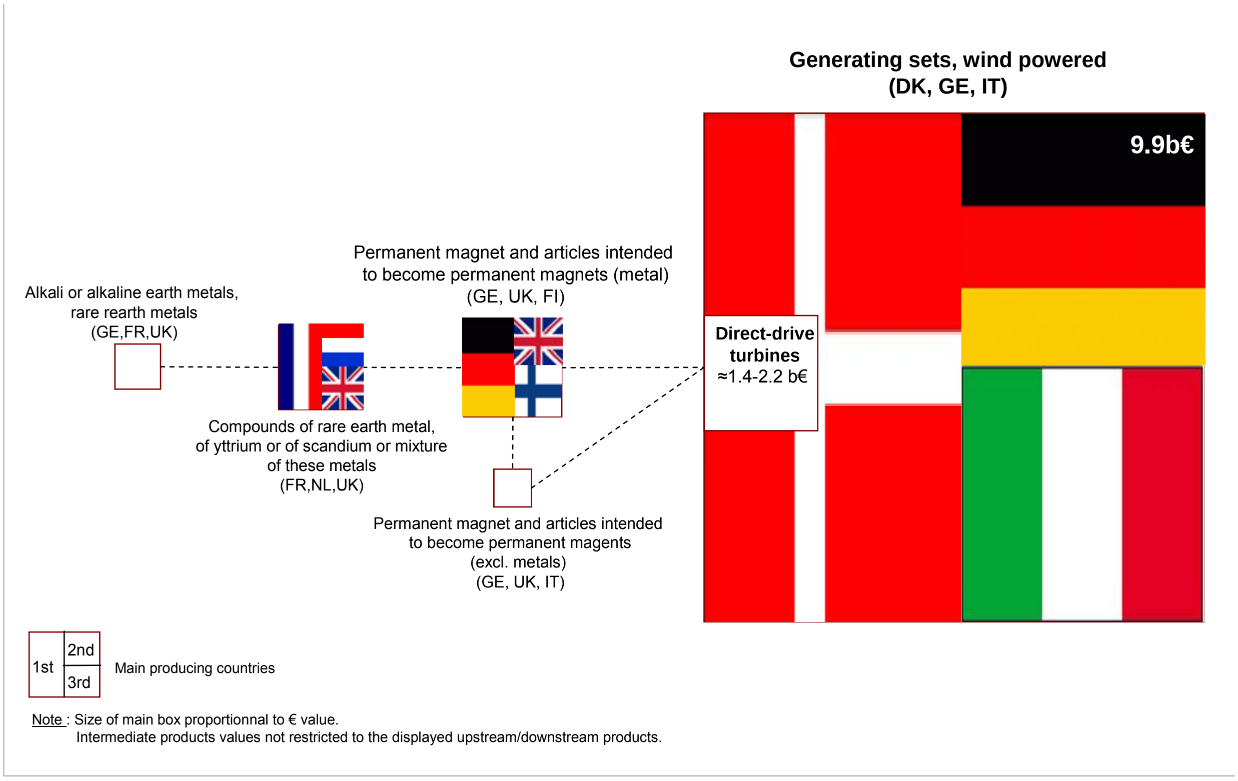

Figure 10: Largest producing countries in EU for wind power.

Wind turbines production supply chain (Figure 10) illustrates the huge presence of Denmark and Germany in the delivery of wind turbine systems, which is consistent with the previous business analysis. With respect to the overall production volume, estimated sales volume for direct-drive turbines (based on ratios) appears relatively small.

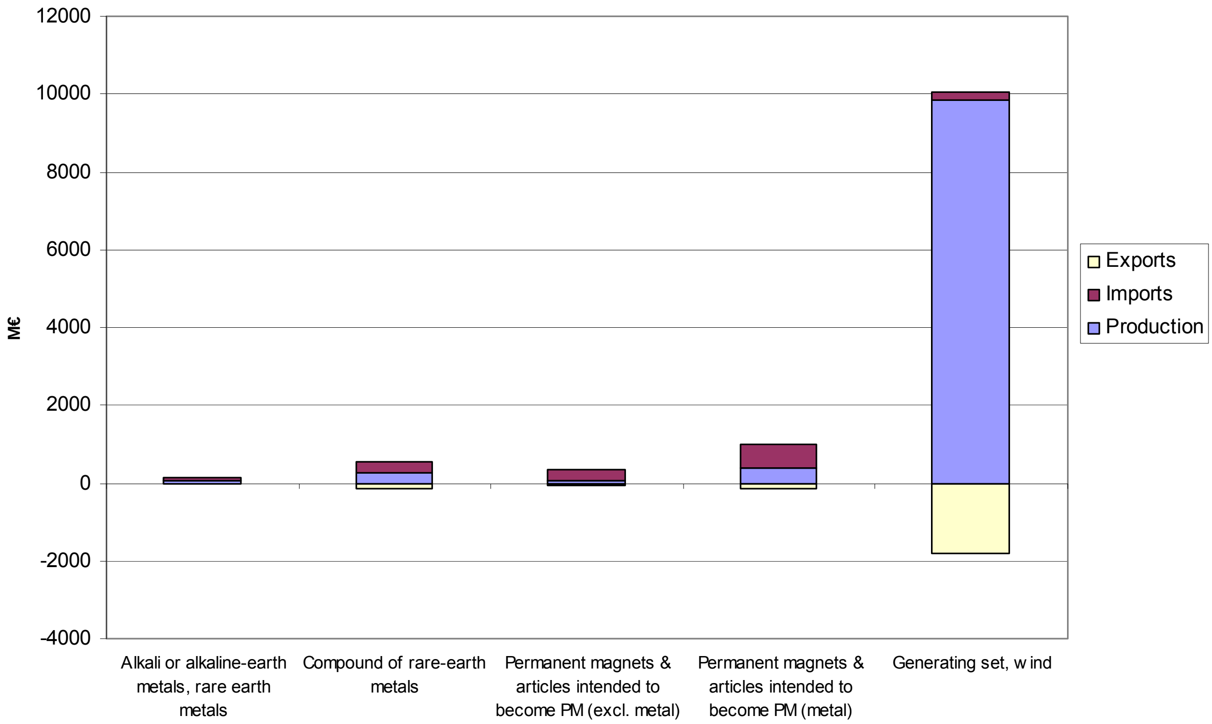

Figure 11: EU production, import and export data along the wind power supply chain

EU dominance in manufacturing of wind-turbines is once again illustrated in Figure 11 by the strong figures of final products exports, combined also with high local production. Despite the strong wind turbine market in the EU, imports of final products from non-EU regions are very low. However, high import figures with respect to local production are seen for materials and particularly permanent magnets, which is consistent with the previous business analysis.

Jobs involved in Europe

Currently the wind power industry represents about 135,000 direct jobs in Europe (238,000 direct and indirect jobs (EWEA, 2012)). Assuming that wind turbine and component manufacturers account for 60% of the jobs, 80,000 FTE (full time employment) are concerned. Assuming that 15% of the latter are related to the wind turbine direct drive industry (same ratio used for the revenue evaluation), it can be estimated that 12,000 FTE are involved in Europe for the wind turbine direct drive industry.

Criticality

How essential is the role of the critical material in the application

REE are by far the most expensive metals in the permanent magnet composition, so cost of raw materials impacts the profit of permanent magnet makers and wind turbine manufacturers. Permanent magnets represent 20% of the demand of REEs by end-use (Brumme A., 2011).

As stated previously, there are about 600 kg of permanent magnets per MW in a direct drive turbine and 200 kg/MW in a half speed hybrid drive turbine (Shaw S. and Constantinides S., 2012). In terms of weighting %, neodymium (Nd) represents 29wt% from the total of permanent magnet; iron (Fe) 66wt% and dysprosium (Dy) 3wt% (JRC, 2011).

Dy, required for neodymium magnets to perform at elevated temperatures, represents the point of vulnerability for REE in wind energy application. Firstly, it is part of the Heavy Rare Earths elements (HRE), less common and more valuable. In addition, new HRE deposits are mainly based on minerals which have never been processed (Pyrochlore, Eudialyte, Catapleite, Fergusonite…).

Considering that 15% of the 12.6 GW new wind power capacity installed in Europe in 2012 are produced with PMDD technology, about 1.9 GW is directly produced with PMDD. Assuming that there is 600 kg of permanent magnets/MW in direct drive turbines, 1,140 tons of permanent magnets were needed in 2012 for direct drive wind turbines. Applying the ratios for all REE content, 330 tons of neodymium and 34 tons of dysprosium were needed.

In 2012, the world production of rare earth oxides (REO) was about 110,000 tons; in 2011, about 90% were produced in China. Global consumption of REO had an approximate value in excess of 7.5 billion €.
China currently represents about 55% of the demand for all rare earths, followed by Japan (27%), and the USA (7%). The rest of 11% of the demand is assumed to be other countries which include the European part. 215,000 tons represents the total market estimation of rare earth oxides for 2020 **(**Shaw S. and Constantinides S., 2012).

Moreover, REEs prices faced high fluctuation between 2009 and January 2013. The price fluctuations are due to a shortage of supply from China associated with export quotas. The price of Dy between 2009 and 2011 ranged from 75 to 370 €/kg and rose up to 2,600 €/kg mid-2011. On the contrary, the second half of the year 2011 and the year 2012 was characterized by a fall in the demand for rare earth elements and therefore a fall in export prices. In January 2013, the price of Dy was at ~560 €/kg.

After a sharp drop in prices in 2012, Nd metal prices continued to decline in 2013, from 70 € (2012) to 55 € (January 2013) per kg of Nd.

How will the vulnerability of the application evolve

Global demand for REE is growing at 9-15% a year (CIBC World Markets, 2011), and according to an Ernst & Young report (2011), the market for REE is currently evaluated at ~2 billion € and is expected to double to ~4 billion € by 2015.

The PM market for wind energy applications is supposed to increase over time due mainly to the replacement of onshore by offshore wind plants. It will evolve from 1,140 tons/year in 2012 (calculated value for 1.9 GW PMDD new installed capacity and 600 kg of PM per MW) to 2,460 tons/year of PM in 2020 (calculated for 20.5 GW new installation capacity and 20% PMDD market share conducting to 4.1 GW PMDD new installed capacity).

The REE vulnerability depends on the type of REE with varying levels of uses and demands. Moreover, the mining projects are not equivalent from a composition and mineralogy point of view. The magnitude and duration of the vulnerability (e.g. shortage in the supply) will mainly be dependant on the success of REE exploration projects.

Vulnerability depends also on the REE substitution in other industries. 96% NdFeB growth is driven by consumer electronics, standard automotive, air conditioning, electric bicycles (Shaw S., Constantinides S 2012). Research and Development on Dy, the limiting factor, is underway in Japan and the USA to identify ways of reducing intensity of use – already cut by half in some magnets. (Shaw S., Constantinides S 2012).

Available substitutes

No substitute seems to be currently available replacing REE in permanent magnets for direct drive wind turbine if efficiency (including weight gains) is supposed to be maintained. No current permanent magnet (PM) materials are competitive enough with REE yet, and the main possible approach at this stage is to decrease the quantity of PM used through design (e.g. hybrid drive, inductive systems…). More general information on the possible substitution or mitigation options for REE-based permanent magnets are discussed in the CRM_InnoNet report 'Raw Material Profiles' (CRM_Innonet, 2013).

Environmental

Impact on European policies in case of disruption

Various governments and industrial users worldwide have begun to develop strategies to safeguard their REE supplies in order to overcome future supply problems. Some industrial users have established joint ventures with mining companies. For example Siemens Drive Technologies Division (EU turbine manufacturer) and the Australian Lynas Corporation Limited (mining company) have signed a letter of intent ("LOI") to establish a joint venture company for the sustainable production of neodymium based rare earths magnets to serve Siemens' production requirements for energy-efficient drive applications and wind-turbine generators.

So far no actor is positioned on the recycling supply chain of REE from PM used in wind energy.

Innovation

Substitution activities already ongoing

Some examples:

- Superconducting generators for large wind power (Jensen B. , 2012, Fair R., 2012) (TRL 7-8);
    - Smaller generator;
    - Less rare earths demand by a three orders of magnitude;
    - But large-scale demonstrators are needed and the cost must come down.
- General magnet research (not specific to wind-turbines):
    - Iron nitride ($Fe_{16}N_2$) magnet (University of Minnesota US);
    - Manganese composite magnets (DOE's Ames Laboratory US);
    - Research on the use of nanostructured REE magnets with 30% lower Nd content (University of Delaware US).

Other resources relating to the use of REE in permanent magnets, and the potential for substitution and mitigation can be found the CRM_InnoNet report 'Raw Material Profiles (CRM_Innonet, 2013).

4.1.3 Wind Power - business summary

Table 5: Summary table of wind energy application.

Dimension	Criterion	Required input
Economic	Economic added value of application in Europe	European market share for turbines containing permanent magnets generators is estimated to ~1,400-2,200 M€ in 2012. REE production is dominated by Asian companies, while the permanent magnets manufacturing is dominated by both Asian and North American companies. European positioning is on the generators and wind turbines manufacturing supply chain steps and is represented by 4 companies in top 10, mainly using hybrid or PM or both technologies, with 38% market share.
	Jobs involved in the EU	~ 12,000 people are estimated to work in the direct drive turbine industry in Europe.
Availability	Amount of CRM involved	In Europe, permanent magnets consumption for direct drive turbine in 2012 is estimated to 1,140 tons for a 1.9 GW new installed capacity, with 330 tons of neodymium and 34 tons of dysprosium. Dy is the point of vulnerability; it is less common and more valuable than Nd.
	Expected future market development	Permanent magnets direct drive turbine market is expected to increase over time due to the increased replacement of on-shore installed energy by off-shore. 2,460 tons/year of PM will be needed in 2020.
	CRM function	Mainly dysprosium, neodymium are REE used in NdFeB permanent magnets from wind generator turbines and account for 95% of the total of PM used in wind energy application.
	Availability and status of substitutes	The shortage is due to China's dominance of REE supply. No substitute is currently available for REE or conceivable for same end permanent magnets properties (resistance and efficiency). Substitution activities already on-going (R&D) on general magnets • Superconducting generators for large wind power plants (TRL 7-8) • Iron Nitride ($Fe_{16}N_2$) magnet • Manganese composite • Nanostructured REE magnets with 30% lower Nd content
Strategic Relevance	Associated to EU policies for CRM supply	Off-shore wind power is an important component of the EU strategy for the development of renewable energy. By 2030, 15% of the EU electricity mix is expected to come from wind power (more than PV), out of which 38% is expected to be from off-shore wind turbines.

Opportunity for Europe	Strong EU positioning on the later stages of the value-chain (component & systems) provides opportunity for increased vertical integration towards permanent-magnets production, or setting strong agreements with suppliers. Recycling of REE in permanent magnets is an area of possible future development.

4.2 *Photovoltaic power*

4.2.1 PV technologies and CRM dependence

Photovoltaic (PV) technologies are obtained by stacking layers of materials with different electric and physical properties, to convert sunlight into electricity. PV cells, often of limited size, are assembled into PV modules which are installed at the production premises (e.g. roof installation, land-based installation…). Additional elements such as support structures, electric convertors, cables, monitoring, are also required to ensure an operational system.

System-level electric components (electric convertors, management system…), physical mounting structures (e.g. aluminium, steel, concrete…) and module-level materials (e.g. glass, ethylene-vinyl acetate (EVA) encapsulation, connection box…) can be considered commodities and have no PV-specific CRM dependence.

At the cell level, several functions and physical material layers are typically encountered:

- Back contacts: typically non-transparent, this layer of high electrical conductivity is required to collect electricity at the back of the PV cell;
- Active layers: these consist of one or more couples of semi-transparent n-p materials, which convert light into electricity. Depending on the PV technology, a single n-p junction can be used with a defined gap-band, or the stacking of several n-p junctions with different materials and different gap-bands to increase the spectrum of light that is converted;
- Front contacts: these contacts aim at collecting the electricity from the active layer on the sun-facing side of the PV cell. A high level of overall transparency is required to avoid masking part of the cell from the sun. This is achieved through either the use of thin lines of contacts printed on the active material, or a continuous layer of contact materials than needs to be transparent in this case;
- Other functions are required from the overall PV cell and/or panel: support for the deposition of active layers, mechanical resistance and handling, protection against aggression (weather), etc. Depending on the PV technology, some functions can be provided by the same material layers as the PV functions (e.g. the silicon wafer of mono/multi-crystalline PV cells provides some mechanical resistance), or by additional layers of material: substrate or superstrate, back-plate, front-plate, frame, electrical connection... Additional treatments aiming at maximizing the amount of light captured by the panel may also be applied e.g. anti-reflexive coating.

A PV cell is thus a highly integrated device. The nature of materials and design choices led to several families of PV cells that can be encountered commercially today, mostly: crystalline silicon PV cells, thin-film (TF) technologies and high-performances multi-junction (IIII-V) cells.

<u>Crystalline silicon solar cells</u>

Crystalline silicon solar cells are the most installed PV cells, with over 80% of the market. Both single-crystalline (s-Si) silicon and multi-crystalline (m-Si) silicon are used, the latter being cheaper and more common, but with slightly lower performance. PV cell design is based on a s-Si or m-Si silicon wafer that is locally doped to create the n-p junction. Front and back contacts are created by a sintered silver paste (front & back) and an aluminium silver paste (back).

Despite the fact that silicon supply faced issues in the mid-2000s, leading to significant increase in prices, the situation is now back to normal and silicon is not identified as facing criticality.

Silver, on the other hand, is a source of concern for the s-Si/m-Si industry. It represents a noticeable part of the cell cost (about 6-14% (IEA-RETD, 2012)), and is subject to attention for new scrap recycling. It is also identified as a potential source of concern on its material availability with respect to the important penetration potential s-Si/m-Si PV technologies in the future. With an estimated 70 g Ag per kWp, s-Si/m-Si PV panels' potential could be limited to only 5.7 TWp (i.e. about 2.5% of energy production in 2100), while existing silver reserves may face depletion in less than 19 years at today's production rate (Tao, 2011). Despite possible discussion about such metrics based on "reserves", this illustrates current concerns about the material availability in this industry. The share of silver used in PV by 2050 may reach between 11% and 39% of today's production (IEA-RETD, 2012), which is likely to create tensions on the silver market in the meanwhile. Silver not being formally a EU-14 CRM, this dependence has not been pursued in this report, but such warnings may be considered.

Thin Films (TF) solar cells

Thin film technologies cover thin layers (few µm thick) of materials, deposited on a substrate or superstrate. Typical technologies today, by order of importance, are:

- Cadmium Telluride (CdTe) cells, today the leading thin-film technology;
- Copper-Indium-(Gallium)-di-Selenide (CIS/CIGS) cells;
- Amorphous Silicon (a-Si) cells, still significant, but with decreasing importance.

Other TF PV technologies also exists (e.g. organic PV (OPV), dye-sensitized solar cells (DSSC), hetero-junction cells), but they are very marginal today and may only take some importance in the future.

The substrate for thin films is usually glass, although flexible substrate (e.g. polymers) may be used in some cases. Additional glass and/or encapsulating material (e.g. EVA) casing may be added for increased protection. These materials have no identified CRM dependence and can be considered as commodities for the analysis.

TF cells use a layer of Transparent Conducting Oxides (TCO) as the electricity collector for the cell front (facing light). Historically, this layer has attracted CRM-related attention due to the frequent use of ITO (Indium-Tin-Oxide) and its dependence on indium. However, most thin films manufacturers have now moved away from ITO in an effort to reduce costs ((IEA-RETD, 2012), (Umicore thin film products – personal communication)) and are using cheaper TCO technologies such as aluminium-doped zinc oxide (AZO), antimony or fluorine doped tin oxide (ATO, FTO). ITO remains used for certain a-Si based technologies (in particular for flexible cells), and some marginal technologies such as micromorph, hetero-junction, organic and dye-sensitized cells (IEA-RETD, 2012). Market share of ITO-dependent PV technologies are thus very limited today and have not been considered a CRM-dependence in the following analysis.

CdTe cells are made from a glass superstrate, by adding a TCO layer, the active (n-CdS, p-CdTe) layers, and then a graphite-paste with copper or metals as back contact. Leaving aside the possible ITO use discussed previously, the only potential material issues identified in the literature are the use of cadmium (possible health concerns, but not the subject of this study), and the possible limitation in tellurium supply.

Tellurium is considered to be the key material dependence of CdTe technology, which already today consumes over one third of the global tellurium supply (IEA-RETD, 2012). Strong development of CdTe technology will thus require important increase of supply, despite the fact that tellurium is 90% produced as a by-product of copper (USGS, 2010b) and thus may have limited elasticity of supply. Based on material reserve estimates, the potential penetration of CdTe could be physically limited to about 816 GWp (0.4% of energy demand in 2100) (Tao, 2012). Tellurium is however not one of the EU-14 CRM considered in the present report.

CIGS cells are manufactured on a glass substrate, using a molybdenum layer as back contact, active layers (CIGS, CdS), and a transparent conducting oxide (e.g. AZO) as front contact. Problematic material dependence relates to the Copper-Indium-Gallium-Selenium ($Cu(InGa)Se_2$) layer of 1-2.5 µm thickness, containing indium and gallium, both on the EU-14 CRM list. Dependence on indium has been particularly addressed in public literature, identifying for example a potential physical limit to CIGS penetration at 650 GWp (0.3% of 2100 energy demand) based on current reserves (Tao, 2012) – not accounting for competing uses (e.g. LCD displays). Due to its strong material dependence and claimed future market potential thanks to its good PV performances, CIGS supply chain analysis will be addressed in this report.

a-Si cells technology had a significant market share (~43%) of thin films in 2010, similar to CdTe, but has seen its market share shrink to only ~25% of thin films in 2012, with respect to CIGS, and projected to decrease further in the future (only ~17% projected by 2016 (GTM Research, 2012)). Single-junction a-Si cells is made from a stacking on a superstrate (e.g. glass) of a transparent conducting oxide layer, the active semi-conducting layers (amorphous-Si based) and a metal back-contact (e.g. aluminium). Metal-based substrates such as stainless steel can also be used. Several single-junction a-Si materials with proper doping elements can be stacked-up to increase overall efficiency. Concerning a-Si, the only material limitation may come from the preferred use of ITO in some specific cases, for example flexible cells. At the PV market scale however, this represents a niche application. This is confirmed by the analysis of the RE-SUPPLY project which formally stated the lack of supply-chain constrain with a-Si (IEA-RETD, 2012).

High-efficiency multi-junction cells and concentrated solar PV

High-efficiency (III-V) multi-junction cells are the highest performing (over 44% efficiency for laboratory-scale quadruple-junctions, over 40% for triple-junctions) and also the most expensive cell design today. Commercial triple-junction III-V cells are complex devices with multiple layers. If front and back contacts may be similar to those of other PV technologies (e.g. silver-based), active layers typically contain gallium, indium, arsenic, aluminium and phosphorous in combination (e.g. GaInP, GaAs, AlGaAs, GaInAs, AlGaInP…) and sometimes germanium metal. Indium, gallium and germanium make this technology dependent on EU-14 CRM.

Due to high costs, high-efficiency multi-junction cells are used essentially in niche high-value applications such as satellites and since very recently in land-based concentrated PV systems (CPV). This leads to a very small market today, although future development of CPV may provide more significant opportunities.

Selection of technologies for supply chain analysis

Table 6: Application decomposition – CRM dependence of PV technologies

	CRM Content	Comments
Photovoltaic Power plant	In, Ga, Ge	
PV Module	In, Ga, Ge	
PV Laminates (different technology options)	In, Ga, Ge	
Cristalline Silicon technologies	Not applicable	
Thin Film PV technologies : a-Si, CdTe, CIGS, OPV	In, Ga	Generic Thin-Film model is taken below. May vary.
Active layers	In, Ga	
CdTe	Not applicable	
CIGS	In, Ga	CIGS technology
CIGS targets	In, Ga	for deposition technologies
CIGS powder	In, Ga	for target production
In metal	In	
Ga metal	Ga	
a-Si	Not applicable	
Front conductive layer and/or contact	(In)	
(ITO)	(In)	In most cases, ITO is only one option of TCO.
(ITO sputtering target)	(In)	In most cases, ITO is only one option of TCO.
(ITO powder)	(In)	In most cases, ITO is only one option of TCO.
(In metal)	(In)	In most cases, ITO is only one option of TCO.
High-efficiency multijunction solar cells	Ge, In, Ga	
Active Layers	Ge, In, Ga	
Combinaison of Ge, In, Ga elements	Ge, In, Ga	multiple layers with different combinaison of these elements
Trimethylgallium (TMG)	Ga	Used for MOCVD deposition processes for growing layers on substrate
Trimethylindium (TMI)	In	Used for MOCVD deposition processes for growing layers on substrate
Germanium (substrate)	Ge	

PV being an active research field with strong pressure on cost/performance ratio, new designs appear on a regular basis, for example hetero-junction cells. Apart from technologies with current market shares, it is however highly uncertain to predict the future potential for such upcoming technologies. The example of the development of thin-film technologies, predicted a few years ago to quickly grow to about 30% of PV market shares and which has seen its market shares reach a low-point in 2012 with only 11% (GMT Research, 2012), demonstrates the dynamic nature of the PV sector.

The study of PV technologies will thus focus on CRM dependence for technologies with an *existing market share* at the date of writing. From the previous analysis, this covers the CIGS technology which has dependences on In and Ga as part of its active materials. As discussed previously, ITO dependence will not be further studied due to the observed trend in the PV industry for substitution by cheaper transparent conducting oxides (e.g Aluminum-doped Zinc Oxides - AZO).

Despite the dependence of high-performance multi-junction cells on several critical materials (Ge, Ga, In), its current niche positioning on high-value systems limits the volume of material demand. In addition, such high-value applications are likely less sensitive to material price fluctuations, leading to a lower sensitivity towards material-related supply-chain issues. This material dependence has thus not been selected for supply chain study, although the currently developing use of multi-junction cells for land-based CPV may change this trend in the future.

Another material, silver for crystalline silicon cells, has been identified. Not being a EU-14 CRM it will however not be pursued here.

As a consequence, the focus of the PV supply chain analysis below has been put on CIGS dependence on indium and gallium (EU-14 CRM) as its active materials.

4.2.2 Analysis of CRM-related PV market and supply chain.

Economics

PV market in the World and in Europe

The PV industry reached 100 GW of PV cumulative installed capacity in the world by the end of 2012 and the demand was about 29 GW. For 2012, Europe retained its dominant position in global PV demand with 16.5 GW, according to (NPD Solarbuzz Marketbuzz, 2013), representing 57% of the global PV demand in 2012. This figure decreased, however, from 68% in 2011 and 82% in 2010. Germany is still leading the market.

Strong demand from Europe was due primarily to premium incentives that remained in place up to 2012, along with lower installed system prices. European incentives declined in value after that year, as administrators followed the downward trajectory in PV system prices.

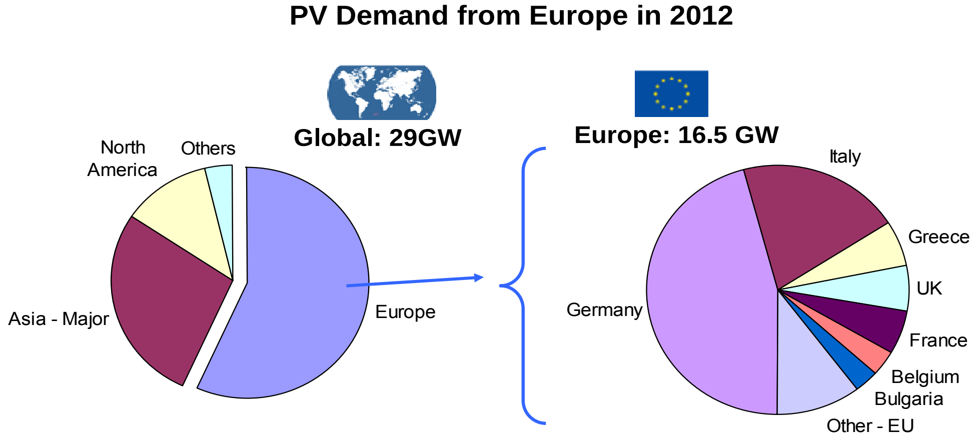

Figure 12: PV demand from Europe in 2012 (NPD Solarbuzz Marketbuzz, 2013).

During 2013, the European market is expected to continue to evolve from a premium-incentives PV environment towards PV electricity being driven in terms of competitive cost. During this transition period, major European markets will see declining PV demand. Demand in Europe could go down to approximately 12 GW in 2013. For the first time, China will outpace Germany to become the leading PV consumer. Under the most-likely forecast scenario, 230 GW of cumulative PV will be required out to 2017. At this time, PV demand in Europe and Asia will be about the same (~35%).

PV energy will represent 10 to 25% of global electricity production in Europe by 2030 according to 3 different EPIA (European Photovoltaic Industry Association) forecast penetration scenarios (base line, accelerated, paradigm shift). An average of 8% by 2020 and 15% by 2030 could be achieved in an accelerated medium scenario demonstrating the importance of this issue for Europe.

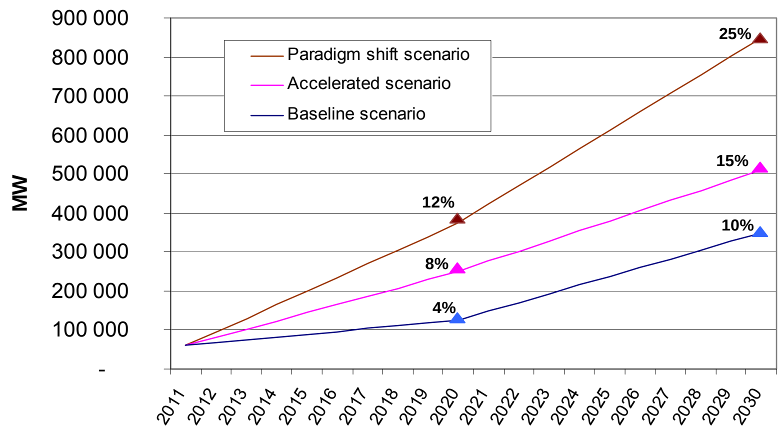

Figure 13: EU PV cumulative capacity forecast (MW) until 2030 (EPIA, 2012).

Thin film market in the World and in Europe

Crystalline silicon PV dominates by far the solar market. Its market share has been rapidly increasing over the last few years with the ramping up of Chinese manufacturers. The surge of low-priced crystalline modules from China has smothered the market for alternative technologies like CIGS thin film which looked very promising a few years ago. In 2008 the market share of thin film technology was estimated for 2012 to be 30% of total global market. In fact, the market share of thin film decreased from 18% in 2009, when the cost advantages of thin film technologies provided a competitive edge (GTM Research, 2012), to 11% in 2011. During the apogee of multi-crystalline silicon bottleneck between 2004 and 2009 (shortage of m-Si and peak prices), shipment of thin film grew from 60 MW to 2 GW representing a compound annual growth rate (CAGR) of 97%. Thin film continued to grow to 3.7 GW in 2011, but cheap crystalline production radically changed the structure of the supply-side.

The actual downward trend is expected to continue. Thin film market share is forecasted to decrease to 7% of new PV production during 2017, with a decline each year up until then ((NPD Solarbuzz, 2013), (GTM Research, 2012)).

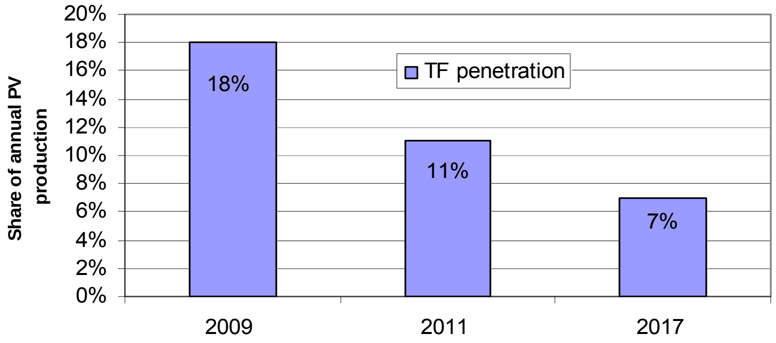

Figure 14: Thin film share of annual PV production (NPD Solar Buzz 2013, GTM Research 2012)

Importance of the CIGS thin film market in the World and Europe

Among the three thin film dominant technologies (Amorphous Silicon (a-Si), Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS)), CIGS technology should gain an increasing share in the coming years (20% in 2011, 38% by 2016). This could lead to 4 GW CIGS capacity by 2016 whereas 750 MW were reached in 2011 which represents only 2.2% of the global PV market share (GTM Research, 2012). The share of the different thin film technologies in 2012 was 55% for CdTe, 27% for CIGS and 18% for a-Si. But forecasts are to be taken with moderate consideration since the PV market is rather unstable.

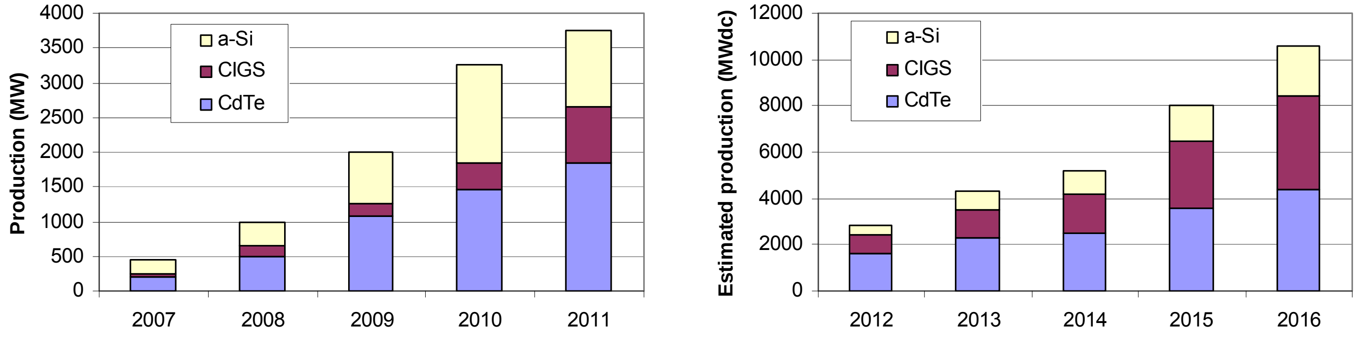

Figure 15: Historical PV Thin Film production and production forecast (GTM Research, 2012)

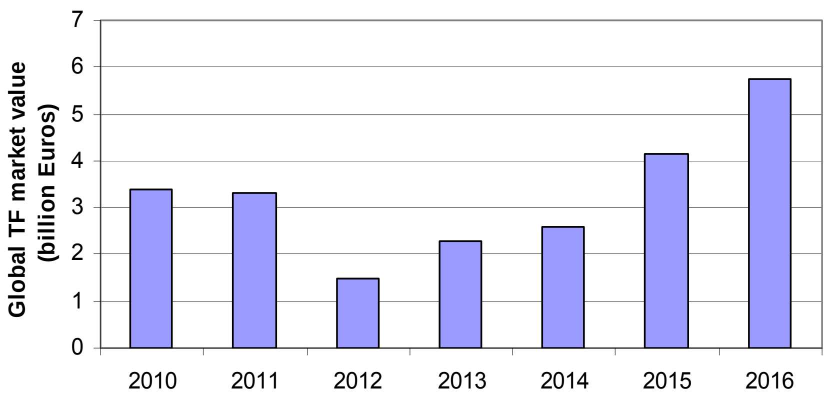

Figure 16: Global Thin Film market value (billion €) (GTM Research, 2012)

Thin-film technologies have variable market values. Total thin film market value declined to 1.5 billion € in 2012 after reaching 3.4 billion € in 2010. This decrease is due to the fall of new installations as a consequence to crystalline-Si solar cells increase. However, recovery in demand is expected by analysts: thin film technologies are forecasted to reach 5.8 billion € in 2016. But once again, one should though be very careful when assessing the impact of TF and CIGS technologies in the next years. European industrial company Umicore Thin film products points out that TF market will not overcome 2.5-3 billion € by 2016. From its perspective CIGS TF PV will stay a niche market for building-integrated PV on external vertical surfaces (facade), with a 2 GW capacity by 2016 (~4 GW in an optimistic scenario) (Umicore thin film products, personal communication 2013). According to the German equipment manufacturer Manz, if CIGS module efficiencies in average in large scale manufacturing do not reach 15-16% by 2015, thin films probably will drop out of the energy market because of the competition with low production costs of c-Si technologies and their better efficiencies (Manz, personal communication 2013).

Economic value of application for EU

According to (EPIA, 2013), Europe is playing an important role: it covered more than 20% of the actual thin film production in 2012 and 18% of its capacity. Germany with mainly CIGS and some CdTe technology production contributes significantly to this share. The APAC (Asia-Pacific) region with Japan as top producer keeps above more than 60% of thin film production.

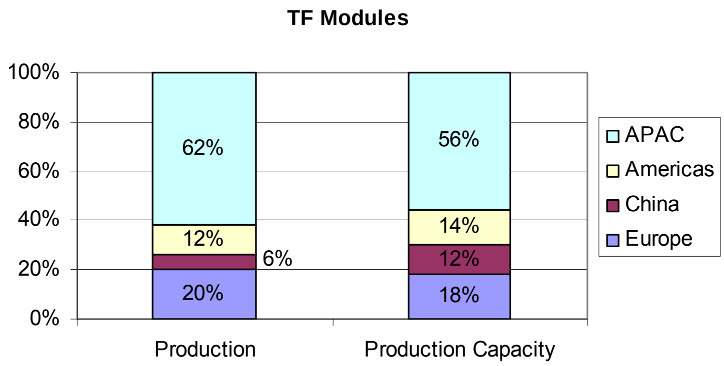

Figure 17: Regional distribution of production capacity and actual production (EPIA, 2013)

Considering that the thin film market reached 1.5 billion € in 2012 worldwide and assuming that the value ratio and the production ratio are the same, the European thin film market value was about 300 million € in 2012. Applying a ratio of 27% to the thin film technology market share, similar to the CIGS technology share, European CIGS market was estimated to be about 80 million € in 2012, which represents a limited EU economic value.

Position of EU on the supply chain

CIGS thin film PV fabrication is globally a one-step manufacturing process. All production steps are in one line, from the intermediate material to the final product (module) ready to be integrated into buildings or electronic devices. Recycling (spent targets within a closed loop and scraps) is a very important step.

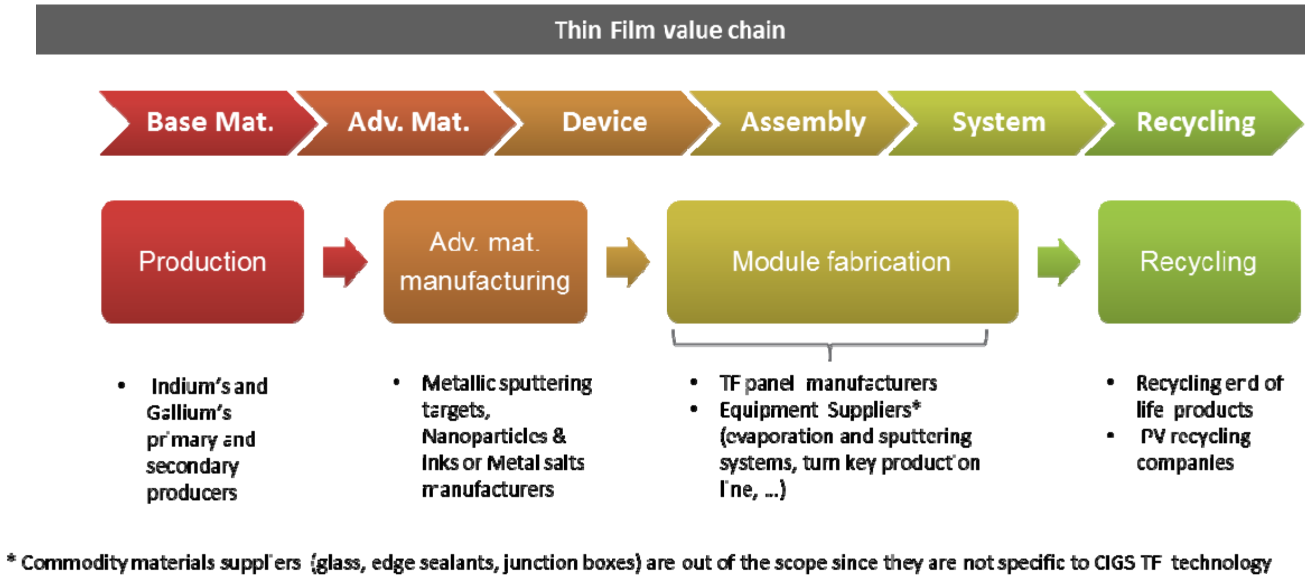

Figure 18: CIGS thin film PV supply chain

Europe plays a major role in three different segments of the CIGS TF PV supply chain: advanced material manufacturing, equipment supplying and recycling. For the two other segments (base material production and thin film panel manufacturers), EU is dominated by North America and/or Asia. Only one EU CIGS thin film PV module manufacturer (Avancis) is part of the top 5 companies but it stopped production mid-June 2013. The market leader is the Japanese company Solar Frontier, which represents ~70% of the global CIGS capacity worldwide (GTM Research, 2013). The polysilicon price drop and the challenge of taking thin-film from lab to fab drove more than 15 CIGS panel manufacturers to bankruptcy or takeover in 2011-2012, mainly in the US and Germany (Solibro, Odersun, Würth Solar, Soltecture, Flexcell, Solarion...).

EU companies have a large share in equipment supply with 4 EU companies, mainly German, in the top 5 (80% market share in vacuum deposition). Nevertheless, the actual downturn in new fabs investments in the CIGS segment and the difficult future market expectations are very risky for the PV equipment supply chain for the next coming years. For example, the EU leader Centrotherm Photovoltaics AG closed down its thin film module activities in Blaubeuren in 2013. The German equipment supplier Manz is planning to stop also its PV activities (CIGS and crystalline) within 2-3 years if the market does not recover. Annual investments in new thin film equipment exceeded 740 million € from 2007 to 2012 with many new companies stepping into thin film production. However, thin film investment is expected to take a plunge in 2013 to just over 250 million € (NPD Solarbuzz, 2013). New investment phases will hopefully be in 2017-2020 (Manz, personal communication 2013).

EU companies are also present in recycling and advanced material supply, both of these segments being linked. The EU global materials technology and recycling group Umicore is leading these market segments and is a key player in Europe being the N°1 primary indium producer in Europe. It combines production of indium with recycling of spent targets (close loop) and CIGS production scrap recycling. Cu, In, Ga and Se are recovered to be used in the PV industry or other industries. In 2012, no CIGS scraps have been recycled in its Hoboken facility because of the poor production of CIGS modules worldwide whereas 30 tons of CIGS waste had been recycled in 2010 (Umicore thin film products, personal communication 2013).

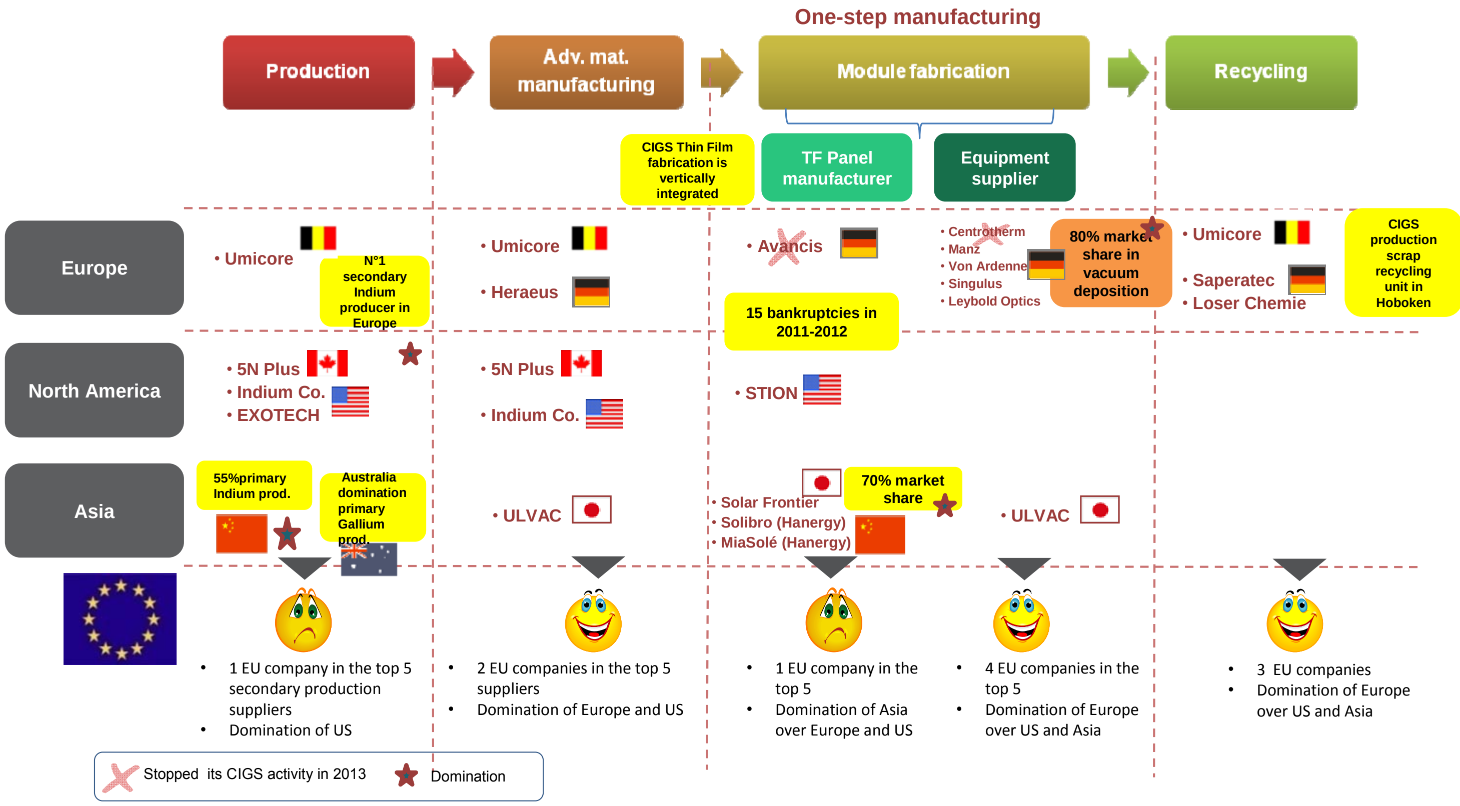

Figure 19: Position of European companies in the CIGS Thin film PV supply chain

Supply chain analysis based in Eurostat/PRODCOM data

The EUROSTAT (PRODCOM) approach has been explained in the corresponding section of section 4.1.2. The same remarks apply here, respectively to the Eurostat-based supply chain analysis of PV. In the following graphs, the notion of *Photosensitive semiconductor devices* covers obviously the different families of PV cells, and in particular silicon-based technologies (majority of the production), but also other electronic devices like photosensitive diodes, etc.

Some articles were also included due to indirect link with the PV supply chain. For example, aluminium frames are used for some PV technologies, which creates some dependence (although probably minor) between the aluminium sector and the PV sector.

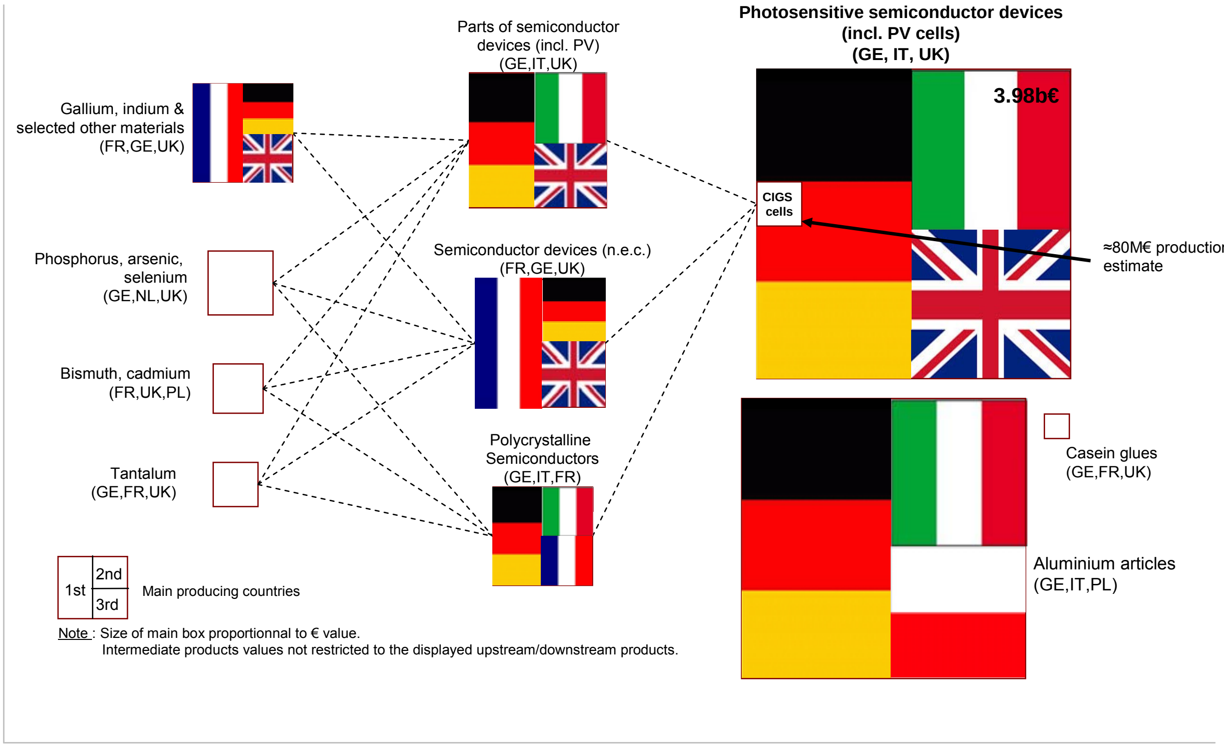

Figure 20: Largest producing countries in EU for PV.

A strong dominance of Germany can be noted in Figure 20 on most part of the PV supply chain, which is consistent with the business analysis performed earlier. CIGS only represents here a small (estimated) fraction of the production, which remains mostly based on other PV technologies and in particular crystalline silicon PV.

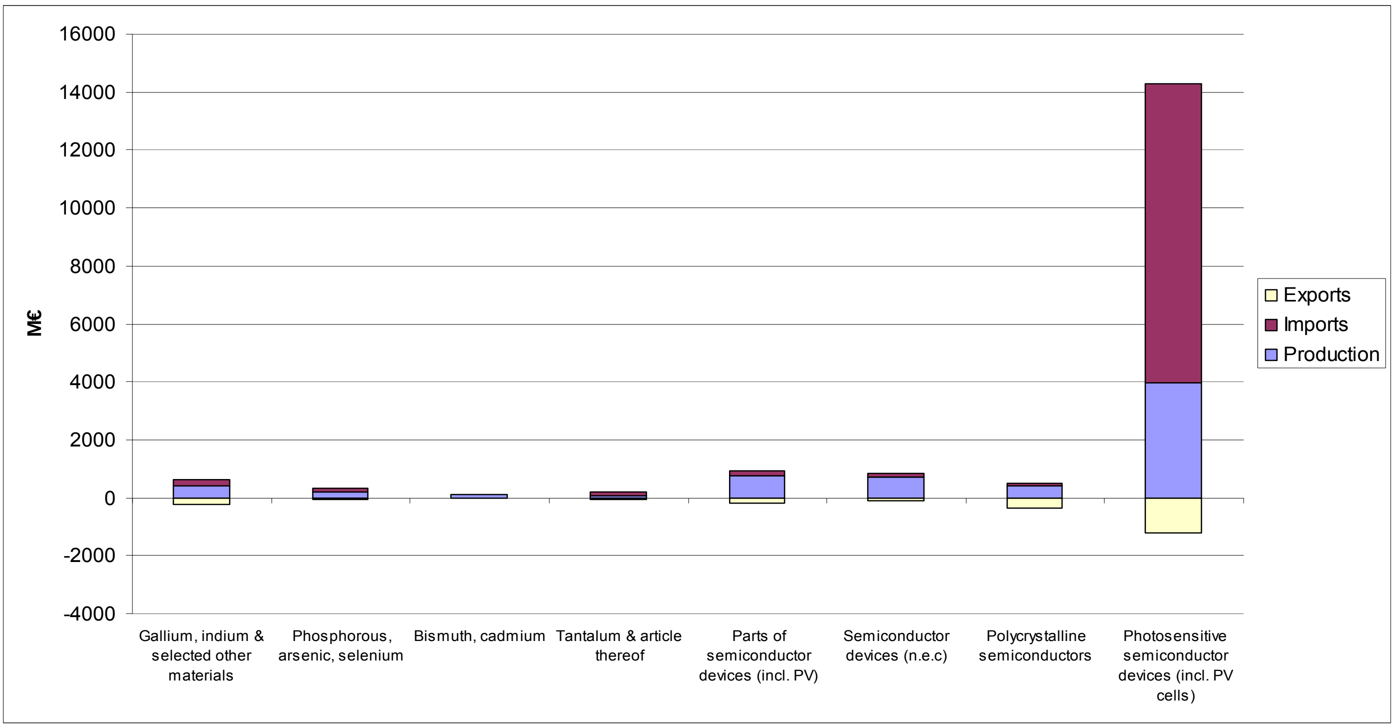

Figure 21: EU production, import and export of components and materials for PV

Concerning Figure 21, import data shows a huge amount of imports for finished photosensitive devices. The comparison of imports versus production along the supply chain shows that the entry of products in Europe is dominated by the end of the supply chain (end-products imports), which is consistent with the market trend of the flooding of the European market by cheap silicon-based PV panels made in China. Intermediate semiconductor components appear to be mainly manufactured locally. Export data does not provide significant learning despite the fact that about 30% of the production appears to be exported.

Jobs involved in EU

The PV industry directly employs about 435,000 people worldwide. In Europe, the number of FTE (full time equivalents) corresponds to around 265,000 direct jobs. Based on EPIA scenarios on the potential annual market until 2020, job creation in Europe could reach 1 million (EPIA, 2012b).

Considering that direct jobs related to thin film technology are about 11% of the global PV employment capacity (similar to the production market share), 30,000 FTE are dependent on the PV thin film industry in Europe in 2012. Half of this figure is linked to the production phases of the PV chain i.e. 15,000 FTE (the other half is linked to installation work according to EPIA). Applying a ratio of 27%, similar to the CIGS technology market share, about 4,000 FTE are involved in the European CIGS thin film industry including commodity material suppliers (glass, junction boxes…). This figure is slightly higher than the industrial estimation which is about 2,000 FTE (Umicore thin film products, personal communication 2013).

Criticality

The role of CRM

The CIGS active layer represents 7% of global production costs for CIGS thin film PV module (0.62 €/Wc) according to the CIGS module manufacturer Hanergy Miasolé, which is an important part. Indium's price is very volatile: it has risen from ~70 €/kg in 2002 to over ~750 €/kg in 2006. The average price of indium in 2012 was ~ 410 €/kg and 220 €/kg for gallium ((metalprices.com), (USGS, 2013), (USGS, 2013b)).

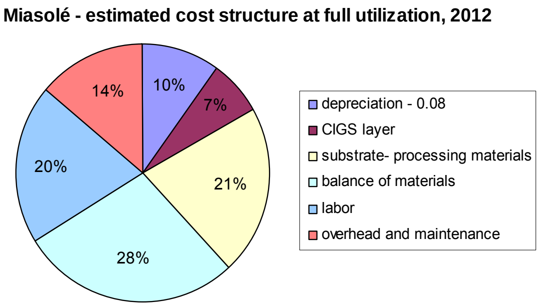

Figure 22: Estimated cost structure of a Hanergy Miasolé CIGS Thin Film PV module at full utilization (GTM Research 2012; Lee M. 2012)

CIGS Thin Film PV manufacturing accounts for a small share of world's indium and gallium application, about 1.5% (~17 tons in 2012 out of the total indium production of 1500 tons) and 1.2 % (5.6 tons out of the global gallium production of 474 tons) respectively. The indium and gallium embodied in CIGS PV modules are currently about 23 tons/GW and about 7.5 tons/GW respectively (NREL, 2012).

Virgin indium is recovered as a by-product from the smelting of zinc-sulfide mineral sphalerite to make zinc metal. Indium does not form primary mineral deposits. Only 37% of global indium production is attributable to primary production, the main part (950 tons) being recovered and recycled predominantly from ITO scrap used for flat panel display screens (USGS, 2013). The flat panel display industry consumes 80% of today's indium supply for ITO (about 55% of total net demand for the metal according to the US Company Indium Corp).

Most gallium is produced as a byproduct of treating bauxite, and the remainder is produced from zinc-processing residues. Recycled gallium from GaAs scrap (produced both in wafer manufacturing and from old electronics) accounts for the major proportion of the metal supply in the market (42% coming from the refined gallium production) (USGS, 2013b).

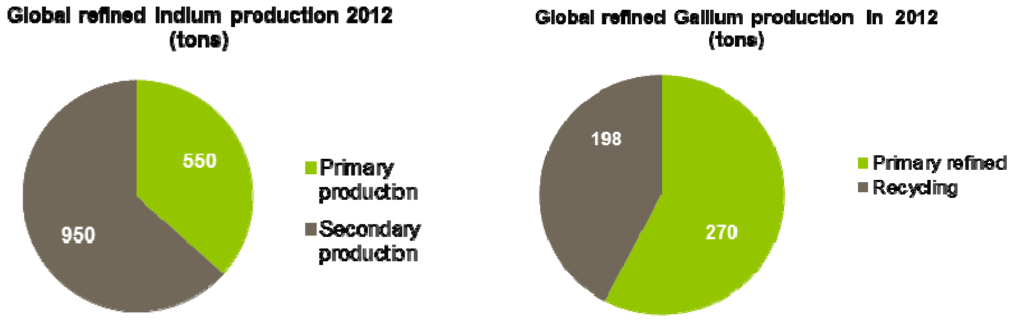

Figure 23: Global refined indium and gallium production in 2012 (tons) ((USGS, 2013), (USGS, 2013b))

How will the vulnerability evolve?

CIGS Thin Film PV technology is forecasted to reach a 2-4 GW CIGS capacity by 2016 depending on the scenario chosen (GTM Research optimistic scenario or Umicore Thin film product pessimistic scenario). The American company Indium Corp. estimated proven indium reserves from existing mines to 50 000 tons, a volume that will be sufficient to satisfy demand for the next 75 years.
92 tons of indium and 30 tons of gallium would be needed for 4 GW CIGS capacity (2016 capacity forecasts worldwide in an optimistic scenario).

CIGS thin film PV growth will have no impact, the vulnerability stays low. According to the German company Manz, the world can produce enough indium for 100 GW CIGS TF PV capacity. Gallium is less critical because of low quantity used.

Indium and gallium availability over time is directly related to the growing market of high value electronic consumer products which accounts for the largest share of demand and, therefore might constitute a threat.

Available substitute and/or mitigation

CIGS thin film technology could be replaced by crystalline PV, which is less expensive, or existing CdTe thin film technology, which has improving efficiency (although it uses environmentally unfriendly materials).

Technological progress could be achieved in a short term period, with a material cost reduction of 50% in a mid-term period (Manz, personal communication 2013). It will serve a variety of objectives:

- Improve material efficiency in deposition process (including recycling) (Candelise, Winksel &Gross, 2011)
- Achieve lower thickness of the active material layer (–30%)
- Use lower purity materials
- Improve packaging.

Securing supply with longer term contracts could also be a simple and effective solution.

Environmental

Impact on European policies in case of disruption

Thin Film CIGS PV is of minor importance for the EU. There will be no impact on mid-term EU policy on renewable energy in case of disruption.

Innovation

Substitution activities already ongoing

Substitution in PV is necessary not because of indium's scarcity but to face pricing problems in the longer term (2025-2030). Substitution is conceivable whatever scenario is studied.

R&D is focused on three main areas at different progress level (TRL: Technology Readiness Level)

- Replacing CIGS layers by
    - Kesterites: e.g. CZTS (Cu Zn Sn S/Se) (TRL3)
    - Sulfosalts: M-'V'-'VI', e.g. Sn-Sb-S (TRL3)
- Organic cells or hybrid cells (inorganic combined with organic) – (TRL5-7)
- High efficiency silicon hetero-junction solar cells (HET) – (TRL9)

For more information about specific material substitution potential, please refer to CRM_InnoNet report "Raw Material Profiles" (CRM_Innonet, 2013).

4.2.3 Photovoltaics - business summary

Table 7: Summary table of PV application.

Dimension	Criterion	Required input
Economic	Economic added value of application in Europe	European CIGS Thin Film PV market is estimated to ~80 M€. CIGS market has been dramatically declining because of the competition of c-Si. The supply chain is dominated by Asian companies except for the equipment supply and recycling market segments which are ruled by European Companies. Vertically integrated industrial Umicore is a key player in Europe.
	Jobs involved in the EU	~ 2,000-4,000 people are estimated to work in the TF CIGS industry in Europe.
Availability	Amount of CRM involved	The indium and gallium embodied in CIGS PV modules are currently about 23 t/GW (In) and 7.5 t/GW (Ga). 23 tons of indium and 5.6 tons of gallium are needed for 750 MW CIGS (2011 capacity worldwide). CIGS layer represents 7% of global production costs of CIGS thin film PV module.
	Expected future market development	92 tons of indium and 30 tons of gallium are needed for 4 GW CIGS capacity (2016 capacity forecasts worldwide in an optimistic scenario) The world can produce enough indium for 100 GW CIGS TF PV capacity.
	CRM function	Indium and gallium are used within Copper Indium Gallium (di)Selenide (CIGS) or Copper Indium Selenide (CIS) which is a I-III-VI2 semiconductor material. It is used as an absorber layer. CIGS has the advantages of being able to be deposited on flexible substrate materials, producing highly flexible, lightweight solar panels.
	Availability and status of substitutes	Substitution is conceivable. CIGS TF technology could be replaced by crystalline PV which is less expensive or existing CdTe TF technology, whose efficiency is improving. Substitution activities already on-going (R&D) • CZTS thin film (TRL3) • Organic PV (TRL5-7) • c-Si heterojunction (TRL9)
Strategic Relevance	Associated to EU policies for CRM supply	No impact on midterm EU policy on renewable energy. TF CIGS PV is of minor importance.

Opportunity for Europe	Dynamic nature of PV enables EU positioning on new PV technologies through R&D. CRM consideration when choosing the technology path may limit the risk to material supply exposure.

4.3 *Energy storage - Batteries*

4.3.1 Battery technologies and CRM dependence

As seen previously, rechargeable (secondary) batteries is only one of numerous solutions for electricity storage. We have seen however that both its potential CRM material dependence and the size of its market in EU required a more detailed analysis.

A battery is typically composed of several cells connected in serial to increase the overall voltage of the battery system. Each cell is composed of two electrodes, a positive and a negative electrode, dipped in an electrolyte. Electrical current is created by the transfer of ions between the electrodes. The nature of the electrodes, the electrolyte and thus the potential CRM dependence is specific to the type of battery. Numerous types of electrochemical batteries exist, the main categories being:

- Lead-acid batteries;
- Alkaline accumulators : Nickel-Cadmium (NiCd) and Nickel-Metal Hydrides (NiMH);
- Lithium-ion batteries (numerous sub-chemistries);
- Molten-salt batteries : Sodium-Sulfur (NaS) and ZEBRA technology;
- Redox-Flow batteries (several underlying technologies).

Lead-acid batteries

Varieties of lead-acid batteries have been optimized for specific uses. Typical setup is composed of a lead (Pb) negative electrode and a lead peroxide (PbO_2) positive electrode, dipped in sulfuric acid (H_2SO_4) and water. Discharging, the battery creates lead sulphate ($PbSO_4$) at both electrodes and the consumption of the electrolyte. The process is inverted during charging.

Several designs exist, whether the battery is “open” (requiring electrolyte maintenance), sealed with a pressure vent, or with a gel-based electrolyte. Electrodes can be stacked with an insulating membrane, or spiralled.

Typically production requires the manufacturing of lead grids, on which active materials (lead peroxide, sponge lead) are deposited. Typical materials used in lead-acid batteries are lead, lead oxides, sulfuric acid, water, polypropylene, glass and antimony (~1%wt) (Sullivan, 2010). Antimony (CRM) is typically used for mechanical strength and casting behaviour of the lead-antimony alloy (SBS, 2013).

NiCd batteries

Alkaline NiCd accumulators are based on the NiOOH/$Ni(OH)_2$ couple at the positive electrode, and the $Cd(OH)_2$/Cd couple at the negative electrode. Globally, during discharging, NiOOH and Cd convert to $Ni(OH)_2$ and $Cd(OH)_2$. The contrary happens when charging.

Constituents of NiCd cell are:

- Positive electrode : high-porosity nickel substrate and mixture of nickel hydroxide ;
- Negative electrode : high-porosity nickel substrate and cadmium hydroxide
- Microporous separator (nylon or polypropylene) ;
- Potassium-based electrolyte.

Material requirements for NiCd are thus limited to Cd, Ni, $Ni(OH)_2$, KOH, plastics, steel, copper, water (Sullivan, 2010b). A 1%wt cobalt (CRM) content is also identified by (BIO-IS, 2011).

NiMH batteries

NiMH alkaline batteries leverage the same NiOOH/$Ni(OH)_2$ couple at the positive electrode as NiCd, but have a M/MH couple (where M is an alloy that can capture hydrogen) at the negative electrode. KOH electrolyte and polypropylene membranes as separator are also used. During discharge, the alloy is oxidized, MH giving away its hydrogen to the electrolyte.

Alloys generally used are rare earths-based in the most common AB_5-type of NiMH batteries, where “A” can be a mischmetal (natural mixture of La, Ce with some Nd and Pr), La, Ce or Ti and “B” can be Ni, Co, Mn, Al (Kopera, 2004). Other NiMH types exist (e.g. AB_2-type, based on Ni, Ti, V, Zr) but are less common.

Typical MiMH material requirements are thus Ni, $Ni(OH)_2$, lanthanides (La, Nd, Pr, Ce), KOH, polypropylene, and steel (Sullivan, 2010b). A 1%wt cobalt (CRM) and some ytterbium are also identified by (BIO-IS, 2011).

Unlike NiCd batteries, for which uses are slowly decreasing, NiMH batteries are still considered a serious option for hybrid-vehicles.

Lithium-ion batteries

Li-ion batteries currently have the largest market share and the highest growth rate in the market. They are massively used in portable devices, and are foreseen to be a key enabler of the electric vehicle market.

A Li-ion accumulator has a negative electrode which is made of a host material that can accept lithium ions, such as graphite deposited on a copper substrate. The positive electrode is made of a lithium-based metallic oxide deposited on an aluminium substrate. The electrolyte is typically composed of $LiPF_6$ salts dissolved in e.g. propylene carbonate or dimethyl carbonate. Current is created when lithium ions transfer between the two electrodes.

Different sub-chemistries of Li-ion batteries exist, depending on the composition of the positive electrode. The main ones are: LCO ($LiCoO_2$ - cobalt-based and dominantly used in portable electronics), NCA (Nickel-Cobalt-Aluminium), NMC (Nickel-Manganese-Cobalt), LFP (Lithium-Iron-Phosphate), LMO (Lithium-Manganese or Nickel-Manganese), LMP (Lithium-Metal-Polymer). Negative electrodes are typically graphite-based, or sometimes lithium salts of titanium oxide (TiO).

Battery format depends on the use, and can be stacked, spiralled (in cylinder metallic container), or prismatic (flattened spiral). The casing can be hard or soft (pouch cells).

Given the different available chemistries, material content for Li-ion cells can vary. Leaving aside commodity materials (e.g. polypropylene separators, steel or aluminium casing, etc., the main potential EU-14 CRM dependence is on:

- Cobalt on positive electrode for some technologies: LCO (main technology for portable electronics currently), NCA, NMC. The active material containing Co represents between 15-27%wt of the cell (Sullivan, 2010b);

- Graphite for negative electrode widely used today. The graphite-containing LiC_6 material represents between 10-18%wt of the cell (Sullivan, 2010b).

Although much less present on the market, an alternative technology is Lithium-Metal-Polymer (LMP) batteries. LMP batteries are based on a lithium metal electrode on one side, a lithium host on the other electrode (e.g. vanadium oxide, graphite and polymers for BATSCAP, the main LMP manufacturer), and a dry polymer electrolyte (e.g. ethylene poly-oxide – POE) (BATSCAP, 2013). Apart from the shared dependence with Li-ion on graphite (CRM), no other information about CRM dependence has been identified.

<u>Molten-salt batteries</u>

Molten-salt batteries are high-temperature batteries (270-350 °C depending on the technology). Two technologies currently exist, one based on Sodium-Sulfur (NaS), and one on Sodium-Nickel-Chlorite (ZEBRA technology). Both are aimed towards stationary electricity storage, although ZEBRA technology still has some potential for transportation.

For NaS batteries, the cathode is molten sulfur (liquid), the anode is molten sodium (liquid) and the electrolyte is beta-alumina (solid). Main material requirements identified by (Sullivan, 2010b) on an example case is sulfur, sodium, alumina (alpha and beta-type), steel, aluminium, graphite, copper, polypropylene, glass and sand. Graphite (CRM) use is limited with ~2%wt.

ZEBRA technology (Dustmann, 2004) uses a porous nickel and NaCl cathode material, impregnated with $NaAlCl_4$. Beta-alumina (Al_2O_3) is used as electrolyte and separator. While charging/discharging, chlorite reacts either with nickel to form $NiCl_2$ (charging) or with sodium to form NaCl (discharge). No detailed material composition was found for this technology, but no CRM was identified in the key materials involved.

Redox-flow batteries

Flow batteries have the advantage of waiving the capacity limitation encountered with other battery types, and related to the accumulation of materials on the electrodes while charging/discharging. This is done through the storage of energy directly in the oxidation/reduction potential of the electrolytes. Two electrolytes are used: one for the positive electrode and one for the negative electrode and separated by a membrane. Electrolytes are circulated in the battery and stored in large quantities in separate storage. Positive electrode proceeds to the reduction of electrolyte while discharging, and oxidation while charging. The opposite takes place on the negative electrode. The membrane separating the electrolytes is semi-permeable, allowing only specific ions shared between the two electrolytes to pass.

This technology enables the decoupling of the battery power, related to the cell and electrodes sizes, and its electricity storage capacity, related to the electrolytes storage capacities.

Three main redox-flow technologies have been developed so far, based on:

- Vanadium and sulfuric acid ;
- Zinc bromide ;
- Sodium bromide and sodium poly-sulphur (but facing strong technical difficulties).

No detailed bill of materials were found in the literature for these technologies, but the description of a typical stack set-up (Robert, 2005) identifies the use of PVC (frame), carbon felt (collector), carbon/polymer composite (bipolar plate) in addition to the electrolytes already mentioned. The capacity of the battery is driven by the quantity of electrolyte, the latter is the most quantitatively important: existing chemistries do not show CRM dependence.

Selection of technologies for supply chain analysis

From the previous analysis, the main CRM dependence identified for electrochemical storage relates to NiMH dependence on lanthanide (AB_5-type NIMH batteries), and the graphite and cobalt dependence of several types of Li-ion batteries.

Other dependence (e.g. antimony for lead-acid batteries, cobalt for NiCd/NiMH) are considered limited, either due to the small amount of material used (typically <2%wt), and/or the currently small market of the application (e.g. molten-salt). They will not be pursued in the following analysis.

Table 8: CRM dependence of Battery technologies

	Typical material involved	CRM Content	Comments
Electricity Storage - Batteries			
Lead-Acid Batteries		(Sb)	
(Sb)		(Sb)	Very low quantity
Ni-Cd Batteries		(Co)	
Electrode		(Co)	
(Co)		(Co)	Few % at most of battery weight (~1%)
Ni-MH batteries		Mischmetal (La, Ce, Nd, Pr), La, Ce, Yb, (Co)	
Cathode		Yb, (Co)	
(Cobalt)		(Co)	Few % at most of battery wright (~1%)
Ytterbium		Yb	
Anode		Mischmetal (La, Ce, Nd, Pr), La, Ce	
Lanthanum		Mischmetal (La, Ce, Nd, Pr), La, Ce	~11% weight
Redox-Flow batteries			
Sodium-Sulfur batteries		(Graphite)	
(Graphite)		(Graphite)	Limited content (2-3%wt)
Li-ion Batteries		Co, Graphite	
Cathode		Co	
Lithium			
Cobalt		Co	For Cobalt-based Lion-ion battery technology (not all Li-ion technologies)
Anode		Graphite	
Graphite		Graphite	Battery-grade, artificial ou natural-graphite sourced
Electrolyte			
Lithium	LiPF6		

As a consequence, the supply chain analysis performed below will focus on Li-ion and NiMH manufacturing industries.

4.3.2 Analysis of CRM-related battery market and supply chain.

Economics

Global rechargeable battery markets

Rechargeable batteries are a continuing strong market, with worldwide sales of 33 GWh in 2011 compared to 25 GWh in 2009. Growth is primarily driven by the lithium-ion (Li-ion) batteries which stand for 26 GWh, Nickel Metal Hydride (NiMH) alkaline batteries accounted only for 3.6 GWh. All together these two technologies represented about 80% of the global demand for rechargeable batteries (Avicenne, 2012).

The global revenue for these two technologies is also expanding. It was worth about 8.5 billion € in 2011, 910 million € for NiMH batteries (10%) and 6,950 million € for Li-ion (80%). The market increased progressively from 2001 to 2011.

The global rechargeable batteries market is forecasted to reach 15 billion € by the year 2017.

Li-ion technology is the fastest growing market with an average Compound Annual Growth Rate (CAGR) of +15% per year. Sales revenues of Li-ion batteries have rapidly outpaced that of NiCd and NiMH batteries since Li-ion batteries were first proposed in the 1970's and commercially developed in the 1990's.

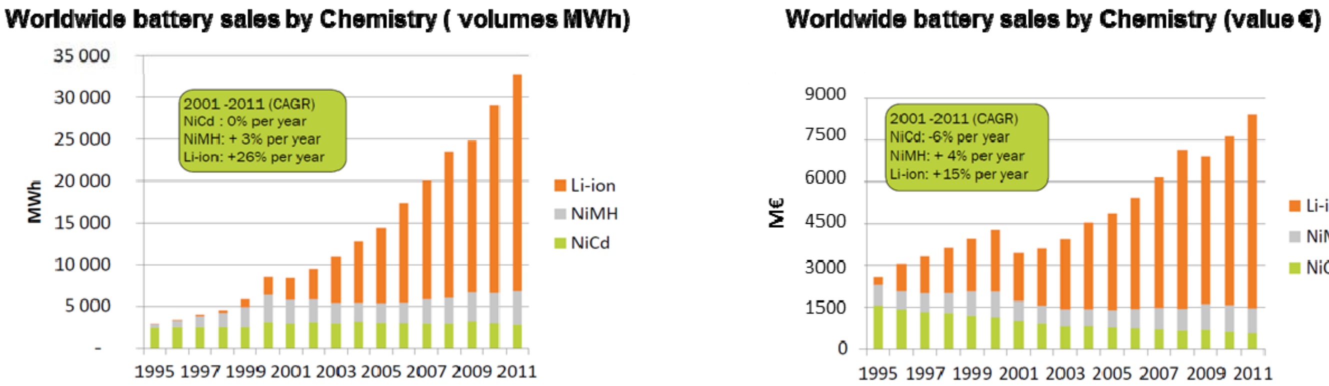

Figure 24: Worldwide rechargeable battery market by chemistry (MWh) and by sales (Million €) (Avicenne, 2012)

Automotive end-use is the key market for NiMH alkaline batteries whereas about 80% of the Li-ion batteries market is driven by portable electronics such as cellular phones, laptops, tablets.

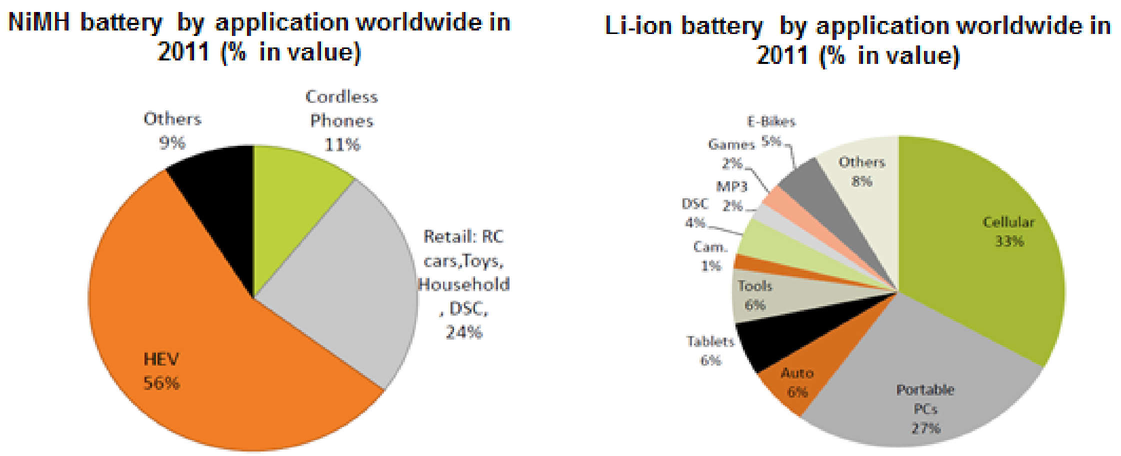

Figure 25: NiMH and Li-ion battery by application worldwide in 2011 (Avicenne, 2012)

The number of Hybrid Electric Vehicles has increased in recent years and the trend is expected to continue. Today most manufacturers use NiMH batteries (i.e. HEV such as Toyota Prius) but Li-ion batteries offer better performance such as lower weight and higher cell potential (Roland Berger Strategy Consultants, 2011).

Electric Vehicles (EV), Plug-In Hybrid Electric Vehicles (PHEV) and Hybrid Electric Vehicles (HEV) are expected to stimulate a new growth in automotive application markets. Compound Annual Growth Rate of +16% is expected for automotive battery needs for 2011-2025.

Nevertheless, the ongoing economic slowdown coupled with the high cost of EVs (mainly due to high battery costs) has resulted in less demand for EVs than expected in the past 1-2 years. The number of EVs on the road is much lower than anticipated a few years ago and this has affected the demand for batteries.

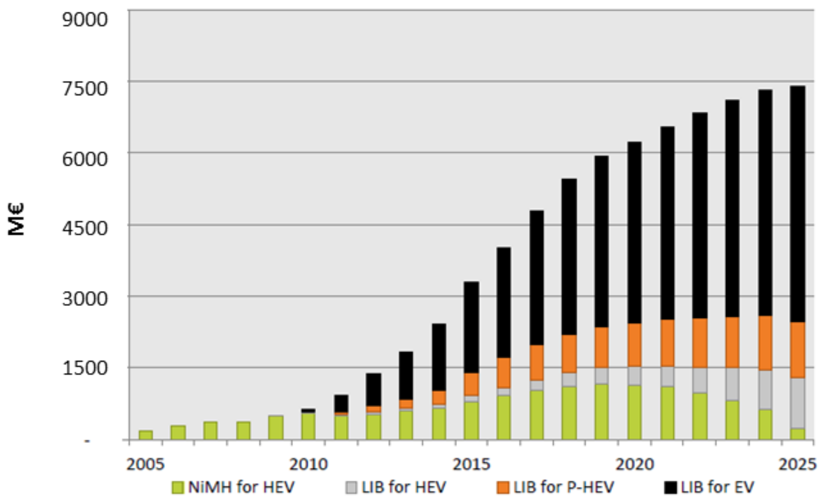

Figure 26: Growth of total battery market for automotive application (in Million €) (Avicenne, 2012)

The battery materials market (cathode, anodes, electrolyte, separators, binders) represented 3.8 billion € in 2012 and is estimated to reach 8.4 billion € by 2018 growing at a CAGR of 13% from 2013 to 2018 (ASD reports, 2013). Cathode suppliers have the biggest market share, with about 55%.

Economic value of the application in Europe

Asia is overwhelmingly the dominant force in the rechargeable battery market with an around 80% market share. Europe is a very small player on the NiMH and Li-ion battery market with an estimated 4% market share which represents around 320 million € revenues (SAFT and CEA, personal communication 2013)

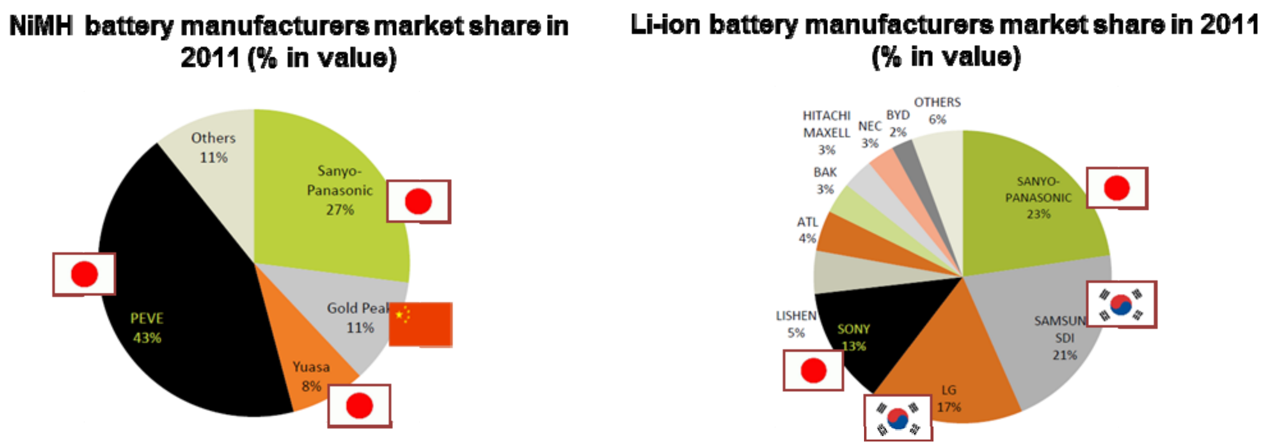

Figure 27: NiMH and Li-ion battery major manufacturers in 2011 (Avicenne, 2012)

Position of EU on the supply chain

The NiMH and Li-ion battery supply chains include companies that:

- produce base and advanced materials;
- produce components (anode, cathode, separators, electrolyte solutions and binders) and electronics;

- assemble these components into battery cells and then into battery packs.

It has been estimated that 70% of the added value in making Li-ion batteries is in making the cells, compared with only 15% for battery assembly and 10% for electrical and mechanical components (Canis B., 2013).

Some battery cells and stacks manufacturers produce theirown components. The battery supply chain is expected to consolidate and to become more and more integrated. Car makers for instance are developing partnering strategies and alliances with battery manufacturers (for example the Joint Venture PEVE (Panasonic/Toyota) is the supplier of NiMH battery packs for Toyota's HEV). Auto plants practice just-in-time manufacturing, with key suppliers located near the assembly plants. Automakers may want their Li-ion battery suppliers near their plants.

By 2020, business models will integrate recycling and new recycling companies will be created. Some new players (from the specialty chemical sector) could enter the market to supply anodes and cathodes especially for automotive and energy storage applications. The cost pressure and the race for innovation could lead to a massive consolidation among Li-ion battery manufacturers. (Roland Berger, 2012)

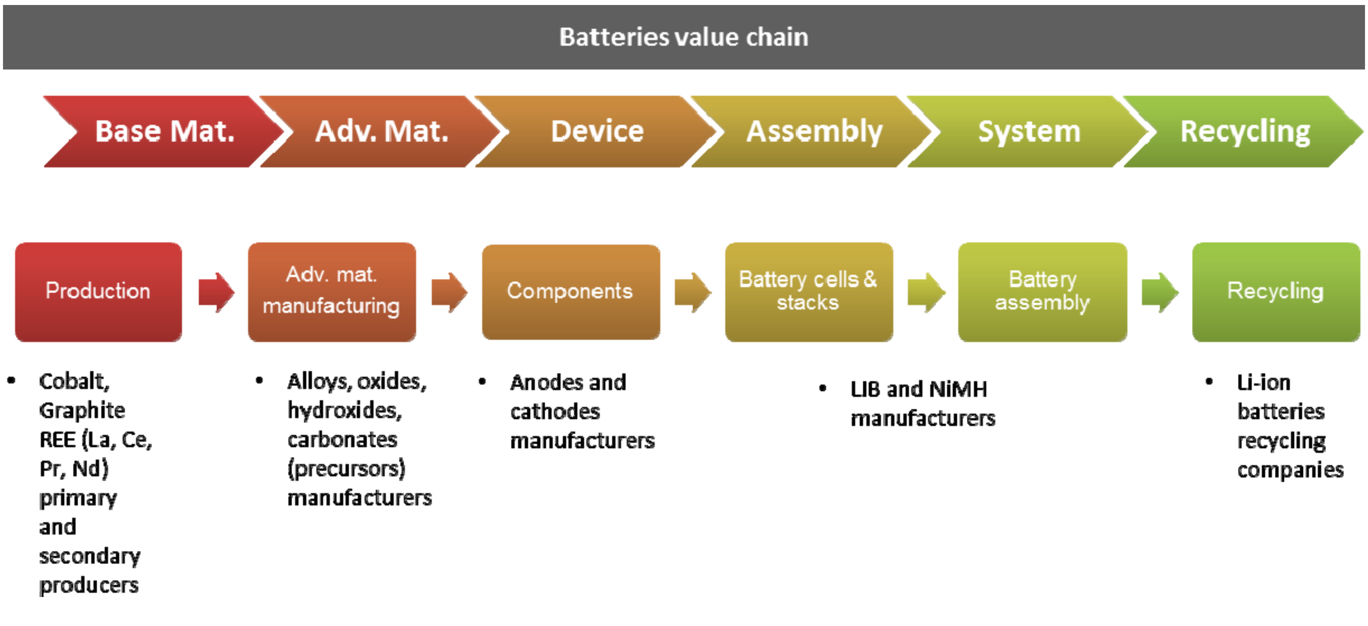

Figure 28: NiMH and Li-ion battery supply chain

Both NiMH battery and Li-ion battery supply chains are dominated by Asian companies with Japan still leading the market but Korea being a serious challenger.
For the cathode component supply and recycling market segments, the major European company Umicore is the world leader for cobalt supply and precious metals recycling with a special Li-ion and NiMH battery pilot line. It is also the world leader for cathode supply with 24% market share. But Umicore cathode production plants are in Asia with headquarters in Korea.

Otherwise, European NiMH and Li-ion battery manufacturers are small (in GWh and value) compared to Asian companies although some of them may be worldwide leaders on niche markets such as French company SAFT (Defence, Space). Many of the American Li-ion companies (e.g. 123 Systems, Valence, Ener1) that have gone bankrupt in the past two years have been acquired by Chinese firms.

If Asian companies are dominating the portable electronic application market segment (over 64% of the Li-ion market in 2012), Europe could be more active on the automotive EVs and HEVs and the industry market (stationary energy storage applications) segments in the next few years and gain new positions (e.g. a third of the Li-ion battery market for transportation by 2018 according to Pike Research). Growth of the industrial Li-ion market in Europe will be driven in part by increased investment in grid-connected storage in Germany.

China is expected to be the largest market for Li-ion automotive batteries in 2016 (40% of the market), due to strong government incentives for EV. North America will remain the largest market for storage application Li-ion batteries in 2016.

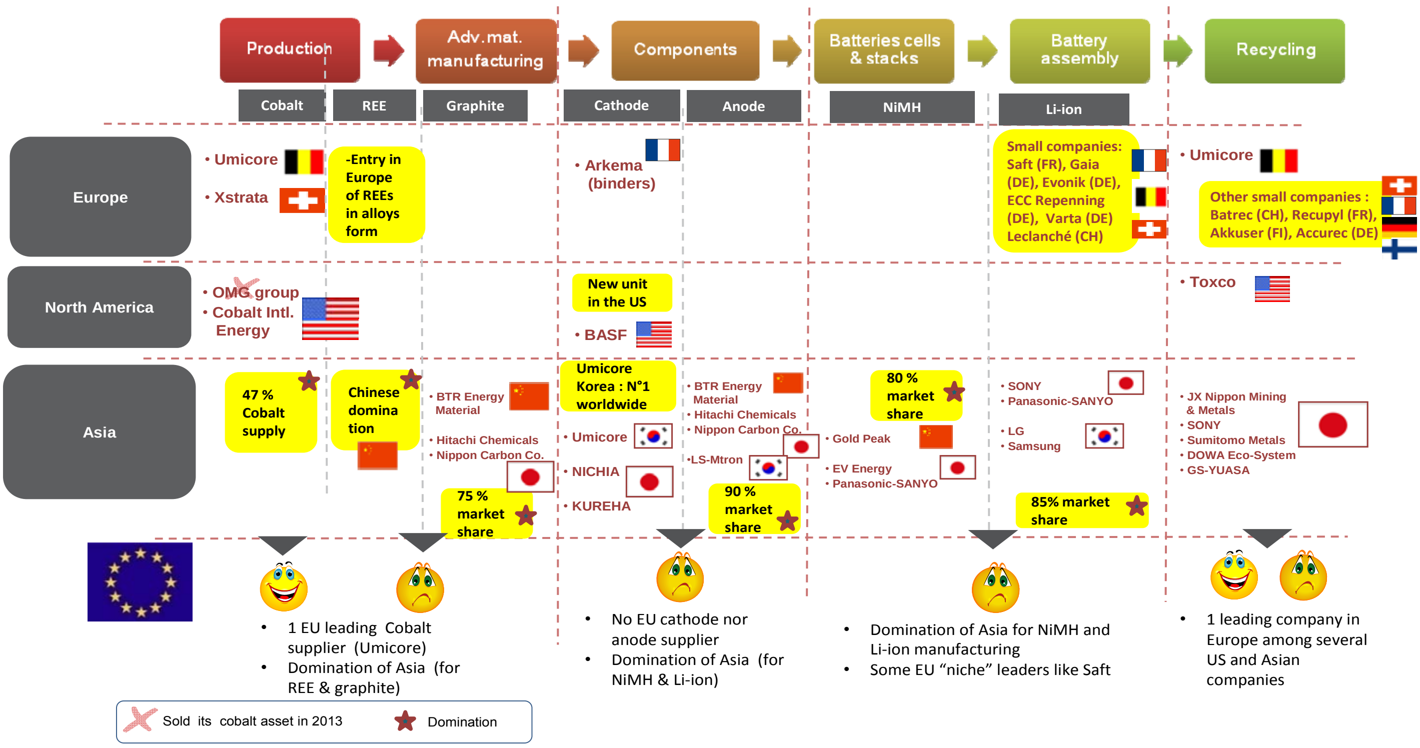

Figure 29: Position of European companies in the NiMH and Li-ion battery supply chain

<u>Supply chain analysis based in Eurostat/PRODCOM data</u>

The EUROSTAT (PRODCOM) approach has been explained in section 4.1.2. The same remarks apply here, with respect to the Eurostat supply chain analysis for batteries (NiMH & Li-ion).

Some articles were also included due to indirect link with the batteries supply chain according to PRODCOM information (e.g. anodizing of metals, inductors…).

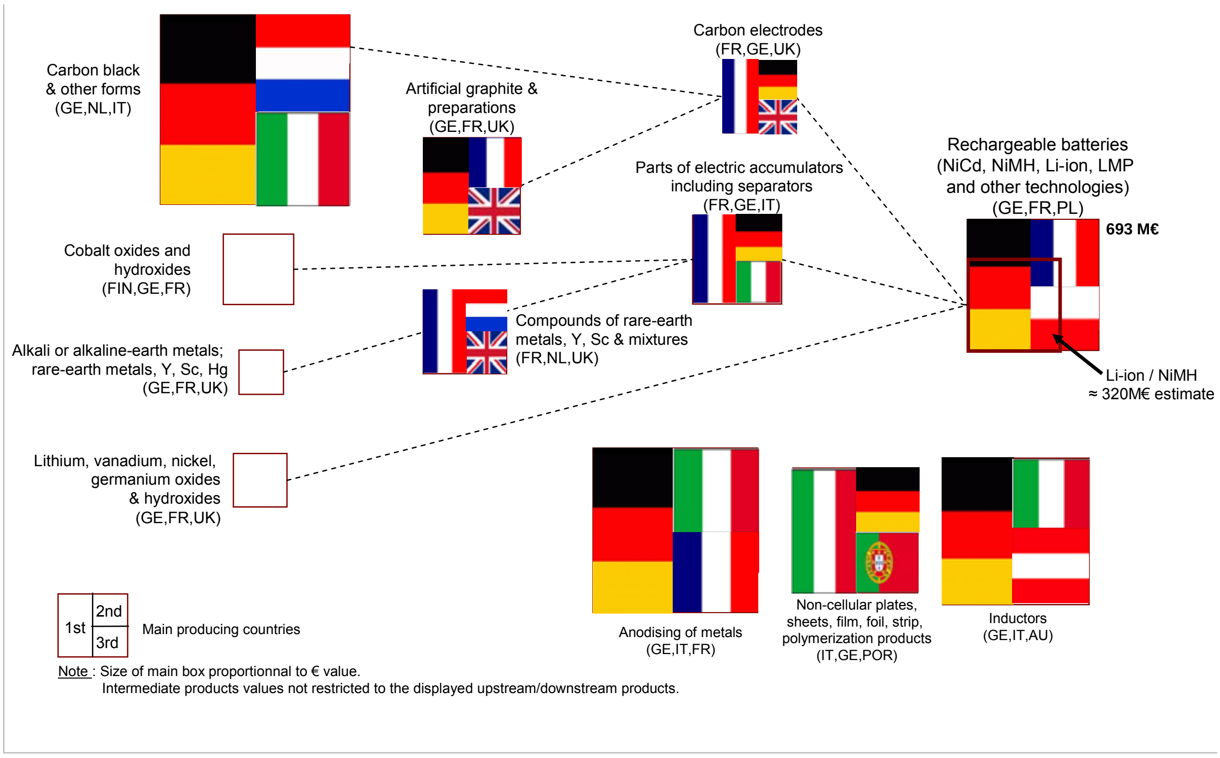

Figure 30: Largest producing countries in EU for rechargeable batteries.

The notable importance of Germany as an EU producer can be seen in Figure 30. However, the limited amount of battery production from EU should also be underlined. A good positioning of Germany on carbon and artificial graphite production can be seen.

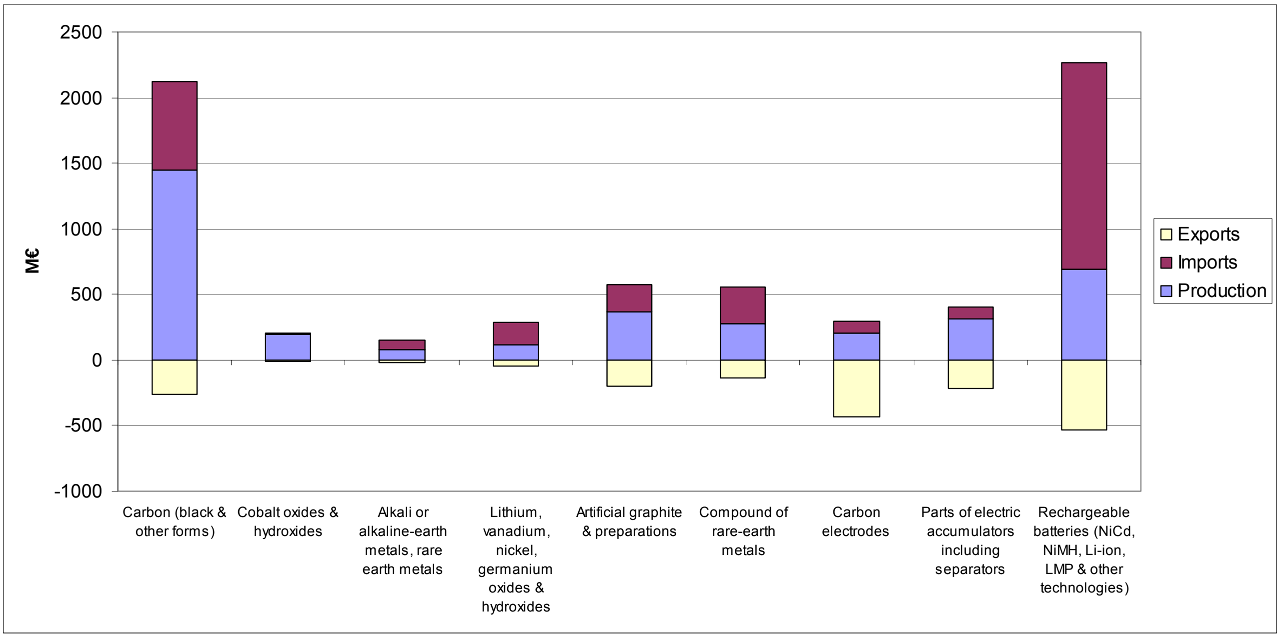

Figure 31: EU production, import and export of components and materials for rechargeable batteries

The importance of imports for rechargeable batteries can be seen in Figure 31, mostly as final products. Export figures do not show specific trends. Despite the Asian dominance on battery production, still significantly strong, notable exports with respect to local production can be noted from EU in this area. This might be re-exporting of integrated batteries, or specific positioning on niche markets (e.g. SAFT).

Jobs involved in EU

Currently about 4,000 people work in the NiMH and Li-ion industry in Europe (Umicore and SAFT personal communication, 2013). The Umicore rechargeable batteries materials employees are not included since the company that produces cathodes has plants in Asia with headquarters in Korea. The precursors of the cathodes (feed material to produce the lithium metal oxide compound) are made in Belgium by Umicore Cobalt and Specialty materials and shipped to Asia. 65-70% of cobalt (metal) is produced in Africa (Republic of the Congo).

Criticality

The role of CRM

Refer to section 4.3.1 for material dependence of Li-ion & NiMH.

Cobalt is used as a cathode material for Li-ion and to some extent in NiMH batteries. Cathode active materials stand for 22% and anode materials for about 7% of the manufacturing costs of auto-use Li-ion batteries. (Deutsche Bank, 2011). The cathode materials used determine the quality of the battery (e.g. capacity, electrical output) and are therefore the most important materials in battery production.

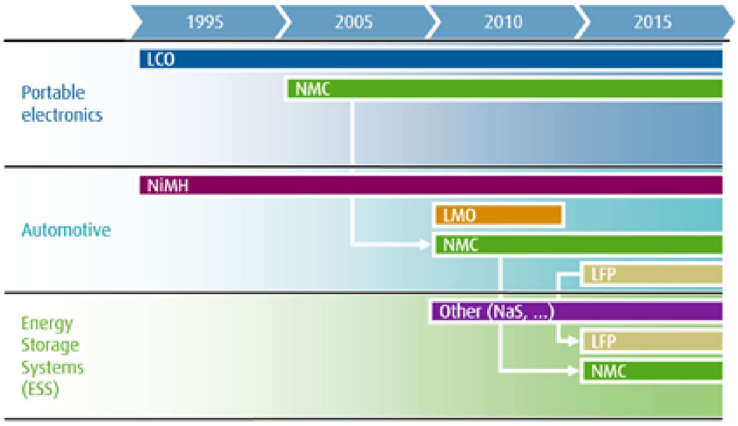

Figure 32: Cathode material versus application requirements (Vandeputte K., 2012)

Lithium Cobalt Oxide (LCO) is the most widely used Li-ion battery cathode material thanks to its high capacity and output and superior performance. High-end mobile terminals (laptops, cells phones) require high performance and high energy density, qualities in which cobalt material excels. However, the material is vulnerable to market price swings for cobalt. 85% of cobalt is produced as a byproduct of nickel and copper operations and 65-70% of cobalt (metal) is produced in Africa. Cobalt's price is very volatile (22€ per kilogram currently, 73€ per kilogram a few years ago according to SFP Metals Limited (UK)). Even at reduced prices, cobalt remains by far the most expensive metal in the cathode material mix of Li-ion battery cells, so the cost of raw materials impacts the battery makers' profit. Cobalt need represented 24,000 tons in 2011 which included 21,000 tons for Li-ion and 2,300 tons for NiMH assuming that 1 gram of cobalt is needed per Wh for a LCO cathode and 0.5 g/Wh for a NiMH cathode. That is roughly 40% of total cobalt production (60,000 -70,000 tons/year)). (Avicenne, 2012)

Graphite is used as an anode material. It can be made from natural graphite ore or artificially (graphite with higher purity). Natural graphite is found in mines worldwide. Major producers include China, Ukraine, Brazil and Sri Lanka. Production is inexpensive for natural graphite, being about two-thirds of artificial graphite's manufacturing cost. Nevertheless, natural graphite prices have trended upward. The average price for 2012 was about 3,000 €/ton. Graphite demand for Li-ion batteries represents 18,000 tons in 2011, which is minor compared to the 1.47 million tons supply capacity. ((Avicenne, 2012), (Byron Capital Markets, 2012)). There is currently no risk of shortage for graphite.

Rare Earth Elements are used for NiMH alkaline battery anodes. The NiMH industry does not need pure metals (as the permanent magnet industry does). It uses natural mischmetals which is an alloy of REE in various naturally occurring proportions (approximately 50% cerium and 25% lanthanum, with small amounts of neodymium and praseodymium). Lanthanum need is about 6.38 gram per NiMH cell ((Oakdene Hollins, 2010), (European Commission, 2011)). As an example, Toyota's Prius hybrid car contains about 10 kilos of lanthanum (Robert Bryce, 2010). Purer lanthanum or cerium may also be used.
Chinese export restrictions are less important for mischmetals than for pure neodymium and praseodymium. The pressure on price and availability is therefore lower than for permanent magnets. For all these reasons, REEs are not critical for NiMH batteries (SAFT, personal communication 2013).

How will the vulnerability evolve

The NiMH battery market is expected to decrease over time. On the contrary the global Li-ion batteries market is expected to reach around 13 billion € by 2016. Li-ion batteries will surpass NiMH as the preferred hybrid battery. Over the next four years, the automotive market share will grow from 14% to 25% of the Li-ion batteries market (CAGR of 37%) while consumer batteries are expected to constitute only 52% compared to about 80% in 2011 (Frost & Sullivan, 2013).

A surplus of cobalt is predicted in the next coming years on the market due to China's slowdown in growth, the resale of stocks, and due to new and re-opened copper mines around the world. No shortage of cobalt is expected for the next ten years. ((Byron, 2011), (Umicore Rechargeable Batteries Material, personal communication 2013))

Looking further ahead, the growth of the Li-ion battery market expected thanks to the market penetration of EVs and industrial applications will not affect the vulnerability. The effect of increased demand of cobalt will be minimized by the implantation of less expensive batteries containing less cobalt (Deutsche Bank, 2011).

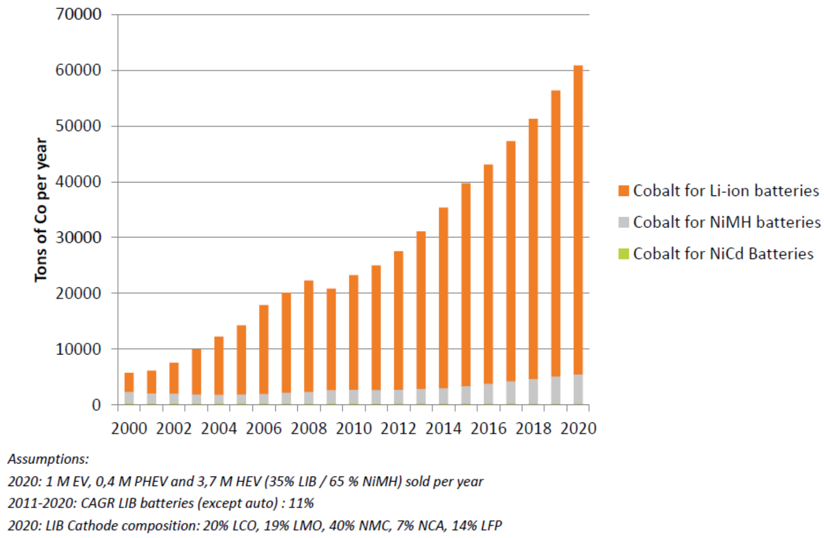

Figure 33: Cobalt demand for rechargeable batteries 2000-2020, metric tons, by battery chemistry (Avicenne, 2012)

Natural graphite demand will continue to grow with a switch to Li-ion market from NiMH but there is no risk of shortage even though additional mines could be needed (Jonathan Lee, 2011). REE demand will decline.

Available substitutes

No substitute is currently available for LCO Li-ion batteries very widely used for portable electronics currently representing 64% of the Li-ion battery market. Moreover, cobalt stocks from cathode suppliers (e.g. Umicore) will not exceed one month's production due to the high price of the metal (Umicore Rechargeable Batteries Materials, personal communication 2013). Substitutes are available for EV and HEV batteries: LFP (Lithium-Iron-Phosphate), LMO (Lithium-Manganese-Oxide) or other cathodes can be used.

Natural graphite can be replaced by synthetic graphite. In 2011, natural graphite counted for 60% and synthetic graphite for 30% of the materials that were used for anode in Li-ion batteries (Avicenne, 2012). LTO (Lithium Titanate), Cu_6Sn_5 (Copper-Tin), $FeSn_5$ (Iron-Tin) or Carbon-Tin can also be used as anode materials. But alternative anode materials are more expensive and less developed than natural graphite. ((Byron Capital Markets Ltd, 2012b), (Jonathan Lee, 2011))

In case of disruption of REE, European NiMH manufacturers such as SAFT say they would produce other technologies (e.g. Li-ion, NiCd) and less NiMH batteries, since these batteries are not strategic in their activities. Nevertheless, it remains interesting to concentrate research on certain rare earth elements less sensitive to price increase (La, Ce and Sm).

Environmental

Impact on European policies in case of disruption

Due to its quickly developing market and good EU positioning on battery R&D, EU may be able to play an increased role in the future in the battery market. Li-ion technologies are today strategic in the penetration on Electric and Plug-in Hybrid vehicle technologies.

Innovation

Europe is the global leader in battery research, with several active R&D projects underway among industrial research centers and universities, whereas most of the research in Japan is carried out by leading battery companies. Germany, France and Switzerland have the main energy storage/battery R&D centers.

Substitution activities already ongoing

Improvements continue on the present generation of batteries in different areas: optimisation of chemistries for applications requirements, functionalisation of materials and global cost reduction. In the longer term, R&D teams are working on new chemistries for Li-ion batteries and next generation batteries.

- Anodes based on silicon & tin (TRL 8-9)
- Cathode: Spinel 5V (TRL 4)
- Beyond Li-ion: Lithium-Sulfur, Lithium-Air, Zinc-Air batteries (TRL 3-4)

4.3.3 Batteries - business summary

Table 9: Summary table of rechargeable batteries application.

Dimension	Criterion	Required input
Economic	Economic added value of application in Europe	European market share of NiMH and Li-ion batteries was estimated as ~4% in 2011 which represents ~320M€. The supply chain is dominated by Asian companies. EU companies are not very representative except for Umicore and BASF (cathode manufacturing) but their divisions are located in Korea and in the USA. European NiMH and Li-ion batteries manufacturers are very small compared to Asian companies although some of them may be worldwide leaders on niche markets such as the French company SAFT (on Defence and space business areas).
	Jobs involved in the EU	~ 4,000 direct jobs are estimated in the NiMH and Li-ion industry in Europe.
Availability	Amount of CRM involved	Cobalt needs for Li-ion & NiMH batteries represent 24,000 tons in 2011 (21,000 tons for Li-ion, 2,300 tons for NiMH i.e. 40% of total cobalt production (60,000 -70,000 tons/year)). Even at reduced prices, cobalt remains by far the most expensive metal in the cathode material mix. Graphite needs for Li-ion batteries reached 18,000 tons in 2011 (compared to a global supply capacity of 1.47 million tons). NiMH batteries' anodes use mischmetals and not pure REE, therefore it is less critical (less restrictive exportation from China). Cathode active materials represent 22% of the whole manufacturing costs of Li-ion cell and anode materials about 7% in the automotive industry.
	Expected future market development	The NiMH battery market is expected to decrease over time. On the contrary the global Li-ion batteries market is expected to double by 2016 (~13 billion €), thanks to EV market.
	CRM function	Cobalt is part of the Li-ion cathode active material mix and graphite is used as an anode material. REE (La, Ce, Pr, Nd) is used in NiMH batteries' anode.

	Availability and status of substitutes	No shortage of cobalt is expected for the next ten years (due to China growth's slowdown and resale of stocks and re-opening of copper mines around the world).The effect of increased demand of cobalt will be minimized by the implantation of less expensive batteries containing less cobalt. Natural graphite demand will continue to grow but the risk of shortage is low. No substitute is currently available for LCO Li-ion batteries used for portable electronics. Substitutes are available for electric and hybrid vehicle batteries like LFP or LMO. Natural graphite for NiMH batteries' anode can be replaced by synthetic graphite. Substitution activities already on-going (R&D): • anodes based on silicon & tin (TRL 8-9) • Cathode: Spinel 5V (TRL 4) • Beyond Li-ion: Lithium-Sulfur, Lithium-Air, Zinc-Air batteries (TRL 3-4)
Strategic Relevance	Associated to EU policies for CRM supply	Li-ion technology is key to electric and plug-in hybrid vehicles. EU has strong R&D on the subject of battery storage.
	Opportunity for Europe	Good positioning of Europe on Battery R&D creates opportunities for positioning on next-generation batteries. Future-developing markets of batteries for electric and hybrid vehicles leave space potential new (local) suppliers. Strong recycling players in Europe (e.g. Umicore) may be leveraged.

5 Conclusion

This report has covered the screening of the energy sector to identify applications with both strategic, economic and CRM relevance. After selecting wind power, PV and battery technologies, a more detailed assessment of the importance of these CRM-dependent applications for EU was performed, from a supply chain perspective.

Important existing and future needs are identified for wind energy technologies. Rare Earths-dependent technologies (hybrid, direct-drive) are great facilitators, and even enablers for off-shore deployment. The EU has a strong position at the end of the supply chain with 4 companies in the top 10 with 38% market share in 2012 being both components and systems manufacturers. The bottleneck lies in the heavy reliance on supply for CRM-based permanent magnets from abroad. Economic and employment risk related to CRM for this application is significant. The European market share for permanent magnet-dependent technologies was estimated to be 1,400 – 2,200 million € in 2012, with about 12,000 direct jobs in the direct drive turbine industry. Joint ventures with mining companies outside China should facilitate the overcoming of any supply shortage due to quotas. Some potential issue with carbon-fiber supply for rotors has also been identified.

Among the PV industry, identified CRM are indium and gallium used in CIGS thin film technology. Although PV has a strong potential, thin-film technologies and especially CIGS are currently a limited part of the market, with a CIGS technology market revenue estimated to about 80 million € in Europe and with 2,000 to 4,000 direct jobs. The highly dynamic market/industry has led to a decrease in EU importance lately, with 15 bankruptcies noted only during the period 2011-2012. The supply chain of CIGS thin film PV application is dominated by Asian companies, except for the equipment supply and the recycling market segments with a stronger presence of EU industries. But European equipment suppliers are tending to stop their PV thin film activities because of a difficult market recovery. Despite the initial interest, Thin-films/CIGS currently represents a very limited CRM-related risk for the EU. Future technologies (e.g. heterojunction, CPV) may change the picture in the PV industry, and through these relatively new technologies represent an opportunity for EU positioning.

For the rechargeable batteries industry, NiMH and Li-ion batteries are both CRM dependent technologies. The European NiMH and Li-ion batteries market share is estimated to 4%, which represents a revenue of 320 million €, with about 4,000 direct jobs. NiMH technology is used nowadays in majority for HEV application. But thanks to their better performance, lower weight and higher cell potential, the Li-ion batteries market is expected to double by 2016 thanks to EV market growth. The supply chain of NiMH and Li-ion batteries application is largely dominated by Asian (Japanese and Korean) companies. European batteries manufacturers are small compared to Asian companies although some of them may be worldwide leaders like SAFT in niche markets (defence and space). Low risk of shortage of CRM is nevertheless expected in this segment. Active research in EU may spawn new Li-ion technologies in EU.

From this analysis, it appears that exposure of EU wind power industry to potential CRM issues is significant. Battery technology may also be a risk, despite the relatively limited EU presence in the domain, but relating to the huge future potentials of Li-ion technologies for transportation.

Concerning the PV industry however, the recent restructuring of the EU industry has significantly decreased the EU exposure to the CRM risks related to CIGS. Despite not being currently considered a CRM, silver may however represent a source of risk.

Finally, neither the nuclear (fission) nor advanced fossil fuel power domain have been studied here from the supply chain perspective, due to lower perceived importance with CRM-related risks and potential impacts.

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Appendix 1 (Wind Power)

Table 10: Breakdown of Wind Power application and corresponding PRODCOM groups

	Typical material involved	CRM content	Comments	Identified PRODCOM categories
Wind Power Plant		Nd, Dy		28112400 Generating sets, wind-powered
Nacelle		Nd, Dy		28112400 Generating sets, wind-powered
Drive-train - Gearless		Nd, Dy		28112400 Generating sets, wind-powered
Permanent-magnet-based Direct-drive		Nd, Dy		28112400 Generating sets, wind-powered
Permanent magnet generator (PMG)		Nd, Dy		28112400 Generating sets, wind-powered
Permanent magnets	Nd, Dy	Nd, Dy		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, Fe, B & Dy powder, separate of mixtures	Nd, Dy	Nd, Dy		20136500 Compounds of rare-earth metals, of yttrium or of scandium or mixtures of these metals
Nd metal	Nd	Nd		20132300 Alkali or alkaline-earth metals; rare-earth metals, scandium and yttrium; mercury
Dy metal	Dy	Dy		20132300 Alkali or alkaline-earth metals; rare-earth metals, scandium and yttrium; mercury
Drive-train - Hybrid		Nd, Dy	Refer to Gearless drive-train	

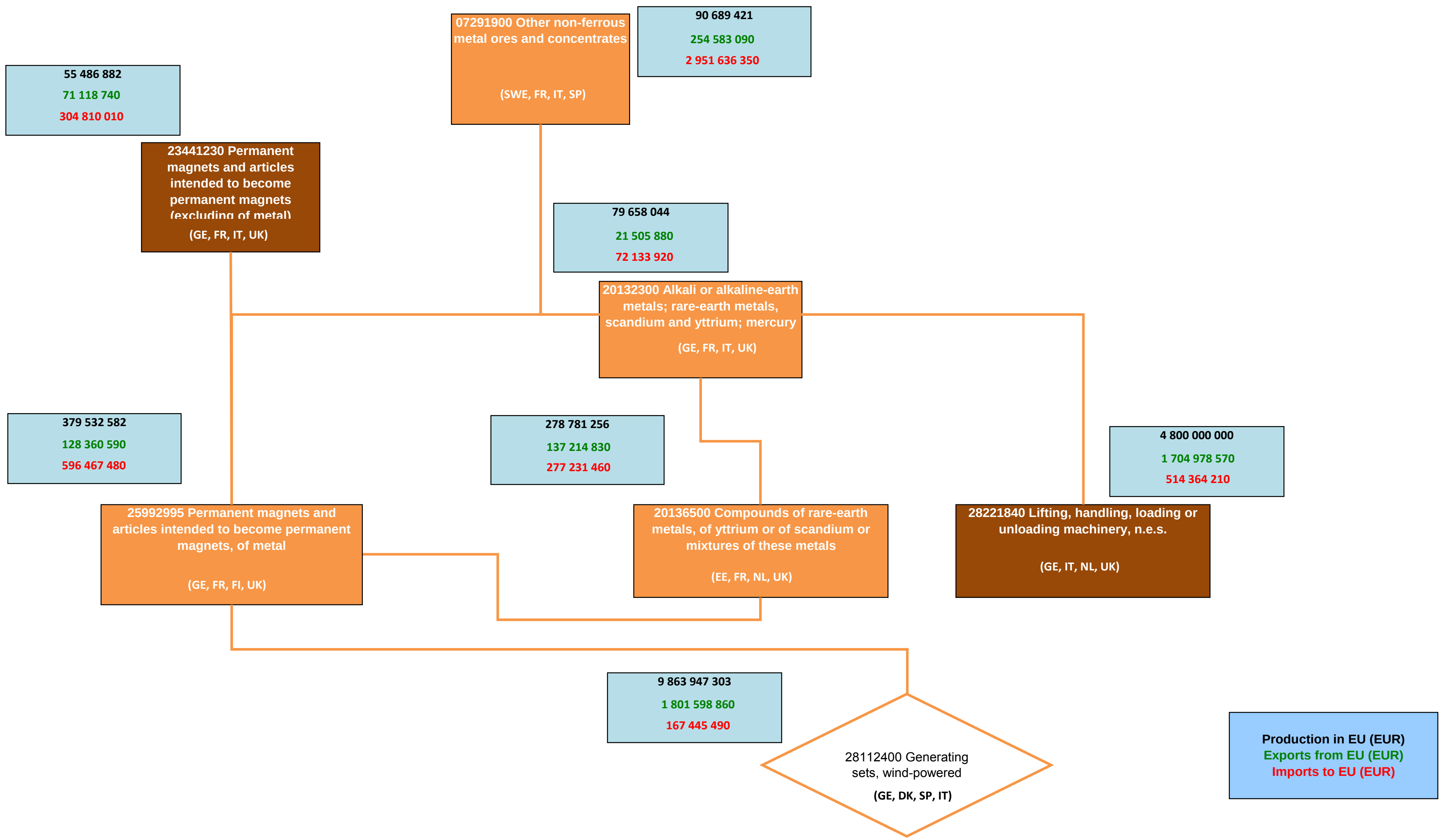

Figure 34: The quantitative supply chain analysis of Wind-power based on information from PRODCOM

Appendix 2 (Photovoltaic Power)

Table 11: Breakdown PV application and corresponding PRODCOM groups

	CRM Content	Comments	Identified PRODCOM categories
Photovoltaic Power plant	In, Ga		26112240 Photosensitive semiconductor devices; solar cells, photo-diodes, photo-transistors, etc
PV Module	In, Ga		26112240 Photosensitive semiconductor devices; solar cells, photo-diodes, photo-transistors, etc
PV Laminates (different technology options)	In, Ga		26112240 Photosensitive semiconductor devices; solar cells, photo-diodes, photo-transistors, etc
PV Cell	In, Ga		26112240 Photosensitive semiconductor devices; solar cells, photo-diodes, photo-transistors, etc
Cell sub-components	In, Ga		27115023 Polycrystalline semiconductors 26114070 Parts of diodes, transistors and similar semiconductor devices, photosensitive semiconductor devices and photovoltaic cells, light-emitting diodes and mounted piezo-electric crystals 26112260 Semiconductor devices (excluding photosensitive semiconductor devices, photovoltaic cells, thyristors, diacs and triacs, transistors, diodes, and light-emitting diodes)
Materials	In, Ga	For deposition technologies	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) 24453030 Bismuth and articles thereof, including waste and scrap, n.e.c.; cadmium and articles thereof (excluding waste and scrap), n.e.c. 24453023 Tantalum and articles thereof (excluding waste and scrap), n.e.c. 20132180 Phosphorus; arsenic; selenium

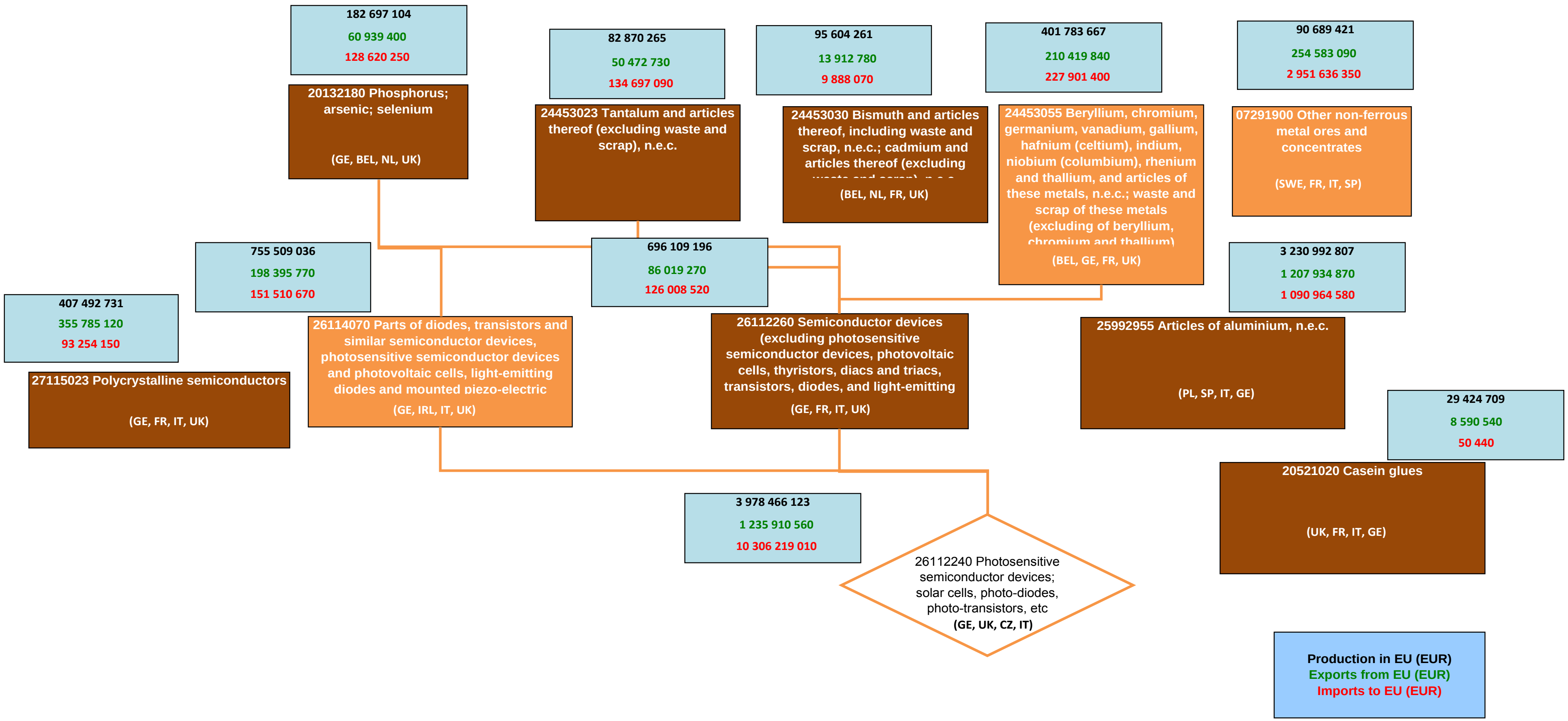

Figure 35: The quantitative supply chain analysis of PV based on information from PRODCOM

Appendix 3 (Batteries)

Table 12: Breakdown of Battery application and corresponding PRODCOM groups

	Typical material involved	CRM Content	Comments	Identified PRODCOM categories
Electricity Storage - Batteries				27202300 Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators
Lead-Acid Batteries		(Sb)	Outside of from considered perimeter	
(Sb)		(Sb)	Outside of from considered perimeter	
NiCd Batteries		(Co)	Outside of from considered perimeter	
Electrode		(Co)	Outside of from considered perimeter	
(Co)		(Co)	Outside of from considered perimeter	
NiMH batteries		Yb, La, (Co)		27202300 Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators
Cathode		Yb, (Co)		27202400 Parts of electric accumulators including separators
(Co)		(Co)		20121930 Cobalt oxides and hydroxides; commercial cobalt oxides
Ytterbium		Yb		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
Anode		La		27202400 Parts of electric accumulators including separators
Lanthanum		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
	Electrolyte				Outside of from considered perimeter	27202400 Parts of electric accumulators including separators
		KOH			Outside of from considered perimeter	
Redox-Flow batteries					Outside of from considered perimeter	
Sodium-Sulfur batteries				(Co)	Outside of from considered perimeter	
	(Cobalt)			(Co)	Outside of from considered perimeter	
Li-ion Batteries				Co, Graphite		27202300 Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators
	Cathode			Co		27202400 Parts of electric accumulators including separators
		Lithium				20121950 Lithium oxide and hydroxide; vanadium oxides and hydroxides; nickel oxides and hydroxides; germanium oxides and zirconium dioxide
		Cobalt		Co		20121930 Cobalt oxides and hydroxides; commercial cobalt oxides
	Anode			Graphite		27901350 Carbon electrodes (excluding for furnaces)
		Graphite		Graphite		20132130 Carbon (carbon blacks and other forms of carbon, n.e.c.) 23991400 Artificial graphite, colloidal, semi-colloidal graphite, and preparations
	Electrolyte					27202400 Parts of electric accumulators including separators 20121950 Lithium oxide and hydroxide; vanadium oxides and hydroxides; nickel oxides and hydroxides; germanium oxides and zirconium dioxide
		Lithium	LiPF6			20121950 Lithium oxide and hydroxide; vanadium oxides and hydroxides; nickel oxides and hydroxides; germanium oxides and zirconium dioxide

Other PRODCOM products with possible link with battery technologies			27115080 Inductors (excluding induction coils, deflection coils for cathode-ray tubes, for discharge lamps and tubes) 22214230 Non-cellular plates, sheets, film, foil, strip of condensation or rearrangement polymerization products, polyesters, reinforced, laminated, supported/similarly comb. with other materials) 25612250 Anodizing of metals

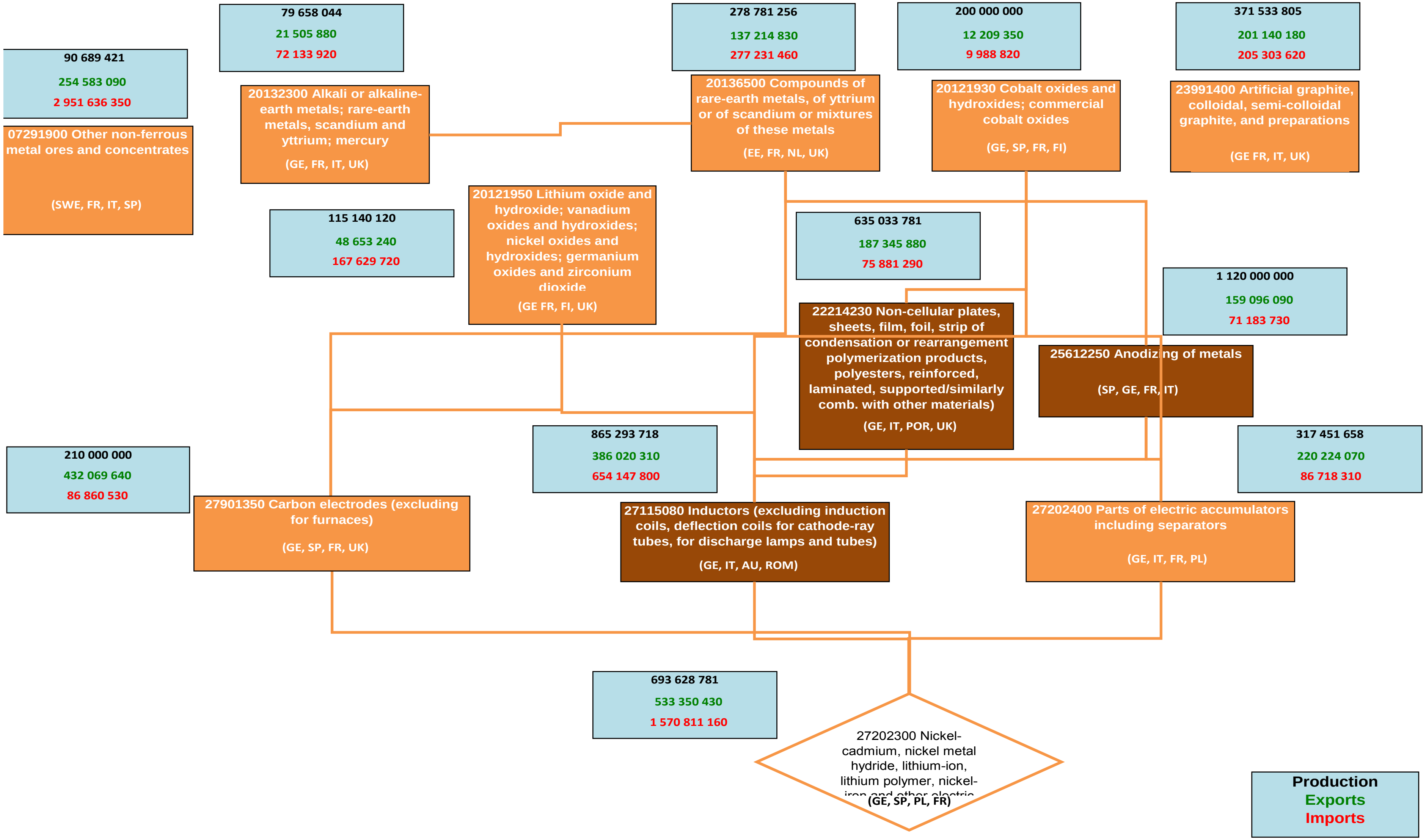

Figure 36: The quantitative supply chain analysis of Batteries based on information from PRODCOM.