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Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU

Wind power, photovoltaic and electric vehicles technologies, time frame: 2015-2030

Darina T. BLAGOEVA, Patrícia AVES DIAS, Alain MARMIER, Claudiu C. PAVEL

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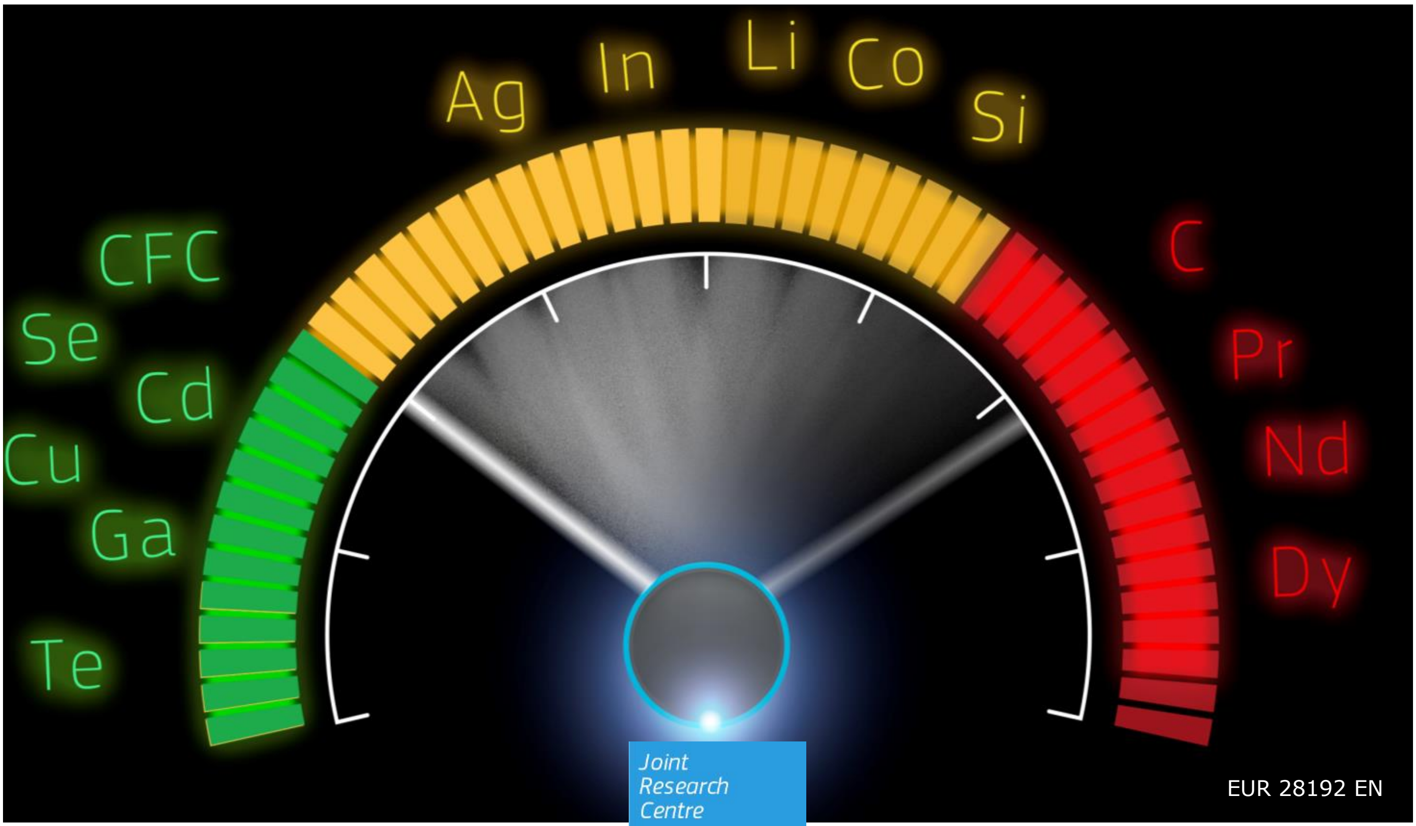

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Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU. Wind power, photovoltaic and electric vehicles technologies, time frame: 2015-2030

Abstract:

The ambitious EU policy to reduce greenhouse gas emissions in combination with a significant adoption of low-carbon energy and transport technologies will lead to strong growth in the demand for certain raw materials. This report addresses the EU resilience in view of supply of the key materials required for the large deployment of selected low-carbon technologies, namely wind, photovoltaic and electric vehicles. A comprehensive methodology based on various indicators is used to determine the EU's resilience to supply bottlenecks along the complete supply chain – from raw materials to final components manufacturing.

The results revealed that, in 2015, the EU had low resilience to supply bottlenecks for dysprosium, neodymium, praseodymium and graphite, medium resilience to supply of indium, silver, silicon, cobalt and lithium and high resilience to supply of carbon fibre composites. In the worst case scenario where no mitigation measures are adopted, the materials list with supply issues will grow until 2030. Indium, silver, cobalt and lithium will add up to the 2015 list.

However, the probability of material supply shortages for these three low-carbon technologies might diminish by 2030 as a result of mitigation measures considered in the present analysis, i.e. increasing the EU raw materials production, adoption of recycling and substitution. In such optimistic conditions, most of the materials investigated are rated as medium or high resilience. The exceptions are neodymium and praseodymium in electric vehicles, for which the EU resilience will remain low.

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Knowledge for Energy Union Unit

- 2016 -

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Executive summary

Policy context

The aim of this study is to give a quantitative indication of the EU's resilience regarding the supply of materials relevant for the deployment of low-carbon energy and transport technologies. The report focuses on *wind, photovoltaic and electric vehicles* within the 2030 time frame. The complete materials supply chain has been considered in this analysis – from raw materials to final components production.

Methodology

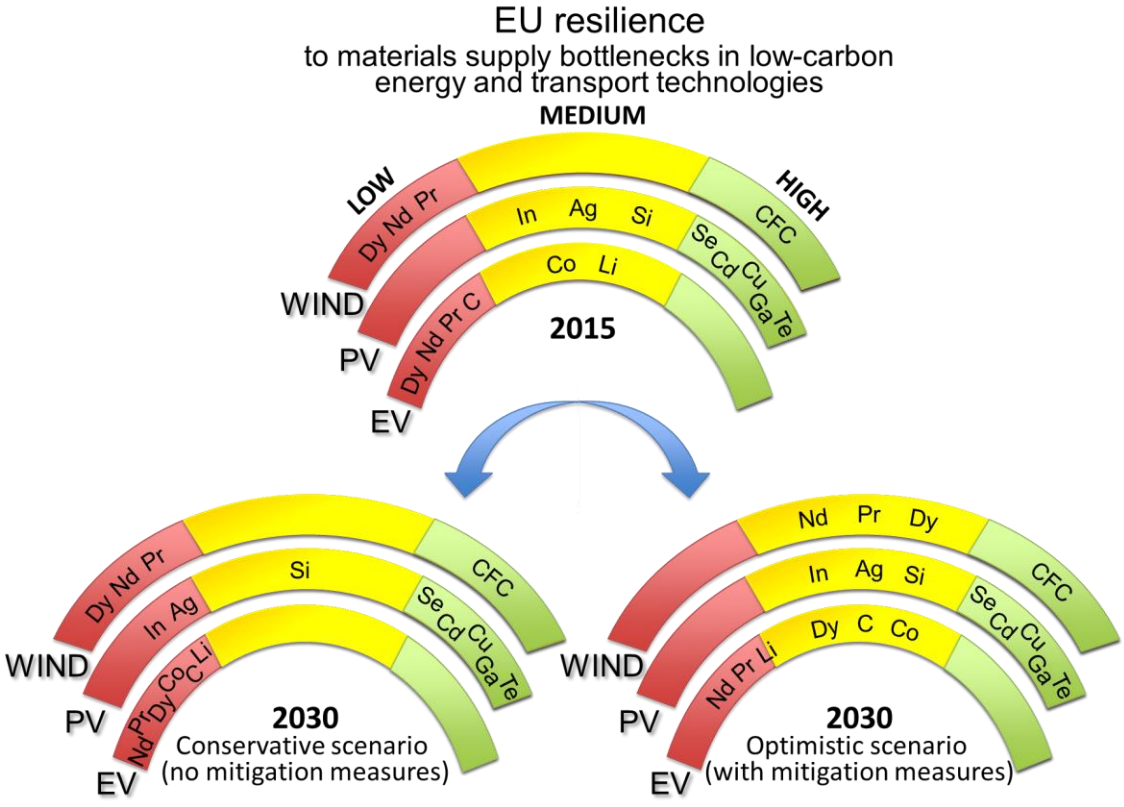
The analysis is based on a comprehensive methodology, which relies on sets of indicators aggregated in two dimensions: upstream and downstream.

The *upstream dimension* is designed to give an indication of the EU's resilience in terms of a secure, sustainable and adequate supply of raw materials. A set of eight indicators in this dimension are developed reflecting different supply aspects. These aspects range from the mineral resources availability, current and potential mining/refining suppliers, EU reliance on imports, macroeconomic, environmental and geopolitical factors to recycling and substitution. Particular attention has been given to estimate the current and future demand for materials required for these technologies in the EU and worldwide to assess the adequacy of the forthcoming materials supply.

To complement the resilience evaluation, the *downstream dimension* – built on a set of three indicators – is designed to address the EU supply chain dependency on processed materials and components required to underpin the deployment of wind, photovoltaic and electric vehicles technologies in the Union. Aspects related to costs, markets and investment capability are also included.

Key conclusions

The main results of this study are presented in the chart below:



The analysis shows that in 2015 the EU had a low resilience to potential bottlenecks in the supply for several materials such as: the rare earths – neodymium (Nd), praseodymium (Pr) and dysprosium (Dy) – used in wind and electric vehicles technologies, as well as for graphite (C) required in rechargeable batteries in electric vehicles. Moderate supply issues are seen for indium (In), silver (Ag) and silicon (Si) in the photovoltaic technology as well as cobalt (Co) and lithium (Li) in electric vehicles. The resilience to supply bottlenecks for carbon fibre composites (CFC) used in wind turbine blades is evaluated as high. The demand for selenium (Se), copper (Cu), gallium (Ga), tellurium (Te) and cadmium (Cd) in photovoltaic technology is marginal compared to the global supply. Therefore, for these materials the estimated EU resilience is also high.

The resilience will change by 2030 mainly due to increasing materials demand as a result of growing deployment rates of these technologies as well as potential adoption of different mitigation measures to improve material supply. Under a conservative scenario, defined here as a baseline scenario where no mitigation measures will be in place, the EU resilience to supply bottlenecks for a larger number of materials is assessed as low. This will include Nd, Pr and Dy for wind turbines and electric vehicles, In and Ag for photovoltaic, as well as Co, graphite and Li for electric vehicles. Some moderate supply issues are expected for Si in photovoltaic while no issues are envisaged for CFC in wind turbine as well as Se, Cd, Cu, Ga and Te in photovoltaic technology.

The EU resilience to materials supply bottlenecks might improve considerably by 2030 if adequate measures to balance the expected growing material demand are taken. Such measures include an increase in the EU raw materials production, recycling or implementing substitution. In such optimistic conditions, the EU resilience to supply bottlenecks of rare earths in wind turbines is expected to evolve from low to medium. A similar transition, from low to medium resilience, could be also seen for In and Ag in photovoltaic technology. The most stringent situation in terms of material supply is expected for electric vehicles. For this technology, the EU resilience to materials supply bottlenecks remains low for Nd and Pr, medium for Dy, graphite and Co, while for Li it is still medium but approaching the low resilience threshold.

Finally, the report identifies the mitigation measures that are best suited to ensure a secure supply along the value chain of materials in each of the investigated technologies. For the majority of the materials, it appears that substitution is the most effective measure to improve the EU resilience to supply bottlenecks, followed by recycling and increasing the EU's production of raw materials. Engagement to promote such mitigation measures is likely to be essential for securing materials supply for the deployment of these three low-carbon technologies.

Future work will look at potential material issues in other sectors such as efficient lighting, energy storage and smart grids.

1 Introduction

1.1 Background

Following the adoption in 2008 of the Raw Materials Initiative, which represents the EU's strategy for securing reliable and unhindered access to raw materials, in 2013, the European Commission moved into the implementation phase of the RMI through the European Innovation Partnership (EIP) on raw materials. The context of the EU's current raw materials policy covers the sustainable sourcing of raw materials from global markets, sustainable and environmentally friendly domestic material production, and resource efficiency and the supply of secondary raw materials.

An overview of the challenges facing the EU related to raw materials is presented in the recently published Raw Materials Scoreboard [RMS, 2016]. Among general aspects on the raw materials policy context and the EIP's general objectives, the Scoreboard specifically highlights that materials are indispensable for the development and large-scale deployment of low-carbon energy technologies in the EU.

Low-carbon technologies play a fundamental role in Europe's transition towards a clean, secure and competitive economy. They are essential for achieving both the EU's climate and energy targets and its policy objectives, as shown in the Energy Union Framework Strategy [EC, 2015]. For instance, these technologies require significant amounts of steel, copper and aluminium as well as a vast array of speciality metals. In most cases, the annual demand for raw materials used in certain low-carbon technologies is projected to increase significantly by 2030 (Figure 1).

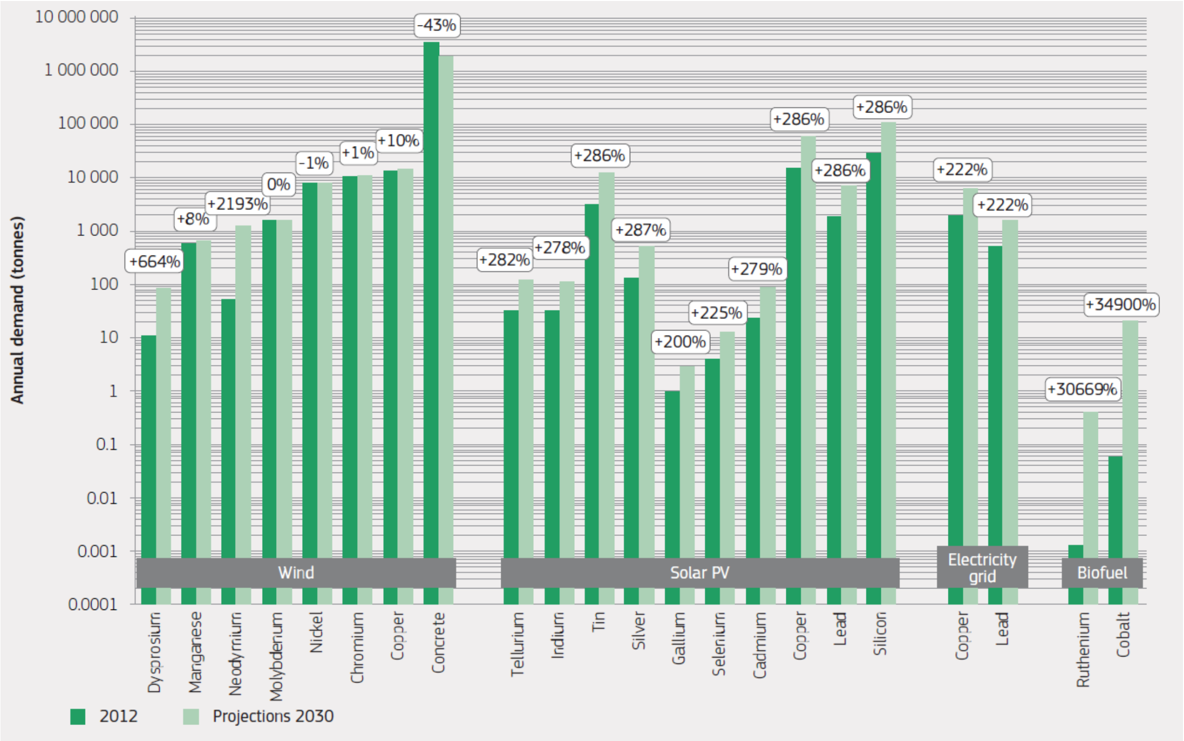


Figure 1: Projected variation in the EU's annual demand for raw materials in selected low-carbon technologies from 2012 to 2030 [RMS, 2016]

Some of the raw materials needed for low-carbon technologies are also used in other European economic sectors, such as construction, transport, ICT, defence, etc. Based on economic importance and the level of risk to supply, some raw materials are evaluated as "critical" and as such are included in the 2014 EU critical raw materials list [EC, 2014].

While the EU criticality assessment addresses the whole European economy, in 2011 and 2013, the JRC carried out and published specific studies on the identification of those materials which could become a bottleneck in the supply chain of various low-carbon energy technologies [JRC, 2011 and 2013]. The latest JRC analysis was based on a three-step bottom-up approach (Figure 2).

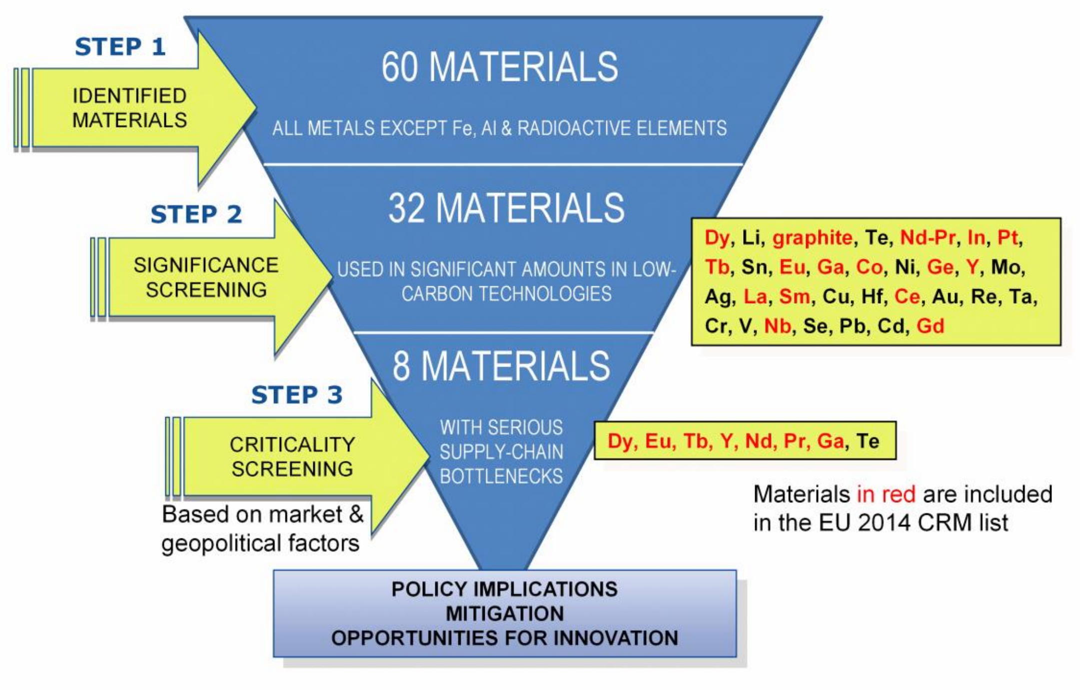


Figure 2: JRC approach applied in 2013 for assessing bottlenecks in material supply in low-carbon energy technologies [JRC, 2013]

In this study, 32 materials were identified as being significant for the decarbonisation of the European energy system. When taking market and geopolitical factors into account, eight of them, namely Dy, Eu, Tb, Y, Pr, Nd, Ga and Te, were classified as "highly critical". The technologies of particular concern, due to their reliance on critical materials listed in the JRC report, were identified as follows: wind energy, electric vehicles, solar photovoltaic and fluorescent lighting [JRC, 2013].

Due to the continuous evolution in the materials supply/demand parameters, technology deployment scenarios, new players and policy context changes, a new investigation is necessary into material supply bottlenecks for low-carbon technologies. This assessment is also intended to reflect the latest market developments as well as recent projections about economic activity in energy and transport, as reflected for instance in the EU reference scenario [EC, 2016a] in view of achieving the EU’s climate and energy targets for 2030 and beyond.

Various methods are used to evaluate the reliability of the materials supply and/or the effect of price volatility on a manufacturer or the economic sector. These methods are needed for monitoring the materials flow and helping decision-makers to prevent or mitigate the effects in case of shortages in supplies. Such assessments are often based on a different set of parameters or indicators. Given the materials supply issues, a specific methodology has been developed in this study to investigate which materials could become a bottleneck in the future high deployment rates forecast for low-carbon technologies in the EU. This methodology is built on previous research conducted by the JRC on material criticality and also takes into account inputs from stakeholders and other insights expressed in the scientific literature. This new approach is applied to materials used in three emerging low-carbon technologies – wind power, photovoltaic and electric vehicles.

1.2 Scope of the study

This study aims to investigate whether the supply of certain materials along their supply chain may represent a barrier to the widespread deployment of low-carbon energy and transport technologies, thereby putting at risk the achievement of the EU's renewable and low-emission mobility goals. In particular, this study examines materials that can either hinder or slow down the forecasted deployment of three low-carbon technologies in the EU by 2030: **wind power, photovoltaic and electric vehicles** (Figure 3).

The analysis is based on a methodology which takes into account various material issues, limitations and dependencies along the supply chain at both the upstream and downstream supply stages. Overall, **15 different materials** are investigated in this study**.**

The results are expressed in terms of EU resilience to material supply shortages for low-carbon technologies.

The methodology developed within this study allows for the assessment of each individual material in relation to its use in a particular technology.

The impact of three main mitigation measures is assessed in relation to overcoming potential bottlenecks, namely recycling, substitution and EU raw materials production. Four different assessment scenarios are considered: baseline scenario, where no mitigation measures are in place and other three scenarios, which combine different mitigation measures. All these scenarios are explained in the next section.

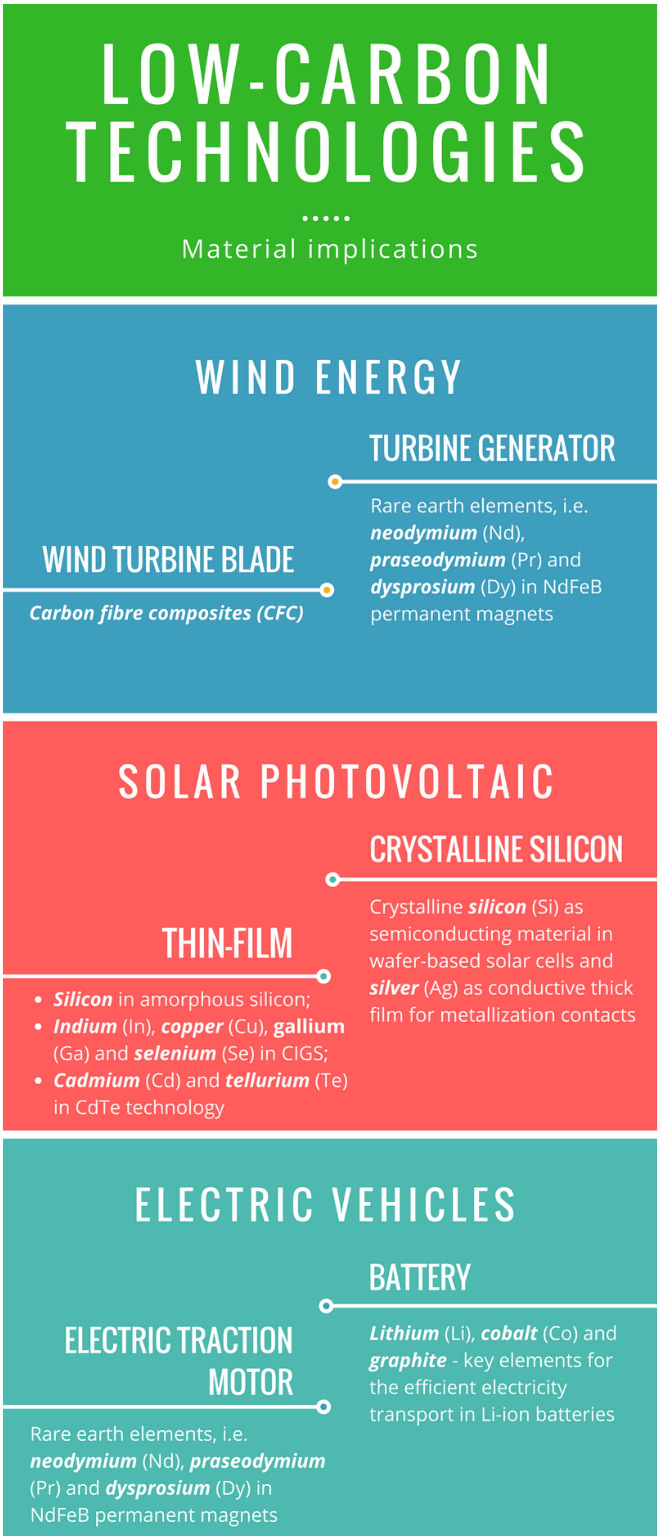


Figure 3: Overview of materials required in the wind power, photovoltaic and electric vehicles technologies analysed in this study

2 Methodology

Materials play a crucial role when it comes to deploying low-carbon technologies (LCT). Potential limitations and bottlenecks in the supply of materials along the entire value chain – from raw materials to the final product – may hinder the deployment of LCT. This is particularly relevant considering the latest EU scenarios which foresee an increase in the share of LCT.

The high degree of resilience desired should be characterised by a sustainable and secure access to raw materials and components, a diversified supply, high recycling rates and substitution alternatives. All these aspects are elements of the proposed assessment methodology which aims to evaluate EU resilience in view of the adequate access to raw materials, processed materials and components required for a given LCT. The considered time horizon ranges from 2015 to 2030.

In more detail, the methodology relies on sets of indicators aggregated in two dimensions: upstream (D1) and downstream (D2), as described below (Figure 4):

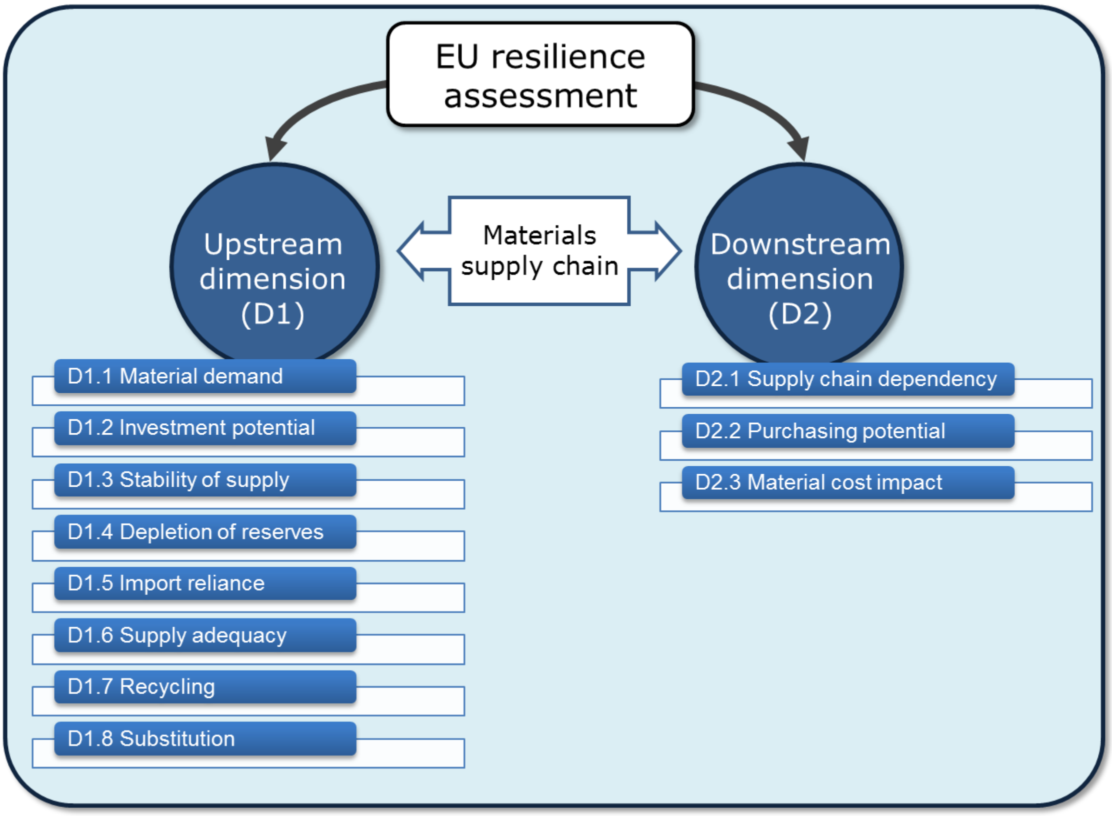


Figure 4: JRC's methodological approach for assessing EU resilience to material supply shortages along its supply chain

The research and information analysed in this study were collected from a wide variety of sources, such as: public databases, industry/consultancy reports, articles, market trend analysis, etc. In some cases, an exhaustive analysis of future developments was difficult to carry out due to limited data. In such cases, appropriate assumptions were made, as explained in Annex B and Annex C.

2.1 Dimensions

The upstream dimension (D1) is designed to give an indication of EU resilience in terms of a secure and sustainable supply of raw materials. D1 comprises eight indicators related to the geological availability of raw materials and their supply, macroeconomic and geopolitical factors, demand, import reliance, recycling and substitution:

- D1.1 is a composite indicator which analyses the progression of EU demand based on the existing deployment scenarios for each LCT. If the demand is <1 % of the global supply it is considered that such a material does not pose issues for the deployment of the given LCT;
- D1.2 analyses the EU's investment power progression in relation to other leading countries: GDP is used as a proxy;
- D1.3 is a composite indicator evaluating the concentration of supply weighted by the political stability of supplier countries;
- D1.4 examines the adequacy of the reserves, as known today;
- D1.5 evaluates the EU's import reliance progression;
- D1.6 estimates the present and future mine capacity utilisation ratio;
- D1.7 considers future recycling trends;
- D1.8 is devoted to the substitution potential.

The downstream dimension (D2) comprises three indicators:

- D2.1 goes beyond the raw materials issue and examines the likelihood of supply shortages that may occur downstream in the material supply chain; thus it covers EU dependence on the supply of processed materials/alloys/compounds as well as components and final products. Another aspect is whether the EU has the manufacturing capacity as well as the suitable infrastructure to supply the required processed materials, components or final products.
- D2.2 indicates whether the EU has sufficient purchasing potential when compared to other competitor countries to respond to an eventual supply shortage along the supply chain or to incentivise and facilitate the penetration of a new technology.
- D2.3 gives a simple economical measure of the contribution of an individual material to the final component/product cost. It is assumed here that if the material is a significant part of the total component cost, an escalation in the eventual material cost may hinder further technology deployment.

More details for each individual indicator are given in section 2.2.

The EU reference scenario and other official EU targets, as well as industry forecasts, latest trends and learning curves are used to establish the evolution in the indicators and to make the necessary projections until 2030. In cases where data is unavailable, a dedicated extrapolation analysis was performed.

2.2 Indicators

The indicators are graded on a scale ranging from 'zero' to 'one'. Zero represents minimum EU resilience and one represents maximum resilience:

1 = max EU resilience

0 = min EU resilience

2.2.1 D1.1 Material demand

D1.1. is a composite indicator consisting of three sub-indicators. The selected sub-indicators represent different aspects of the material demand, bearing in mind that there is competition for the same material globally (worldwide) as well as within EU. They also consider that the same material is used for different end-uses/sectors.

Details of each sub-indicator are given below:

D1.1.1 Annual EU demand for a material in a specific technology as a fraction of its annual global (world) demand in all end-uses/sectors

$$D1.1.1 = \frac{EU\ material\ demand\ per\ technology}{Global\ demand}$$

D1.1.1 compares the EU's material needs for the deployment of a given technology with the global demand for such material. If the EU demand represents a significant fraction, there is a high likelihood of a shortage in supply that may affect a given technology deployment in the EU. Conversely, it is assumed that if a technology requires only a very small fraction of the global demand, the likelihood of supply shortage is very low. A threshold value of 1 % is assumed for D1.1.1. If D1.1.1 < 1 %, the material will not represent a bottleneck in the deployment of this specific technology, and this is also used as a significance screening.

D1.1.1 is a function of time and is calculated based on the expected average growth rates of the selected technology within the EU. Relevant documents, such as the EU scenarios, roadmaps, strategies, etc. are used to assess the projected demand. Data are also taken from relevant material/technology sources, as well as available commercial information. Scientific publications are used to identify the material intensity in the selected technology.

D1.1.2 Annual EU demand for a material for a specific technology as a fraction of its annual EU demand in all end-uses/sectors

$$D1.1.2 = \frac{EU\ material\ demand\ per\ technology}{EU\ material\ demand\ for\ all\ sectors}$$

D1.1.2 represents the sectorial competition within the EU for the evaluated material. The technology being considered will compete with other sectors requiring the same material. While, in general, more conventional sectors register a steady increase of a few percentages per annum, the emerging technologies can even double each year (e.g. electric vehicle deployment rates have been higher than 100 % in recent years). Greater sectorial competition even within the EU implies a higher likelihood of supply difficulties.

D1.1.3 Annual EU demand for a material in all end-uses/sectors as a fraction of the global material demand

$$D1.1.3 = \frac{EU\ material\ demand\ for\ all\ sectors}{Global\ demand}$$

D1.1.3 gives an approximation on how the EU is competing with the rest of the world for a particular material, bearing in mind all the main applications of this material. If the demand for a given material also increases significantly worldwide, this may put pressure on the continuity of its supply.

The combination of the three sub-indicators is done by the weighted average. The weighting factors are chosen to give more emphasis on D1.1.1 which is considered to be the leading one in the formula below. These three sub-indicators and their weighted average measure the likelihood of a shortage of supply in raw materials due to demand increase:

$$D1.1 = 1 - (60\,\% * D1.1.1 + 10\,\% * D1.1.2 + 30\,\% * D1.1.3)$$

D1.1 is, of course, time dependent and is consistently calculated in this way for each year between 2015 and 2030.

Note: Since several deployment scenarios have been considered here for each technology, D1.1 indicator has been calculated for each deployment scenario. The final D1.1 is then taken as the arithmetic average of the D1.1 indicators obtained for each deployment scenario.

2.2.2 D1.2 Investment potential

D1.2 indicates the EU’s relative investment potential compared to other big world economies considered as possible EU competitors. It is assumed that a higher potential to invest may better facilitate possible expansion of the materials supply chain upstream. Besides financial means, environmental constraints are also considered.

For instance, expanding or opening new mines and/or refining capacities requires significant investments, which are only possible when sufficient purchasing power is available, as well as suitable environmental conditions (leaving apart the availability of geological resources). Therefore, countries with higher investment potential and fewer environmental restrictions (providing that they also have resources) may be better placed when it comes to a secure supply of raw materials.

Indicator D1.2 has more of a market and geopolitical relevance than specific material or technology pertinence; thus, it is assumed equal for all materials/technologies considered in this report.

A country’s GDP gives a broadly accepted proxy of its economic and financial performance. Countries with fast-growing GDP have more potential to invest and attract more foreign investments. For this analysis, countries with GDP comparable to that of the EU are possible competitors of the EU in terms of investment potential, especially if they have a higher GDP Annual Growth Rate (AGR). The following countries have been identified as the EU’s potential competitors, i.e. having similar GDP and similar or higher GDP–AGR: USA, China, Japan, Brazil, India, Russia, Canada, Australia and South Korea.

Countries’ GDPs are then weighted using the Environmental Performance Index (EPI) which ranks how well countries perform on high-priority environmental issues [EPI, 2016]. The EPI is used as a proxy of the environmental constraints on expanding existing facilities and/or opening new mines in order to increase production of raw materials. The EPI values are higher for countries with higher environmental standards or, in other words, more environmental restrictions on opening new mines or extending existing ones. Therefore, (1-EPI) is used to give more weight to countries with fewer environmental constraints.

Thus, the EU’s investment potential is presented as the ratio between EU GDP and the total GDP, being the summation of EU GDP and the non-EU GDP of the nine competitor countries selected for the analysis. All countries’ GDPs are weighted by their EPIs as follows:

$$D1.2 = \frac{\sum_{i=1}^{28}\left(GDP_{EU_i} * \left(1 - EPI_{EU_i}\right)\right)}{\sum_{j=1}^{9}\left(GDP_{non-EU_j} * \left(1 - EPI_{non-EU_j}\right)\right) + \sum_{i=1}^{28}\left(GDP_{EU_i} * \left(1 - EPI_{EU_i}\right)\right)}$$

D1.2 is calculated for 2015 and 2030 using 2015 GDP data and 2030 projections from the Organisation for Economic Co-operation and Development’s database [OECD, 2016b]. For the years 2020 and 2025, a linear data interpolation has been done.

The most recent EPI values for the EU and non-EU countries have been used for the entire period since no future EPI projections can be found.

2.2.3 D1.3 Stability of supply

D1.3 is a composite indicator measuring the stability of supply for both mining (D1.3 $_{\text{mining}}$) and refining (D1.3 $_{\text{refining}}$) stages.

The supply of specific material could be constrained if production is concentrated in a limited number of countries which lack political stability. Such circumstance may lead to disruptive events such as supply shortages or price escalation. The conventional approach to measuring the concentration of supply is based on the Herfindahl-Hirschman index (HHI). HHI is the sum of the squares of the market shares of the supplier countries, and can range from close to zero to 10 000. One country supplier of a given raw material will result in the highest market concentration close to a monopoly, i.e. 100 % share. Then HHI = (100^2) = 10 000. If hundreds of countries are competing as suppliers, their market share will be close to 0 %, resulting in an HHI close to zero.

It is also important to take into account the reliability of each supply country. For this purpose, the World Governance Index (WGI), commonly accepted as a proxy of a country's political stability, is used as a weighting factor [WGI, 2015]. The WGI is a cross-country indicator of governance and covers over 200 countries and territories, measuring six dimensions of governance: voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law and control of corruption. The WGI values ranging originally from '-2.21' to '+1.87' are re-scaled from 0 to 1 to fit the present methodology. Thus, more stable countries have a higher WGI (closer to 1).

In this analysis, for both the mining and refining stages, the current (2015) concentration of supply is weighted by (1-WGI) using the following equitation, which is a modified version of the conventional HHI:

$$HHI_{WGI\ weighted\ (mining)} = \sum_i (Mining\ Share_i^2 * (1 - WGI_i))$$

$$HHI_{WGI\ weighted\ (refining)} = \sum_i (Refining\ Share_i^2 * (1 - WGI_i))$$

where '*i*' is the number of suppliers.

(1-WGI) is used as a weighting factor to give more weight to the more stable countries. By so doing, the concentration of supply can be mitigated (improved) if the major suppliers are politically stable countries.

D1.3 $_{\text{mining}}$ and D1.3 $_{\text{refining}}$ are then assessed as follows:

$$D1.3\ mining = 1 - \frac{HHI_{WGI\ weighted\ (mining)}}{10000}$$

$$D1.3\ refining = 1 - \frac{HHI_{WGI\ weighted\ (refining)}}{10000}$$

Different weights are used to sum the two components:

$$D1.3 = 70\% * D1.3_{mining} + 30\% * D1.3_{refining}$$

A larger weighting factor is applied to the mining stage to reflect the higher risk profile of the extraction phase.

For each raw material under consideration, both present and future production scenarios until 2030 are assessed. The actual production shares are normally available for most raw materials, which are used to calculate HHI for 2015.

Future potential supply statistics in terms of mining and refining shares are however not available. For the mining stage, supply predictions until 2030 were made from information on the production capacities of operating mines and projects currently on the development stage. Capacity expansions of operating mines are also taken into consideration. For this purpose, an inventory of anticipated mine production capacities of mines in the preproduction stage and planned capacities of projects in 'reserves development', 'pre-feasibility' and 'feasibility' stages was compiled. However uncertainties exist in relation to the completeness of the used data sets as well as market conditions which are critical for the timing of the additional production capability. For example, very often projects have indication of planned production capacity without year of commencement. To make allowance for delays in the delivery of mine projects, fixed development timeframes were applied to the projects in the production pipeline: mines currently under construction are expected to 'be operational in 2018; projects under feasibility-stage (either started or completed) are expected to come on-stream in 2020; supply from 'prefeasibility' and 'reserves development-stage' projects is expected to be available only beyond 2025.

Unlike for the mining stage, there is less extensive and structured information available for the refining stage. Regarding the data on future refining capacities, the present refining capacities are used and, where possible, are complemented with new data.

Since no WGI forecasting is available, the latest WGI values available for 2014 are used for the whole period from 2015 until 2030.

D1.3 is time dependent and is calculated in this manner for each year between 2015 and 2030.

2.2.4 D1.4 Depletion of reserves

D1.4 indicator gives a rough estimation of the future availability of the materials and aims to give an indication of the long-term sustainable access to a certain commodity. It is based on the ratio between reserves and consumption over time.

The resources and reserves situation is often included in criticality studies with a long-term focus. Reserves refer to those amounts of raw materials which have been confirmed and can be economically recovered with currently available technology.

The static Reserves Depletion Index (RDI) is utilised to provide a conservative estimation. It gives the number of years of consumption using the known global reserves and forecasted global consumption.

The reserves of each subsequent year are obtained by extracting the global production in the previous year, leading to the depletion in reserves.

$$RDI_{year\ n} = \frac{Reserves_{year\ (n-1)} - Consumption_{year\ (n-1)}}{Consumption_{year\ n}}$$

Here, the consumption is assumed to be equal to the forecasted global demand, calculated within D1.1 indicator, thus:

$$RDI_{year\ n} = \frac{Reserves_{year\ (n-1)} - Demand_{year\ (n-1)}}{Demand_{year\ n}}$$

For the majority of raw materials, the RDI is greater than 15 years. This indicates adequate reserves and therefore no issues concerning future access over the considered time frame. D1.4 is then assumed to be equal to 1, giving the maximum contribution to the D1 resilience dimension.

In the few cases, the RDI is less than 15 years. In such cases, D1.6 is progressively reduced down to the value of 0.7 to reflect a smaller contribution to the D1 resilience dimension.

In other words, RDI above 15 years is considered as a benchmark for an acceptable situation, while values below 15 years are considered as a potential supply issue.

As mentioned before, the selected approach is conservative. In fact, the reserves and their static lifetime are by no means fixed amounts. It is common for mineral resources to be upgraded to ore reserves and subsequently mined. Moreover, additions to the reserve base are expected to be achieved and credited to exploration work involved in establishing new deposits. Historical analyses show that the static lifetime of reserves tends to be maintained over time.

D1.4 is calculated in this way for each year between 2015 and 2030.

2.2.5 D1.5 Import reliance

Import reliance must be taken into account when assessing bottlenecks which can impede the deployment of a certain technology. A high degree of import reliance on raw materials from outside implies a high likelihood of supply shortages and/or price increase, specifically when combined with a high concentration of supply.

In general, the import reliance is calculated as the ratio between the net import and net consumption:

$$IR = \frac{Net\ Import}{Net\ Consumption}$$

where

$$Net\ Import = Import - Export$$

$$Net\ Consumption = Domestic\ Production + Import - Export$$

Only the current EU imports and exports of different commodities are available in the Eurostat database, while no import/export data are available for the future. To deal with this, the following logic is considered to calculate the IR for a given commodity: raw materials not mined in the EU, not recycled in the EU and not substituted will have to be imported to satisfy EU demand.

The EU net import is approximated as follows:

$$EU\ net\ import = EU_{demand} - EU_{Production} - Recycled\ material_{EU} - Substituted\ material_{EU}$$

The EU net consumption is assumed to be equal to the EU demand.

In this case, the general formulation of IR becomes:

$$IR = \frac{EU_{demand} - EU_{Production} - Recycled\ material_{EU} - Substituted\ material_{EU}}{EU_{demand}}$$

The methodology aims to measure EU resilience but higher import reliance leads to lower resilience (low D1.5 value). Conversely, marginal IR will lead to high resilience. Indicator D1.5 is then defined as follows:

$$D1.5 = 1 - IR$$

Domestic EU production, recycling and substitution are different ways to reduce the import reliance and increase the resilience. D1.5 is also time dependent and is calculated in this way for each year between 2015 and 2030.

Note: The EU import reliance is calculated for each deployment scenario. The average value is taken consequently to estimate the import reliance for each assessment scenario.

2.2.6 D1.6 Supply adequacy

Increasing material demand is a common feature of growing economies and is not a limiting factor per se if the supply capacity can grow accordingly to cope in a timely way with the demand; this is referred to as supply adequacy. Sufficient capacity must be in place to satisfy a sudden increase in the demand. D1.6 indicator assesses the supply adequacy of raw materials on a global scale until 2030.

One of the distinctive characteristics of the mining industry is the industry's slow response time to changes in the rhythm of demand, normally referred to as supply inelasticity [Humphreys, 2012]. While the establishment of a new mine takes significant time, an existing mine provides certain elasticity to supply – companies very often enjoy spare capacities that are strategic assets to maximise profits as prices increase. Use of the mine capacity tends to fluctuate with business cycles, with companies adjusting production volumes in response to changing demand. The capacity utilisation rate, used in this analysis as a measure of supply adequacy, measures the proportion of potential output that is actually achieved. In response to market signals, a company with less than 100 % utilisation can theoretically increase production without incurring expensive overhead costs.

In mining, however, production can be suppressed far below capacity unintentionally. Reasons for this include geological problems, such as faulting or unexpected ore-grade declines, mining issues such as pit-wall failures or rock bursts, and a long list of more random events like strikes, mechanical failures, accidents, power outages and weather events [Humphreys, 2012].

To perform the calculations, current demand and demand projections for a raw material over time (again considered to match production in a given year), are compared with existing and forecast capacities to give the capacity utilisation rate:

$$Capacity\ utilisation\ rate = \frac{Demand}{Mining\ capacity}$$

The extent to which capacity utilisation would have to be pushed forward to cope with the demand levels forecast is then assessed and scored.

In most cases, capacity utilisation rate is below 70 % which gives a sufficient margin to increase the production in a timely manner and avoiding a supply disruption event. In the present analysis, this is anticipated as an appropriate supply adequacy. Consequently, D1.6 is then assumed to be equal to 1, giving maximum contribution to the D1 resilience dimension. A higher rate of capacity utilisation indicates a reduced potential to respond to a sudden increase in demand. In these few cases, D1.6 is progressively reduced up to the value of 0.7 to reflect a lower contribution to the D1 resilience dimension.

D1.6 is time dependent and is calculated in this manner for 2015, 2020, 2025 and 2030.

2.2.7 D1.7 Recycling

Recycling is a way to reduce the demand for primary raw materials by generating the so-called secondary materials flows. Although recycling rates for some materials are very low today, a significant increase in secondary flows is expected in the next five to 10 years, not least thanks to different policy initiatives taken at both the EU level and globally. This time horizon is the estimated time for the development, demonstration and market introduction of new recycling technologies. Improving the collection rates of end-of-life products is also a priority for the EU, which is expected to generate significant flows of secondary materials.

D1.7 indicator represents the overall recycling rate for each material as explained herein. It accounts for the potential of the global future secondary materials supply as a means of mitigating the growing global demand for primary raw materials and thereby decreasing the pressure on their supply. In addition, such global secondary flows of materials also offer a diversification in supply which is a positive factor for the EU’s resilience, and in cases where recycling takes place outside the EU, too.

Information on technological and additional economical aspects are necessary in order to estimate the potential recycling rates of materials until 2030, starting from today's negligible recycling rate.

For example, the main obstacles for the mass recycling of many materials nowadays are economic factors rather than technological difficulties. If the price of the recycled material is several times higher than the price of the freshly mined material, the industry does not have any incentive to invest in recycling capacities and develop/improve recycling technologies.

For simplicity and as a conservative approach, only the potential increase in recycling rates in the future is considered for materials that are already being recycled. For example, if the global end-of-life recycling rate of a given material is currently 30 % but has the potential to increase to 70 % over the next 10 years, only the additional 40 % is considered gradually (using an S-shape learning curve) as a means to increasing the future supply during this period.

Depending on the available information on recycling of new (usually referred to as production) scrap and old (end-of-life) scrap, both are considered for the calculation of indicator D1.7. This is done for the different end-uses/sectors for the material being investigated, also taking into account the collection rate (CR) and recovery rate (RR).

$$D1.7(2030) = \sum_i \left(\frac{Material\ share_i * (CR\ new\ scrap * RR\ new\ scrap + CR\ old\ scrap * RR\ old\ scrap)_i}{2} \right)$$

where *'i'* is the number of end-uses/sectors.

As can be seen, the defined recycling rates from old and new scrap for the different end-uses/sectors are summed up after weighting them by the relevant material shares in these end-uses/sectors.

For materials for which collection and recovery rates from new and old scrap are not available, the most logical assumptions are made based simply on potential future shares of the materials in the different end-use/sector. Such assumptions have been validated by industry experts.

The import reliance on certain materials can also be mitigated via recycling. Therefore, potential future recycling rates have also been taken into account in indicator D1.5. However, only quantities recycled within the EU are assumed to have the potential to reduce the EU import dependency on primary materials. If specific details are not available on future recycling facilities to be commissioned in the EU, information on global estimations is used assuming that the EU will follow the global evolution as regards developments in recycling. Recycling is already an essential part of the EU’s Circular Economy Package. To confirm the assumption and to get a more realistic picture on the future recycling rates for different materials within the EU, opinions of experts from companies operating in the recycling business, such as Umicore, have been taken into account.

2.2.8 D1.8 Substitution

Substitution is a sustainable strategy to moderate the demand of some critical materials and thus reduce the pressure on their supply. Beyond reducing pressure on supply, it can be also an innovative way to create diversification and contribute to the D1 resilience dimension.

D1.8 represents the overall substitution rate for each material, as explained below.

The materials substitution possibilities are analysed for their main end-uses/sectors by determining the material use and its share in these sectors. Further, the substitution potential until 2030 is defined for each end-use/sector based on the latest technological developments and R&D findings. Not only is the straightforward case of 'material for material' substitution considered, but alternative technologies may also be regarded de facto as a form of substitution and therefore considered in the analysis. The defined substitution rates for the different end-uses/sectors are summed up after weighting them by their relevant material shares in these end-uses/sectors. In this way, the overall material substitution rate for 2030 is defined.

Once again for simplicity and as a conservative approach, the substitution rate for each material is assumed to be zero in 2015. It gradually reaches the calculated overall 2030 substitution rate by following an S-shape curve.

In addition, substitution is meant to reduce the EU import dependence on certain materials by moderating its demand for these materials. Thus, the substitution effect was also considered for indicator D1.5.

Note: For materials which are extremely abundant in nature (e.g. silicon and carbon in this study) the indicators related to recycling and substitution are less pertinent and therefore should not be taken into account. For these materials, only the six other indicators are considered within the upstream dimension.

2.2.9 D2.1 Supply chain dependency

D2.1 is a composite indicator giving an indication of the EU dependency of the downstream supply for each material and for each step of the supply chain pertinent to a specific technology. The supply chain steps are identified for each technology excluding the mining and refining stages which have already been addressed in the upstream dimension. Thus, the supply chain steps investigated within this indicator range from materials processing to manufacturing of semi-finished/final products, such as special alloys, composites, etc. and components.

The key supply chain steps are identified and where necessary clustered to reflect data availability. For each selected step, supply chain analysis is conducted resulting in the definition of two parameters: concentration of supply weighted by WGI, as parameter *'A'* (see indicator D1.3) and EU supply share, as parameter *'B'*.

High dependency on different stages in the supply chain will increase the likelihood of potential supply chain bottlenecks and thus reduce EU resilience downstream. Conversely, low dependency along the supply chain indicates high EU resilience for the deployment of a specific technology.

Since D2.1 indicates 'dependency', thus parameter *'A'* representing the concentration of supply is calculated as the complement to 1 for each supply chain step (similarly to indicator D1.3):

$$A_i = 1 - \frac{HHI_{WGI\ weighted\ (i)}}{10000}$$

where

$$HHI_{WGI\ weighted\ (i)} = \sum_{j} Capacity\ Share_j^2 * (1 - WGI_j)$$

where *'i'* is the number of the identified steps and *'j'* is the number of suppliers in each step.

The EU countries' shares are grouped together and a WGI equal to 1 is assigned, indicating maximum security of supply. There are also a few unknown suppliers. In this case, WGI is assumed to be equal to 0.5.

As for parameter *'B'*, a higher EU share for each supply chain step also indicates higher resilience; thus a direct relation is used:

$$B_i = EU\ share_i$$

D2.1i for each step *'i'* is then calculated as the arithmetic average of the two parameters – *'Ai'* and '*Bi*'.

$$D2.1i = \overline{A_\iota * B_\iota}$$

Lastly, the overall D2.1 is the average of D2.1i determined for all identified steps.

The calculation of D2.1 is done for every five-year interval between 2015 and 2030. Data on 2015 capacities are well established. When available, newly announced capacities are added to the existing capacity in 2015 to update the A and B parameters.

2.2.10 D2.2 Purchasing potential

In a similar way to D1.2, D2.2 measures the EU's relative potential to purchase, using the countries' GDP as a proxy. Since Dimension 2 is dedicated to downstream supply chain limitations, besides the countries' investment potential, it is also important to consider the individual purchasing power of those citizens ready to pay higher price for a product (EVs in this case). Therefore, both the GDP at country level and the GDP per capita are taken into consideration when estimating the D2.2 indicator.

While the first indicator within dimension 2 gives an indication of the EU dependency and limitations along the material/technology supply chain, the second indicator evaluates the EU's potential capability to respond to supply shortages as well as increased prices.

Growing competition may be expected in coming decades since the nine large economies selected here have already announced their plans to significantly increase the share of renewables and to deploy EVs extensively. This may restrict the supply to the EU and/or push up the prices of processed materials and components.

Furthermore, the deployment rate of an emerging technology depends to a larger extent on the infrastructural developments and support: e.g. deployment of EVs is largely dependent on the availability of charging stations, suitable grid, and maintenance facilities, etc. Incentivising is another mechanism which contributes to achieving faster deployment rates. Adequate infrastructural support and incentives are dependent on a country's ability to invest in emerging technologies until the technology becomes competitive.

Moreover, factors such as environmental restrictions in different countries, as well as the support given by various governments to the deployment of green technologies, also play a significant role when evaluating how promptly and easily an emerging technology will be deployed. To account for this, countries' GDP and GDPs per capita are both weighted using the EPI related to the climate and energy indicator, which includes access to electricity, trends in CO_2 emissions per KWh, and trends in carbon intensity. The EPI values are higher for those countries which comply better with the above parameters. More weight is thus given to those countries which will become stronger competitors.

The following formula is applied to calculate the D2.2 indicator:

$$D2.2 = \frac{C + D}{2}$$

where

$$C = \frac{\sum_{i=1}^{28}\left(GDP_{EU_i} * \left(1 - EPI_{EU_i}\right)\right)}{\sum_{j=1}^{9}\left(GDP_{non-EU_j} * \left(1 - EPI_{non-EU_j}\right)\right) + \sum_{i=1}^{28}\left(GDP_{EU_i} * \left(1 - EPI_{EU_i}\right)\right)}$$

and

$$D = \frac{\overline{GDP_{per\ capita\ EU_i} * EPI_{EU_i}}}{\overline{GDP_{per\ capita\ EU_i} * EPI_{EU_i}} + \overline{GDP_{per\ capita\ non-EU_j} * EPI_{non-EU_j}}}$$

D2.2 is calculated for 2015 and 2030 using 2015 GDP data and 2030 projections from the OECD database. Similarly, to calculate the GDP per capita, OECD data on countries' populations for 2015 and projections for 2030 were utilised. For the years 2020 and 2025, linear data interpolation is done.

The most recent EPI values have been used for the entire period since no future EPI projections are found.

2.2.11 D2.3 Material cost impact

D2.3 is designed to give an indication of the impact on the individual material cost on the major component/product cost (for simplicity, this is referred to as component cost). Material prices are subjected to extreme variability. Depending on a manufacturer's degree of reliance on a given material, this aspect may be significant. If the material cost is a significant part of the total component cost, an eventual escalation in the material cost may hinder the deployment of a specific technology. A recent example of such an impediment concerns the rare-earth elements crisis in 2010-2011 when the prices of these materials rapidly increased several fold.

It is recognised that more accurate cost integration in the methodology would require the full material transformation costs associated with all the manufacturing steps needed to transform a raw material into a component. However, this is very difficult to do for several reasons: availability of data, varying transformation costs due to country differences (e.g. different labour, electricity costs, etc.), and different raw material costs depending to a larger extent on the volumes purchased. The relationship established between the technology manufacturer and raw materials supplier is another factor affecting the cost.

Therefore, a simplified approach is taken to calculate D2.3, based on the following input parameters:

(E) unitary cost of raw material (USD/tonne)

(F) material intensity (amount of material used per unit of energy/power, tonne/kW(h))

(G) component cost (per unit of energy/power, USD/kW(h))

The material cost impact is calculated as follows:

$$D2.3 = \frac{G - E * F}{G}$$

To determine the D2.3 evolution until 2030, the raw material costs, materials intensity as well as future component cost forecasts are taken from open sources and proprietary data. The same intensity of materials has been used consistently to calculate the material demand (D1.1 indicator).

2.3 Indicator aggregation and data visualisation

As mentioned above, the indicators are aggregated in two dimensions. D1 is obtained as the arithmetic average of its eight constituent indicators. D2 is the weighted average (50 %:20 %:30 %) of its three constituent indicators.

The EU resilience is shown for each material in each technology for a given year. The upstream (D1) and downstream (D2) dimensions represent the 'X' and 'Y' axis, respectively, of the so-called materials resilience chart (Figure 5).

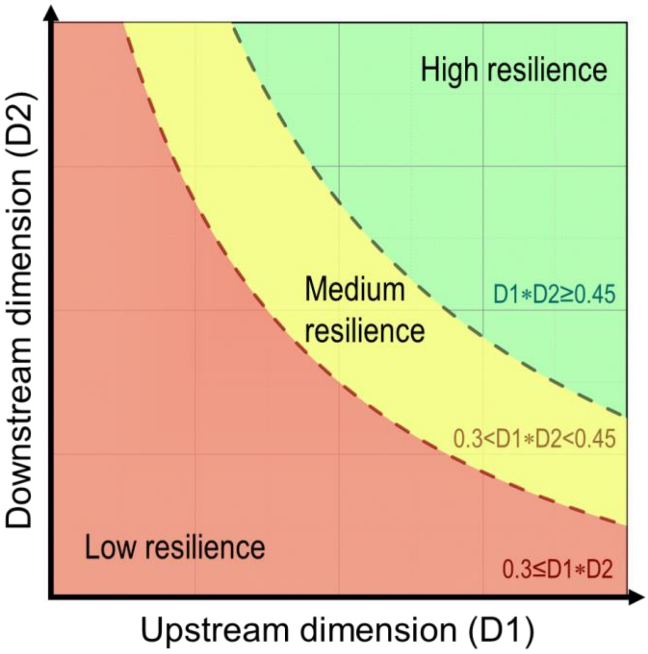


Figure 5: Material resilience chart

Dimensions are expected to evolve with time. The assessment results for each material are represented for 2015, 2020, 2025 and 2030. The product of the two resilience dimensions (D1*D2) is finally used as a simple way to quantify by a single arbitrary number, called resilience score, the overall resilience. This is particularly useful to rank the resilience, allowing also for quantitative comparison of the evolution, for example in terms of % variation with time.

Constant product curves are used to define the resilience areas to enable the ranking of materials up to 2030:

- For materials positioned in the green area (D1*D2 ≥ 0.45), the expectation is that no supply issues will be encountered along the supply chain, which indicates **high EU resilience**.
- Materials positioned between the green and the red lines – the middle yellow area (0.3 < D1*D2 < 0.45) have a moderate likelihood of supply shortages – anticipated as **medium EU resilience**.
- Materials positioned below the red line (D1*D2 ≤ 0.3) represent a high likelihood of supply shortages – anticipated as **low EU resilience**.

The thresholds values (0.3 and 0.45) separating the various zones in the resilience chart are selected according to a given logic, reflecting also up-to-date common knowledge and well based assumptions.

The low resilience threshold curve (separating the low and medium resilience zones) is in fact chosen using the rare earths as a benchmark for 2015. Rare earths have been assessed as critical materials for the EU in different studies as well as in the previous JRC 2013 report. The low resilience threshold curve is then drawn in order to leave the rare earths in the low resilience zone for 2015; approximately 20% in terms of resilience score below the curve.

The high resilience threshold curve (separating the medium- and high-resilience zones) has been set at 0.45, thus adding in terms of resilience a further margin of 50%.

2.4 Assessment scenarios

The EU resilience is assessed according to four different scenarios. Such scenarios allow for an individual analysis of the impact of the three mitigation measures under consideration – recycling, substitution and materials domestic production.

The **baseline scenario** assumes that ***none of the considered mitigation measures*** will be in place in the considered time frame. The analysis based on such scenario – being a 'conservative scenario' – shows the evolution over time of EU resilience to material supply bottlenecks for each technology.

Assessment scenario 1 (AS1), simply denoted further as **scenario 1**: takes into account any possible increase in ***EU raw materials domestic production*** and as such is less conservative than the baseline scenario.

Assessment scenario 2 (AS2), simply denoted further as **scenario 2**: considers ***recycling* and *EU raw materials domestic production*** as possible mitigation measures.

Assessment scenario 3 (AS3), simply denoted further as **scenario 3**: considers ***all three mitigation strategies***, namely recycling, EU raw materials domestic production and substitution, and is thus the most optimistic scenario.

Since the mitigation measures being considered only influence the upstream dimension, the above assessment scenarios are only applied to D1.

3 Determination of material supply bottlenecks in the wind power sector

3.1 Market and wind technology background

Wind energy is one of the most advanced and mature renewable energy technology which will play a significant role in meeting the Europe 2020 and 2030 climate and energy goals [JRC, 2015a]. The EU has long been the front runner in wind power generation. At the end of 2015, on average, wind power produced about 315 TWh of electricity, representing 11.4 % of the EU's total electricity production, through the cumulative installed capacity of 142 GW (of which 11 GW is offshore) [EWEA, 2016]. In terms of new installation capacity, in 2015, wind power registered the highest installation rate: 12.8 GW (9.8 GW onshore and 3 GW offshore), accounting for 44 % of all new installations in the EU [EWEA, 2016].

Implementation of EU and national specific policies and support schemes for renewable energy sources (RES) will drive an even broader penetration of wind energy in future power generation. Different scenarios describe the evolution of wind energy in the EU. According to the EU Reference Scenario 2016, wind power will supply 14.4% of total net electricity generation in 2020, increasing to 18 % in 2030 and 25 % by 2050 [EC, 2016a]. This electricity will be generated by a total wind capacity in the EU of 207 GW in 2020, 255 GW in 2030, and 367 GW in 2050 [EC, 2016a]. The EWEA's new Central Scenario forecasts an installed wind capacity of 192 GW in 2020, increasing to 320 GW by 2030, of which 254 GW will be onshore and 66 GW offshore [EWEA, 2015a]. On a levelised basis, the current cost of onshore wind energy attained a lower price than that produced from coal and gas in several European countries [BNEF, 2016a]. This is the result of lower equipment costs and higher efficiency in new wind turbines.

Today, a mix of wind turbine types is used to meet the various specific onshore and offshore site conditions. They are specifically designed to enhance their performance in terms of energy production, reliability, operation, maintenance, capital cost and transportation. Modern wind turbines integrate a series of highly optimised components to produce the lowest possible energy costs. The major components of standard upwind turbine architecture are shown in Figure 6.

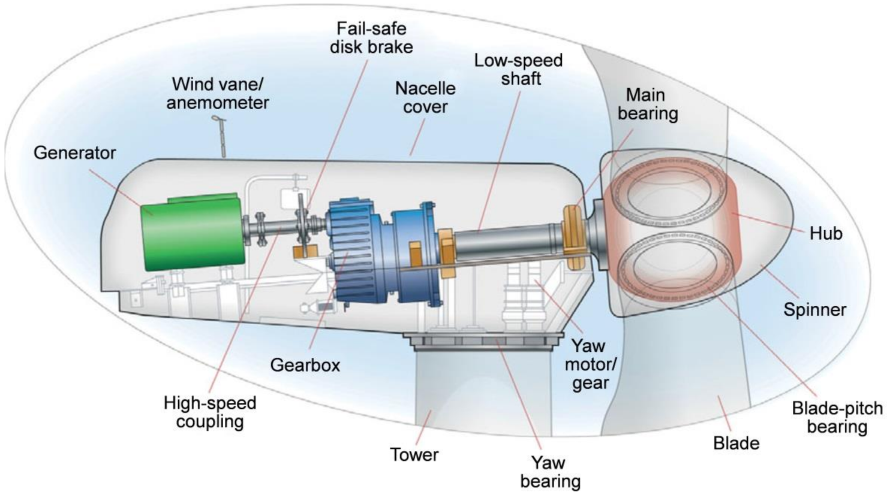


Figure 6: Major components in a modern wind turbine with a gearbox configuration Source: [MRS, 2011]

The cost of wind turbines can be influenced by metal prices, in particular in the case of those turbines using generators containing rare-earth elements. Concerns that the supply of rare earths may not be sufficient to meet the growing demand for the global transition to a sustainable energy future have grown considerably since the rare earths ‘crunch’ in 2011 when near-monopolistic China imposed export restrictions. The rare earths, i.e. neodymium, praseodymium and dysprosium, are key ingredients in the most powerful magnet material, namely neodymium-iron-boron (NdFeB). This magnet is used to manufacture permanent magnet synchronous generators (PMSG), which are used in all major wind turbine configurations: low speed (direct drive), mid speed and high speed (Figure 7).

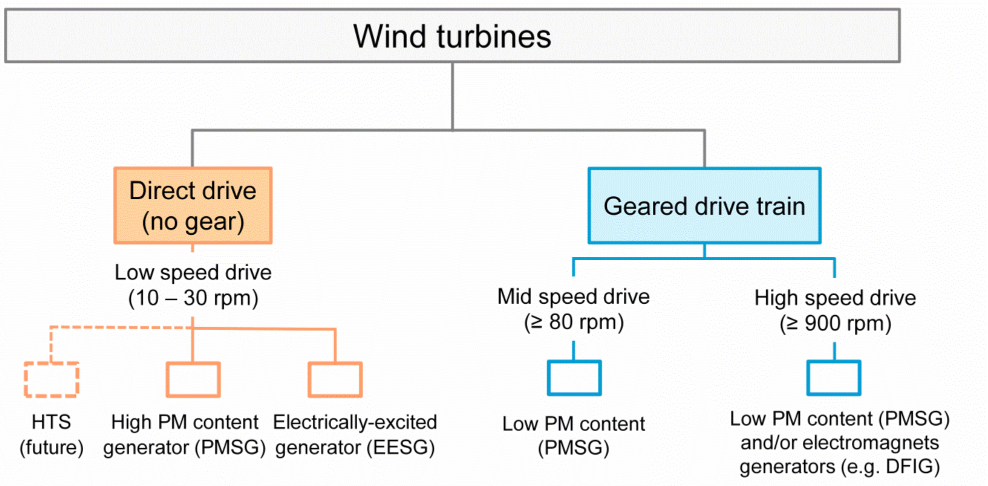


Figure 7: Principal wind turbines types according to drive train configuration

In 2015, the global market share of direct drive PMSG was estimated at 19 %, 1 % for mid-speed drive and 3 % for high-speed PMSG technologies (by capacity installed) [JRC, 2016]. Different amounts of permanent magnets are required in PMSG configurations. About 2 tonnes of permanent magnets are used in 3 MW DD-PMSG turbine (low-speed design), or approximately 650 kg PM per MW of generator capacity [JRC, 2015a]. In contrast, a PMSG that is attached to a gear and rotates at mid speed may operate with a 160 kg magnet per MW. This amount decreases up to 80 kg per MW in a high-speed PMSG configuration [JRC, 2012 and 2015]. The overall rare earth content in an NdFeB magnet is about a third of the magnet’s weight.

The blade is another key component of a wind turbine. It allows loads to withstand the continuously varying wind speeds. These loading conditions, in combination with the low gravitational forces required, lead to a selection of materials that combine high strength-to-weight with high stiffness and fatigue resistance. Glass-fibre composite layups are commonly used for blade fabrications, although carbon fibre might represent the next standard in wind turbine reinforcement. Today, it is estimated that about 17 % of total carbon fibre demand comes from the global wind power sector [CEMAC, 2016c]. Is is expected that the European wind power sector will account for the major share of total worldwide wind energy carbon fibre demand, i.e. about 65 % in 2020, due to its renewable energy targets and leadership in offshore wind sector [CEMAC, 2016c].

Wind energy is one of the most cost-effective technologies for climate-change mitigation and is a growing sector in the EU industrial base. Further penetration of wind technology in the EU and global markets is dependent on its techno-economic characteristics alongside regulatory frameworks and the effectiveness of energy policies. It will also be influenced by the stability of material supply and evolution of material prices.

This study addresses three rare-earth elements, namely neodymium, praseodymium and dysprosium, required in wind generators as well as carbon fibre composite (CFC) required for the manufacture of blades. The analysis focuses on identifying which of these materials might become a bottleneck to the widespread adoption of wind energy in the EU by 2030.

3.2 Materials for wind turbine generators

Three materials were investigated for wind turbine generators: Nd, Pr and Dy, required for the generator's permanent magnet.

The calculated values of the indicators for both dimensions are shown in a form of polar charts for 2015, 2020, 2025 and 2030.

Figure 8 and Figure 9 show the evolution of the upstream D1 indicators under the most conservative baseline (BL) and most optimistic scenario, respectively, for neodymium required in wind turbines for the period 2015-2030.

The evolution of D2 indicators for neodymium in wind turbines is shown in Figure 10 for the period 2015-2030.

Note: the D2 indicators are not affected by the assessment scenarios under consideration and therefore only one set of results is given for each material later in the report.

The evolution of EU resilience for neodymium in all assessment scenarios is shown in Figure 11. Similarly, Figure 12, Figure 13, Figure 16 and Figure 17 show the evolution of the upstream D1 indicators under the most conservative baseline (BL) and most optimistic scenario, respectively, for praseodymium and dysprosium required in wind turbines for the period 2015-2030. The evolution of D2 indicators for praseodymium and dysprosium in wind turbines is shown in Figure 14 and Figure 18 for the period 2015–2030.

The evolution of EU resilience for praseodymium and dysprosium for all assessment scenarios is shown in Figure 15 and Figure 19.

3.2.1 Neodymium

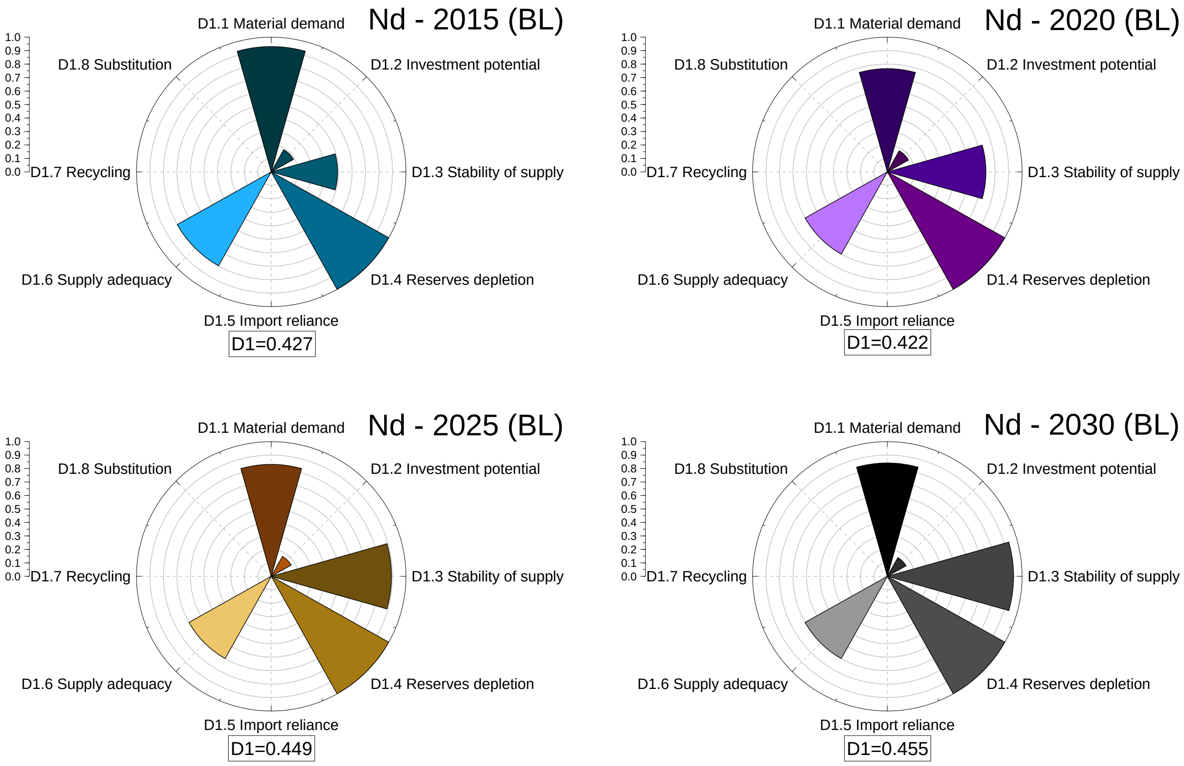


Figure 8: Evolution of D1 indicators according to the conservative baseline (BL) scenario for neodymium in wind turbines, 2015-2030

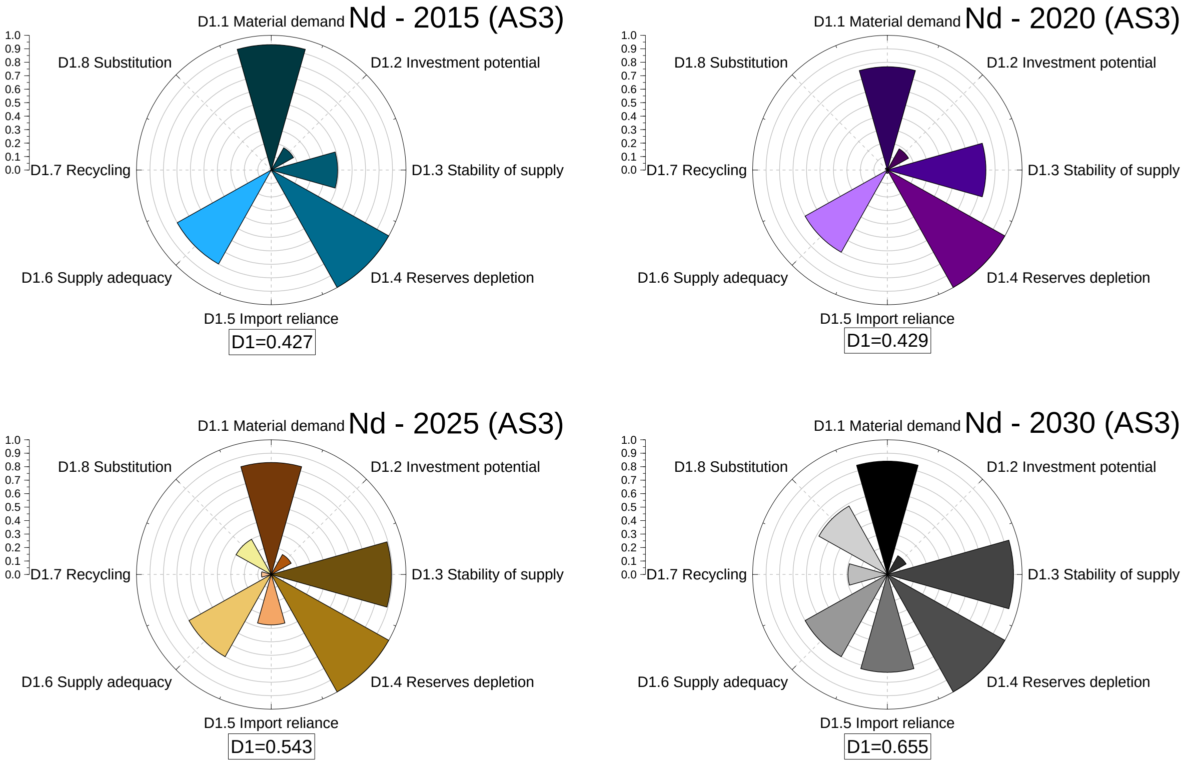


Figure 9: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for neodymium in wind turbines, 2015-2030

Figure 10: Evolution of D2 indicators for neodymium in wind turbines, 2015-2030

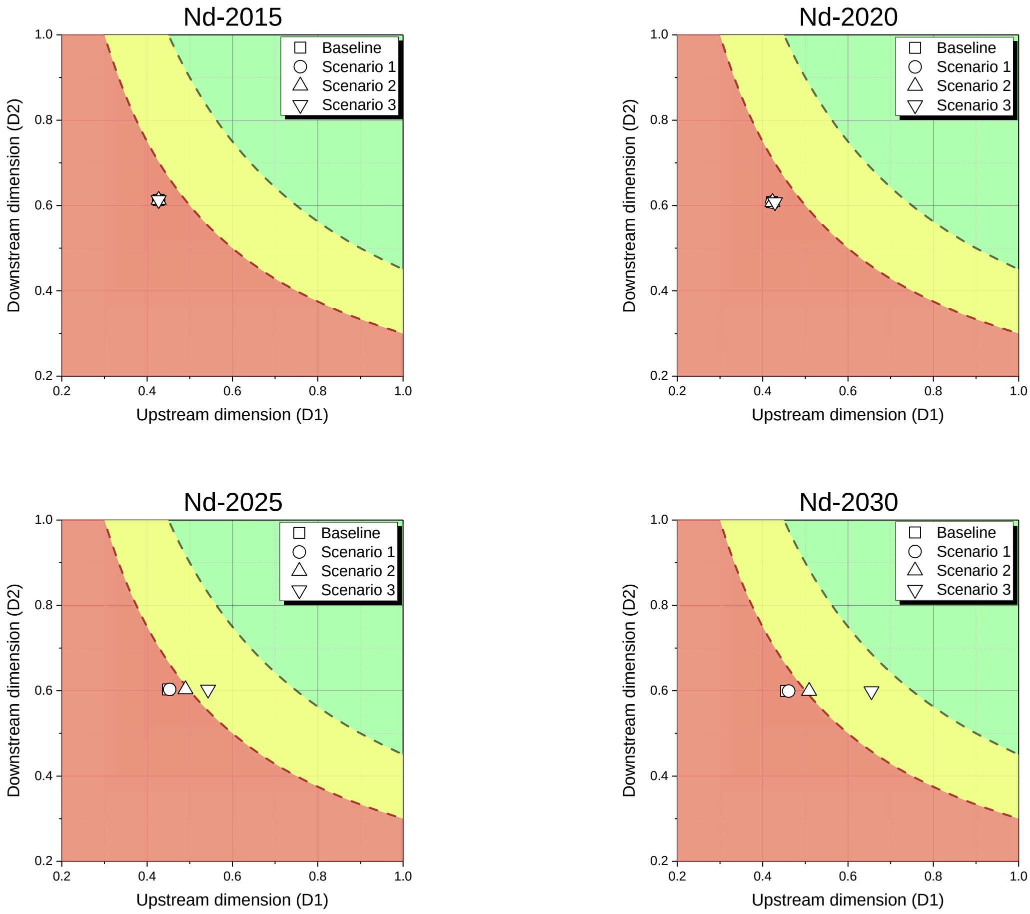


Figure 11: Evolution of resilience for neodymium in all scenarios, 2015-2030

3.2.2 Praseodymium

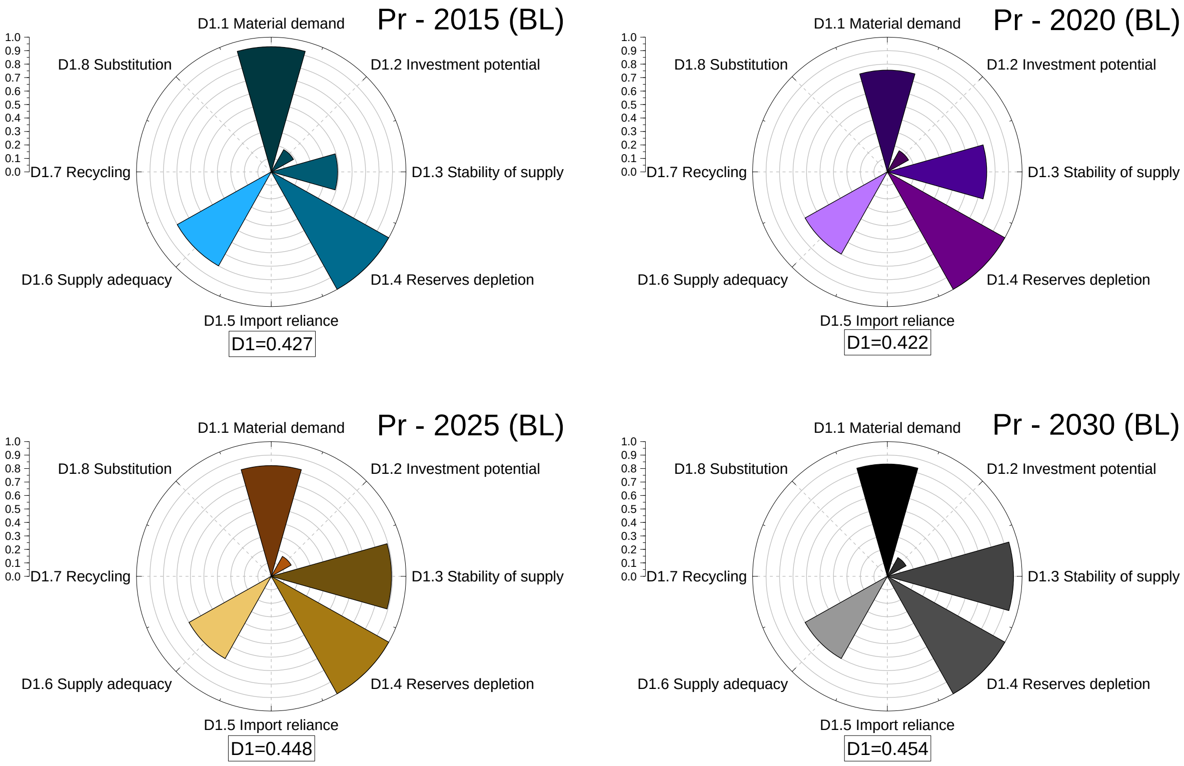


Figure 12: Evolution of D1 indicators according to conservative baseline (BL) scenario for praseodymium in wind turbines, 2015-2030

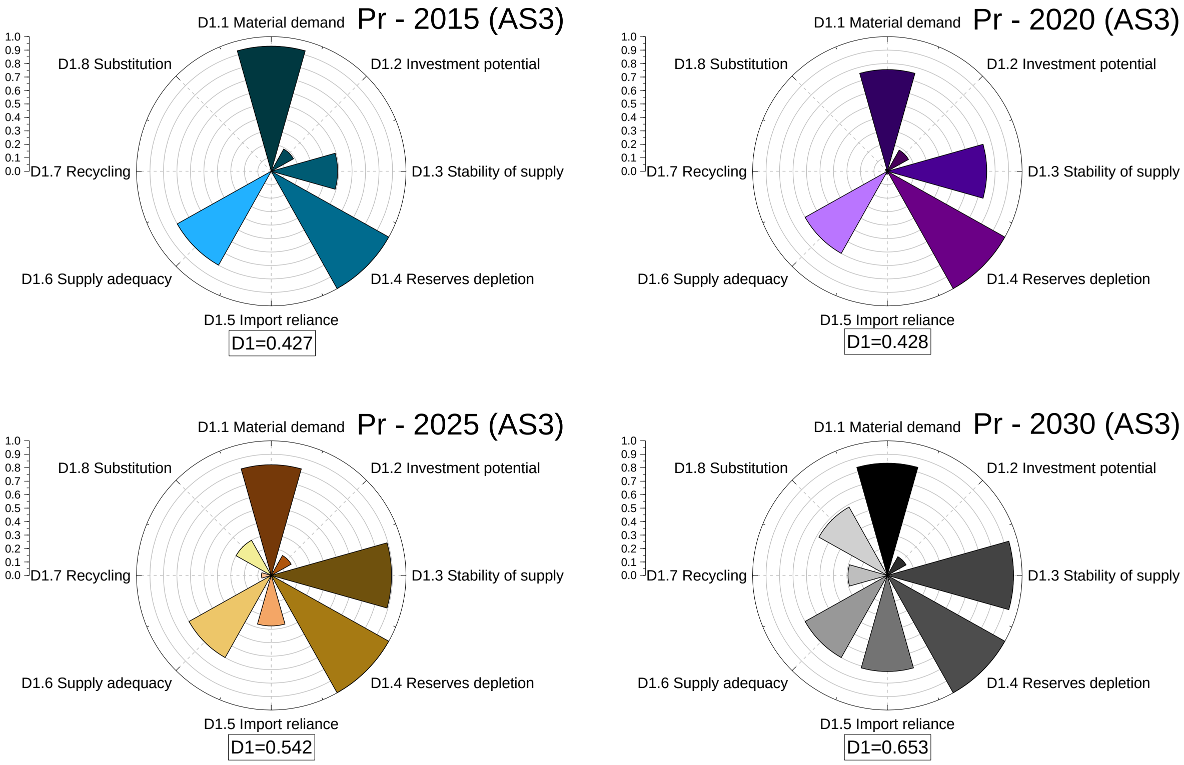


Figure 13: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for praseodymium in wind turbines, 2015-2030

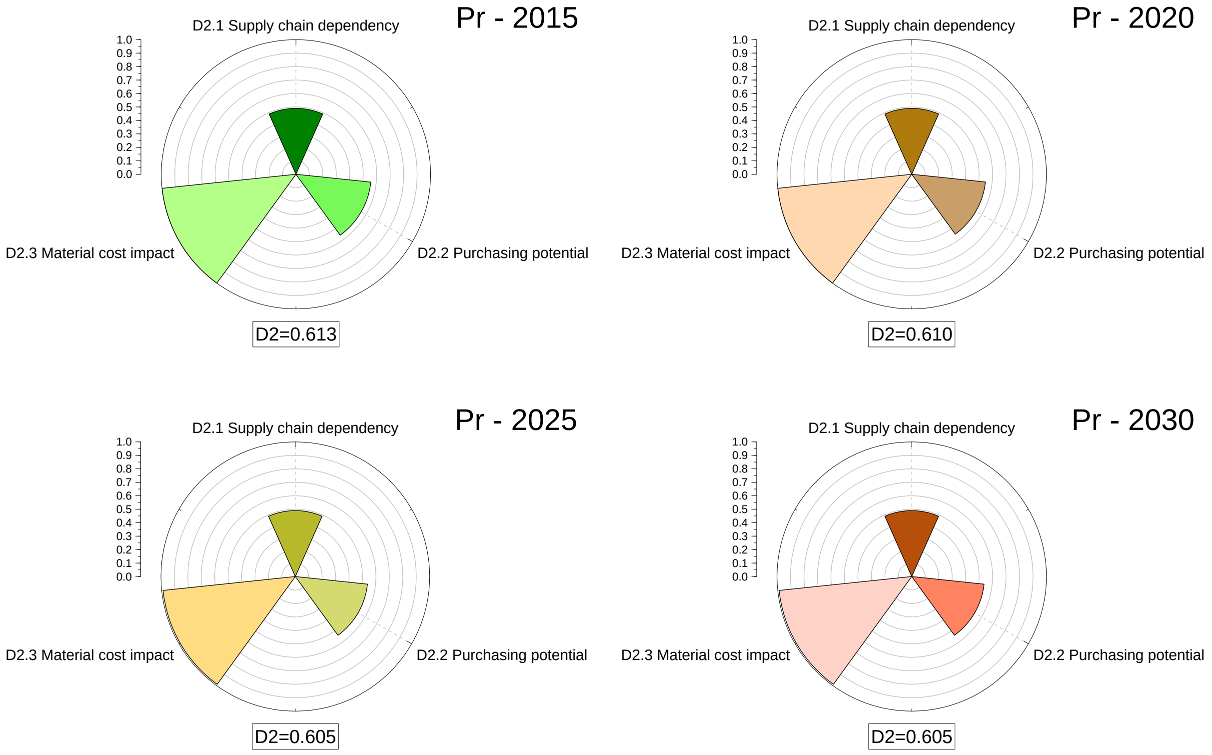


Figure 14: Evolution of D2 indicators for praseodymium in wind turbines, 2015-2030

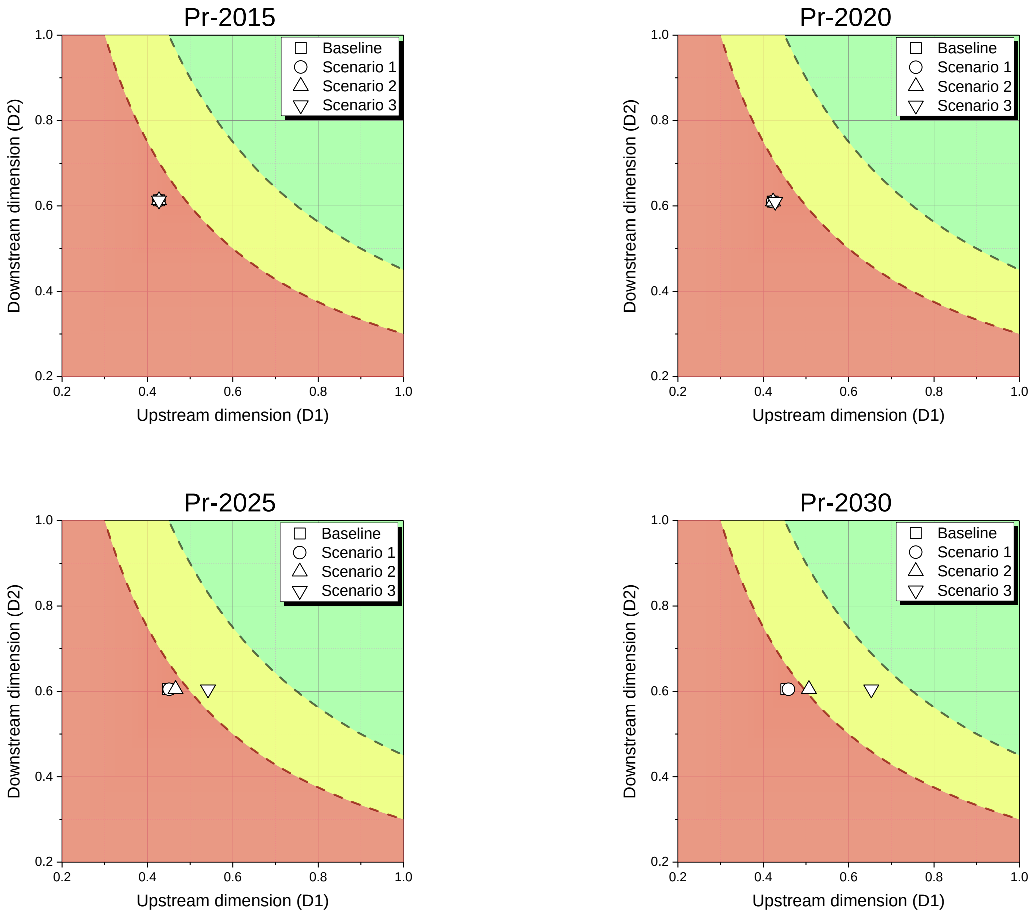


Figure 15: Evolution of resilience for praseodymium in all scenarios, 2015-2030

3.2.3 Dysprosium

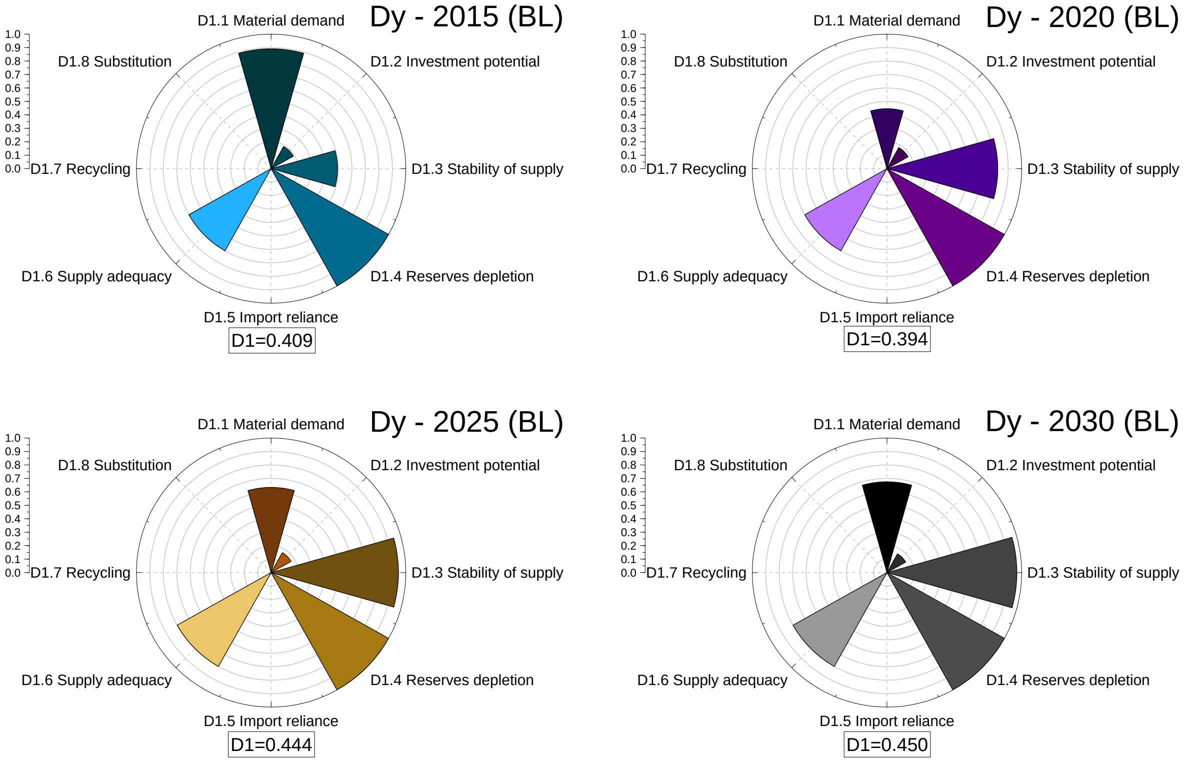


Figure 16: Evolution of D1 indicators according to the conservative baseline (BL) scenario for dysprosium in wind turbines, 2015-2030

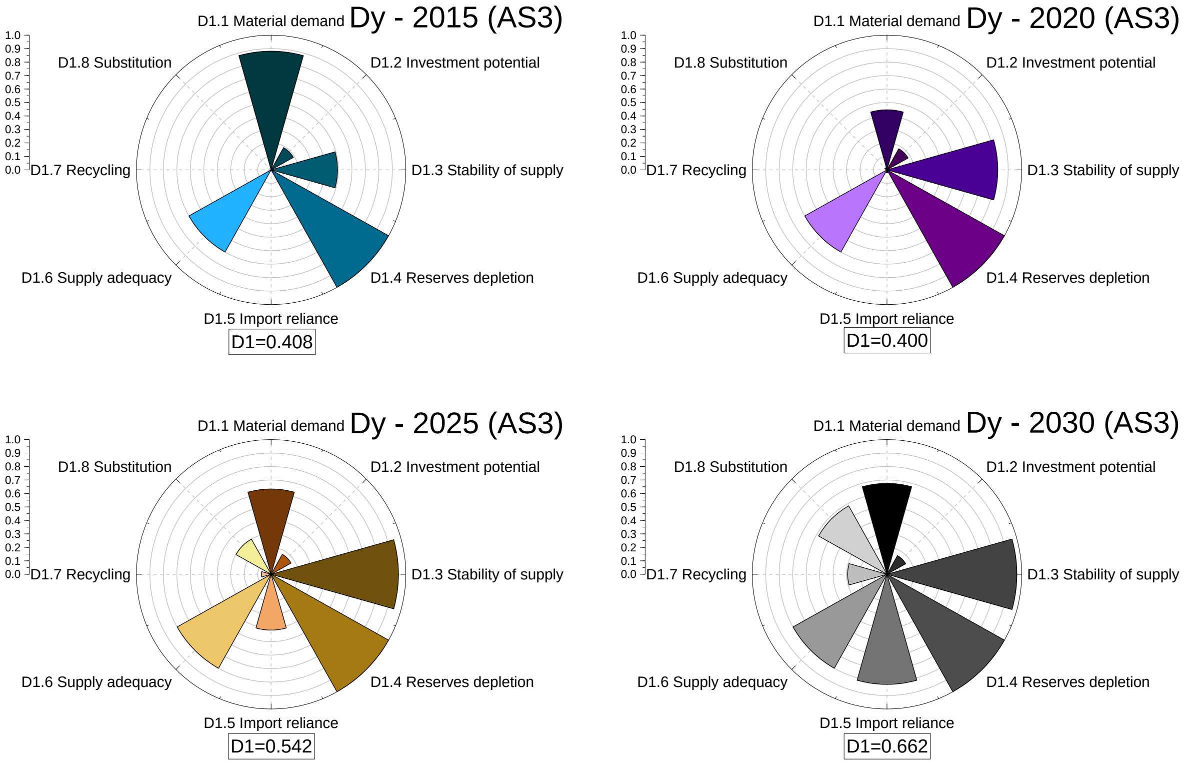


Figure 17: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for dysprosium in wind turbines, 2015-2030

Figure 18: Evolution of D2 indicators for dysprosium in wind turbines, 2015-2030

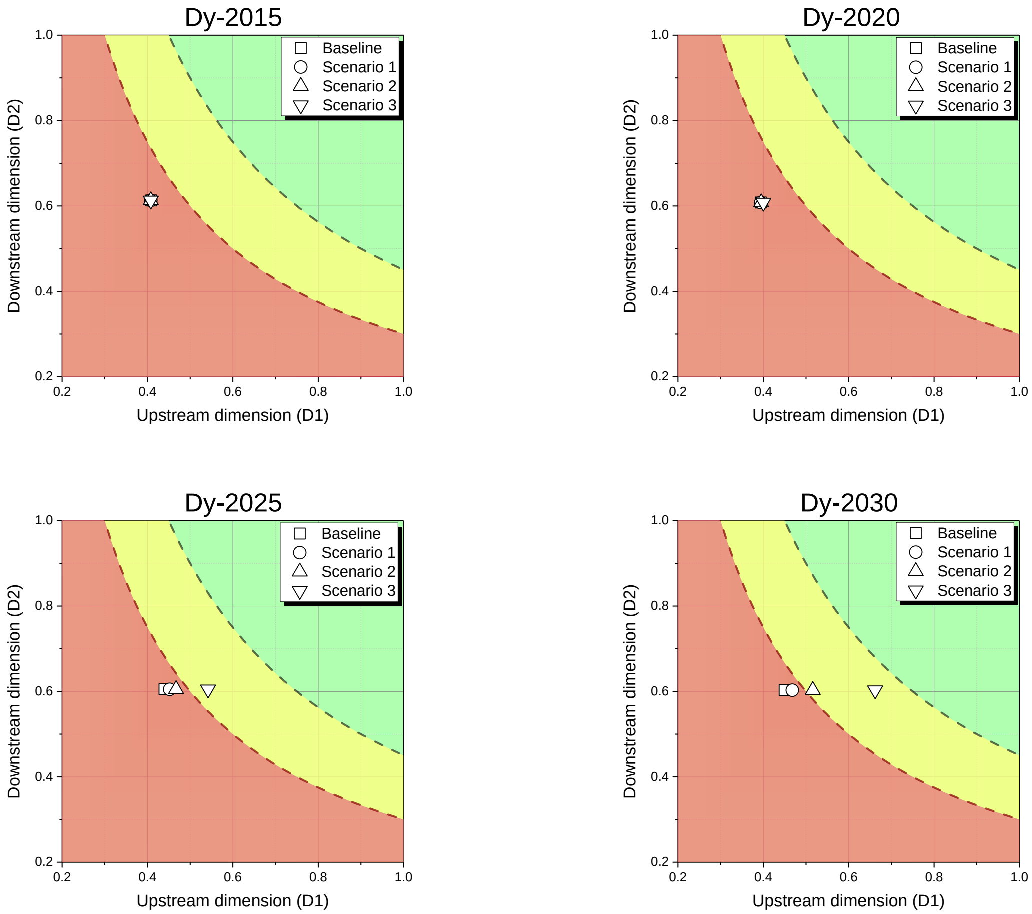


Figure 19: Evolution of resilience for dysprosium in all scenarios, 2015-2030

3.3 Materials for turbine blades

Currently, both glass and carbon fibre composites are used for blade manufacture. However, the latest tendency is to progressively switch to carbon fibre composites (CFC) which produce stiffer and lighter blades. Although more expensive than glass-fibre composites, the CFC allow for less-robust turbine and tower components, thereby reducing the cost of the turbine. In particular, the CFC blades are an important advantage for the next generation of offshore turbines.

CFC are already considered as an enabling technology by major EU turbine manufacturers such as Vestas (Denmark) and Gamesa (Spain). Therefore, only CFC have been assessed as the material which will be mostly applicable for blades until 2030.

CFC are assessed for only one scenario, as it is assumed that recycling and substitution are not applicable. In fact, so far turbine blades are not included in the recycling flows of wind turbine components. The recycling of blades is not yet technologically or economically feasible due to several factors, including the low maturity of potential recycling companies, a lack of legislative measures to stimulate and support the growth of this industry, uncertainties related to required upfront investments to build necessary facilities, and the market for after-recycling products.

However, in recent years, a number of solutions have been developed to recycle wind turbine blades. The potential uses for recycled blades range from heating and/or electricity production, use as a filling material, for cement production and pyrolysis [EWEA, 2015b]. One potential use can be the reuse of reworked blades which is judged economically viable but difficult to implement due to the different types of fibres, the purity of the materials and the small quantities.

As for the substitution of CFC in blades, as mentioned above, glass-fibre composites can be regarded as substitute material, but this is not likely to be the trend for the next decades.

For the time frame of this report, recycling and substitution of blades are not considered.

The evolution of D1 and D2 indicators for CFC required in wind turbine blades is shown in Figure 20 and Figure 21, respectively, for the period 2015-2030. The evolution of EU resilience for CFC is shown in Figure 22.

3.3.1 Carbon fibre composite (CFC)

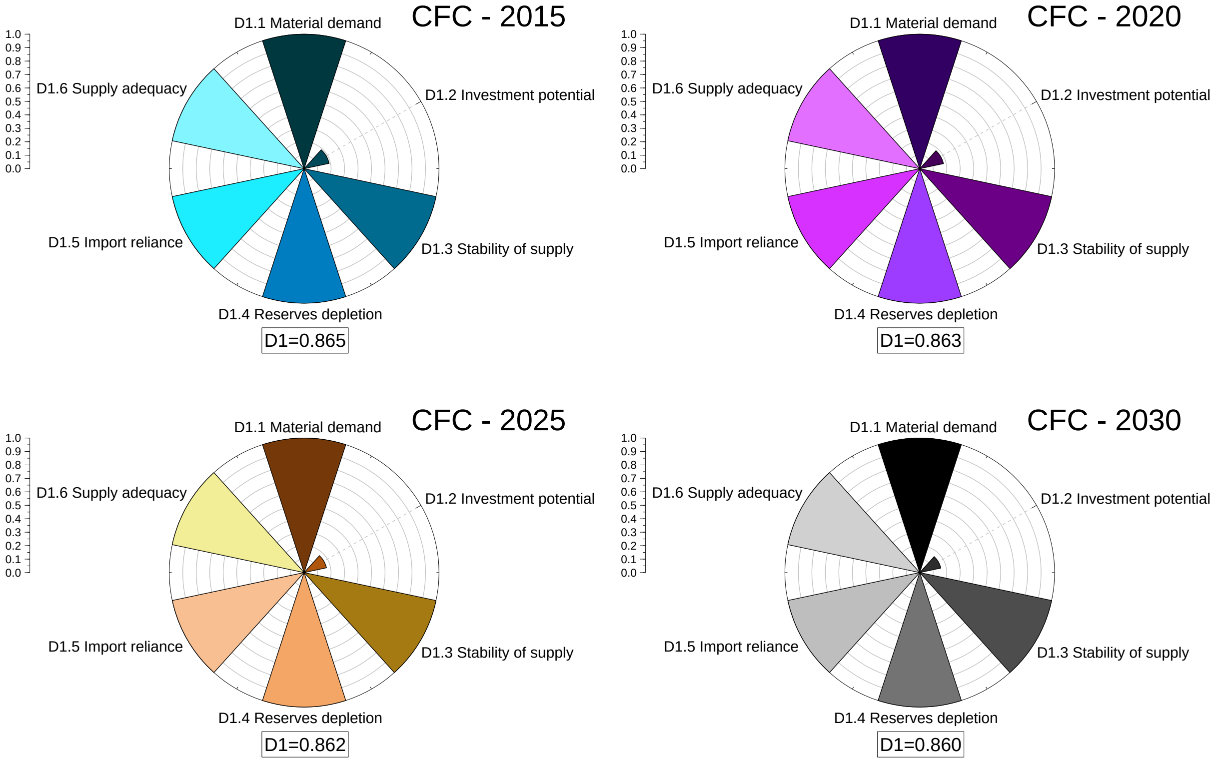


Figure 20: Evolution of D1 indicators for carbon fibre composite (CFC) in wind turbines, 2015-2030

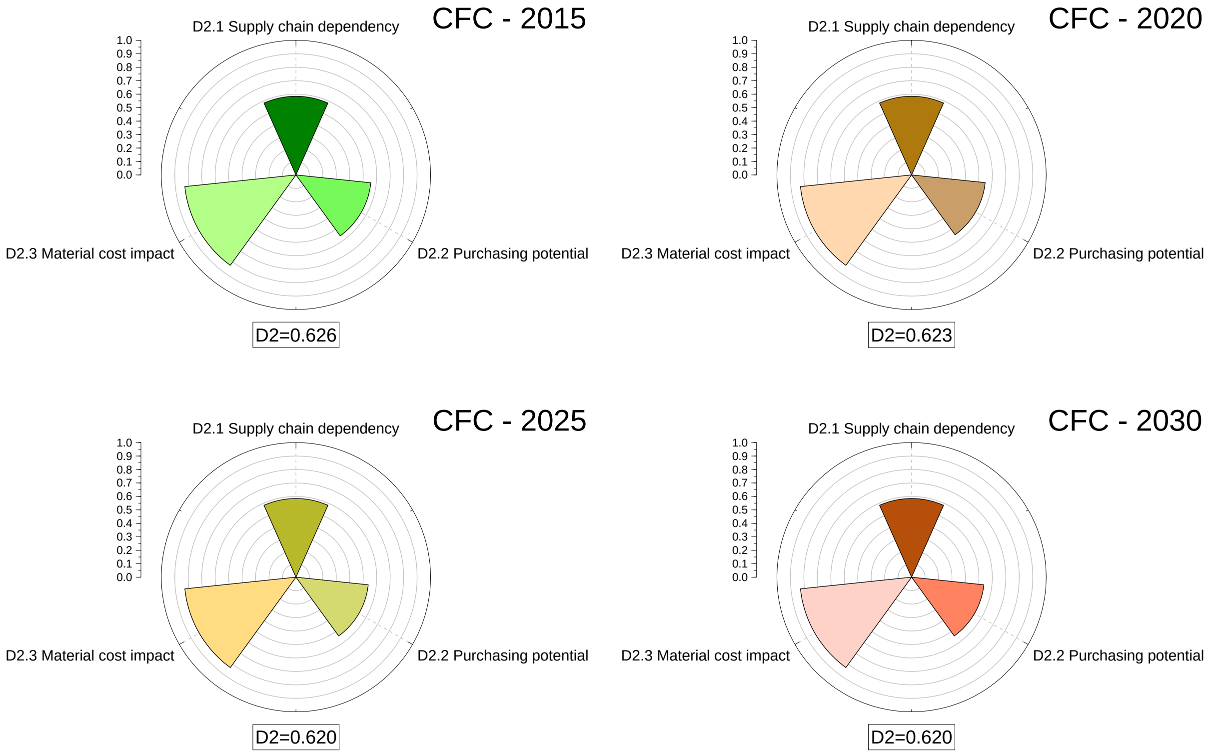


Figure 21: Evolution of D2 indicators for carbon fibre composite (CFC) in wind turbines

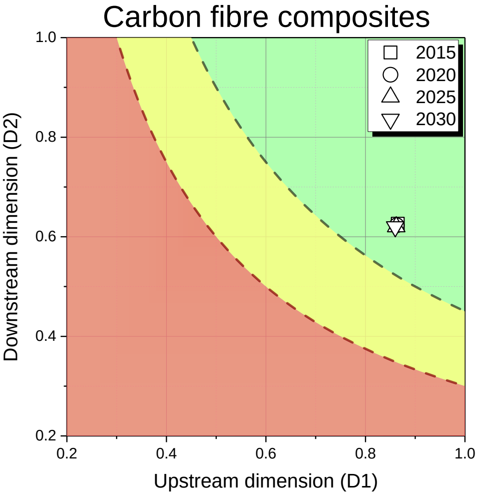


Figure 22: Evolution of resilience for carbon fibre composites from 2015 to 2030

3.4 Wind technology resilience charts

The resilience charts of all materials required in wind turbines in 2015, 2020, 2015 and 2030 for baseline and scenario 3 are presented in Figure 23 and Figure 24 below.

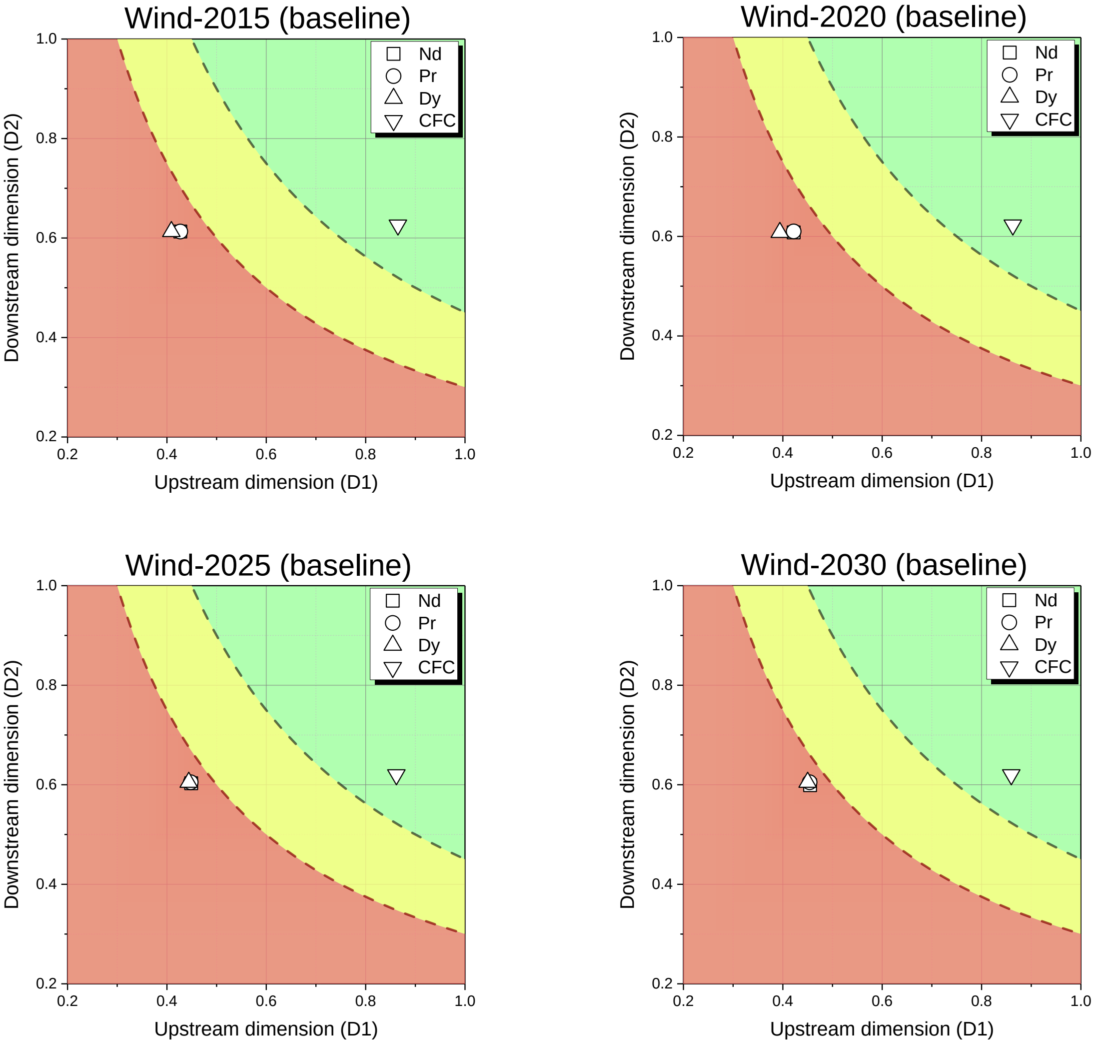


Figure 23: Resilience charts of materials required in wind turbines in 2015, 2020, 2025 and 2030 for conservative baseline scenario

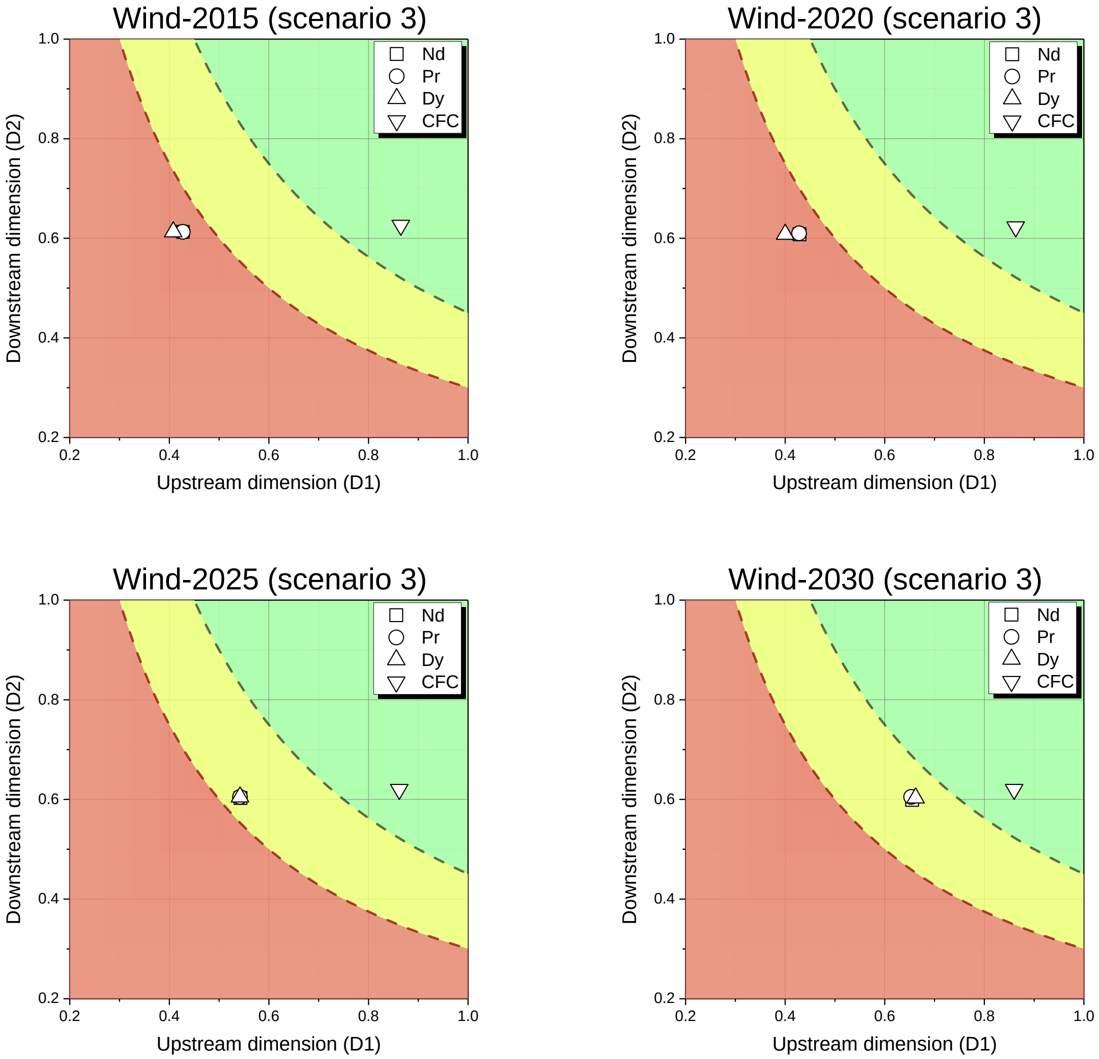


Figure 24: Resilience charts of materials used in wind turbines in 2015, 2020, 2025 and 2030 for the most optimistic assessment scenario 3

Note: Since mitigation measures are not considered, CFC is only assessed under the baseline scenario. Its resilience under scenarios 1 to 3 is assumed to match its resilience under the baseline scenario.

As regards the wind energy sector, EU resilience to bottlenecks in the supply of neodymium, praseodymium and dysprosium used in turbine generators is currently low (2015 data). As for carbon fibre composite (CFC), used in turbine blades, there are no specific concerns about the supply of this material, which has been rated with a high resilience score (Figure 25).

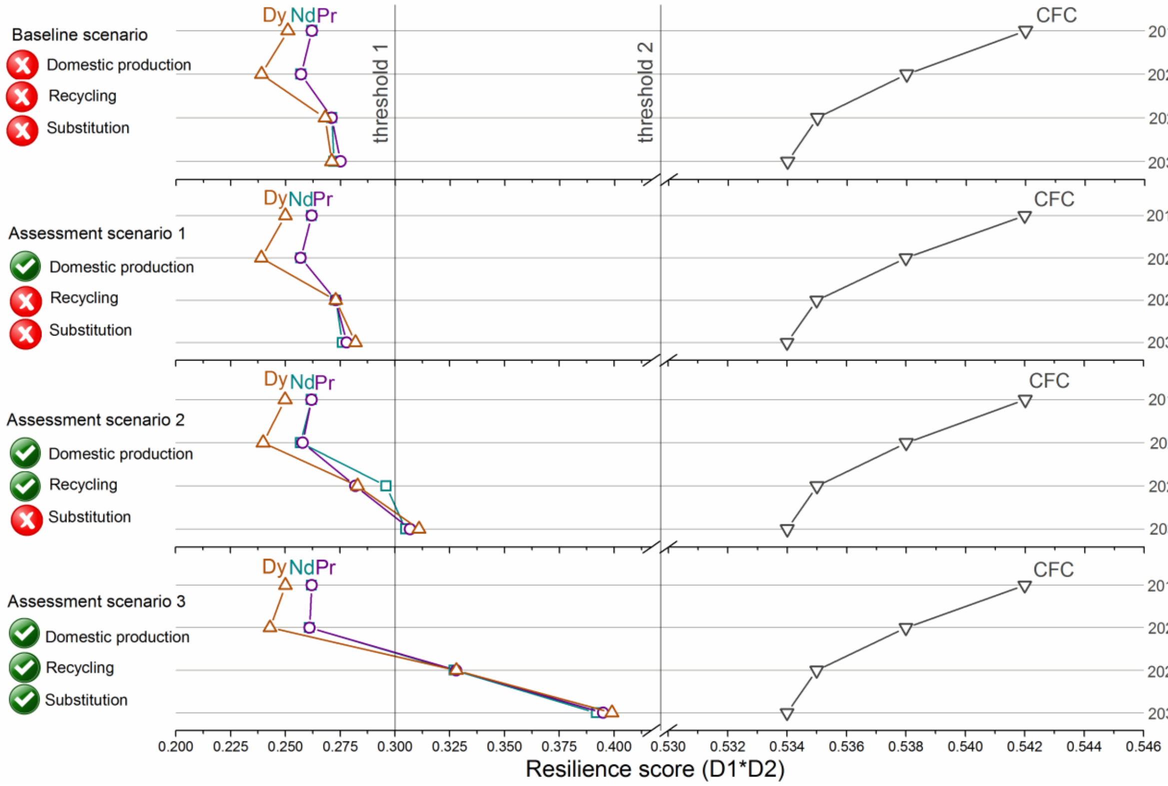


Figure 25: Variation in EU resilience to supply bottlenecks of materials used in the wind power sector; thresholds 1 and 2 (at 0.3 and 0.45) represent the borders between low-medium resilience, and medium-high resilience, respectively

Neodymium, praseodymium, dysprosium

The EU resilience for these three materials remains low for all scenarios until 2020: slightly decreasing for Nd and Pr (between -0.3 % and -1.8 %) and Dy (between -3 % and -4.6 %), depending on the assessment scenario.

During the 2020-2025 period, a substantial increase in resilience is observed for all materials:

- For the baseline scenario: +5.5 %, +5.4 % and +12.2 % for Nd, Pr and Dy, respectively, thanks to improved diversification of supply;
- For scenario 1: +6.3 % for Nd, +6.1 % for Pr and +14.2 % for Dy for the above-mentioned materials, due to a potential increase in EU mine production, thereby reducing reliance on imports, plus a diversified supply;
- For scenario 2: +15 % for Nd, +9.3 % for Pr and +17 % for Dy, thanks to additional recycling;
- For scenario 3: +26 % for Nd, +26 % for Pr and +35 % for Dy is observed, based on a substitution potential of around 60 %.

Nd, Pr and Dy cross the low resilience threshold curve in 2025, entering the medium-resilience zone for scenario 3, when substitution is taken into account.

In the last five-year period (2025-2030), the EU resilience increases further for all materials and all scenarios. A marginal increase of up to +1.3 % is achieved for all materials in the baseline scenario, as a result of new suppliers coming on to the market. A slight increase – between +1.1 % (Nd) and +3.1 % (Dy) – is observed for scenario 1 because of the potential development of additional mine capacities in the EU. Further increases of +3.2 % (Nd), +8.7 % (Pr) and +10 % (Dy) are evident in scenario 2 when recycling is increased to up to 30 %. The greatest increments of +20 % (Nd), +20 % (Pr) and +22 % (Dy) could be achieved for scenario 3, which assumes that around 60 % of these materials will be replaced.

In 2030, all three materials cross the low resilience threshold curve, entering the medium-resilience zone for scenarios 2 and 3. Even if all the mitigation measures considered are in place, the resilience to supply bottlenecks of these three materials will not reach the high-resilience zone in 2030.

To summarise, the resilience situation regarding the supply of Nd, Pr and Dy seems to improve until 2030, thanks to the potential diversification of supply sources and greater EU mine production. If a high degree of substitution and significant recycling rates are achieved, the EU resilience can be increased to the medium level. Substitution and recycling seem to be the most effective measures to enhance the EU resilience to supply of Nd, Pr and Dy.

Carbon fibre composite (CFC)

Although a slight decline of 2 % in the resilience to the supply of CFC is observed between 2015 and 2030, it remains in the high-resilience zone over the same period. No specific supply issues are expected for CFC used for manufacturing of blades within the time frame under consideration.

4 Determination of material supply bottlenecks in the solar PV sector

4.1 Market and PV technology background

This study addresses photovoltaic technology and its principal constituent materials. It does not cover concentrated solar power systems.

A wide adoption of photovoltaic energy technology, which provides for the direct conversion of solar energy into electricity, represents a viable path to generating clean energy. For years, the high cost of photovoltaic power represented a significant shortfall in this technology. However, a combination of technology innovation, economies of scale and manufacturing experience led to an exponential decline in the cost of crystalline silicon PV modules from USD 72/W in 1976 to USD 0.6/W in 2015 (a learning rate of 26.5 %) [BNEF, 2016b]. It is estimated that the competitiveness of photovoltaic technology will continue to improve due to falling costs and an increase in efficiency, driving a 60 % reduction in cost by 2040 [BNEF, 2016b].

Photovoltaic energy has gained significant relevance in power systems around the globe, increasing from about 1 GW of cumulative installed capacity in 2000, to 39 GW in 2010 and 229 GW in 2015 [IEA, 2015; SPE, 2016]. The EU has been at the forefront of the PV market, accounting for more than 75 % of newly installed capacity in 2010. At the end of 2015, Europe still held the major global share with its 97 GW total capacity [SPE, 2016]. In 2015, 50.6 GW solar PV were installed and commissioned worldwide, of which 8.2 GW were in Europe [SPE, 2016]. After several years of decline, the solar PV sector in Europe registered a 15 % market growth in 2015. There are indications that the EU will return to a constant growth path as of 2017, driven by support schemes, cheaper solar panels and increased competitiveness. As a result, the EU reference scenario indicates a rise in the total PV capacity in Europe, reaching 137.5 GW in 2020, 183 GW in 2030 and 299 GW in 2050 [EC, 2016a]. According to SolarPower Europe, the European PV power market could grow in the short term (2020) by over 75 % to 170.9 GW under a high scenario or by 33 % in a low scenario, resulting in 129.6 GW of cumulative solar power [SPE, 2016]. In terms of electricity generated, solar PV supplies 4 % of the electricity demand in the EU [SPE, 2016]. This share is expected to increase to 4.8 % in 2020, 7 % in 2030 and up to 11 % in 2050 [EC, 2016].

Commercial PV technologies include wafer-based crystalline silicon (c-Si) (either mono-crystalline or multi-crystalline silicon) and thin-film (TF) using amorphous silicon (a-Si), copper-indium-gallium-diselenide-disulphide (CIGS) and cadmium-telluride [IRENA, 2013]. The global production of solar PV accounted for 63.2 GWp in 2015, of which 93.4 % was c-Si, the rest being TF (Figure 26) [ISE, 2016].

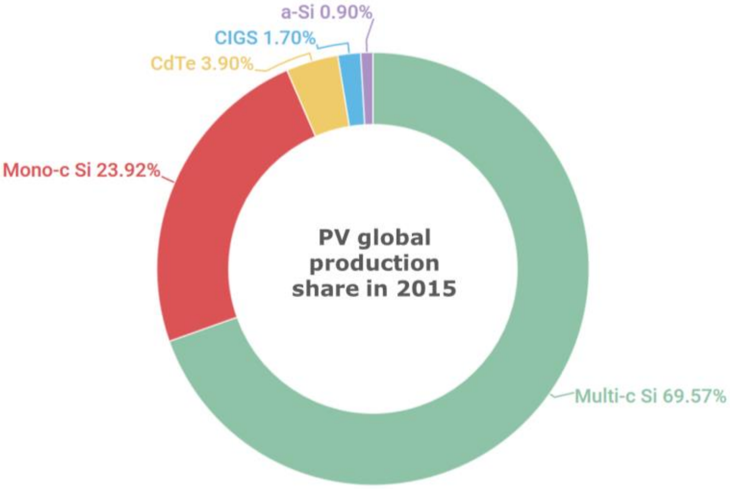


Figure 26: Global share of PV production by technology in 2015 [ISE, 2016]

In addition to the commercial technologies, a vast array of new PV technologies is currently being developed, e.g. multi-junction cells or hybrid devices at the nanoscale level. These new concepts show potential as regards significant increases in efficiency and/or reductions in cost through improvements in device architecture and material functionality. Due to the uncertainty around the market adoption of these new concepts, the present study will be limited to the current commercially available technologies, such as crystalline silicon (poly-/multi- and mono-crystalline Si) and thin-film technologies (i.e. a-Si, CIGS and CdTe). An overview of the commercial PV technologies, their performance and materials addressed in this study is presented in Table 1.

Table 1: Principal characteristics of commercial PV technologies addressed in this study. Data from [IRENA, 2013] and [ISE, 2016]

PV technology	Efficiency (%)		Area/kW (m^2/kW)$^{(1)}$	Lifetime (year)	Main characteristics	Materials analysed in this study
	Record cell lab	Module				
			Crystalline silicon			
Poly-c Si	20.8	12-18	8	25-30	- high maturity and efficiency - low cost - long lifetime	Silicon and silver
Mono-c Si	25.6	15-22	7	25-30		
			Thin-film			
a-Si	14	7-12	15	25	- mature technology - low cost and low efficiency	Silicon
CIGS	20.5	8-14	10	25	- good electronic-optical properties - challenging scale-up production	Indium, copper, selenium and tellurium
CdTe	21	10-15	10	25	- low-cost manufacturing - moderate efficiency	Cadmium and tellurium

Note: (1) a module efficiency of 10 % corresponds to about $100 W/m^2$

Manufacturers have struggled to improve the efficiency of PV modules while, at the same time, reducing costs and material use. The higher efficiency attained by photovoltaic cells in the laboratory indicates the potential to increase efficiency in future commercial technologies, too. In the past (2007-2008), the rapid growth of the PV industry led to an increase in the cost of purified silicon, and thus more expensive PV modules. Projected high growth rates in the PV industry and market dynamics forced manufacturers to explore the reduction of silicon and other materials in the production process. As a result, since 2006, the average use of silicon in solar cells has fallen by around 30 % to about 5.5 g/Wp for multi-crystalline and 4.8 g/Wp for mono-crystalline in 2014 [JRC, 2014]. The target is to reach 3 g Si/Wp or less between 2030 and 2050 [IRENA, 2013].

Silicon metal and indium are critical raw materials for the EU economy [EC, 2014]. Other materials such as copper, gallium, cadmium, selenium, silver and tellurium have different criticality ratings according to the latest JRC study [JRC, 2013]. The potential supply constraints for these eight materials along their value chain are evaluated in the light of the large deployment scenarios for PV technology by 2030 in the EU.

4.2 Materials in crystalline silicon technology

Two materials were investigated for c-Si PV technology: silicon (Si) and silver (Ag).

The calculated values of the indicators for both dimensions are shown in a form of polar charts for 2015, 2020, 2025 and 2030.

Figure 27 and Figure 28 show the evolution of the upstream D1 indicators under the most conservative baseline (BL) and most optimistic scenario, respectively, for silicon required in c-Si modules for the period 2015-2030.

The evolution of D2 indicators for silicon in c-Si PV is shown in Figure 29 for the period 2015-2030.

The evolution of the EU resilience for silicon for all assessment scenarios is shown in Figure 30.

Similarly, Figure 31 and Figure 32 show the evolution of the upstream D1 indicators under the most conservative baseline (BL) and most optimistic scenario, respectively, for silver required in c-Si modules for the period 2015-2030.

The evolution of D2 indicators for silver in c-Si PV is shown in Figure 33 for the period 2015-2030.

The evolution of the EU's resilience for silver in all the assessment scenarios is shown in Figure 34.

4.2.1 Silicon

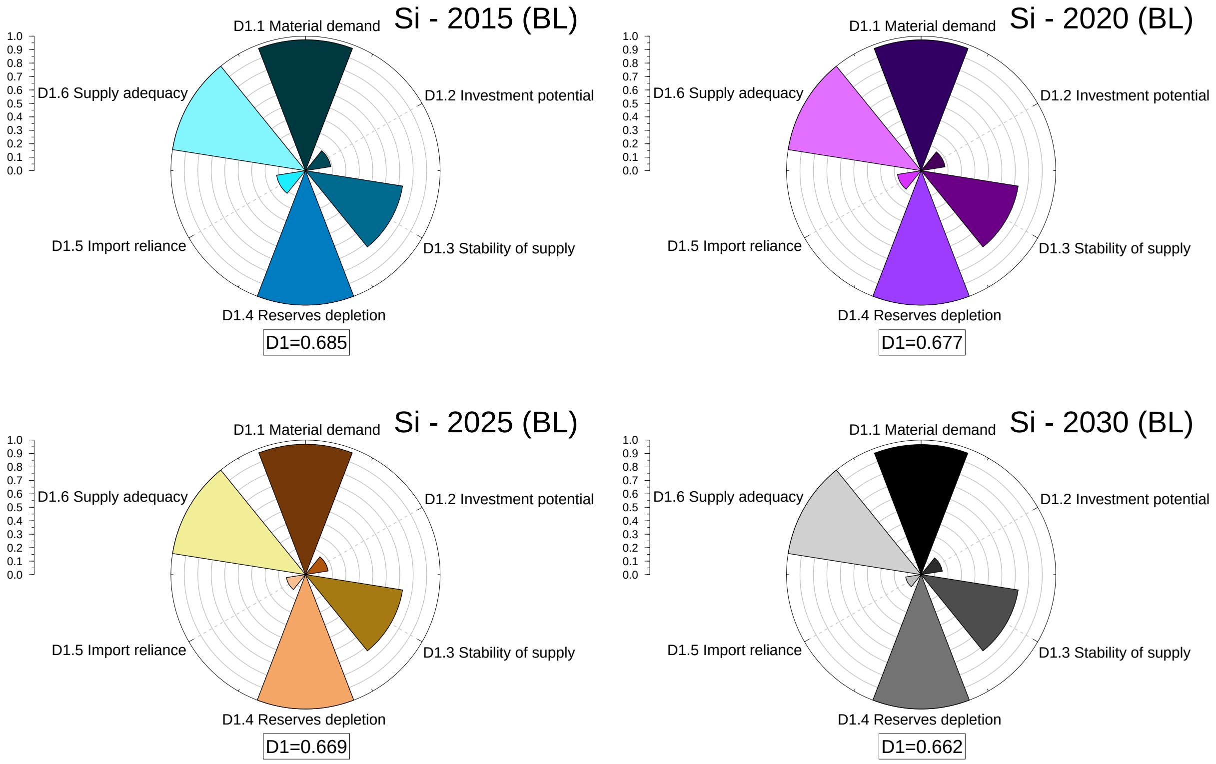


Figure 27: Evolution of D1 indicators according to the conservative baseline (BL) scenario for silicon in c-Si, 2015-2030

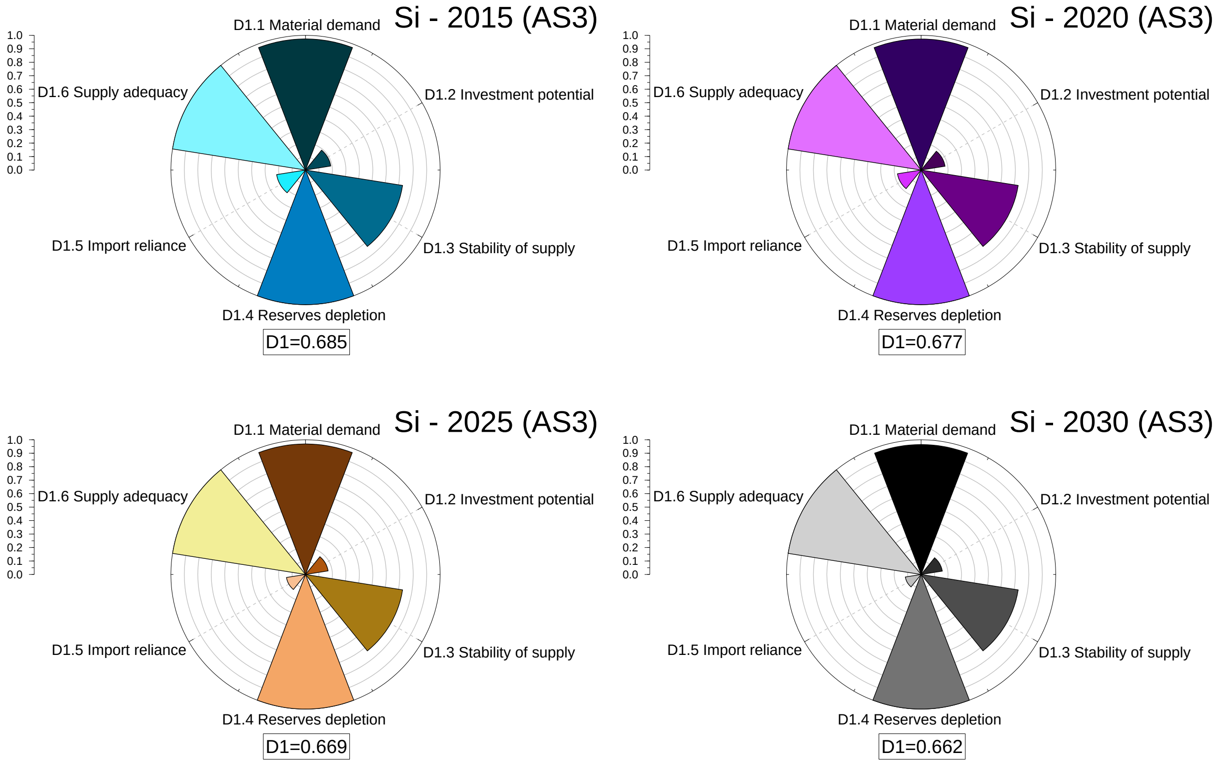


Figure 28: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for silicon in c-Si, 2015-2030

Figure 29: Evolution of D2 indicators for silicon in c-Si, 2015-2030

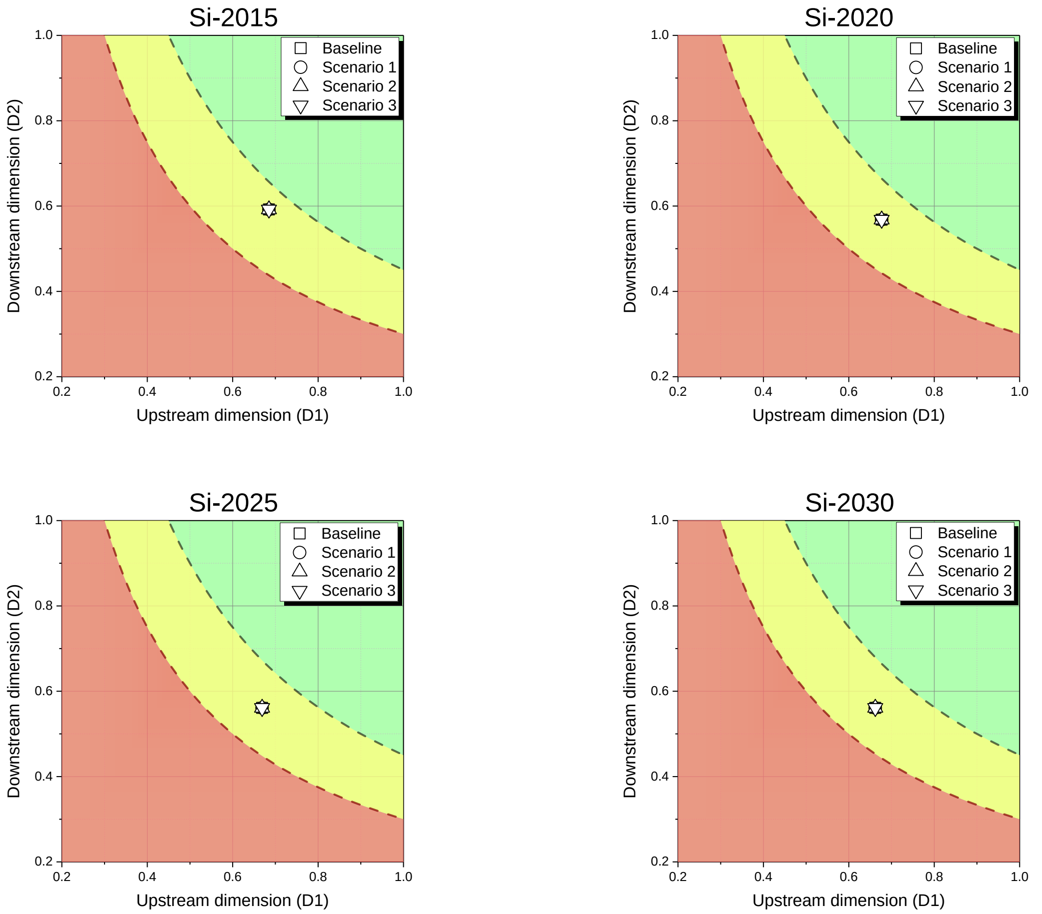


Figure 30: Evolution of resilience for silicon in c-Si for all scenarios, 2015-2030

4.2.2 Silver

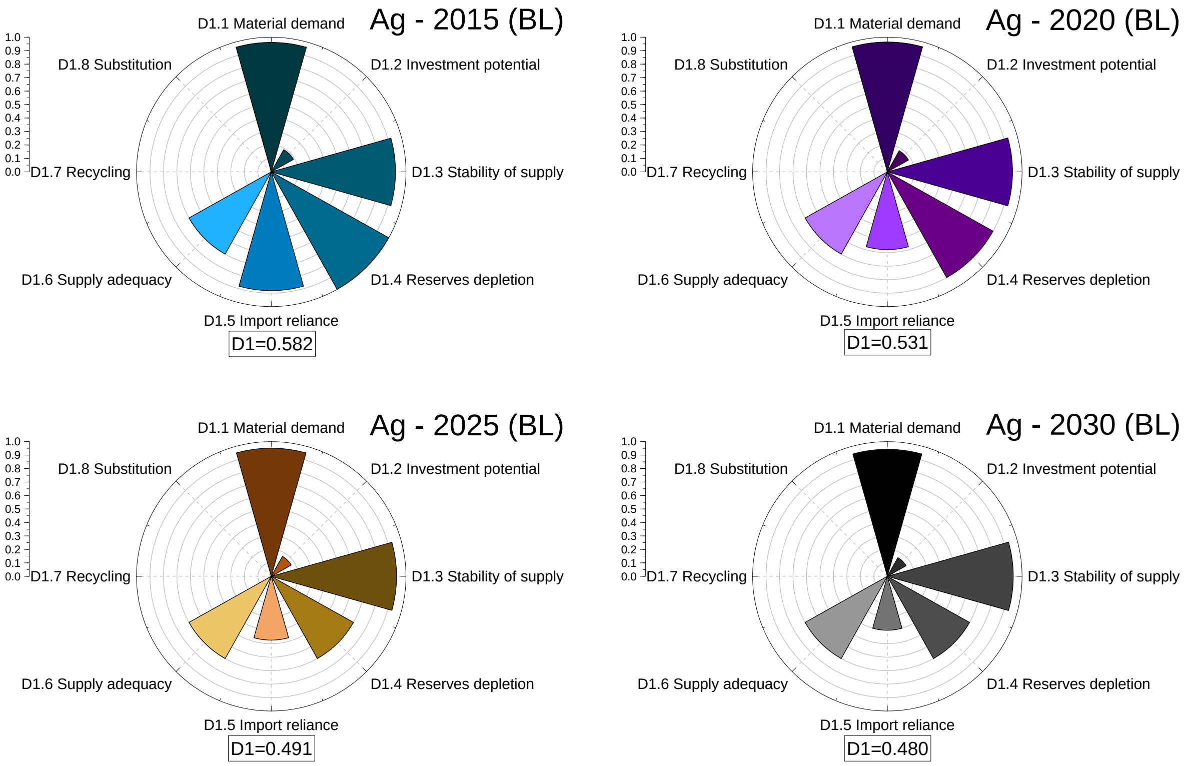


Figure 31: Evolution of D1 indicators according to the conservative baseline (BL) scenario for silver in c-Si, 2015-2030

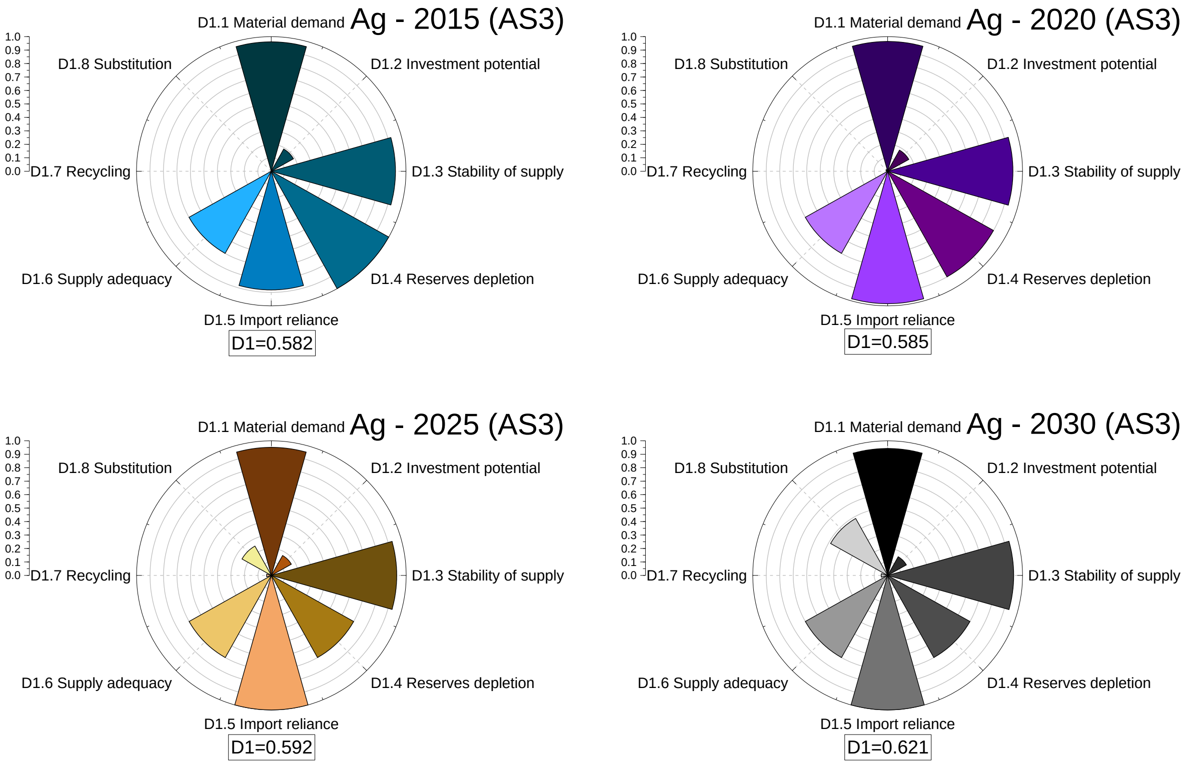


Figure 32: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for silver in c-Si, 2015-2030

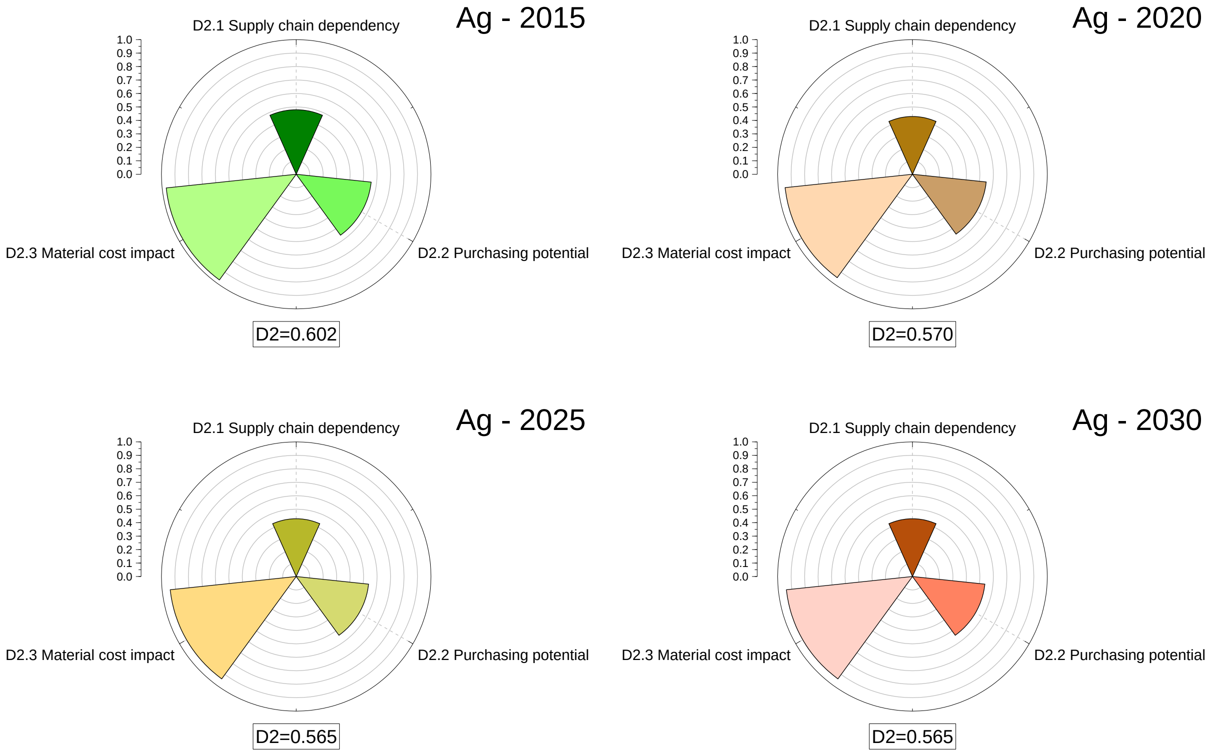


Figure 33: Evolution of D2 indicators for silver in c-Si, 2015-2030

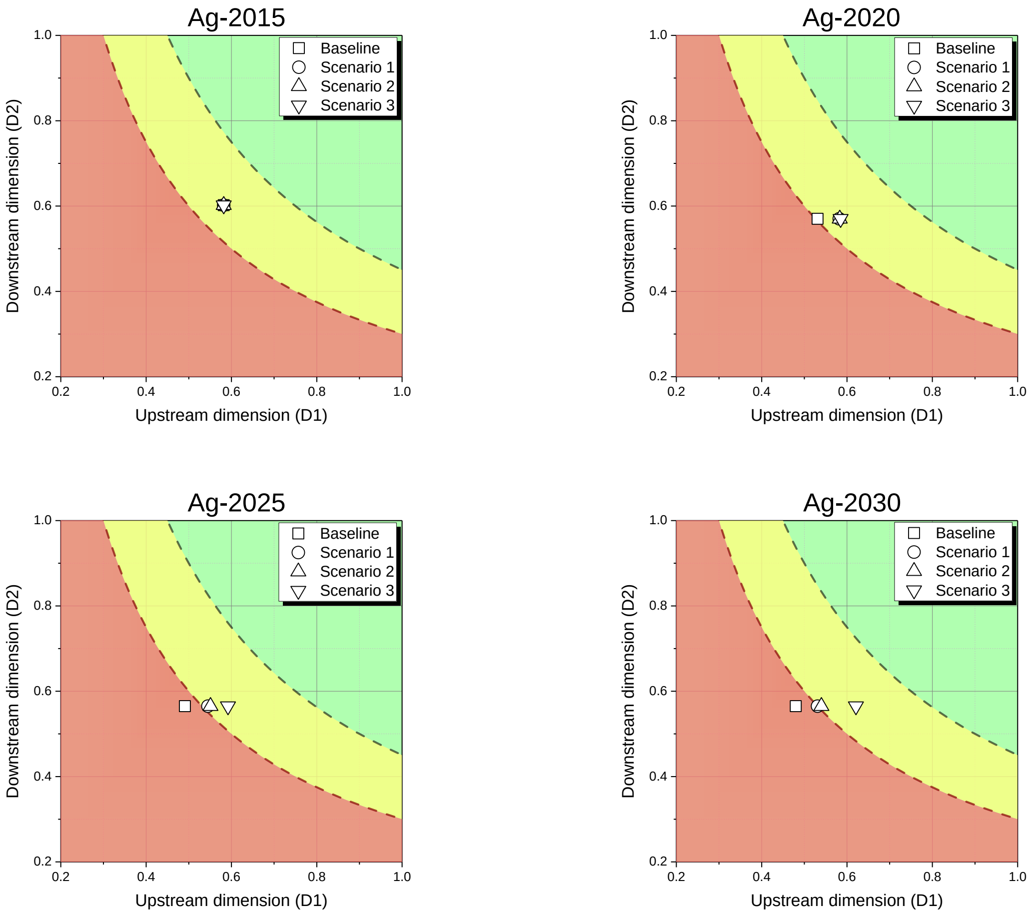


Figure 34: Evolution of resilience for silver in c-Si for all scenarios, 2015-2030

4.3 Materials in thin-film amorphous silicon technology

4.3.1 Silicon

The amount of Si needed for amorphous Si thin-film PV is negligible when compared to polycrystalline and monocrystalline silicon PV. Only 33 tonnes of Si were required for amorphous Si thin-film due to the very low deployment rate versus 31 555 tonnes required for poly- and monocrystalline silicon PV together. Since amorphous Si thin-film PV is not expected to increase its share until 2030, no further evaluation has been done for this particular PV technology.

4.4 Materials in thin-film CIGS technology

Four materials were investigated for c-Si PV technology: indium (In), copper (Cu), gallium (Ga) and selenium (Se).

According to the methodology, if the demand for a particular material is less than 1 % of the global supply in the considered time frame, this material is not deemed to be a potential bottleneck material and thus has not been evaluated further. From the four screened materials, only indium passed the significance screening – showing >1 % of the global supply of indium. Since the demand for the other three materials is <1 %, no further evaluation has been done.

Copper, gallium and selenium are not seen as potential bottleneck materials for the deployment of CIGS PV technology in the EU until 2030. More details are given later in this section.

It should be noted that only the indium content of the CIGS absorber layer has been estimated. Indium is also used as a transparent conductive oxide (TCO) coating but the amount is minor and therefore not considered in the estimation of demand for indium in solar thin-film cells. In addition, substitution alternatives for indium tin oxide (ITO) already exist for this application and their use in the next generation thin-film solar cell is foreseen.

The calculated values of the indicators for both dimensions for indium are represented in the polar charts for 2015, 2020, 2025 and 2030.

Figure 35 and Figure 36 show the evolution of the upstream D1 indicators under the most conservative baseline (BL) and the most optimistic scenario, respectively, for indium required in CIGS modules for the period 2015-2030.

The evolution of D2 indicators for indium in CIGS PV is shown in Figure 37 for the period 2015-2030.

The evolution of EU resilience for indium for all assessment scenarios is shown in Figure 38.

4.4.1 Indium

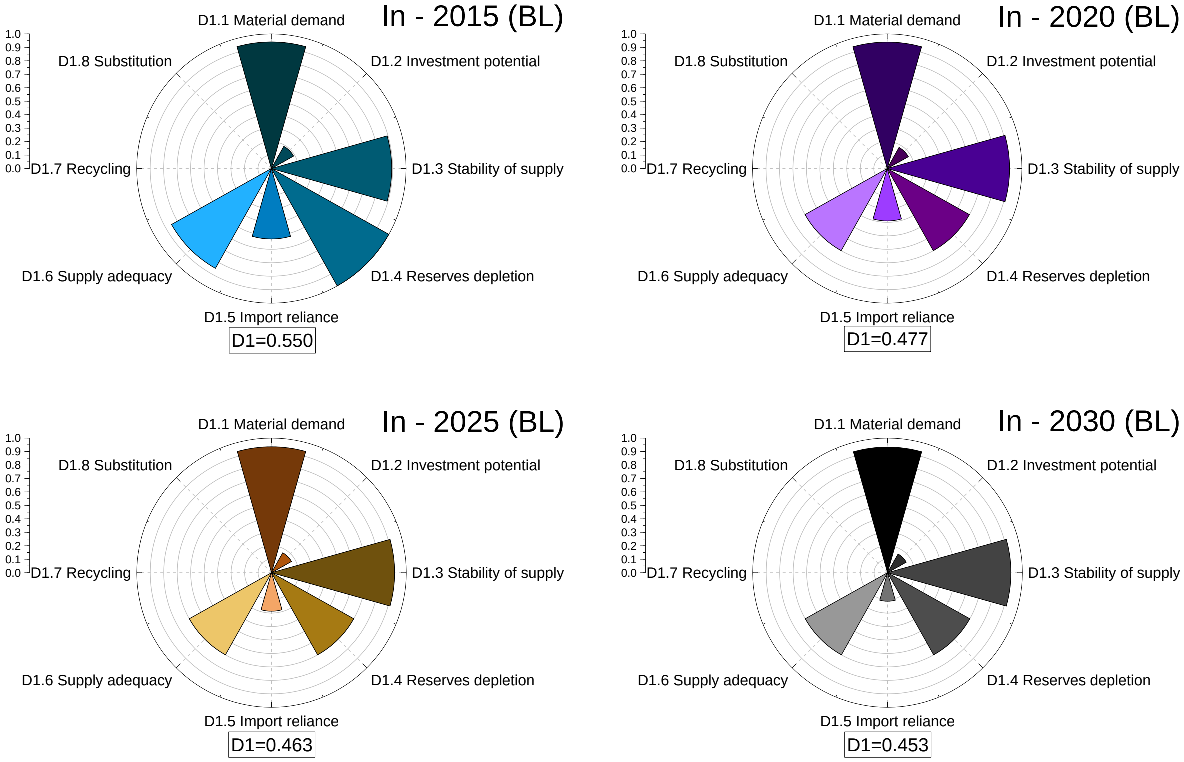


Figure 35: Evolution of D1 indicators according to the conservative baseline (BL) scenario for indium in CIGS, 2015-2030

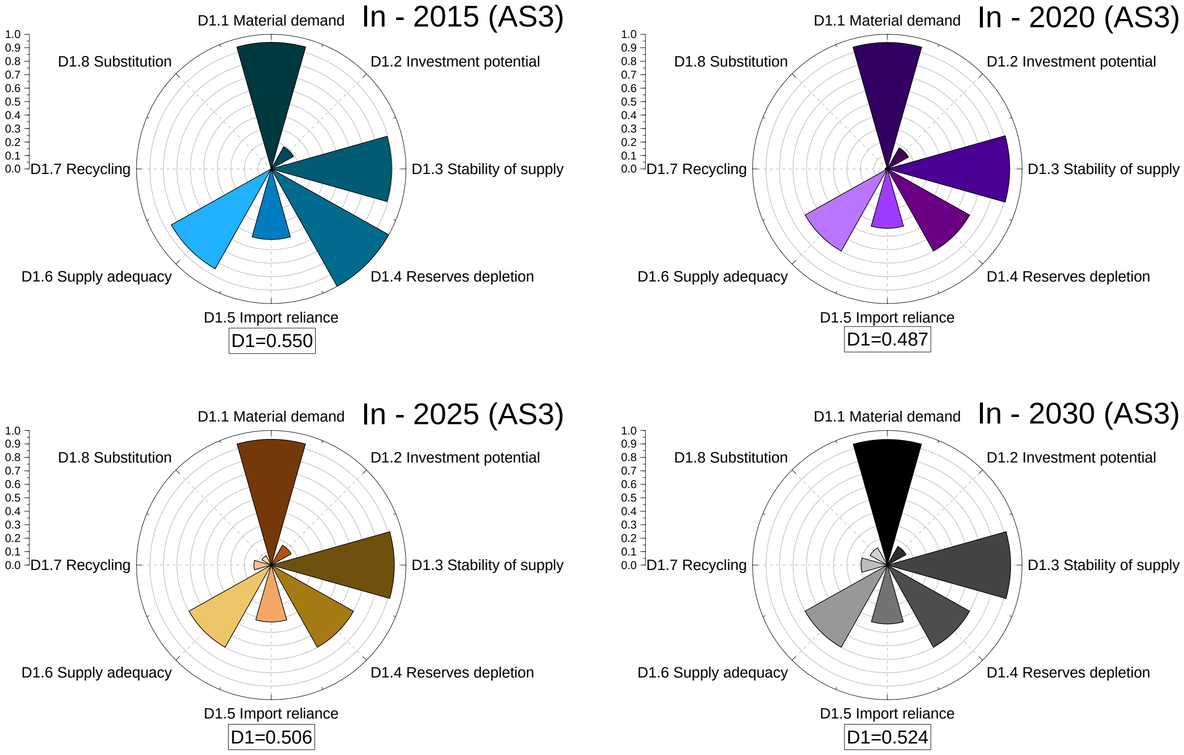


Figure 36: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for indium in CIGS, 2015-2030

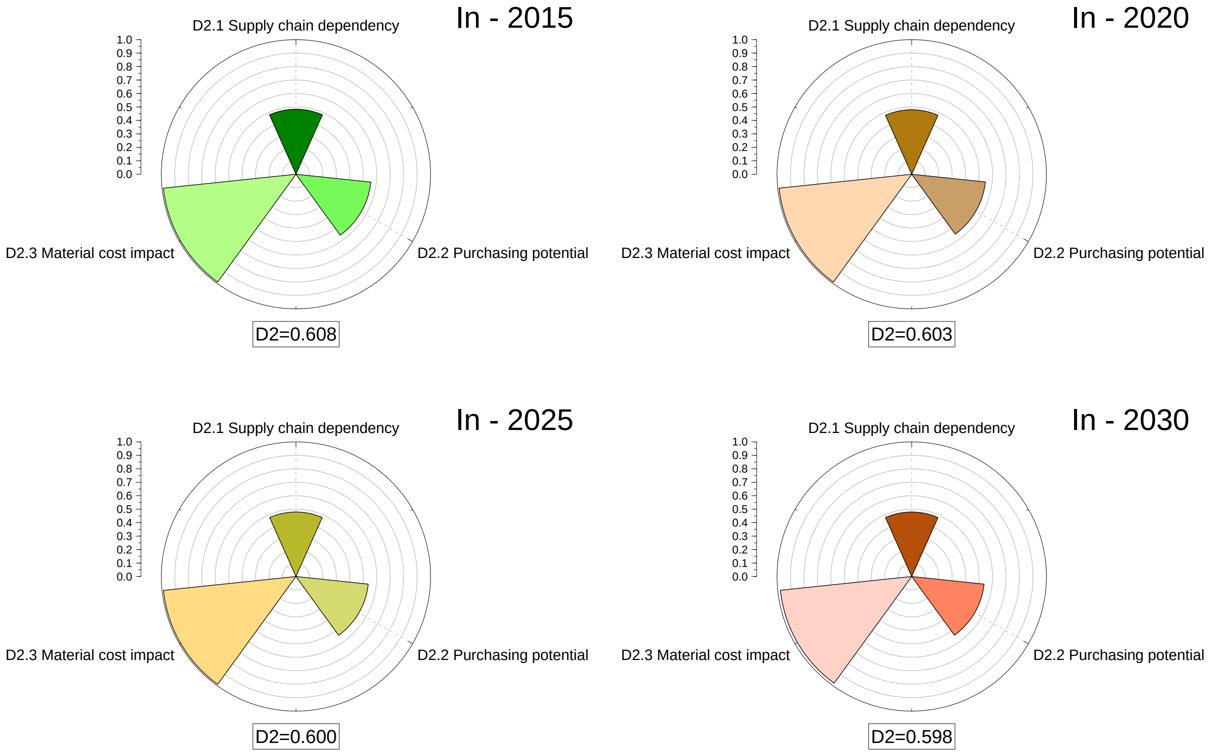


Figure 37: Evolution of D2 indicators for indium in CIGS, 2015-2030

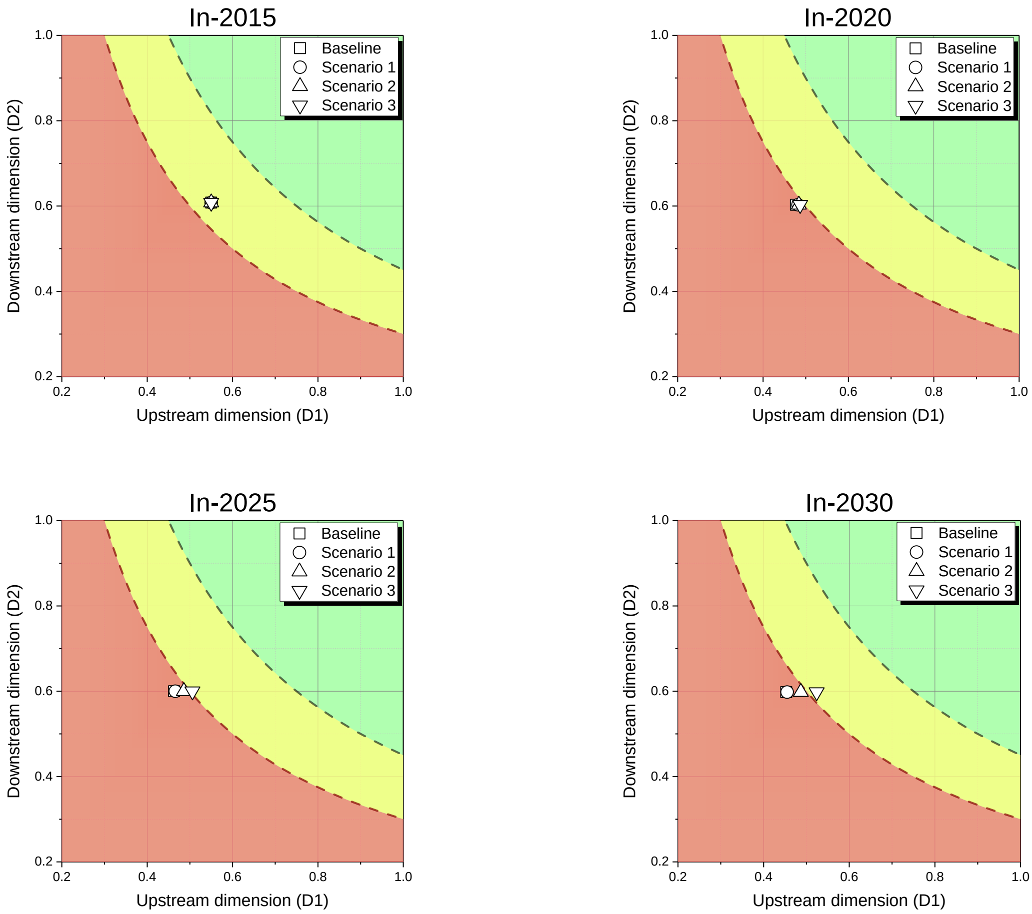


Figure 38: Evolution of resilience for indium in CIGS for all scenarios, 2015-2030

4.4.2 Copper

The EU demand for copper (Cu) in thin-film CIGS PV solar technology is calculated according to the procedure presented in Annex B. The amount of Cu required per 1MWp is multiplied by both the currently installed (2015) and expected MWp until 2030 (the average MWp by 2030 calculated from the different deployment scenarios). This resulted in 4.06 tonnes of Cu being required in the EU for this technology in 2015. Such an amount represents less than 1 % of the 2015 Cu global supply of 18 700 tonnes [USGS, 2016]. Since the deployment rate of CIGS PV is expected to remain marginal until 2030 and because of the material efficiency factor (less Cu required per MWp by 2030), Cu is not assessed further in the report.

4.4.3 Gallium

The EU demand for gallium (Ga) in thin-film CIGS PV solar technology is calculated according to the procedure presented in Annex B. The amount of Ga required per 1MWp is multiplied by both the currently installed (2015) and expected MWp until 2030. This resulted in 0.83 tonnes of Ga required in the EU for this technology in 2015. Such an amount represents less than 1 % of the 2015 Ga global supply of around 111 tonnes (USA not included) [By-products, 2015]. The deployment rate of CIGS PV is expected to remain marginal until 2030, as stated above. Moreover, Ga is not consistently used in all thin-film PV while less Ga will be required per WMp by 2030 because of the materials efficiency factor.

4.4.4 Selenium

EU demand for Se in thin-film CIGS PV solar technology is calculated according to the procedure presented in Annex B (section 6.3). The amount of Se required per 1MWp is multiplied by both the currently installed (2015) and expected MWp until 2030. This resulted in 6.67 tonnes of Se required in the EU for this technology in 2015. Such an amount represents less than 1 % of the 2015 Se global supply of 2340 tonnes (USA not included [USGS, 2016]. Since the deployment rate of CIGS PV is also expected to remain marginal until 2030 and because of the material efficiency factor (less Se required per MWp by 2030) Se is not assessed further in the report.

4.5 Materials in thin-film CdTe technology

Two materials were investigated for thin-film CdTe PV technology – cadmium (Cd) and tellurium (Te). Neither of them passed the significance screening: the demand for cadmium and tellurium for the EU is <1 % of the global supply of these two materials (see details below).

4.5.1 Cadmium

EU demand for Cd in thin-film CdTe PV solar technology is calculated according to the procedure presented in Annex B. The amount of Cd required per 1MWp is multiplied by both the currently installed (2015) and expected MWp until 2030. This resulted in 1.29 tonnes of Cd required in the EU for this technology in 2015. Such an amount represents less than 1 % of the 2015 Cd global supply of 24 200 tonnes (USA not included) [USGS, 2016]. Since the deployment rate of CdTe PV is also expected to remain marginal until 2030 and due to the material efficiency factor, Cd is not assessed further in the report.

4.5.2 Tellurium

EU demand for Te in thin-film CdTe PV solar technology is calculated according to the procedure presented in Annex B. The amount of Te required per 1MWp is multiplied by both the currently installed (2015) and expected MWp until 2030. This resulted in 1.45 tonnes of Te required in the EU for this technology in 2015. Such an amount represents less than 1 % of the current Te global supply of 169 tonnes [By-products, 2015]. As for

Cd, due to the low deployment rate of CdTe PV by 2030 and the material efficiency factor, Te is not assessed further in the report.

4.6 PV technology resilience charts

A full assessment is performed for three materials required for solar PV in the EU: Si, Ag and In. The resilience charts for PV technology in 2015, 2020, 2025 and 2030 under both the baseline and scenario 3 are presented below (Figure 39 and Figure 40).

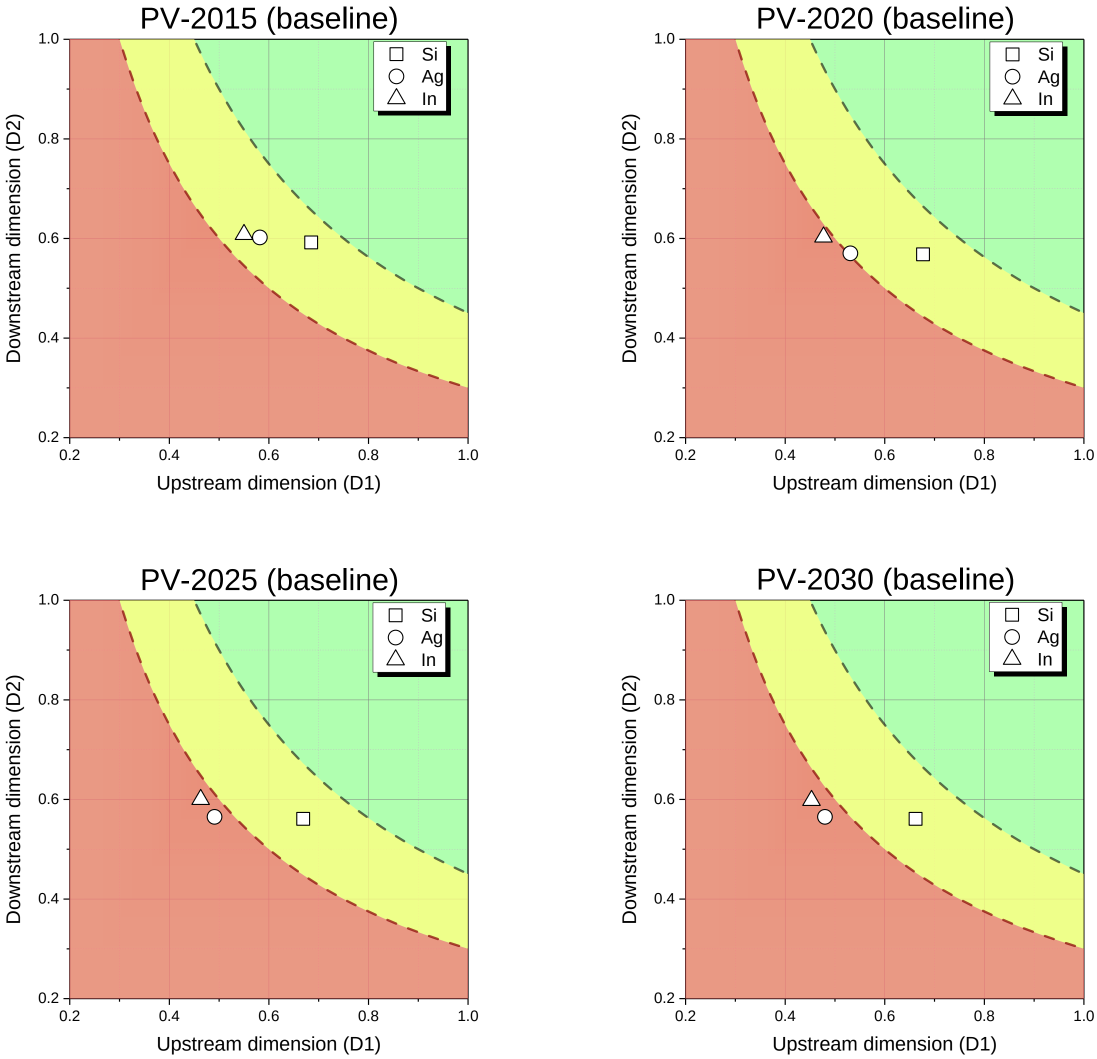


Figure 39: Resilience charts for materials required in PV technology in 2015, 2020, 2025 and 2030 for the conservative baseline scenario

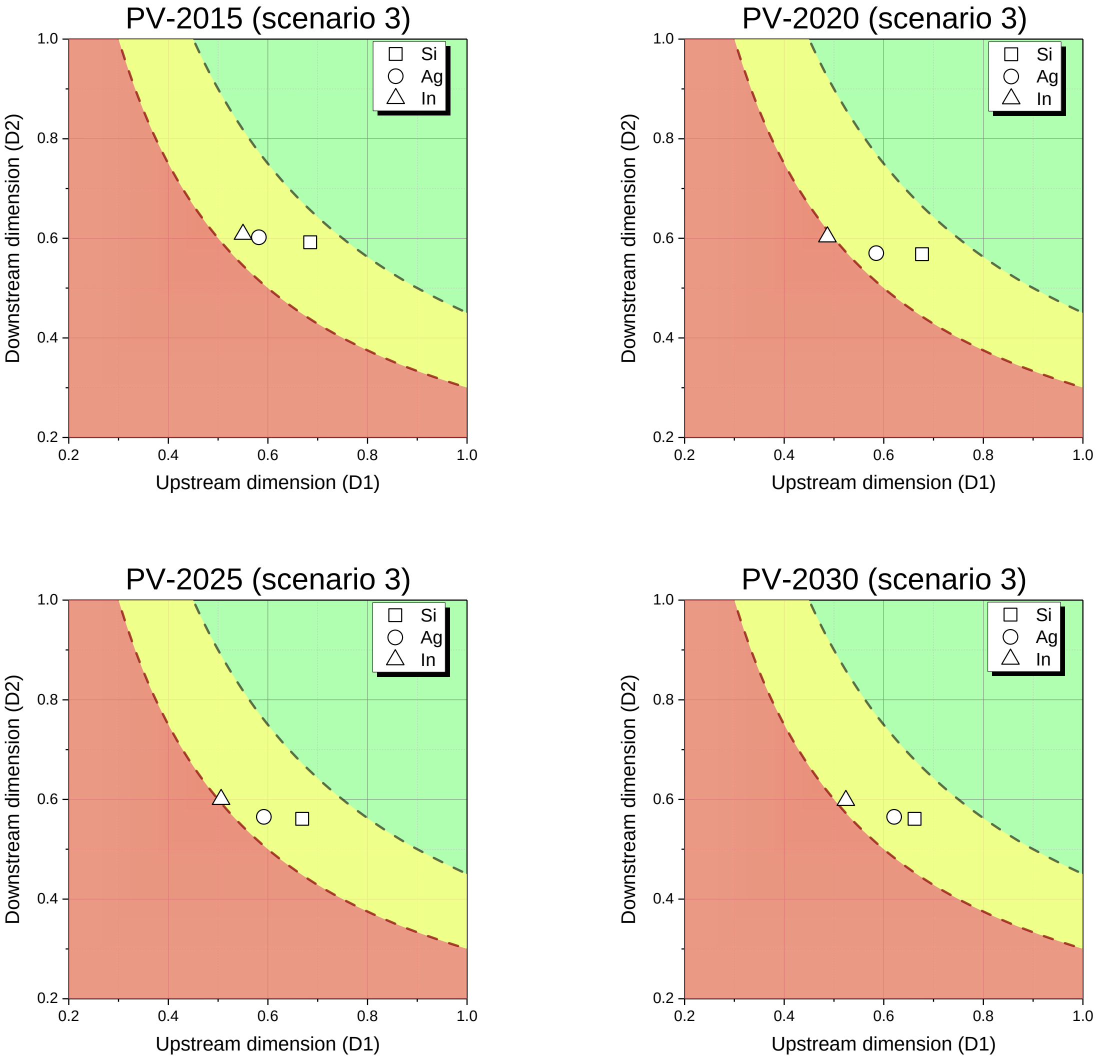


Figure 40: Resilience charts for materials required in PV technology in 2015, 2020, 2025 and 2030 for the most optimistic assessment scenario 3

As regards materials required for the photovoltaic energy sector, (2015) EU resilience to bottlenecks in the supply of silicon, silver and indium is currently assessed as medium (Figure 41).

For the other materials screened here, namely Cu, Ga, Se, Te and Cd, no potential supply bottlenecks are expected for the time frame being considered.

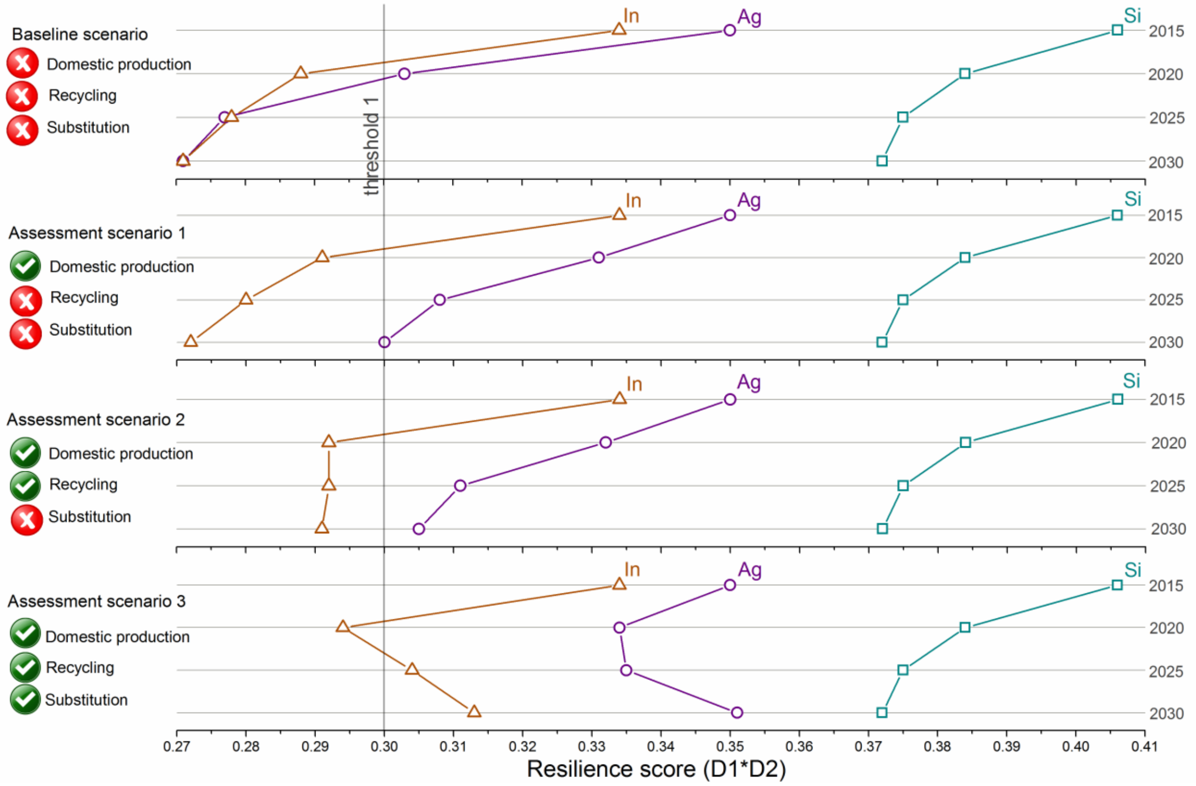


Figure 41: Variation in EU resilience to supply bottlenecks of materials used in solar photovoltaic; threshold 1 fixed at 0.3 represents the border between low and medium resilience

Silicon

The EU resilience to bottlenecks in the supply of Si evolves in a similar way for all scenarios:

- It deteriorates significantly until 2020 (-5.2 % decrease) due to the higher demand expected during this period;
- During the period 2020-2025, the EU resilience decreases progressively in all scenarios by -2.4 %;
- In the last five-year period (2025-2030) the resilience situation for Si degrades slightly (-1 %) in all four scenarios, although it remains in the medium zone.

To summarise, the EU resilience for silicon is similar in all the assessment scenarios being considered and remains in the medium zone between 2015 and 2030.

Silver

In the baseline scenario, the situation for Ag deteriorates significantly until 2020 (-13.7 %). In the other three scenarios, the decline is considerably smaller: only around 5 % less due to new EU production of silver. The fact remains that the combined mitigation measures cannot compensate for the increased demand for Ag during this period.

In the period between 2020 and 2025, the EU resilience further deteriorates in the baseline scenario (-8.5 %), scenario 1 (-7.1 %) and scenario 2 (-6.3 %), while a slight improvement is attained for scenario 3 (+0.3 %). The EU resilience to the supply of Ag in 2020 stays in the medium zone for all scenarios, with the exception of the baseline scenario where it is placed in the low resilience zone. The improvement in scenario 3 is mainly due to the effect of substitution.

In the last five-year period (2025-2030) the situation for Ag further deteriorates in the baseline scenario (-2.2 %), scenario 1 (-2.6 %) and scenario 2 (-1.9 %), reaching the low-resilience threshold. The situation improves for scenario 3 in which growth of around 5 % can be achieved, mainly due to substitution, for which a potential of around 50 % is anticipated. Nevertheless, the situation for silver only recovers in this one situation, returning to the 2015 resilience level.

To summarise, substitution is the mitigation measure with the highest potential in the 2030 time frame, coupled with relevant silver production in the EU. However, Ag recycling will not yield an increase in tangible resilience. Nonetheless, these measures will be sufficient to maintain the current medium-resilience level. Potential improvements could also be realised downstream by enhancing EU production at different stages in the supply chain, in particular increasing solar cell production in the EU.

Indium

The EU resilience to bottlenecks in the supply of In deteriorates considerably until 2020 (between -11 % and -13 %), reaching the low-resilience zone in all scenarios.

In the period between 2020 and 2025, EU resilience falls progressively in both the baseline scenario (-3.5 %) and scenario 1 (-3.7 %). Almost no change is observed in scenario 2 and a slight improvement is noted for scenario 3 (+3.4 %), which is sufficient to return to the medium-resilience zone in 2025.

In the last five-year period (2025-2030) the situation for In either further deteriorates in the baseline scenario (-2.6 %) and scenario 1 (-2.7 %) or remains unchanged (scenario 2) thanks to some recycling efforts. In all three cases, the EU resilience remains low. The situation improves in scenario 3 because of the potential to increase global recycling (up to 20 %) and substitution rates. Even in this positive case, the EU resilience to bottlenecks in the supply of In does not return to its 2015 level.

To summarise, the forecasted EU domestic production is not expected to influence its resilience to bottlenecks in the supply of In. Substitution and recycling have the highest potential by 2030. Their joint influence is effective in preventing this material from moving to the low-resilience zone. In all cases, resilience is expected to fall compared to its 2015 level.

5 Determination of material supply bottlenecks in the electric vehicles sector

5.1 Market and EV technology background

The European transport sector, which is essentially still running on oil products, is the main cause of air pollution as it is responsible for more than 30 % of the EU's total energy consumption. At the global scale, transport accounts for about one-quarter of energy-related GHG emissions, more than half of which is related to road passenger transport [UNFCCC, 2015]. To ensure Europe will be able to respond to the increasing mobility needs of people and goods while, at the same time, safeguarding the transition to a low-carbon European economy, the Commission has recently set up a strategy to give guidance to EU Member States to prepare for future low-emission mobility [EC, 2016b]. Electromobility in various transport modes coupled with a low-carbon power system are seen as the most promising sustainable solutions, which will contribute to reaching the climate objectives of the EU and other countries. According to the International Energy Agency (IEA), in order to meet the objective set by the Paris Agreement, e.g. limiting the global temperature increase to below 2 degrees Celsius, at least 20 % of all road transport vehicles globally will need to be electrically driven by 2030, alongside the rail transport electrification (already under way) [UNFCCC, 2015]. To achieve this goal, the IEA's model indicates that all electric drive vehicles, including passenger electric vehicles, two and three wheelers, light commercial vans, trucks, etc., must represent 35 % of global sales in 2030 [UNFCCC, 2015]. In this context, the global deployment target for the stock of passenger electric vehicles (EV) is set at 20 million EV by 2020, increasing to 100 million EV or even 150 million following a more ambitions pathway by 2030 [IEA, 2016]. At the end of 2015, the global EV stock was 1.26 million [IEA, 2016]. Achieving the global EV deployment targets for 2020 and 2030 implies substantial market growth, which should be sustained by massive investments, business solutions and policy support. To contribute to this goal, the EC proposed a set of targets to steer the R&I actions and guide coordination of EU and Member States funding. In the case of EV, areas concerned are materials research, nanotechnology, electrochemistry, manufacturing processes and manufacturing technologies [SET-Plan, 2016].

In 2015, seven countries around the globe reached over 1 % EV market share, six of them in Europe (the Netherlands, Norway, Sweden, Denmark, France and the United Kingdom). In the same year, the Netherlands and Norway registered the highest EV market share with about 10 % and 23 %, respectively [IEA, 2016]. In terms of annual sales, in 2015, the EU-28 accounted for approximately 150 000 EVs (around 30 % of the global market). About 60 % of total EV sales in the EU were plug-in electric vehicles (PHEV), the rest being battery electric vehicles (BEV) [EAFO, 2016]. In addition, about 192 000 hybrid electric vehicles (HEV) were sold in the EU in 2015 [JATO, 2016].

To create an integrated electromobility ecosystem and the national roadmaps necessary to gather support from policy-makers, several countries have set up ambitious sales and/or stock targets for vehicle electrification. According to the European Roadmap for Electrification of Road Transport, over 5 million EVs will be on EU roads by 2020, increasing to 15 million by 2025 [ERERS, 2012]. To accomplish the emission reduction goals, McKinsey puts forward even more ambitious targets of 8-9 million EVs on the road by 2020 [McKinsey, 2014]. However, specific targets and timelines are subject to negotiation with the EU's Member States.

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

In particular, the report focuses on certain materials required in two key components in the electric powertrain:

- ***Rechargeable batteries***, which allow on-board storage of electrical power from electricity grid and releasing it when requested. Among the options in terms of rechargeable batteries, lithium-ion batteries (LIB) are expected to dominate the market for EV in medium to long-term e.g. [Avicenne, 2015]. LIB can employ as cathode different chemistries such as LCO (lithium-cobalt-oxide), NMC (nickel-manganese-cobalt), LMO (lithium, manganese, phosphate) or LFP (lithium-iron-phosphate), with performances suited to different applications. According to Darton Commodities [Darton, 2016], until recently the cathode chemistry of choice for the majority of BEV and PHEV producers was a combination of NMC with a non-cobalt chemistry material, mainly LMO. The spreading trend is that an increasing number of automakers are choosing full NCM chemistry to achieve higher energy density and thus longer distances per charge. Natural graphite on is the reference anode material for LIB. In comparison to available alternatives (artificial graphite, mesocarbon microbeads, Si and Sn composites/alloys, and LTO – lithium-titanium-oxide), natural graphite received a 64 % share in 2014 [Avicenne, 2015]. The following materials will be thus analysed: lithium, cobalt and graphite.
- ***Electric traction motors*** are used for the propulsion of electric vehicles. The majority of traction motors use high-performance rare-earth magnets which contain neodymium, praseodymium and dysprosium.

There is a large diversity of electric powertrain systems available on the automotive market (Figure 42).

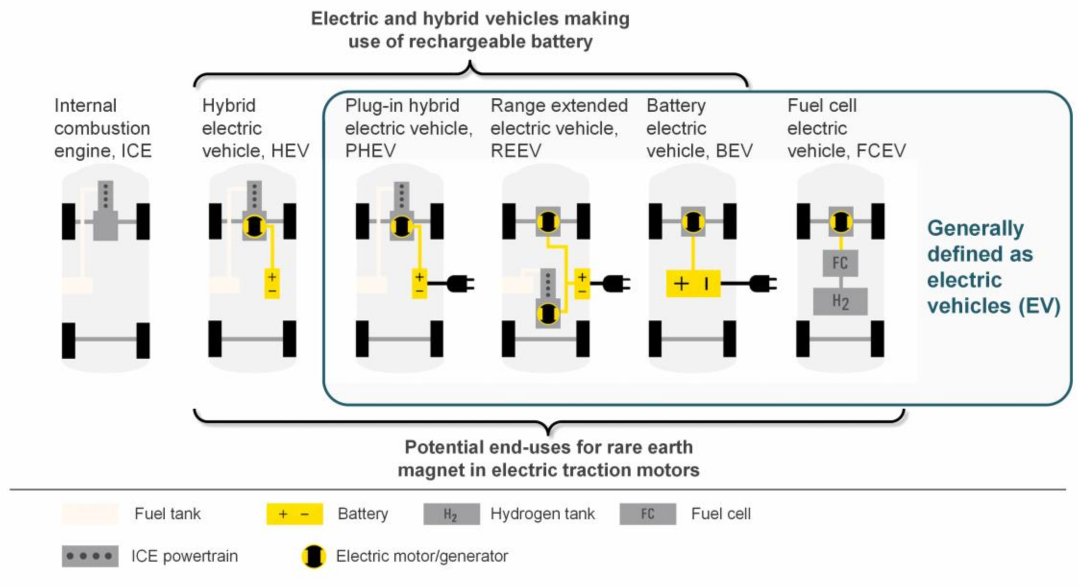


Figure 42: Electric powertrain concepts compared to conventional internal propulsion engine (ICE) system; representation adapted from [Fraunhofer, 2011]

It is worth pointing out that not all vehicles which can be propelled by electric traction motors are part of the electric vehicles group. This applies to HEVs where the electric motor represents a secondary source of propulsion in parallel configuration with ICE drive. Since the HEV does not use electric power from the grid, it is not defined as an electric vehicle.

Currently, BEV, PHEV and HEV types are the most common variants on the electric and hybrid vehicles market. These three vehicle types are characterised as follows:

- BEVs run exclusively with one or more electric motors; they are powered by a rechargeable battery, thus using energy stored in the grid;
- PHEVs include rechargeable batteries that can be plugged into an external electric power source for charging; they also have ICE to extend the range of vehicles;

- HEVs combine an internal combustion engine (ICE) and one or more electric motors. The full hybrid electric vehicle could be propelled solely by the electric motor under certain operating conditions.

Depending on the car model and type of powertrain adopted, electric and hybrid vehicles may make use of lithium, cobalt and graphite in Li-ion batteries (with the exception of FCEVs which use a fuel cell instead of a battery) and neodymium, praseodymium and dysprosium for the NdFeB permanent magnet in electric traction motors. The present report refers to all six materials used in the electric and hybrid vehicles commercialised today or forecast to be adopted by 2030. The rare earths – neodymium, praseodymium and dysprosium – are evaluated as critical materials in an EC study [EC, 2014], and their supply issues in the EV sector are similar to those for wind turbines. Cobalt and graphite are also considered critical materials for the EU economy [EC, 2014]. Although lithium is not perceived as a critical material in terms of supply risk and economic performance, latest developments in the automotive sectors and increasing demand for rechargeable batteries call for a new assessment.

5.2 Materials in rechargeable batteries: lithium-ion battery (LIB)

Three materials have been investigated for LIB in hybrid and electric vehicles: lithium (Li), cobalt (Co) and graphite (C), which are the reference materials for LIB electrodes.

The calculated values of the indicators for both dimensions are represented as polar charts for 2015, 2020, 2025 and 2030.

Figure 43 and Figure 44 show the evolution of the upstream D1 indicators according to the most conservative baseline (BL) and the most optimistic scenario 3, respectively, for the lithium required in LIBs for the period 2015-2030.

The evolution of D2 indicators for lithium in LIBs is shown in Figure 45 for the period 2015- 2030.

The evolution of EU resilience for lithium for all assessment scenarios is shown in Figure 46.

Similarly, Figure 47, Figure 48, Figure 51 and Figure 52 show the evolution of the upstream D1 indicators according to the most conservative baseline (BL) and the most optimistic scenario 3, respectively, for cobalt and graphite required in LIBs for the period 2015-2030.

The evolution of D2 indicators for cobalt and graphite in LIBs is shown in Figure 49 and Figure 53, respectively, for the period 2015-2030.

The evolution of EU resilience for cobalt and graphite required in LIB for all assessment scenarios is shown in Figure 50 and Figure 54, respectively.

5.2.1 Lithium

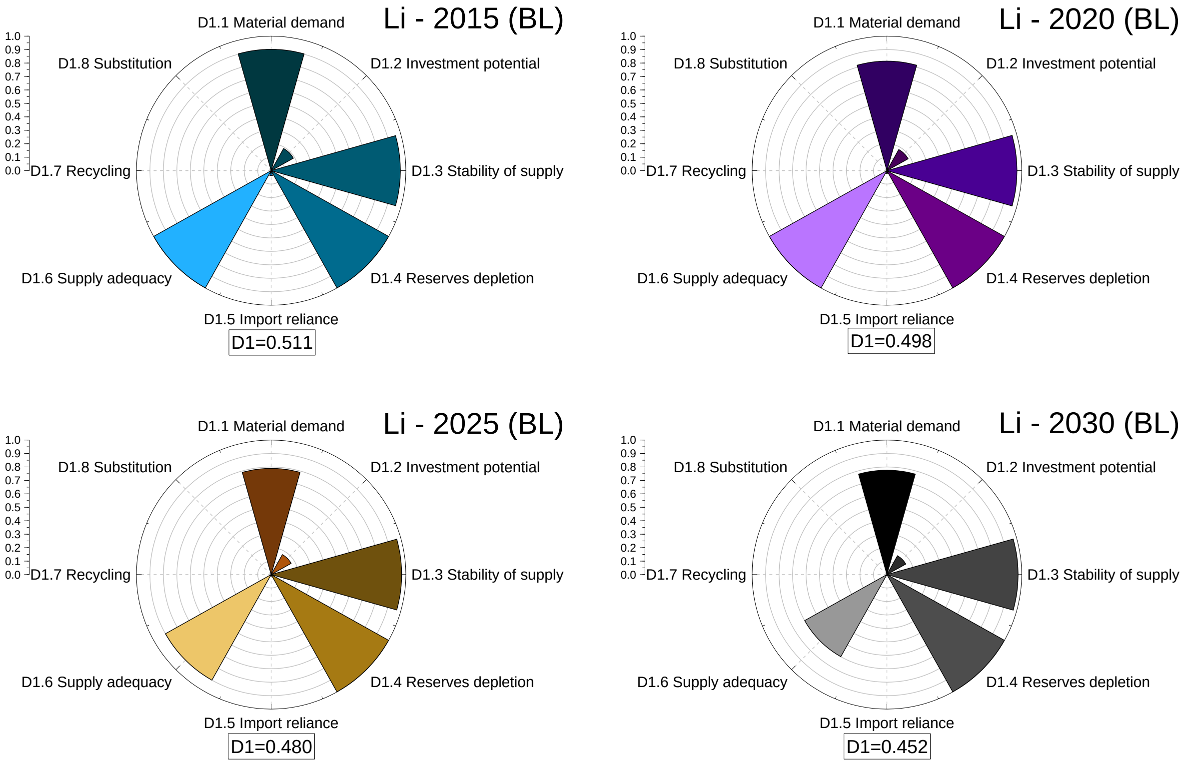


Figure 43: Evolution of D1 indicators according to the conservative baseline (BL) scenario for lithium in EVs, 2015-2030

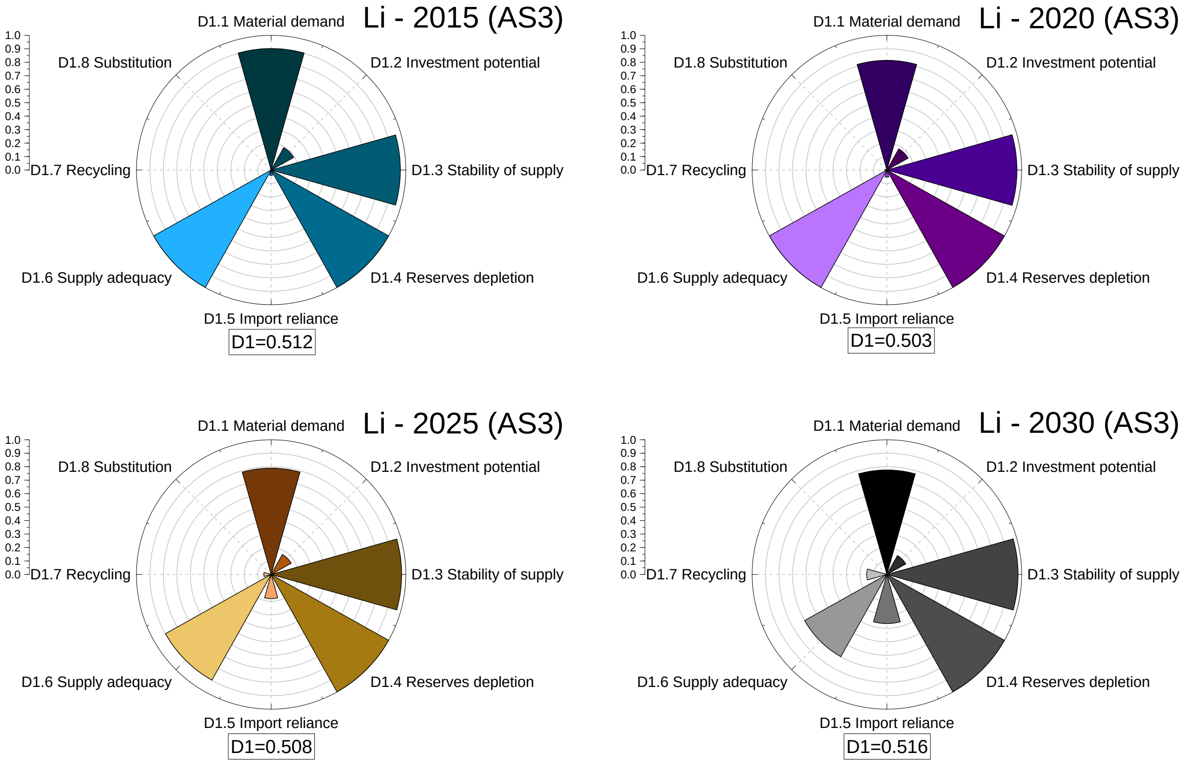


Figure 44: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for lithium in EVs, 2015-2030

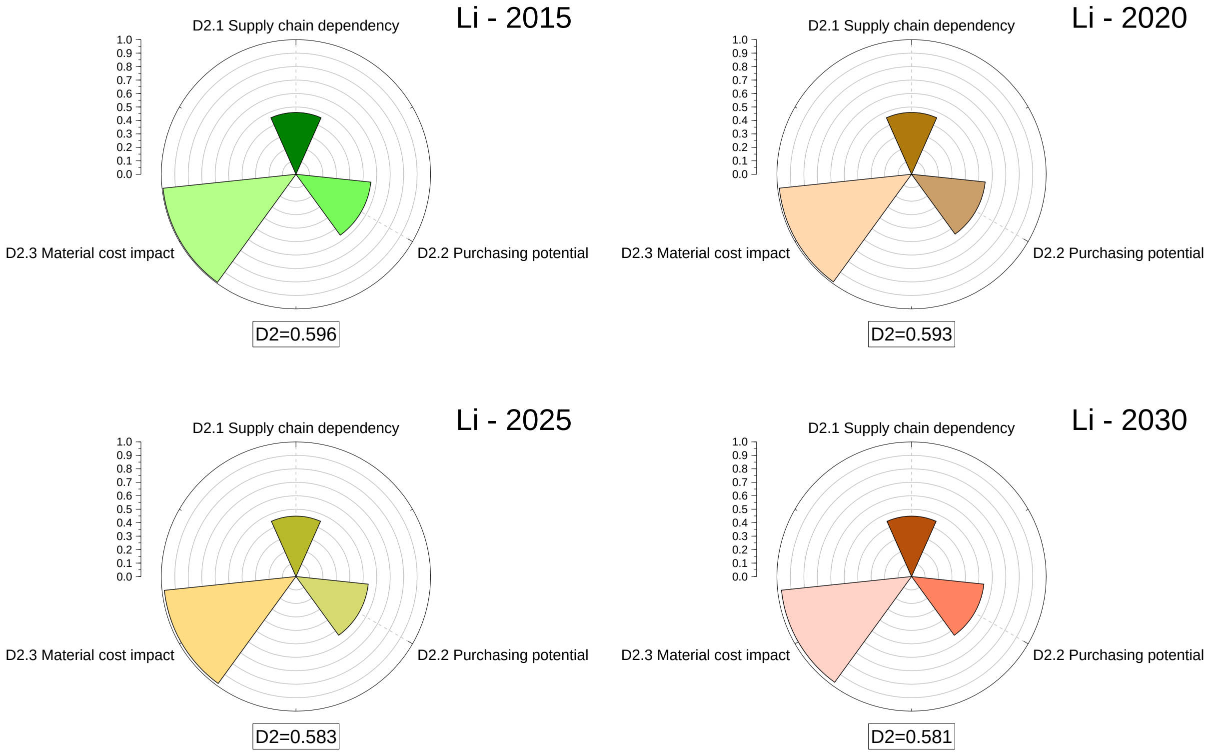


Figure 45: Evolution of D2 indicators for lithium in EVs, 2015-2030

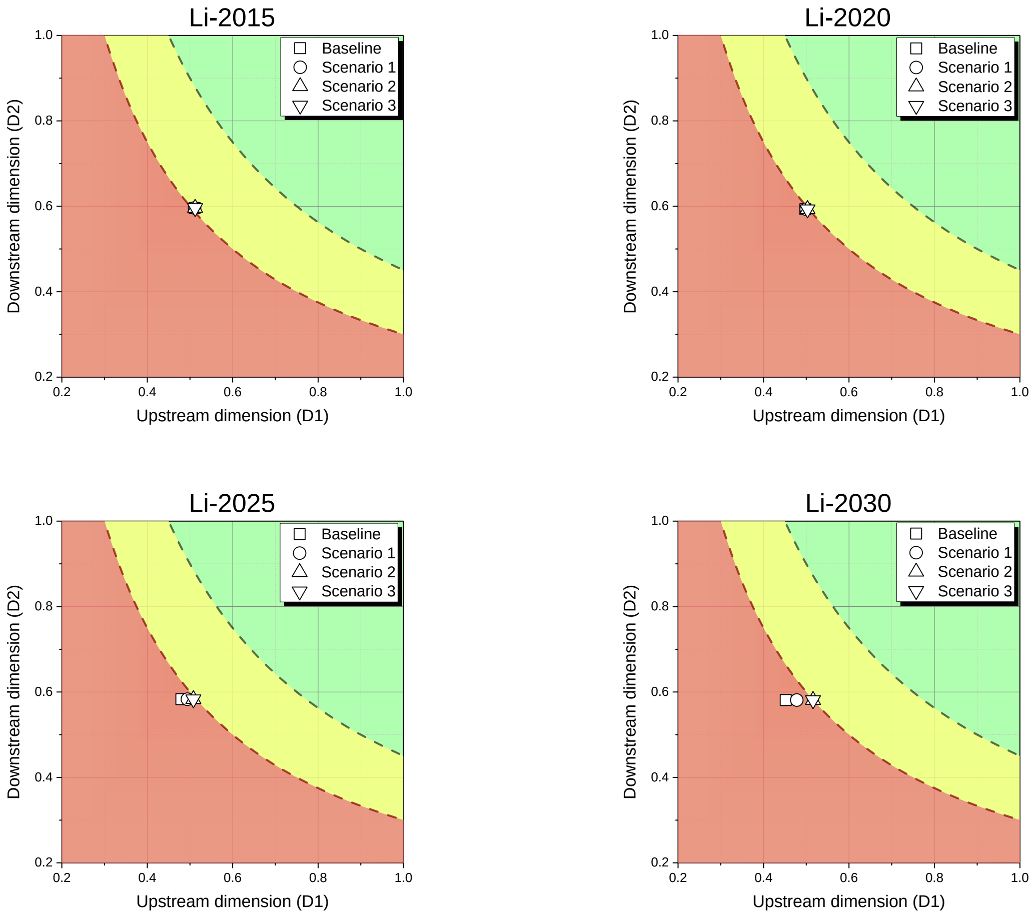


Figure 46: Evolution of resilience for Li in EVs for all assessment scenarios, 2015-2030

5.2.2 Cobalt

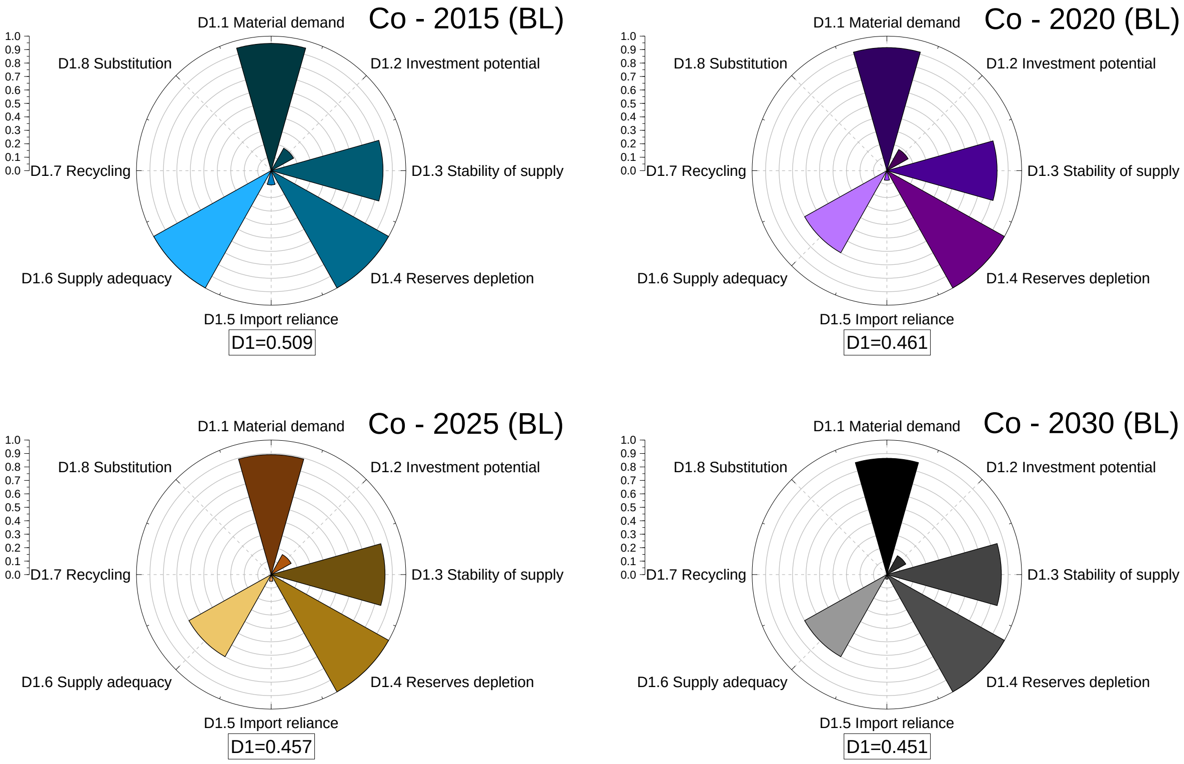


Figure 47: Evolution of D1 indicators according to the conservative baseline (BL) scenario for cobalt in EVs, 2015-2030

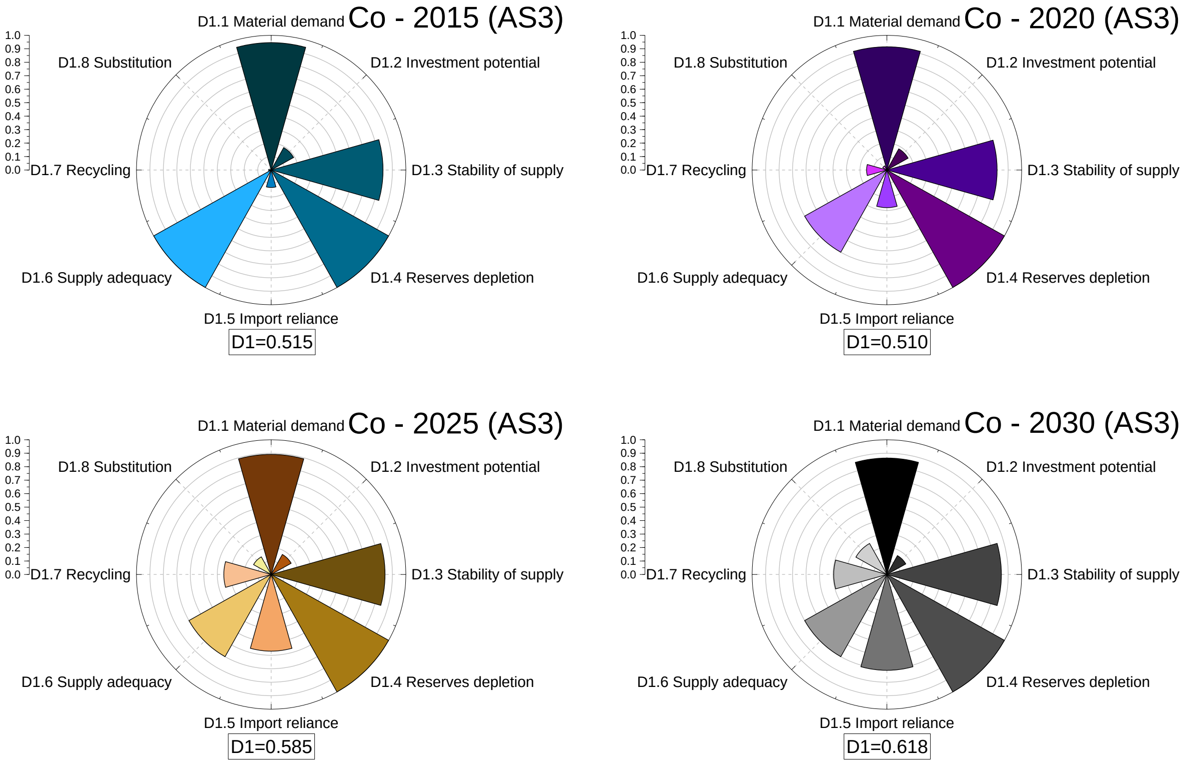


Figure 48: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for cobalt in EVs, 2015-2030

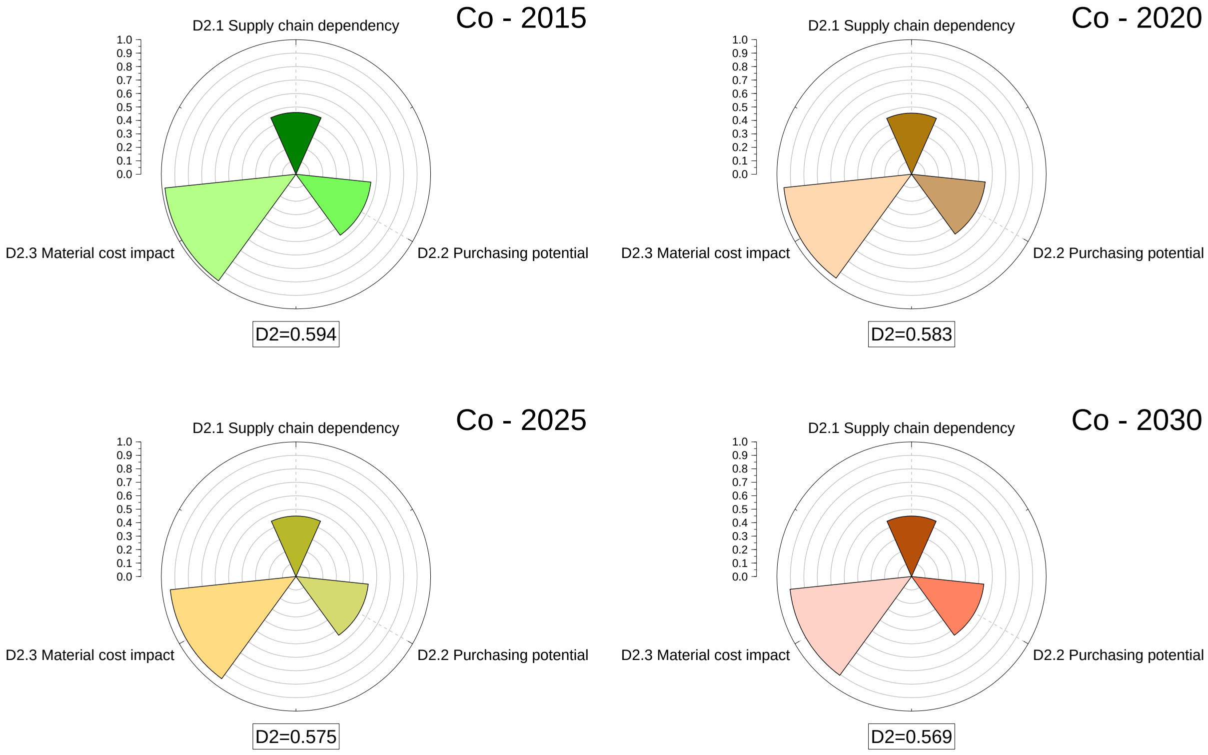


Figure 49: Evolution of D2 indicators for cobalt in EVs, 2015-2030

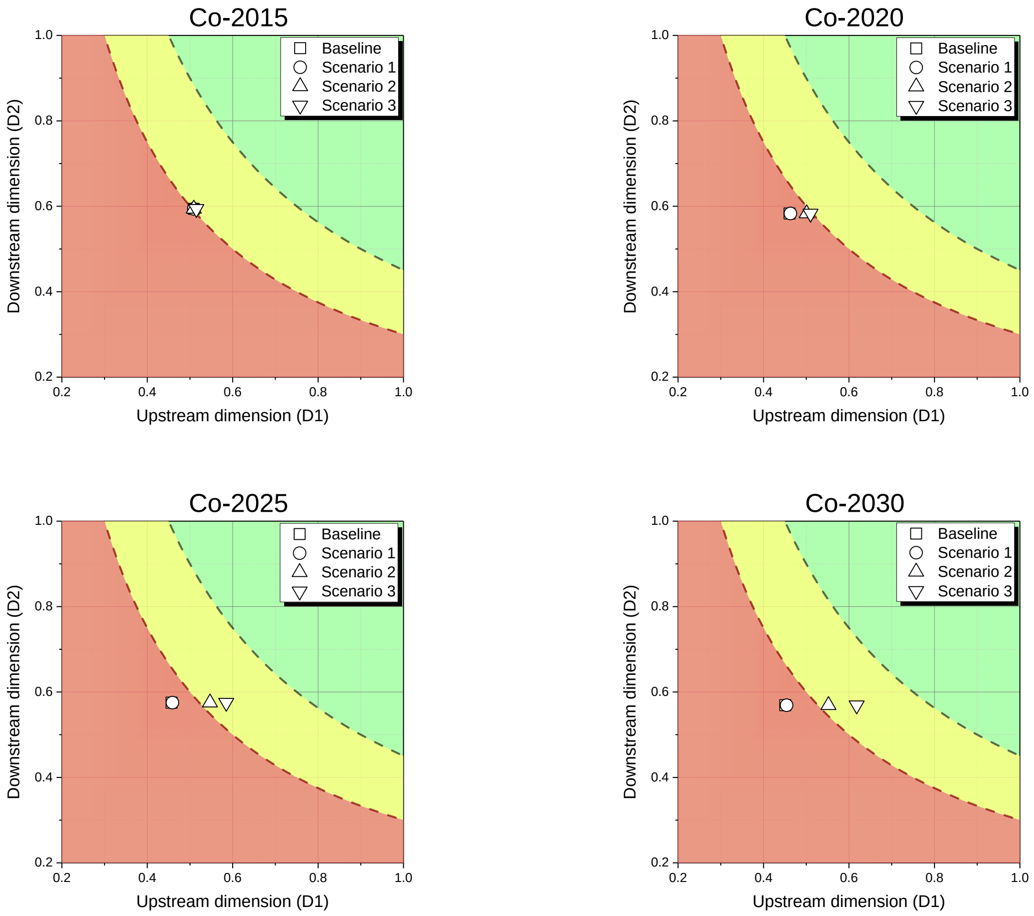


Figure 50: Evolution of resilience for cobalt in EVs for all scenarios, 2015-2030

5.2.3 Graphite

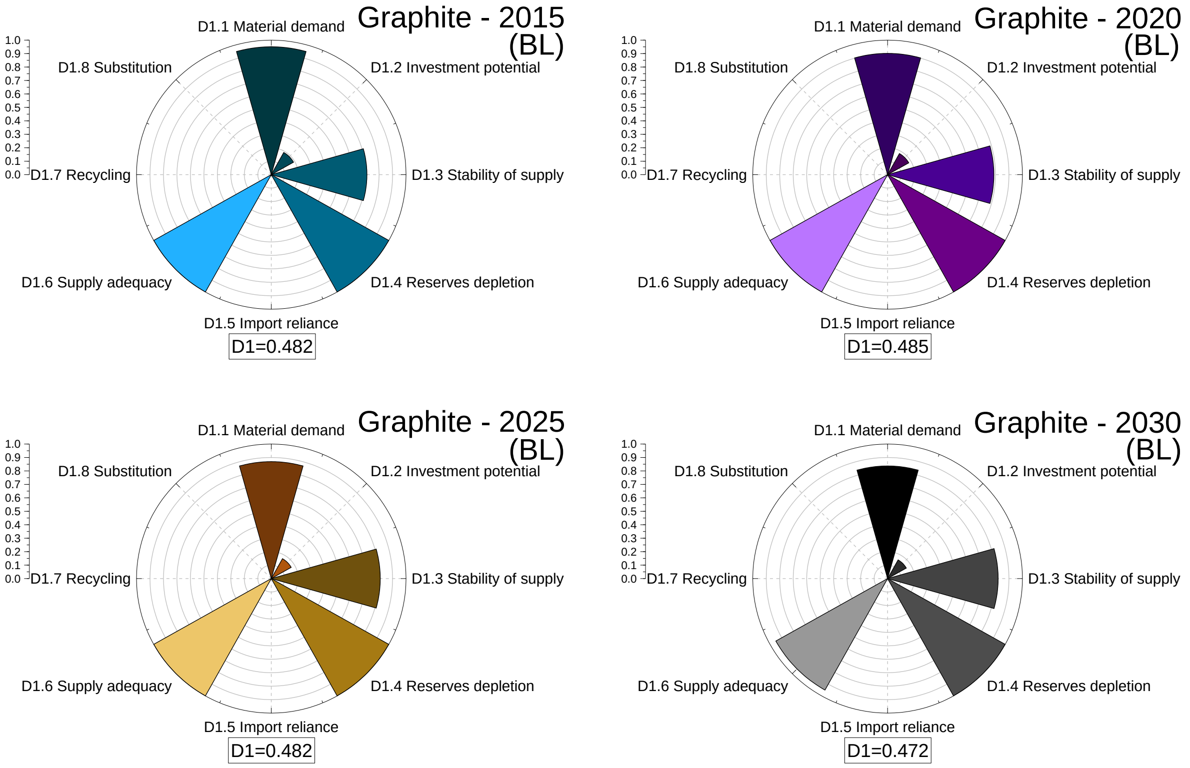


Figure 51: Evolution of D1 indicators according to the conservative baseline (BL) scenario for graphite in EVs, 2015-2030

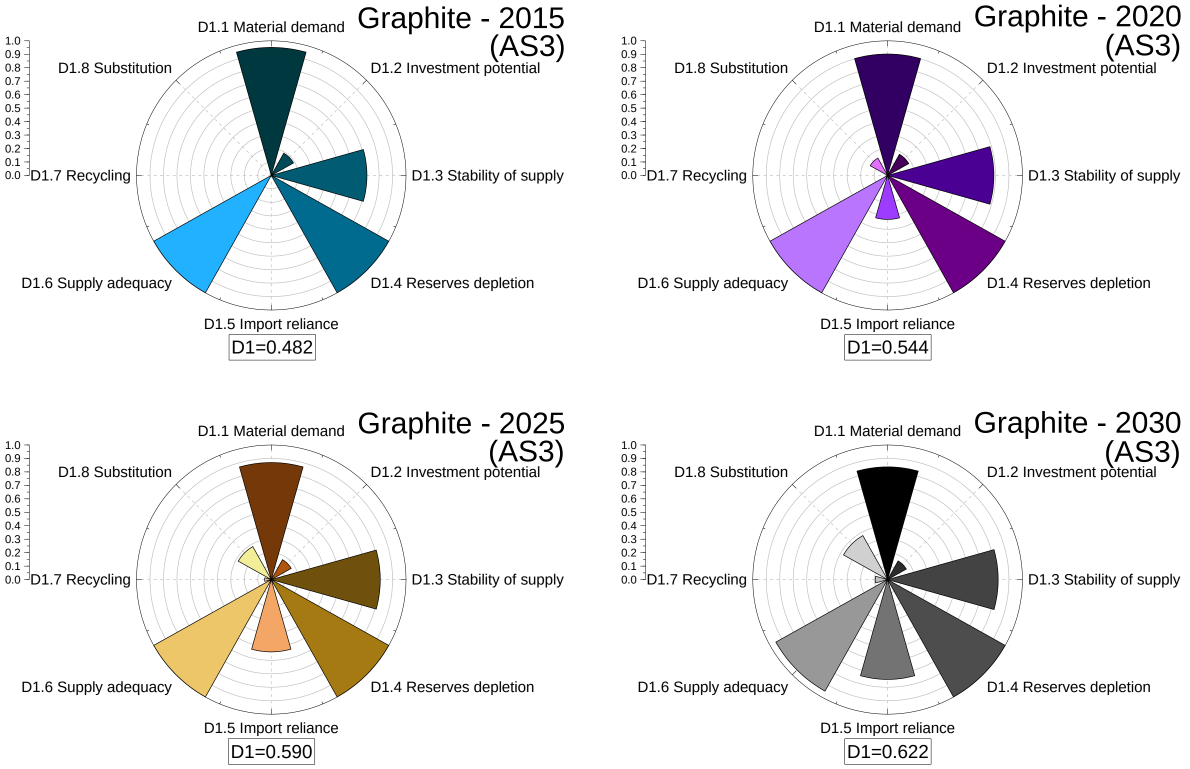


Figure 52: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for graphite in EVs, 2015-2030

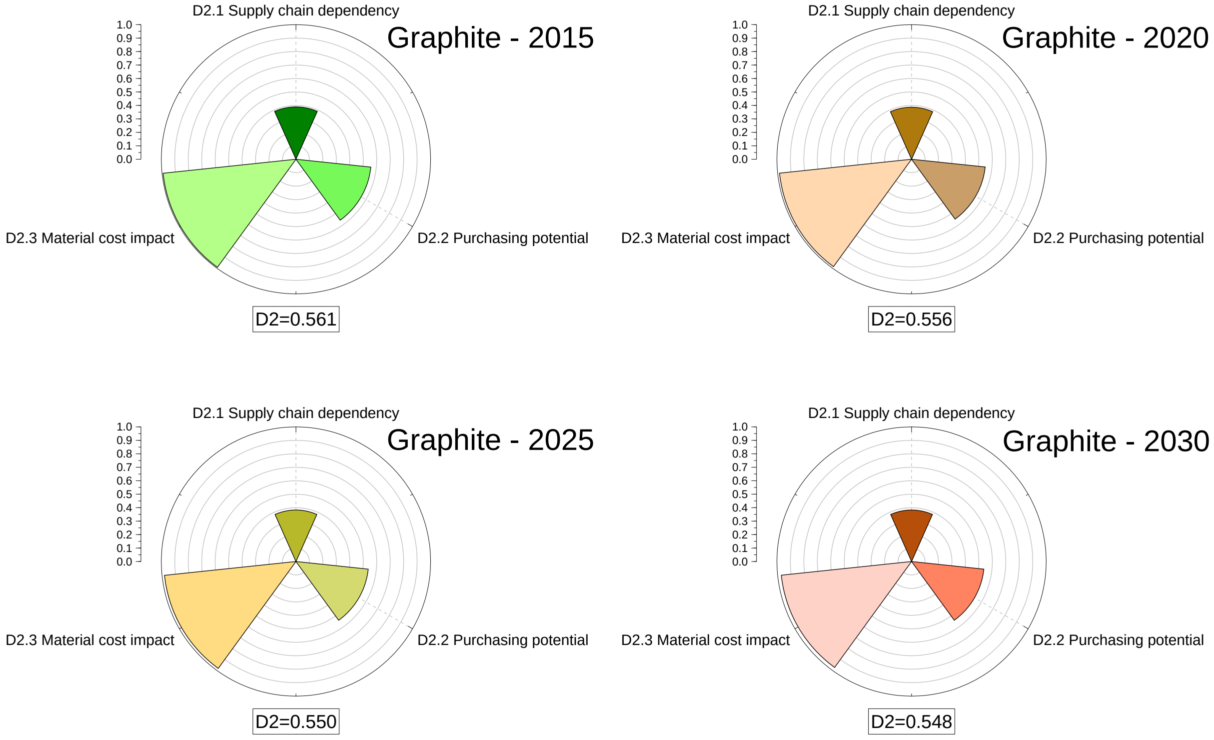


Figure 53: Evolution of D2 indicators for graphite in EVs, 2015-2030

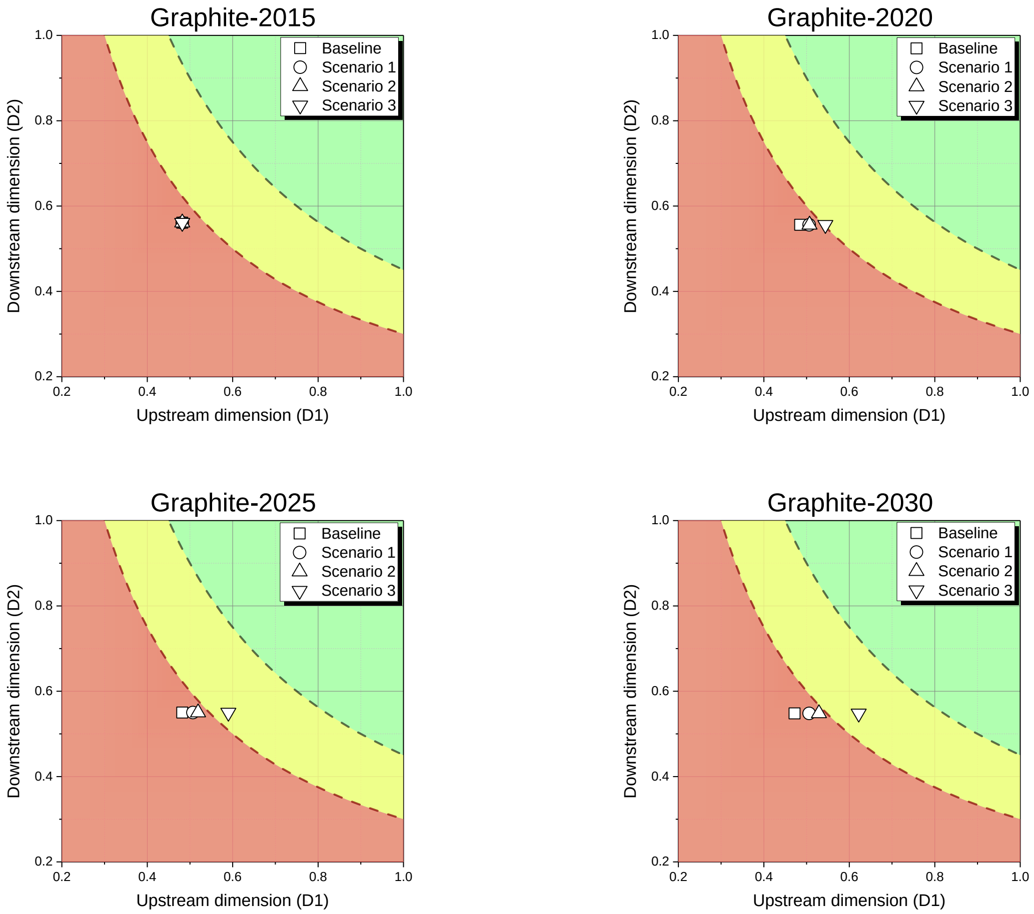


Figure 54: Evolution of resilience for graphite in EVs for all scenarios, 2015-2030

5.3 Materials in electric traction motors

Three materials were investigated for electric traction motors in hybrid and electric vehicles: Nd, Pr and Dy, which are the materials required for a motor’s permanent magnets.

The calculated values of the indicators for both dimensions are represented as polar charts for 2015, 2020, 2025 and 2030.

Figure 55 and Figure 56 show the evolution of the upstream D1 indicators according to the most conservative baseline (BL) and the most optimistic scenario 3, respectively, for neodymium required in EV electric traction motors for the period 2015-2030.

The evolution of D2 indicators for neodymium required in EV electric traction motors is shown in Figure 57 for the period 2015-2030.

The evolution of EU resilience for neodymium in EV electric traction motors for all assessment scenarios is shown in Figure 58.

Similarly, Figure 59, Figure 60, Figure 63 and Figure 64 show the evolution of the upstream D1 indicators according to the most conservative baseline (BL) and the most optimistic scenario 3, respectively, for praseodymium and dysprosium required in EV electric traction motors for the period 2015-2030.

The evolution of D2 indicators for praseodymium and dysprosium in EV electric traction motors is shown respectively in Figure 61 and Figure 65 for the period 2015-2030.

The evolution of EU resilience for praseodymium and dysprosium in EV electric traction motors for all assessment scenarios is shown in Figure 62 and Figure 66, respectively.

5.3.1 Neodymium

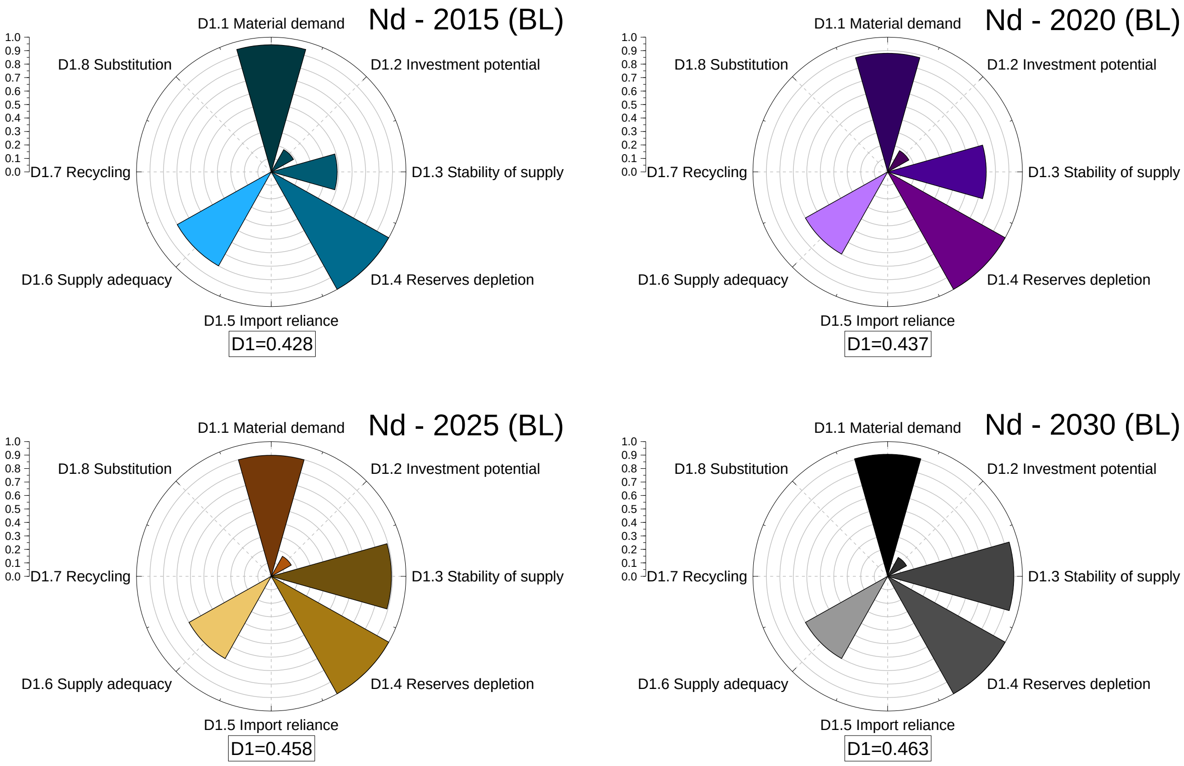


Figure 55: Evolution of D1 indicators according to the conservative baseline (BL) scenario for neodymium in EVs, 2015-2030

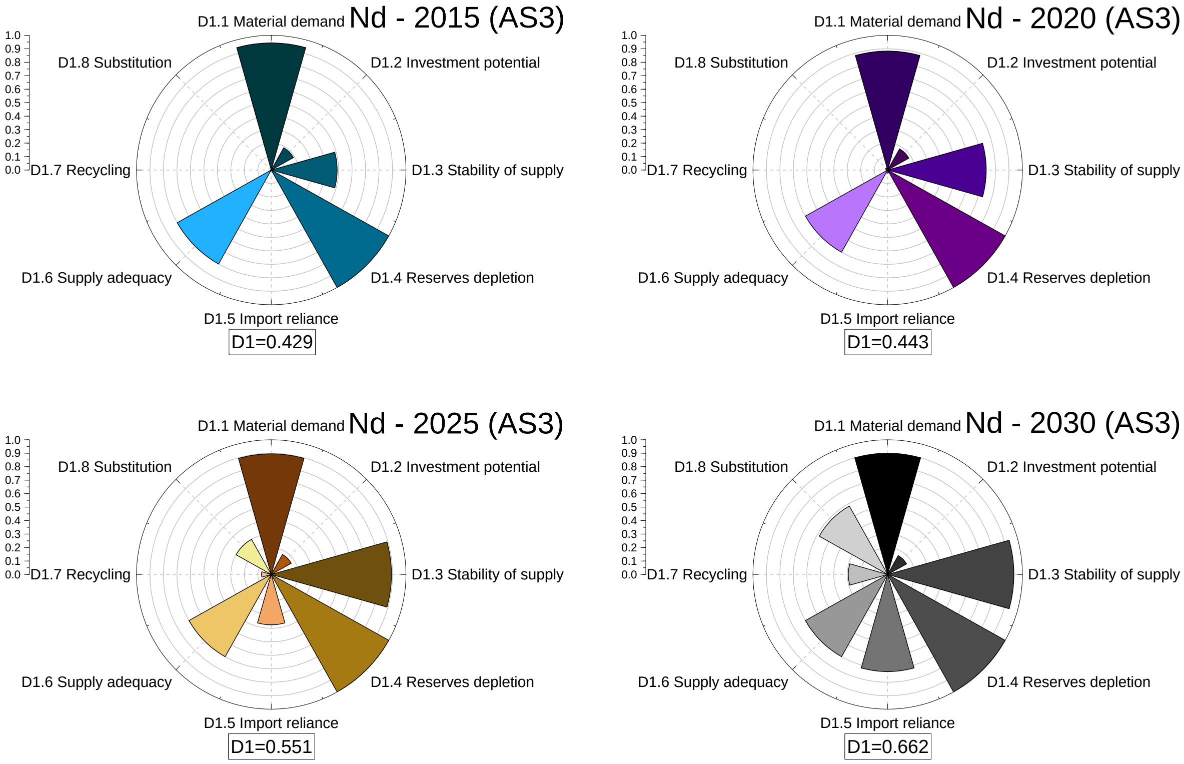


Figure 56: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for neodymium in EVs, 2015-2030

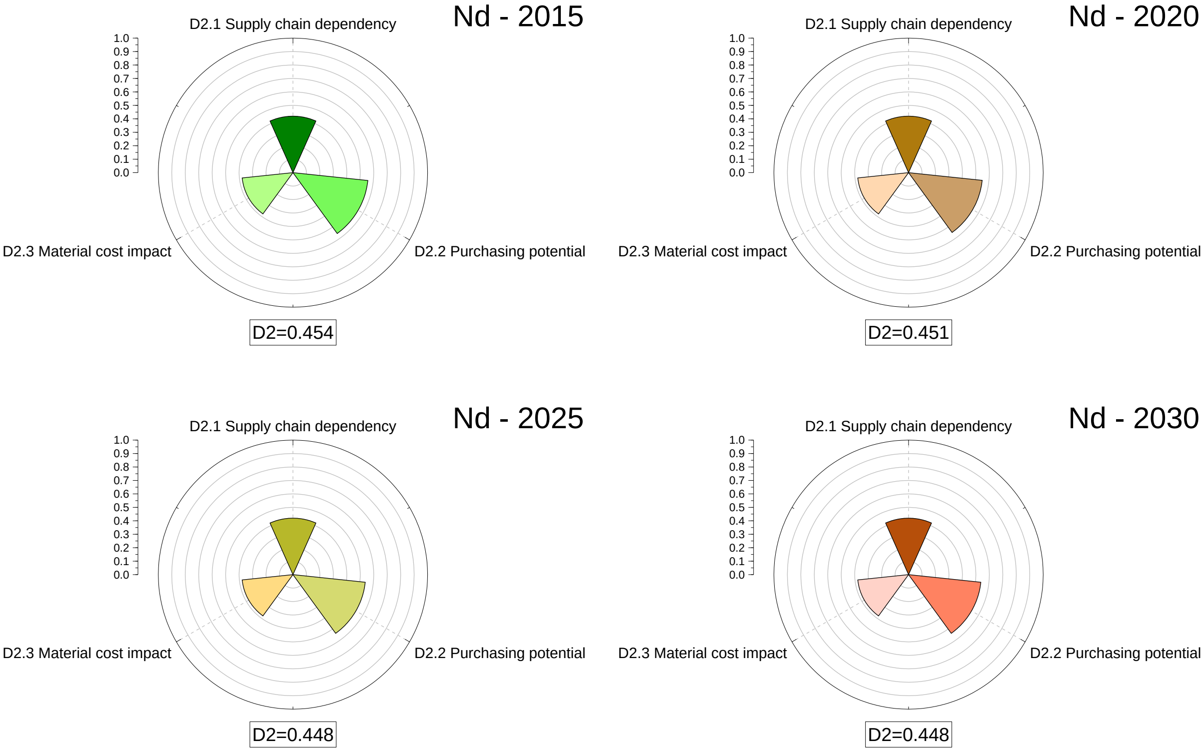


Figure 57: Evolution of D2 indicators for neodymium in EVs, 2015-2030

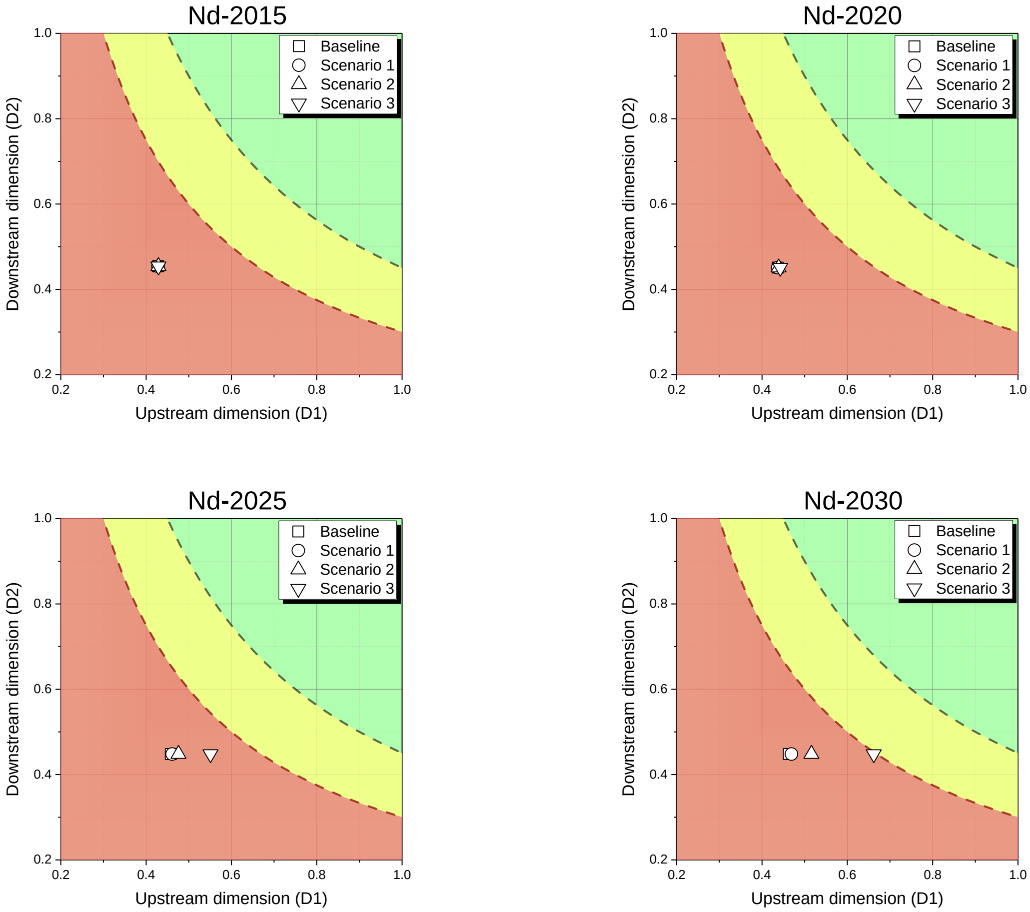


Figure 58: Evolution of resilience for neodymium for all scenarios, 2015-2030

5.3.2 Praseodymium

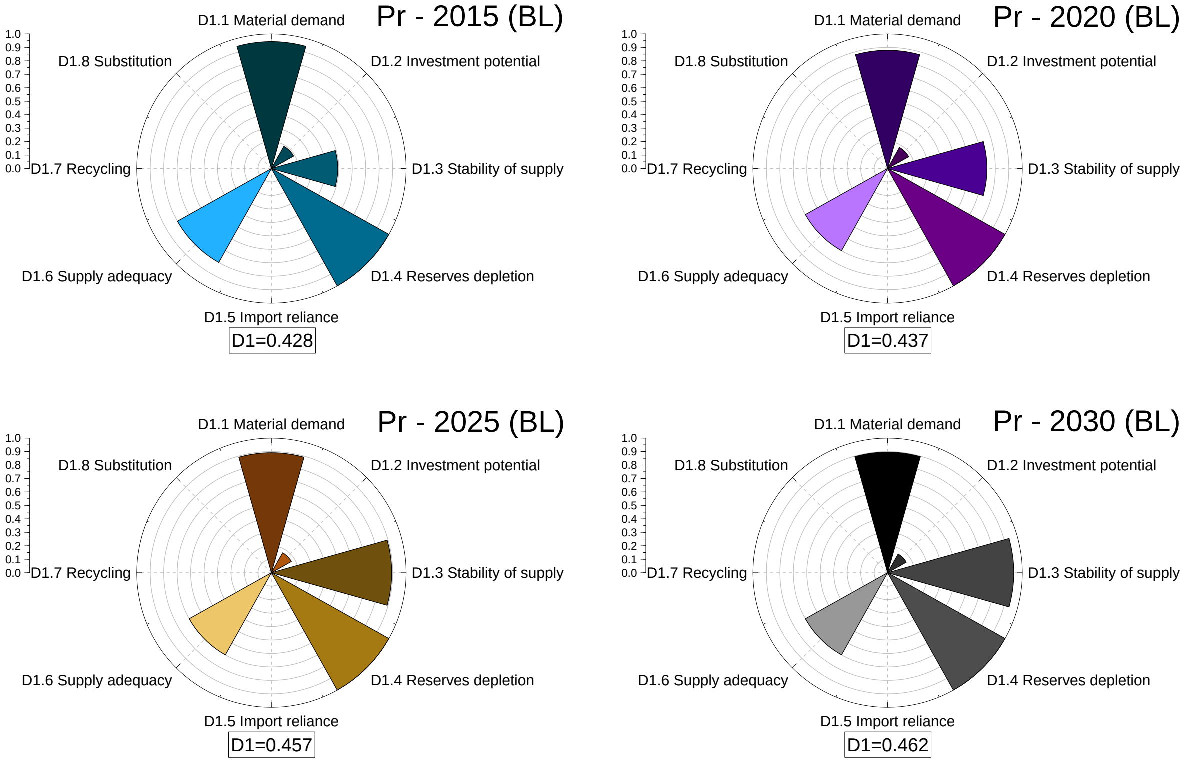


Figure 59: Evolution of D1 indicators according to the conservative baseline (BL) scenario for praseodymium in EVs, 2015-2030

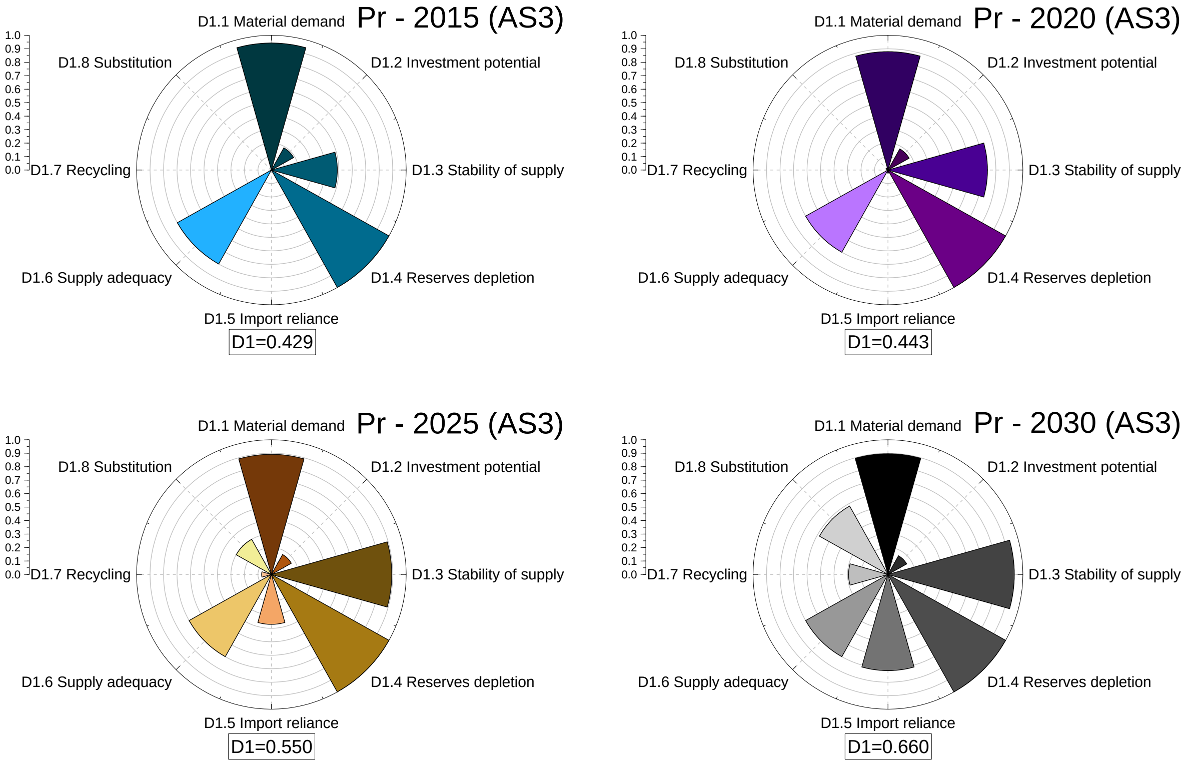


Figure 60: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for praseodymium in EVs, 2015-2030

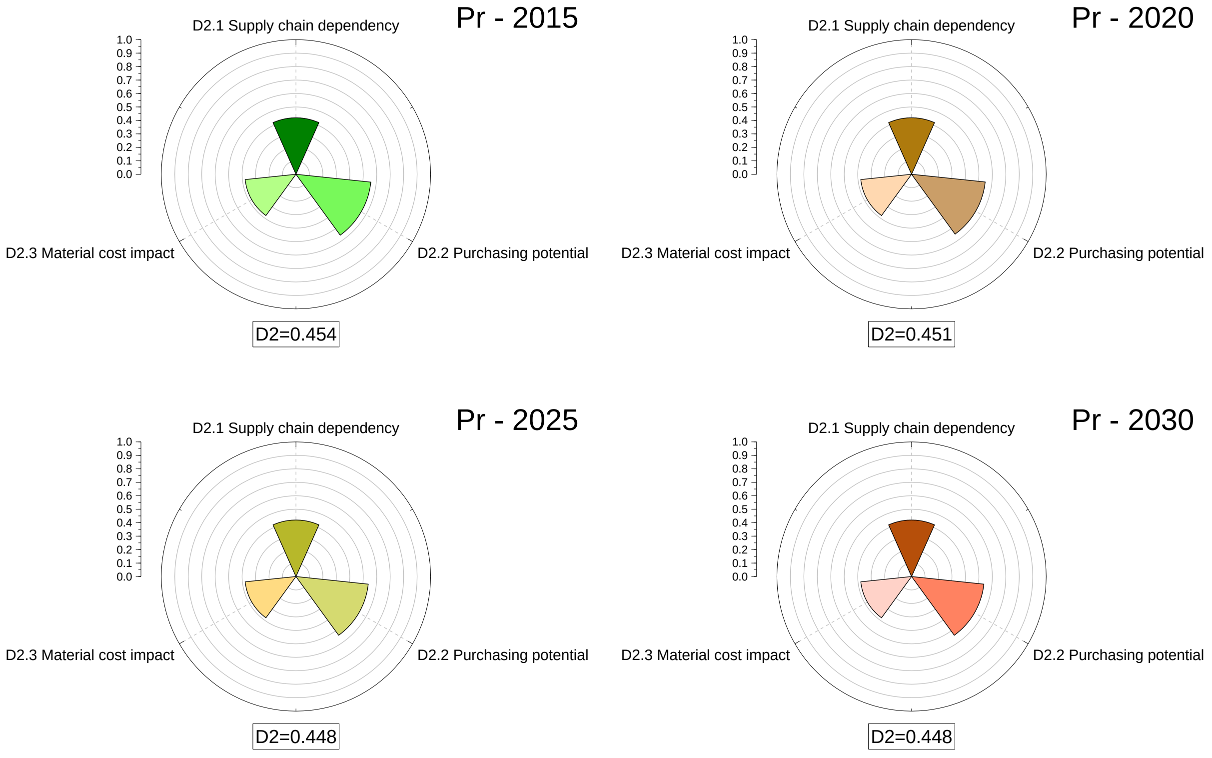


Figure 61: Evolution of D2 indicators for praseodymium in EVs, 2015-2030

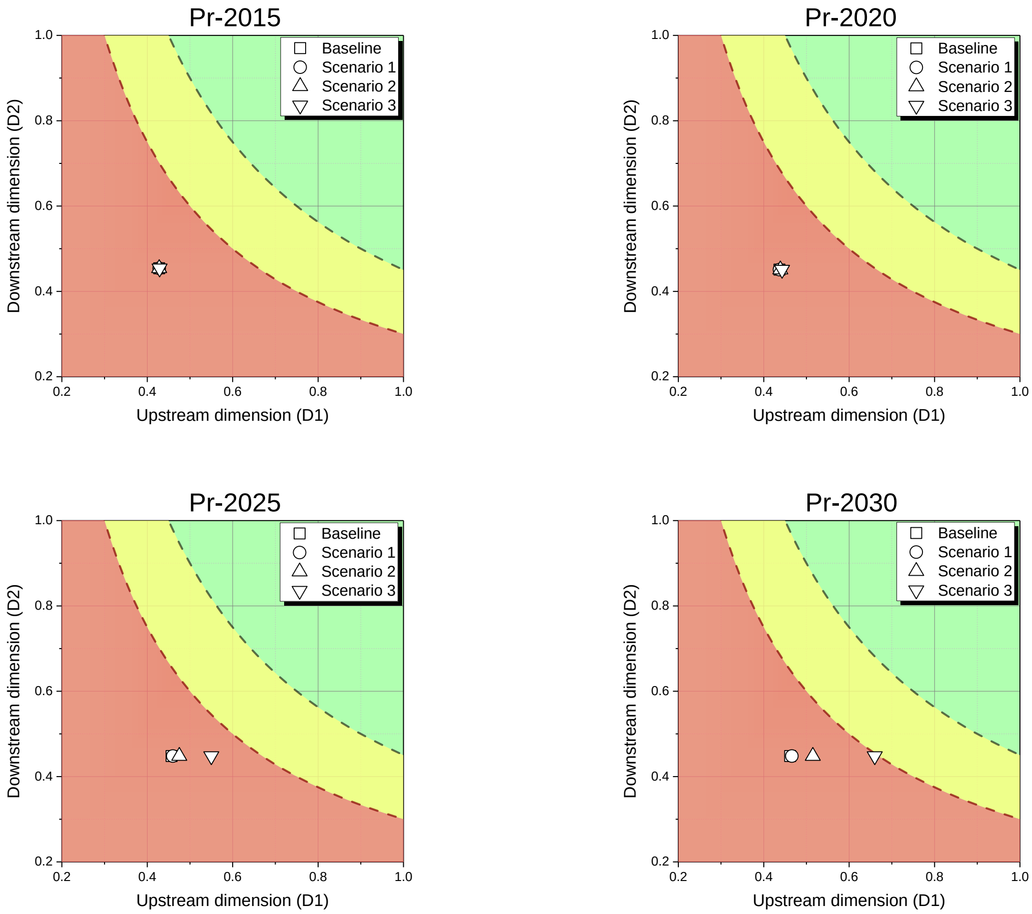


Figure 62: Evolution of resilience for praseodymium in EVs for all scenarios, 2015-2030

5.3.3 Dysprosium

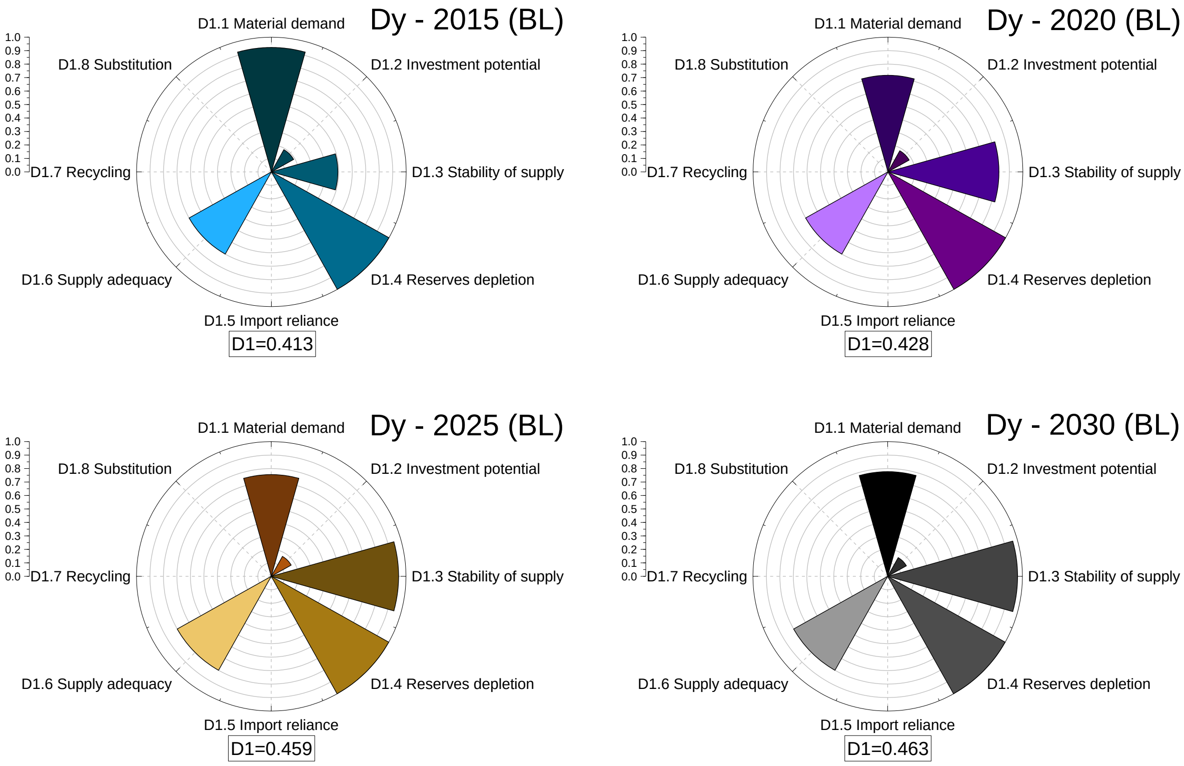


Figure 63: Evolution of D1 indicators according to the conservative baseline (BL) scenario for dysprosium in EVs, 2015-2030

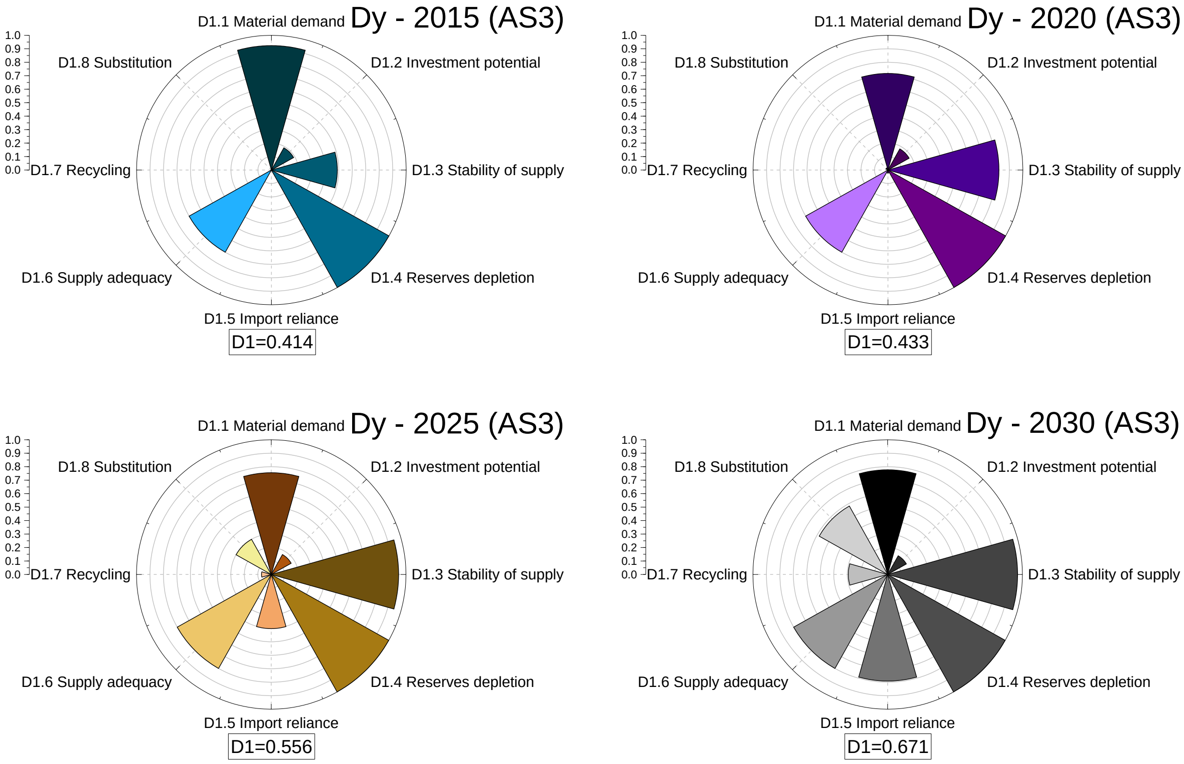


Figure 64: Evolution of D1 indicators according to the most optimistic assessment scenario 3 (AS3) for dysprosium in EVs, 2015-2030

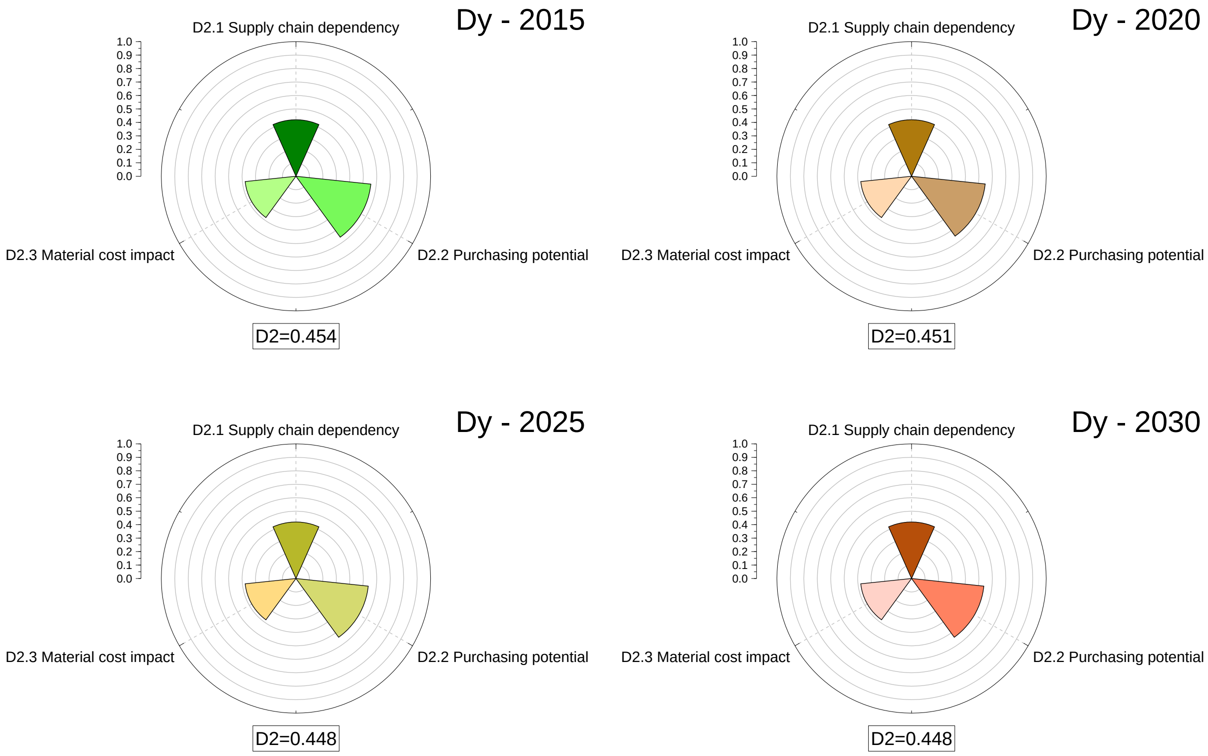


Figure 65: Evolution of D2 indicators for dysprosium in EVs, 2015-2030

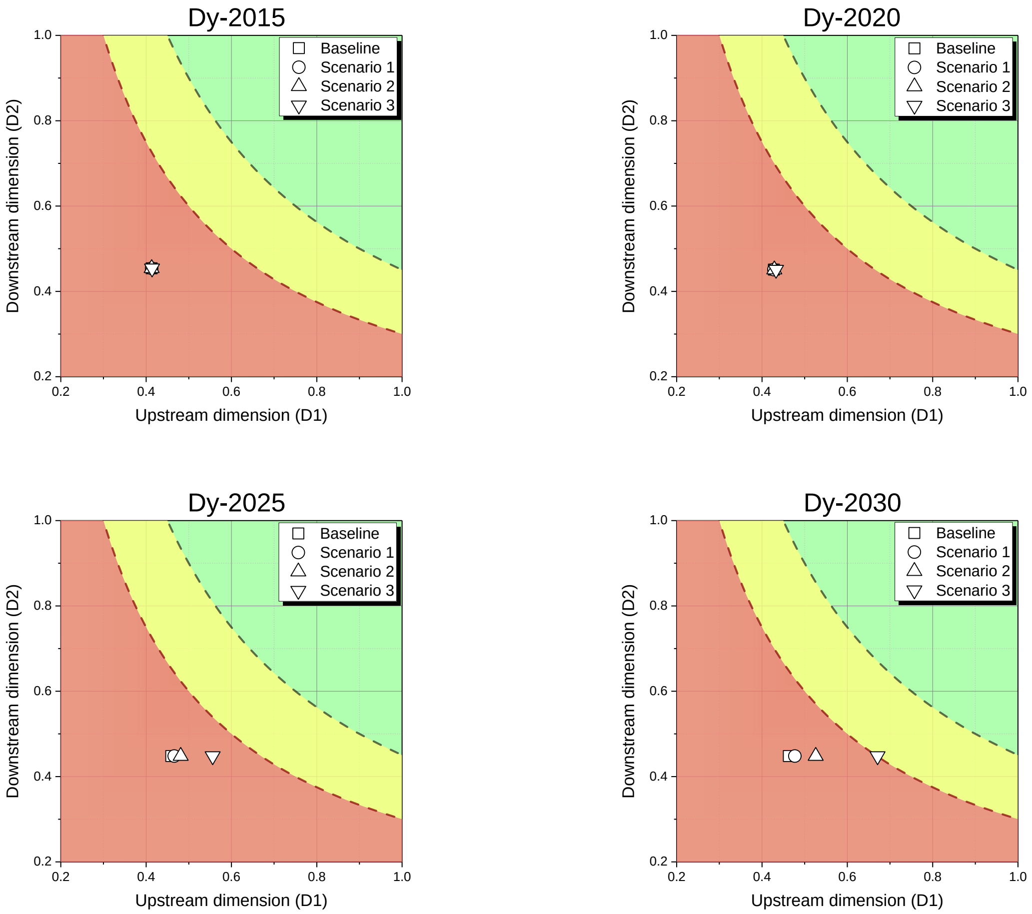


Figure 66: Evolution of resilience for dysprosium in EVs for all scenarios, 2015-2030

5.4 EV technology resilience charts

The resilience charts for EV technology in 2015, 2020, 2025 and 2030 under the baseline and assessment scenario 3 are presented below (Figure 67 and Figure 68).

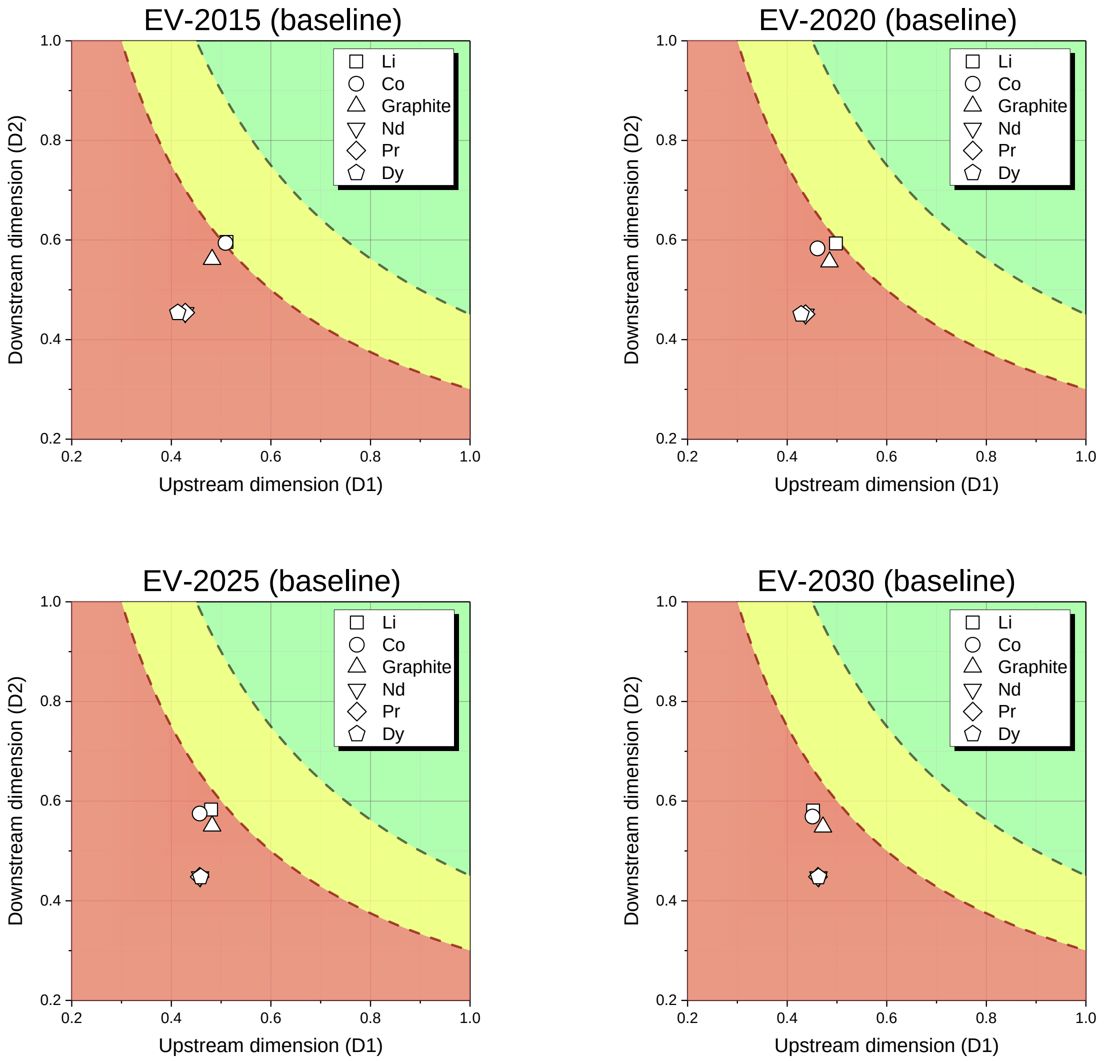


Figure 67: Resilience charts for materials required in EV technology in 2015, 2020, 2015 and 2030 for the conservative baseline scenario

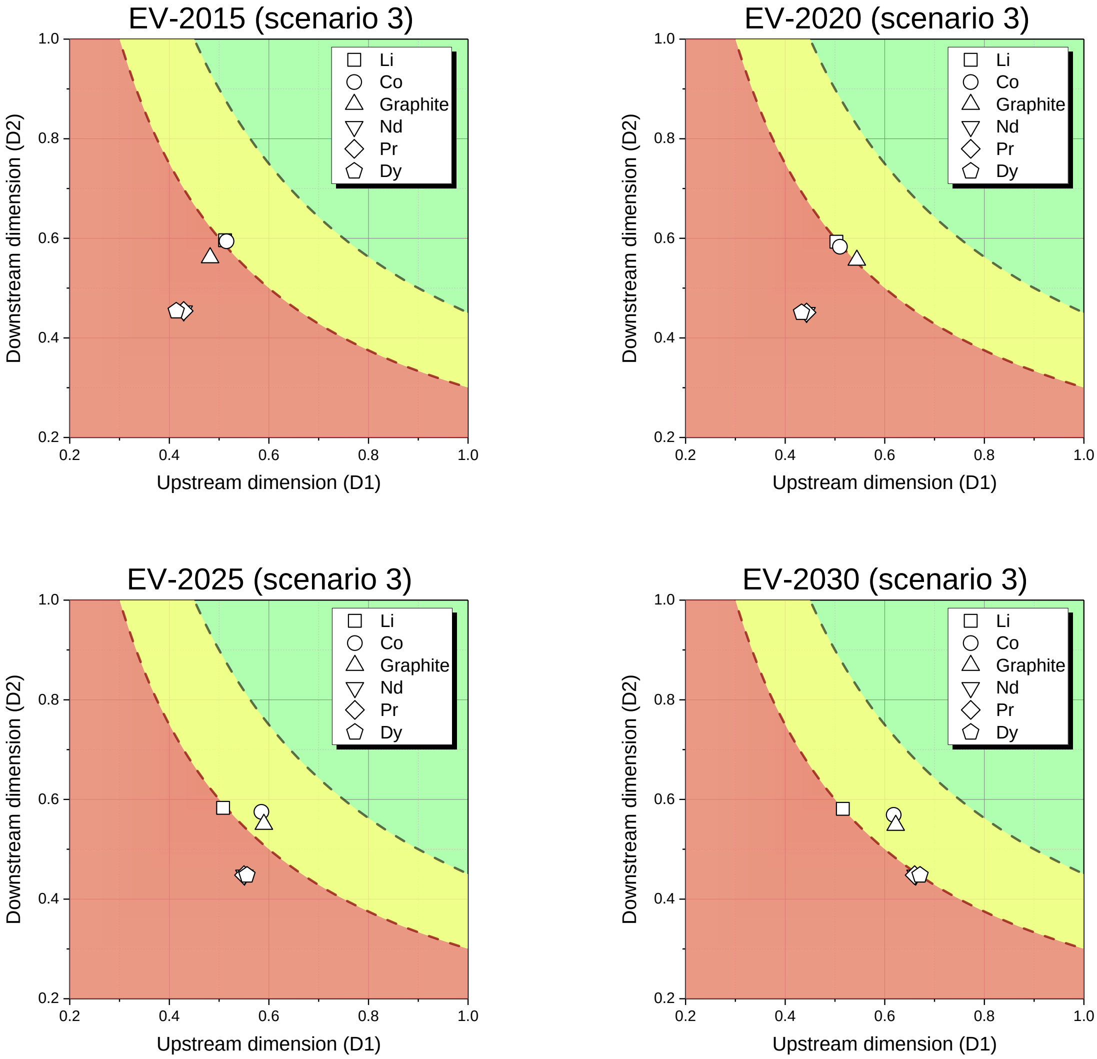


Figure 68: Resilience charts for materials required in EV technology in 2015, 2020, 2025 and 2030 for the most optimistic assessment scenario 3

Two components pertinent to electric vehicles were assessed in the present study: batteries and electric traction motors.

As regards the materials required for EV batteries, current EU resilience to supply bottlenecks is low for graphite (C) and medium for lithium (Li) and cobalt (Co). Over time, for these three materials the resilience remains very close to the border between the low- and medium-resilience zones (Figure 69).

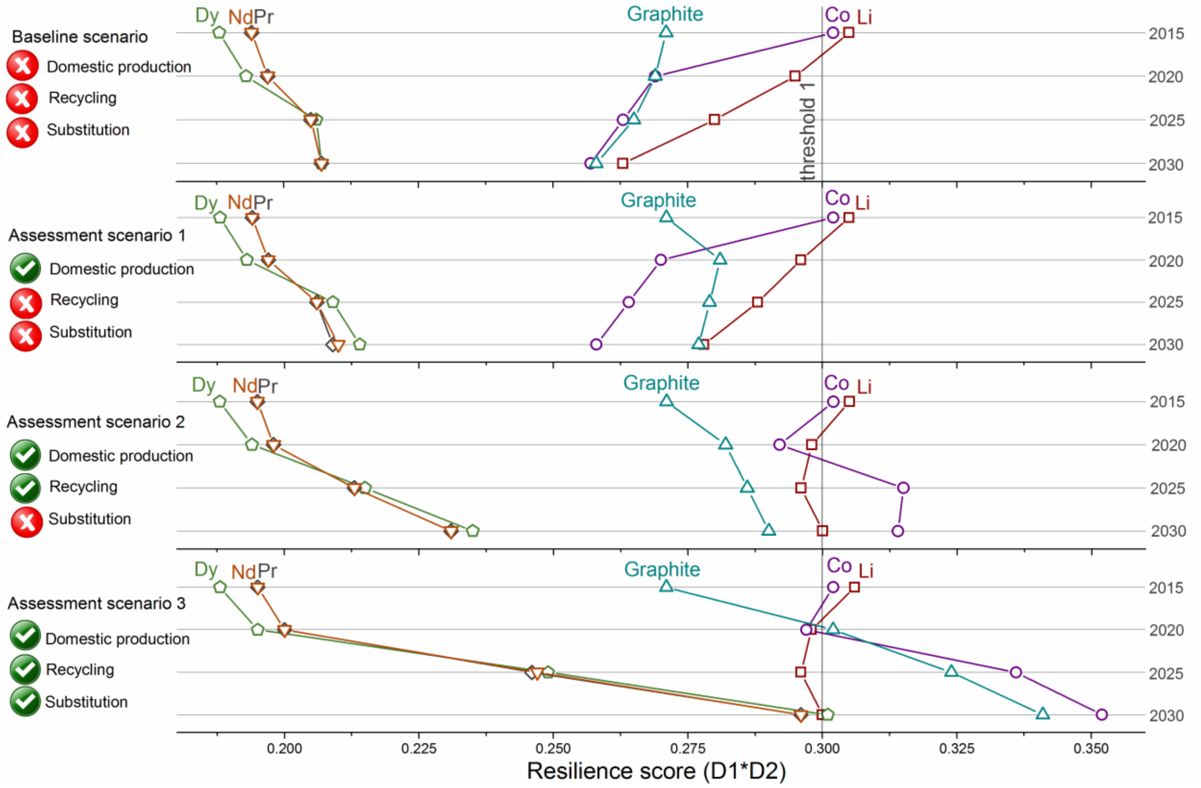


Figure 69: Variation in EU resilience to supply bottlenecks of materials used in electric vehicles; threshold 1 fixed at 0.3 represents the border between low and medium resilience

Lithium

The situation for Li deteriorates until 2020 in all scenarios due to an increase in demand. Over these five years, EU resilience decreases by -3.3 % in the baseline scenario, -2.8 % for scenario 1 and -2.3 % for the other two scenarios, thereby moving to the low-resilience zone. In all scenarios, EU resilience remains in the low-resilience zone in 2020.

In the period between 2020 and 2025, EU resilience falls progressively in the baseline scenario (-5 %) and scenario 1 (-2.7 %), while there is no significant change for scenarios 2 and 3 (<1 % drop). In other words, increasing EU Li production and recycling can mitigate the drop in resilience marginally, while no substitution effects are expected during this period. Increasing the EU domestic production could have a slightly larger effect on resilience (+2.3 %) than recycling (+2 %).

In the last five-year period (2025-2030) the situation for Li further deteriorates in the baseline scenario (-6.2 %) and scenario 1 (-3.5 %) compared to the previous period. For scenarios 2 and 3, EU resilience recovers slightly by 1.1 % thanks to recycling. In these two cases, resilience reaches the threshold between the low and medium zones. However, Li does not recover to its initial (2015) resilience level in any of these scenarios.

To summarise, Li recycling coupled with its production in the EU are the mitigation measures with highest potential in the 2030 time frame. However, these will not be sufficient to induce medium-resilience levels. Moreover, an alternative technology to Li-ion batteries seems unlikely in the period under consideration. To secure the deployment of EVs in the EU, as regards the supply of batteries, the downstream dimension needs to be strengthened by increasing the production of processed materials, initiating cell-manufacturing activities within EU as well as assuring long-term contracts with component suppliers outside the EU.

Cobalt

Similarly to Li, the EU resilience deteriorates notably in 2020 in the baseline scenario and scenario 1. Over these five years, it drops by around 11 % in these two scenarios. The decrease is far smaller in the other two scenarios (-3.4 % and -2.8 %). In all the scenarios, however, the EU resilience drops from medium in 2015 to low in 2020.

In the period between 2020 and 2025, the EU resilience further decreases in the baseline scenario and scenario 1 (~ -2 %). A noticeable increase in resilience is observed for scenario 2 (+7.7 %) and scenario 3 (+13 %), thanks primarily to recycling and to substitution measures, returning to the medium-resilience zone in these two scenarios, well above the 2015 level.

Between 2025 and 2030, the situation for Co further deteriorates in the baseline scenario and scenario 1 (-2.4 %). This indicates that an increase in demand adversely affects resilience in the baseline scenario, and that new EU mine production cannot counter this effect (scenario 1). In scenario 2, the EU resilience does not change significantly (-0.2 %), while in scenario 3 a further large increase is achieved (+4.6 %) over the same period. In other words, recycling alone can cope with the higher demand but potential substitution measures have an even greater impact during this period. Overall, resilience to bottlenecks in the supply of Co increases in scenarios 2 and 3 between 2015 and 2030.

To summarise, both recycling and substitution can provide the most influential mitigation strategy in the 2030 time frame. These measures will increase the resilience to supply bottlenecks of Co, which would remain in the medium zone. Reinforcement of the downstream production is also an important step for cobalt.

Graphite

The EU resilience for graphite remains low for all scenarios until 2020, except for scenario 3 where it crosses the threshold into the medium-resilience zone. While it drops in the baseline scenario (<1 %), it improves by 3.8 %, 4.2 % and 11.7 % in the other three scenarios, respectively.

In the period between 2020 and 2025, a slight fall is observed in the EU resilience in the baseline scenario (-1.6 %) and scenario 1 (-0.7 %). A small increase in resilience is observed for scenario 2 (+1.3 %) due to recycling efforts. A much larger increase is achieved for scenario 3 (+7.2 %) as a result of the addition of substitution.

Between 2025 and 2030, the situation for graphite further deteriorates in the baseline scenario (-2.5 %) and scenario 1 (-0.6 %) compared to the previous period. In scenario 2, it improves (+1.5 %), although not sufficiently to leave the low-resilience zone. In scenario 3, a further large increase is achieved (+5.1 %), yet not enough to reach the threshold with the high-resilience zone.

To summarise, substitution is an effective mitigation strategy for graphite, while potential EU domestic production increase and recycling also play important roles. Yet the combination of all three measures is not sufficient to assure a high level of resilience by 2030. The independence and adequacy of the downstream supply are also crucial in the case of graphite.

As regards the materials required for EV electric traction motors – neodymium (Nd), praseodymium (Pr) and dysprosium (Dy) – the current EU resilience (2015 data) is low in terms of their supply – a long way from the threshold between the low and medium zones.

Neodymium, praseodymium, dysprosium

The EU resilience for these three materials remains low in all scenarios until 2020 with marginal increases (up to +2.6 % for Nd, +2.5 % for Pr and +4 % for Dy) mainly due to the enhanced diversification of supply.

During the 2020-2025 period, the EU resilience rises slightly, even in the baseline scenario: ~ +4 % for Nd and Pr and +6.6 % for Dy. A steady increase is also observed for Nd and Pr in scenario 1 (~ 4.5 %) and +8.2 % growth is reached for Dy. A larger increase is observed for scenario 2: +7.5 % for Nd and Pr and +11 % for Dy. As for scenario 3, a significant increase is achieved: +23 % for Nd and Pr and +27 % for Dy. Moreover, in 2025, the EU resilience for the three materials remains low in all scenarios.

In the last five-year period (2025-2030), the EU resilience increases slightly (between 0.8 and 1.2 % for all three materials) in the baseline scenario as a result of diversified supply and between 1.5 and 2.5 % in scenario 1 (resulting from potential increase in mine production in the EU). A large increase is observed for all materials for scenario 2 (~ +8-9 %) and an even larger one, of around 20 %, is visible in scenario 3. In this favourable scenario, Nd and Pr move close to the border between low- and medium-resilience zones, while Dy moves into the medium-resilience zone.

To summarise, even though the resilience situation for the supply of Nd, Pr and Dy seems to improve until 2030, thanks to enhanced stability of supply and the expansion of EU mine capacity, potential increases in both the degree of substitution and in the recycling rate will be most effective in bringing the EU resilience to a near-medium level in 2030.

6 Conclusions

This study addresses materials supply issues in meeting the EU's increasing deployment rates of three important low-carbon technologies: wind energy, solar (photovoltaic) energy and electric vehicles.

A specific methodology has been developed allowing for the assessment of the EU resilience to potential bottlenecks in the supply of materials along their value chain. In total, 15 materials have been screened. The results are expressed in terms of EU resilience to material supply bottlenecks.

Currently (2015 data), as expected, the EU has low resilience to the supply of rare earth elements – neodymium, praseodymium and dysprosium – for the permanent magnets required for the wind and electric vehicle sectors. The analysis shows that the current resilience to supply constraints on graphite for lithium-ion batteries is also low, although to a lesser extent. The EU shows slightly better resilience, defined here as medium, for the silicon, silver and indium required for the photovoltaic sector, as well as lithium and cobalt for electric vehicle batteries. No supply issues are currently related to carbon fibre composite (CFC) for wind turbine blades. In view of low demand levels, several materials – namely copper, gallium, selenium, cadmium and tellurium – required for the photovoltaic sector do not face potential supply bottlenecks either today or until 2030. According to the proposed methodology, a full assessment of the EU resilience related to the supply of these materials has not been performed.

The EU resilience to potential bottlenecks in the supply of materials is expected to change until 2030, driven by a number of factors. Besides the expected evolution of supply actors over time, with variable impacts on the stability of the supply of both raw and processed materials, these factors encompass developments in the recycling and substitution fields as well as advances in the EU mine production. The extent to which they can influence the EU resilience has been assessed in three different scenarios, as follows:

- Assessment scenario 1 considers increasing EU mine production;
- Assessment scenario 2 builds on scenario 1 and also takes into account secondary production (recycling);
- Assessment scenario 3 adds substitution to scenario 2.

The above scenarios are assessed against a conservative baseline scenario which does not include any of these three mitigation measures, namely increasing EU mine production, recycling and substitution. The role of these mitigation measures and their combination is assessed for each material in the present analysis.

As regards the wind sector, the EU resilience remains low for neodymium, praseodymium and dysprosium until 2030 if there are no mitigation measures in place (baseline scenario). The potential to increase mine production in the EU, based on an assessment of current development-stage projects (scenario 1), has limited impact on the resilience of these rare earth elements. The analysis shows that recycling (scenario 2), if developed as forecasted could have a more tangible effect on improving resilience, although this is not sufficient to reach the medium-resilience level in 2025. It is only thanks to substitution, applied in addition to an increase in mining production and recycling (scenario 3), that EU resilience can improve to medium level for the three rare earth elements in 2025. In 2030, increased recycling rates, as envisaged in scenario 2, might just be sufficient to raise EU resilience to the medium level. However, the supply situation for the three rare earth elements can only be substantially improved if substitution measures are applied, moving them closer to the high resilience zone in 2030.

No specific resilience issues are foreseen today or until 2030 for the Carbon Fibre Composites used for wind turbine blades.

With respect to the photovoltaic sector, the EU resilience to the supply of indium is deteriorating rapidly, and is already low in 2020 in all scenarios. It remains low in all scenarios until 2030, except for scenario 3 where, thanks to the potential for substitution, it increases to medium level. The EU resilience to the supply of silver could fall from 2025 onwards to a low level if mitigation measures are not taken. With mitigation measures in place, the resilience for silver is evaluated as medium in all scenarios. The EU resilience related to the supply of silicon, although progressively decreasing over time, remains medium in all scenarios.

In the electric vehicle sector, the EU resilience to bottlenecks in the supply of neodymium, praseodymium and dysprosium remains low until 2030, despite improving slightly. The only exception is in scenario 3 when the EU resilience to the supply of dysprosium reaches the medium-resilience threshold, underlining yet again the importance of substitution. As regards the supply of graphite, the EU resilience is low in all scenarios, except for scenario 3 where it increases to medium in 2020. Already, in 2020, the EU resilience to the supply of lithium deteriorates to low and falls even further until 2030 if no recycling measures are in place. Even if such measures are in place, the resilience will never return to the 2015 level, although it recovers slightly. Similarly to the case for lithium, the EU resilience to the supply of cobalt is already deteriorating to low in 2020 in all scenarios. If no recycling and substitution are in place, the situation continues to deteriorate until 2030. Recycling would contribute to returning the EU resilience to the medium level, even exceeding the 2015 level. Substitution further improves the situation in 2030, although not enough to reach a high level of resilience.

Different mitigation measures are best suited to specific materials. For the majority of the materials investigated, it appears that substitution has been found to be the most effective measure for increasing resilience, followed by recycling and upscaling the EU’s production of raw materials.

For the wind and electric vehicle sectors, the substitution of rare earths in permanent magnets and the substitution of graphite in batteries would seem to be the most efficient mitigation measures for raising EU resilience to the supply of these materials, followed by recycling and finally ramping-up the EU raw material production. A significant effort is already ongoing at both the EU level and globally on substitution of rare earths in permanent magnets, either via reducing their content or by using an alternative technology. Such alternative technologies are available for both wind generators and electric vehicle motors, in particular for battery electric vehicles, although they are not immune to technical and economic limitations.

In the case of the lithium required for electric vehicle batteries, the EU resilience could be improved mainly by recycling as well as boosting EU primary lithium production, while substitution has no impact within the 2030 time frame. This indicates that recycling, if set up correctly, has the potential to create a continuous and secure secondary stream of lithium supply for the EU in the future. Policies and incentives need to be streamlined to jointly cope with a higher demand for lithium in the future and the growing pile of batteries considered as waste. In the longer term – beyond 2030 – substitution might also play a substantial role for lithium.

In the case of cobalt, which is also required in batteries, if developed at the levels forecast, recycling and substitution would improve EU resilience to supply bottlenecks, while the extent to which cobalt production can be increased in EU is not likely to have an impact.

As concerns the photovoltaic sector, increasing the EU production of silver and silicon is the mitigation measure with the greatest potential, whilst recycling indium mainly from new scrap appears to achieve the most relevant effects. In fact, the recycling of indium from end-of-life applications is expected to be limited because of the diffuse nature of its use.

The analysis has also shown inadequacies in the EU's manufacturing capacity for processing materials and components in the wind energy, photovoltaic and electric vehicle sectors. The independence and adequacy of manufacturing capacities in all steps in the downstream supply chain would be highly beneficial to secure the smooth deployment of these technologies. This is particularly true for electric vehicles where the EU is very dependent on manufacturing capacities along the whole supply chain, and this supply is mainly concentrated in a few Asian countries.

In the wind and photovoltaic sectors, the EU dependency on manufacturing capacities is slightly lower than for electric vehicles. However, improvements in downstream production would also be beneficial, in particular for rare earth elements – neodymium, praseodymium and dysprosium. This can be achieved by expanding existing EU production capacities and building new manufacturing capacities, along the complete materials supply chain.

Finally, this analysis has highlighted the intrinsic difficulty to forecast the future EU resilience due to limited and not always coherent data, uncertainties related to the future technological development as well as actual deployment scenarios. This is particularly evident for the downstream stages of the supply chain.

In addition, large uncertainties related to the implementation of the considered mitigation measures could have significant effect on the determination of the EU resilience.

In spite of such limitations and uncertainties, the present report gives a clear quantitative indication of the EU resilience evolution in view of material supply bottlenecks which may hinder the deployment of low carbon technologies.

In addition, it highlights the importance of the different mitigation measures as well as the necessity to strengthen the EU manufacturing potential along the complete value chain.

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List of abbreviations and definitions

BEV	Battery electric vehicles
CAGR	Cumulative annual growth rate
CIGS	Copper indium gallium diselenide disulphide
CFC	Carbon fibre composites
CR	Collection rate
EV	Electric vehicles
EIP	European Innovation Partnership
EPI	Environmental performance index
GDP	Gross domestic product
GHG	Greenhouse gas emissions
HEV	Hybrid electric vehicles
HHI	Herfindahl-Hirschman Index
ICE	Internal Combustion Engine
IR	Import reliance
JRC	Joint Research Centre
LCO	Lithium cobalt oxide
LCT	Low-carbon technology
LFP	Lithium iron phosphate
LIB	Lithium-ion batteries
LMO	Lithium manganese oxide
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel cobalt manganese oxide
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PHEV	Plug-in electric vehicles
PMSG	Permanent magnet synchronous generators
PV	Photovoltaic
RDI	Reserves depletion index
RMI	Raw Materials Initiative
RMSG	Raw Materials Supply Group
RR	Recovery rate
TCO	Transparent conductive oxide
TF	Thin film
WGI	World Governance Index

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Annex A. Overview of indicators

The following tables give the values of all indicators and an average of each of two dimensions relative to all materials investigated per technology. These values are also shown for the four different assessment scenarios, as described in chapter 2.

Table 2: Scores for indicators and dimensions for neodymium in wind turbines

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.931	0.767	0.831	0.842	0.931	0.767	0.831	0.842	0.931	0.767	0.831	0.842	0.931	0.767	0.831	0.842
D1.2 Investment potential	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160
D1.3 Stability of supply	0.493	0.732	0.892	0.937	0.493	0.732	0.892	0.937	0.493	0.732	0.892	0.937	0.493	0.732	0.892	0.937
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.000	0.000	0.000	0.000	0.000	0.000	0.027	0.047	0.001	0.000	0.256	0.142	0.001	0.025	0.374	0.726
D1.6 Supply adequacy	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.007	0.073	0.292	0.001	0.007	0.073	0.292
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.018	0.300	0.582
D1 Upstream dimension	0.427	0.422	0.449	0.455	0.427	0.422	0.453	0.461	0.427	0.423	0.490	0.509	0.427	0.429	0.543	0.655
D2.1 Supply chain dependency	0.490	0.490	0.490	0.490	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	1.000	0.990	0.980	0.960												
D2 Downstream dimension	0.613	0.608	0.603	0.599	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 3: Scores for indicators and dimensions for praseodymium in wind turbines

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.930	0.755	0.823	0.834	0.930	0.755	0.823	0.834	0.930	0.755	0.823	0.834	0.930	0.755	0.823	0.834
D1.2 Investment potential	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160
D1.3 Stability of supply	0.493	0.738	0.893	0.937	0.493	0.738	0.893	0.937	0.493	0.738	0.893	0.937	0.493	0.738	0.893	0.937
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.000	0.000	0.000	0.000	0.000	0.000	0.022	0.039	0.000	0.005	0.072	0.134	0.001	0.022	0.376	0.714
D1.6 Supply adequacy	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.007	0.073	0.292	0.001	0.007	0.073	0.292
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.018	0.300	0.582
D1 Upstream dimension	0.427	0.422	0.448	0.454	0.427	0.422	0.451	0.459	0.427	0.423	0.466	0.507	0.427	0.428	0.542	0.653
D2.1 Supply chain dependency	0.490	0.490	0.490	0.490	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	1.000	1.000	0.990	0.990												
D2 Downstream dimension	0.613	0.610	0.605	0.605	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 4: Scores for indicators and dimensions for dysprosium in wind turbines

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.891	0.446	0.634	0.676	0.880	0.446	0.634	0.674	0.880	0.446	0.634	0.674	0.882	0.446	0.634	0.675
D1.2 Investment potential	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160
D1.3 Stability of supply	0.493	0.823	0.946	0.965	0.493	0.823	0.946	0.965	0.493	0.823	0.946	0.965	0.493	0.823	0.946	0.965
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.000	0.000	0.000	0.000	0.000	0.000	0.065	0.142	0.000	0.005	0.115	0.237	0.001	0.022	0.415	0.818
D1.6 Supply adequacy	0.700	0.700	0.800	0.800	0.700	0.700	0.800	0.800	0.700	0.700	0.800	0.800	0.700	0.700	0.800	0.800
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.007	0.073	0.292	0.001	0.007	0.073	0.292
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.018	0.300	0.582
D1 Upstream dimension	0.409	0.394	0.444	0.450	0.408	0.394	0.452	0.468	0.408	0.395	0.467	0.516	0.408	0.400	0.542	0.662
D2.1 Supply chain dependency	0.490	0.490	0.490	0.490	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	1.000	0.990	0.990	0.980												
D2 Downstream dimension	0.613	0.608	0.605	0.603	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 5: Scores for indicators and dimensions for carbon fibre composites in wind turbines

Indicator / Dimension	All scenarios			
	2015	2020	2025	2030
D1.1 Material demand	1.000	1.000	1.000	1.000
D1.2 Investment potential	0.190	0.180	0.170	0.160
D1.3 Stability of supply	1.000	1.000	1.000	1.000
D1.4 Reserve depletion	1.000	1.000	1.000	1.000
D1.5 Import reliance	1.000	1.000	1.000	1.000
D1.6 Supply adequacy	1.000	1.000	1.000	1.000
D1.7 Recycling	n.a.	n.a.	n.a.	n.a.
D1.8 Substitution	n.a.	n.a.	n.a.	n.a.
D1 Upstream dimension	0.865	0.863	0.862	0.860
D2.1 Supply chain dependency	0.585	0.585	0.585	0.585
D2.2 Purchasing potential	0.560	0.550	0.540	0.540
D2.3 Material cost impact	0.83	0.83	0.83	0.83
D2 Downstream dimension	0.626	0.623	0.620	0.620

Table 6: Scores for indicators and dimensions for silicon in solar PV

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.974	0.973	0.970	0.967	0.974	0.973	0.970	0.967	0.974	0.973	0.970	0.965	0.974	0.973	0.970	0.965
D1.2 Investment potential	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160
D1.3 Stability of supply	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.217	0.178	0.143	0.116	0.217	0.178	0.143	0.116	0.217	0.178	0.143	0.119	0.217	0.178	0.143	0.119
D1.6 Supply adequacy	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.7 Recycling	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1.8 Substitution	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1 Upstream dimension	0.685	0.677	0.669	0.662	0.685	0.677	0.669	0.662	0.685	0.677	0.669	0.662	0.685	0.677	0.669	0.662
D2.1 Supply chain dependency	0.480	0.450	0.450	0.450	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	0.920	0.890	0.870	0.870												
D2 Downstream dimension	0.592	0.568	0.561	0.561	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 7: Scores for indicators and dimensions for silver in solar PV

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.962	0.965	0.952	0.943	0.962	0.965	0.952	0.943	0.962	0.965	0.952	0.943	0.962	0.965	0.952	0.943
D1.2 Investment potential	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160
D1.3 Stability of supply	0.922	0.930	0.930	0.935	0.922	0.930	0.930	0.935	0.922	0.930	0.930	0.935	0.922	0.930	0.930	0.935
D1.4 Reserve depletion	1.000	0.900	0.700	0.700	1.000	0.900	0.700	0.700	1.000	0.900	0.700	0.700	1.000	0.900	0.700	0.700
D1.5 Import reliance	0.882	0.578	0.474	0.401	0.882	0.979	0.909	0.811	0.882	0.981	0.919	0.835	0.882	0.984	1.000	1.000
D1.6 Supply adequacy	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.009	0.037	0.049	0.001	0.009	0.037	0.049
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.250	0.485
D1 Upstream dimension	0.582	0.531	0.491	0.480	0.582	0.582	0.545	0.531	0.582	0.583	0.551	0.540	0.582	0.585	0.592	0.621
D2.1 Supply chain dependency	0.480	0.430	0.430	0.430	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	0.970	0.950	0.940	0.940												
D2 Downstream dimension	0.602	0.570	0.565	0.565	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 8: Scores for indicators and dimensions for indium in solar PV

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.941	0.940	0.935	0.933	0.941	0.940	0.935	0.933	0.941	0.940	0.935	0.933	0.941	0.940	0.935	0.933
D1.2 Investment potential	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160
D1.3 Stability of supply	0.893	0.909	0.914	0.915	0.893	0.909	0.914	0.915	0.893	0.909	0.914	0.915	0.893	0.909	0.914	0.915
D1.4 Reserve depletion	1.000	0.700	0.700	0.700	1.000	0.700	0.700	0.700	1.000	0.700	0.700	0.700	1.000	0.700	0.700	0.700
D1.5 Import reliance	0.524	0.390	0.286	0.212	0.524	0.427	0.313	0.233	0.524	0.429	0.343	0.290	0.525	0.442	0.423	0.438
D1.6 Supply adequacy	0.850	0.700	0.700	0.700	0.850	0.700	0.700	0.700	0.850	0.700	0.700	0.700	0.850	0.700	0.700	0.700
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.017	0.129	0.195	0.001	0.017	0.129	0.195
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.012	0.080	0.148
D1 Upstream dimension	0.550	0.477	0.463	0.453	0.550	0.482	0.466	0.455	0.550	0.484	0.486	0.487	0.550	0.487	0.506	0.524
D2.1 Supply chain dependency	0.483	0.480	0.480	0.480	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	0.990	0.990	0.990	0.980												
D2 Downstream dimension	0.608	0.603	0.600	0.598	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 9: Scores for indicators and dimensions for lithium in electric vehicles

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.903	0.814	0.789	0.776	0.903	0.814	0.789	0.776	0.903	0.814	0.789	0.776	0.903	0.814	0.789	0.776
D1.2 Investment potential	0.190	0.181	0.170	0.161	0.190	0.181	0.170	0.161	0.190	0.181	0.170	0.161	0.192	0.181	0.170	0.161
D1.3 Stability of supply	0.960	0.965	0.969	0.974	0.960	0.965	0.969	0.974	0.960	0.965	0.969	0.974	0.960	0.965	0.969	0.974
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.038	0.021	0.012	0.008	0.038	0.039	0.123	0.216	0.041	0.053	0.180	0.366	0.041	0.053	0.180	0.366
D1.6 Supply adequacy	1.000	1.000	0.900	0.700	1.000	1.000	0.900	0.700	1.000	1.000	0.900	0.700	1.000	1.000	0.900	0.700
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.014	0.055	0.150	0.003	0.014	0.055	0.150
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
D1 Upstream dimension	0.511	0.498	0.480	0.452	0.511	0.500	0.494	0.478	0.512	0.503	0.508	0.516	0.512	0.503	0.508	0.516
D2.1 Supply chain dependency	0.460	0.460	0.450	0.450	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	0.993	0.988	0.983	0.972												
D2 Downstream dimension	0.596	0.593	0.583	0.581	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 10: Scores for indicators and dimensions for cobalt in electric vehicles

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.947	0.916	0.892	0.864	0.947	0.916	0.892	0.864	0.947	0.916	0.892	0.864	0.947	0.916	0.892	0.864
D1.2 Investment potential	0.192	0.181	0.170	0.161	0.192	0.181	0.170	0.161	0.192	0.181	0.170	0.161	0.192	0.181	0.170	0.161
D1.3 Stability of supply	0.831	0.818	0.846	0.850	0.831	0.818	0.846	0.850	0.831	0.818	0.846	0.850	0.831	0.818	0.846	0.850
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.106	0.072	0.050	0.035	0.106	0.093	0.067	0.052	0.106	0.244	0.419	0.448	0.131	0.279	0.569	0.712
D1.6 Supply adequacy	1.000	0.700	0.700	0.700	1.000	0.700	0.700	0.700	1.000	0.700	0.700	0.700	1.000	0.700	0.700	0.700
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.151	0.352	0.396	0.019	0.151	0.352	0.396
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.036	0.150	0.264
D1 Upstream dimension	0.509	0.461	0.457	0.451	0.509	0.463	0.459	0.453	0.509	0.501	0.547	0.552	0.515	0.510	0.585	0.618
D2.1 Supply chain dependency	0.460	0.455	0.450	0.450	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	0.979	0.954	0.938	0.908												
D2 Downstream dimension	0.594	0.583	0.575	0.569	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 11: Scores for indicators and dimensions for graphite in electric vehicles

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.951	0.902	0.870	0.837	0.951	0.902	0.870	0.837	0.951	0.902	0.870	0.837	0.951	0.902	0.870	0.837
D1.2 Investment potential	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160
D1.3 Stability of supply	0.710	0.788	0.809	0.820	0.710	0.788	0.809	0.820	0.710	0.788	0.809	0.820	0.710	0.788	0.809	0.820
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.007	0.006	0.005	0.005	0.007	0.176	0.210	0.282	0.004	0.180	0.256	0.370	0.004	0.327	0.538	0.742
D1.6 Supply adequacy	1.000	1.000	1.000	0.950	1.000	1.000	1.000	0.950	1.000	1.000	1.000	0.950	1.000	1.000	1.000	0.950
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.008	0.050	0.092	0.001	0.008	0.050	0.092
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.148	0.281	0.375
D1 Upstream dimension	0.482	0.485	0.482	0.472	0.482	0.506	0.507	0.506	0.482	0.507	0.519	0.529	0.482	0.544	0.590	0.622
D2.1 Supply chain dependency	0.390	0.387	0.383	0.383	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	0.992	0.986	0.982	0.973												
D2 Downstream dimension	0.561	0.556	0.550	0.548	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 12: Scores for indicators and dimensions for neodymium in electric vehicles

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	**2020**	**2025**	**2030**	**2015**	**2020**	**2025**	**2030**	**2015**	**2020**	**2025**	**2030**	**2015**	**2020**	**2025**	**2030**
D1.1 Material demand	0.944	0.881	0.899	0.906	0.944	0.881	0.899	0.906	0.944	0.884	0.896	0.900	0.944	0.884	0.896	0.900
D1.2 Investment potential	0.190	0.181	0.170	0.161	0.190	0.181	0.170	0.161	0.192	0.181	0.170	0.161	0.190	0.181	0.170	0.161
D1.3 Stability of supply	0.490	0.732	0.892	0.937	0.490	0.732	0.892	0.937	0.493	0.732	0.892	0.937	0.490	0.732	0.892	0.937
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.052	0.000	0.005	0.074	0.139	0.005	0.022	0.374	0.722
D1.6 Supply adequacy	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.007	0.073	0.292	0.003	0.007	0.073	0.292
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.018	0.300	0.582
D1 Upstream dimension	0.428	0.437	0.458	0.463	0.428	0.437	0.461	0.469	0.429	0.439	0.476	0.516	0.429	0.443	0.551	0.662
D2.1 Supply chain dependency	0.420	0.420	0.420	0.420	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	0.380	0.380	0.380	0.380												
D2 Downstream dimension	0.454	0.451	0.448	0.448	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 13: Scores for indicators and dimensions for praseodymium in electric vehicles

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.944	0.879	0.892	0.896	0.944	0.879	0.892	0.896	0.944	0.879	0.892	0.896	0.944	0.879	0.892	0.896
D1.2 Investment potential	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160
D1.3 Stability of supply	0.493	0.738	0.893	0.937	0.493	0.738	0.893	0.937	0.493	0.738	0.893	0.937	0.490	0.738	0.893	0.937
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.000	0.000	0.000	0.000	0.000	0.000	0.021	0.036	0.000	0.005	0.071	0.132	0.005	0.022	0.371	0.714
D1.6 Supply adequacy	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700	0.800	0.700	0.700	0.700
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.007	0.073	0.292	0.003	0.007	0.073	0.292
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.018	0.300	0.582
D1 Upstream dimension	0.428	0.437	0.457	0.462	0.428	0.437	0.460	0.466	0.428	0.439	0.475	0.515	0.429	0.443	0.550	0.660
D2.1 Supply chain dependency	0.420	0.420	0.420	0.420	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	0.380	0.380	0.380	0.380												
D2 Downstream dimension	0.454	0.451	0.448	0.448	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Table 14: Scores for indicators and dimensions for dysprosium in electric vehicles

Indicator / Dimension	Baseline scenario				Scenario 1				Scenario 2				Scenario 3			
	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
D1.1 Material demand	0.924	0.717	0.756	0.778	0.924	0.717	0.756	0.778	0.924	0.717	0.756	0.778	0.924	0.717	0.756	0.778
D1.2 Investment potential	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160	0.190	0.180	0.170	0.160
D1.3 Stability of supply	0.493	0.823	0.946	0.965	0.493	0.823	0.946	0.965	0.490	0.823	0.946	0.965	0.490	0.823	0.946	0.965
D1.4 Reserve depletion	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D1.5 Import reliance	0.000	0.000	0.000	0.000	0.000	0.000	0.052	0.114	0.002	0.005	0.102	0.209	0.004	0.022	0.402	0.792
D1.6 Supply adequacy	0.700	0.700	0.800	0.800	0.700	0.700	0.800	0.800	0.700	0.700	0.800	0.800	0.700	0.700	0.800	0.800
D1.7 Recycling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.007	0.073	0.292	0.002	0.007	0.073	0.292
D1.8 Substitution	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.018	0.300	0.582
D1 Upstream dimension	0.413	0.428	0.459	0.463	0.413	0.428	0.466	0.477	0.413	0.429	0.481	0.526	0.414	0.433	0.556	0.671
D2.1 Supply chain dependency	0.420	0.420	0.420	0.420	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			
D2.2 Purchasing potential	0.560	0.550	0.540	0.540												
D2.3 Material cost impact	0.380	0.380	0.380	0.380												
D2 Downstream dimension	0.454	0.451	0.448	0.448	Idem baseline scenario				Idem baseline scenario				Idem baseline scenario			

Annex B. Supporting information for calculation of indicators

Annex B presents the data, information and assumptions used to perform the calculation of the indicators.

B.1 Wind power sector

B.1.1 Deployment scenarios

The wind power capacity installed and grid-connected in the EU during 2015 was 12.8 GW, of which 9.8 GW was onshore and 3 GW offshore [EWEA, 2016a].

Four scenarios have been considered for the deployment of wind power in the EU until 2030 to calculate the future material demand [EWEA, 2015; EC, 2016a]:

1) **EWEA low scenario**

2) **EWEA central scenario**

3) **EWEA high scenario**

4) **EU reference scenario**

EWEA low scenario: EWEA's low scenario only foresees 251 GW of wind power installations.

EWEA central: EWEA's new central scenario foresees 320 GW of wind power capacity to be installed in the EU in 2030.

EWEA high scenario: The high scenario foresees 392 GW of wind power installed in 2030.

EU reference scenario: The 2016 EU reference scenario foresees 267 GW of wind power installed in 2030: 229 GW onshore and 38 GW offshore.

B.1.2 Assumptions

Penetration rate of the different turbine types

The 2014 share for onshore DD-PMG turbines is 10 % of the total installed onshore capacity [JRC data, partially published in Serrano-González, 2016]. It is assumed that this share will increase to 29 % in 2020 and 44 % in 2030.

The 2014 share for onshore MS/HS-PMG turbines is 18 % of the total installed onshore capacity [JRC data, partially published in Serrano-González, 2016]. It is assumed that this share will increase to 24 % in 2020 and 28 % in 2030.

The 2014 share for offshore DD-PMG turbines is 21 % of the total installed offshore capacity [JRC data, partially published in Serrano-González, 2016]. It is assumed that this share will increase to 84 % in 2020 and 100 % in 2030.

Average turbine capacity

The average turbine capacity for onshore and offshore wind applications was used to derive the number of turbines required to be installed up to 2030 to fulfil the four deployment scenarios considered in the assessment.

The average onshore turbine capacity is considered to be 3 MW in 2015; it is assumed that the average capacity will increase to 4 MW in 2020, 6 MW in 2025 and 10 MW in 2030 (JRC expert opinion).

The average offshore turbine capacity is considered to be 4.2 MW in 2015; it is assumed that the average capacity will increase to 8 MW in 2020, 11 MW in 2025 and 15 MW in 2030 (JRC expert opinion).

Material efficiency

The weight of the permanent magnet required per 1 MW power is considered to be 0.675 tonnes/MW for DD-PMG turbine and 0.12 tonnes/MW for MS/HS-PMG turbine, respectively. The Nd content is calculated as 22.5 % of the permanent magnet weight, Dy content as 4.5 % and Pr content as 7.5 % [Zepf, 2013; Pavel, 2016].

Material cost impact

Since the three materials – Nd, Pr and Dy – are always used in combination to produce a permanent magnet, a common material cost impact (D2.3 indicator) is anticipated and used consistently for all three materials.

Determining the EU demand

The EU demand for Nd, Dy and Pr for the deployment of wind power is calculated on a yearly basis up to 2030 as the sum of the demand of these three materials in the three types of turbines: DD-PMG onshore, MS/HS-PMG onshore and DD-PMG offshore.

Blades

It is assumed that no bottlenecks can occur in the upstream dimension for blades. As noted in the methodology, the recycling and substitution contributions are not taken into account for the assessment of very abundant materials (in this case carbon). Therefore, besides indicator D1.2 (the same for all materials) the rest of the indicators were assumed to be equal to 1, or maximum EU resilience. A full assessment for blades is performed along the downstream dimension.

B.1.3 Indicator D1.1 Material demand

Table 15: Data for calculating D1.1 material demand for neodymium

Neodymium	2015	2020	2025	2030
EU demand for wind (EWEA low scenario)	356	2610	3364	5610
EU demand for wind (EWEA central scenario)	356	6063	5986	7427
EU demand for wind (EWEA high scenario)	356	8798	10363	15638
EU demand for wind (EC reference scenario)	356	2684	693	1156
EU demand, all sectors (EWEA low scenario)	3502	8302	12701	20573
EU demand, all sectors (EWEA central scenario)	3502	11754	15324	22390
EU demand, all sectors (EWEA high scenario)	3502	14490	19700	30602
EU demand, all sectors (EC reference scenario)	3502	8375	10031	16120
Global demand, all sectors	20320	33024	53671	87226
D1.1.1 EWEA 2030 low scenario	0.02	0.08	0.06	0.06
D1.1.1 EWEA 2030 central scenario	0.02	0.18	0.11	0.09
D1.1.1 EWEA 2030 high scenario	0.02	0.27	0.19	0.18
D1.1.1 EC reference scenario	0.02	0.08	0.01	0.01
D1.1.2 EWEA 2030 low scenario	0.10	0.31	0.26	0.27
D1.1.2 EWEA 2030 central scenario	0.10	0.52	0.39	0.33
D1.1.2 EWEA 2030 high scenario	0.10	0.61	0.53	0.51
D1.1.2 EC reference Scenario	0.10	0.32	0.07	0.07
D1.1.3 EWEA 2030 low scenario	0.17	0.25	0.24	0.24
D1.1.3 EWEA 2030 central scenario	0.17	0.36	0.29	0.26
D1.1.3 EWEA 2030 high scenario	0.17	0.44	0.37	0.35
D1.1.3 EC reference scenario	0.17	0.25	0.19	0.18

Note: Demand figures are given in tonnes.

The global demand for Nd and its annual growth rate (10.2 %) until 2030 was estimated combining information from multiple sources: [Roskill, 2015a; Alonso, 2012; Gschneidner, 2012]. The EU demand for Nd was calculated based on information from [MSA, 2015].

Table 16: Data for calculating D1.1 material demand for praseodymium

Praseodymium	2015	2020	2025	2030
EU demand for wind (EWEA low scenario)	119	870	1121	1870
EU demand for wind (EWEA central scenario)	119	2021	1995	2476
EU demand for wind (EWEA high scenario)	119	2933	3454	5213
EU demand for wind (EC reference scenario)	119	895	231	385
EU demand, all sectors (EWEA low scenario)	1095	2643	4020	6492
EU demand, all sectors (EWEA central scenario)	1095	3794	4894	7098
EU demand, all sectors (EWEA high scenario)	1095	4705	6353	9835
EU demand, all sectors (EC reference scenario)	1095	2667	3130	5008
Global demand, all sectors	6350	10266	16598	26835
D1.1.1 EWEA 2030 low scenario	0.02	0.08	0.07	0.07
D1.1.1 EWEA 2030 central scenario	0.02	0.20	0.12	0.09
D1.1.1 EWEA 2030 high scenario	0.02	0.29	0.21	0.19
D1.1.1 EC reference scenario	0.02	0.09	0.01	0.01
D1.1.2 EWEA 2030 low scenario	0.11	0.33	0.28	0.29
D1.1.2 EWEA 2030 central scenario	0.11	0.53	0.41	0.35
D1.1.2 EWEA 2030 high scenario	0.11	0.62	0.54	0.53
D1.1.2 EC reference scenario	0.11	0.34	0.07	0.08
D1.1.3 EWEA 2030 low scenario	0.17	0.26	0.24	0.24
D1.1.3 EWEA 2030 central scenario	0.17	0.37	0.29	0.26
D1.1.3 EWEA 2030 high scenario	0.17	0.46	0.38	0.37
D1.1.3 EC reference scenario	0.17	0.26	0.19	0.19

Note: Demand figures are given in tonnes.

The global demand for Pr and its annual growth rate (10.1 %) until 2030 was estimated combining information from multiple sources: [Roskill, 2015a; Alonso, 2012; Gschneidner, 2012]. The EU demand for Pr was calculated based on information from [MSA, 2015].

Table 17: Data for calculating D1.1 material demand for dysprosium

Dysprosium	2015	2020	2025	2030
EU demand for wind (EWEA low scenario)	71	522	673	1122
EU demand for wind (EWEA central scenario)	71	1213	1197	1485
EU demand for wind (EWEA high scenario)	71	1760	2073	3128
EU demand for wind (EC Reference Scenario)	71	537	139	231
EU demand, all sectors (EWEA low scenario)	225	989	1413	2236
EU demand, all sectors (EWEA central scenario)	225	1679	1937	2600
EU demand, all sectors (EWEA high scenario)	225	2226	2812	4242
EU demand, all sectors (EC Reference Scenario)	225	1003	879	1346
Global demand, all sectors	1270	2140	3606	6076
D1.1.1 EWEA 2030 low scenario	0.06	0.24	0.19	0.18
D1.1.1 EWEA 2030 central scenario	0.06	0.57	0.33	0.24
D1.1.1 EWEA 2030 high scenario	0.06	0.82	0.57	0.51
D1.1.1 EC reference scenario	0.06	0.25	0.04	0.04
D1.1.2 EWEA 2030 low scenario	0.32	0.53	0.48	0.50
D1.1.2 EWEA 2030 central scenario	0.32	0.72	0.62	0.57
D1.1.2 EWEA 2030 high scenario	0.32	0.79	0.74	0.74
D1.1.2 EC reference scenario	0.32	0.53	0.16	0.17
D1.1.3 EWEA 2030 low scenario	0.18	0.46	0.39	0.37
D1.1.3 EWEA 2030 central scenario	0.18	0.78	0.54	0.43
D1.1.3 EWEA 2030 high scenario	0.18	1.04	0.78	0.70
D1.1.3 EC reference scenario	0.18	0.47	0.24	0.22

Note: Demand figures are given in tonnes.

The global demand for Dy and its annual growth rate (11 %) until 2030 was estimated combining information from multiple sources: [Alonso, 2012; Gschneidner, 2012; Hoenderdaal, 2013; Venkatesan, 2014; Roskill, 2015a]. The EU demand for Dy was calculated based on information from [MSA, 2015].

B.1.4 Indicator D1.2 Investment potential

Table 18: Data for calculating D1.2 investment potential for non-EU countries

Non-EU countries	GDP 2015 (bn USD)	GDP 2030 (bn USD)	EPI
Australia	911	1503	63
Brazil	2174	3222	56
Canada	1386	1880	75
China	13325	26307	75
India	4751	11162	67
Japan	4153	4878	59
Russia	2557	4001	84
South Korea	1687	2571	62
USA	15423	22482	81
Total	**46371**	**78008**	**-**

Table 19: Data for calculating D1.2 investment potential for EU countries

EU countries	GDP 2015 (bn USD)	GDP 2030 (bn USD)	EPI
Austria	318	433	79
Belgium	376	521	81
Czech Republic	257	422	91
Denmark	187	247	89
Estonia	26.6	41.7	77
Finland	170	245	90
France	2012	2909	80
Germany	2984	3462	78
Greece	228	379	70
Hungary	177	234	91
Ireland	171	234	91
Italy	1601	2163	79
Luxembourg	37.5	53.7	74
Netherlands	620	899	75
Poland	762	1040	89
Portugal	224	299	91
Slovak Republic	121	184	91
Slovenia	50.5	70.9	82
Spain	1236	1644	82
Sweden	358	532	93
UK	2228	3332	85
Rest(1)	363(2)	368(3)	86
Total	**14508**	**19713**	**-**

Note: (1) Rest includes: Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Malta and Romania. (2) [World Bank, 2016]. The average EPI for these countries was used to scale their GDP total. (3) The 2030 GDP projection for the rest of the countries was obtained using the average GDP-CAGR for the EU-28 for the period 2015 - 2030.

GDP in 2015 and GDP projections in 2030 are taken from the OECD database [OECD, 2016a, OECD, 2016b, World Bank, 2016]. EPI (Environmental Performance Index) refers to the climate & energy indicator, retrieved from [EPI, 2016].

B.1.5 Indicator D1.3 Stability of supply

Table 20: Country production share, HHI and WGI for mining neodymium

Country	2015		2020		2025		2030		WGI scaled
	share	HHI	share	HHI	share	HHI	share	HHI	
Australia	1.51		9.96		11.50		9.79		0.94
Brazil	0.20		0.00		1.22		2.83		0.53
Burundi	0.00		0.00		0.41		0.96		0.30
Canada	0.00		1.36		9.25		16.81		0.95
China	95.13		68.83		42.09		30.65		0.44
Germany	0.00		0.00		0.13		0.09		0.93
Greenland	0.00		5.19		11.02		8.71		0.89
Kenya	0.00		0.00		1.12		2.58		0.40
Kyrgyzstan	0.00		0.11		0.23		0.16		0.35
Madagascar	0.00		0.00		0.49		1.13		0.35
Malawi	0.00		0.00		0.49		1.14		0.44
Mozambique	0.00		0.00		0.17		0.28		0.41
Namibia	0.00		0.00		0.02		0.04		0.61
Russia	1.27		0.85		3.57		7.43		0.38
South Africa	0.00		0.81		3.27		3.85		0.60
Sweden	0.00		0.00		0.49		1.14		0.97
Tanzania	0.00		4.07		8.25		5.94		0.43
USA	1.72		7.75		5.63		6.03		0.84
Vietnam	0.16		1.08		0.64		0.45		0.43
Total	**100**	**9057**	**100**	**4944**	**100**	**4944**	**100**	**1555**	

Note: Production shares in 2015 are calculated based on 2015 data available from [MSA, 2016]. For consistency purposes, production allocated to Malaysia in that study was added up to Australia production. The production centre in Malaysia is known to be a processing plant of rare earths mined in Mount Weld, Australia. Production projections in 2020, 2025 and 2030 were obtained according to the procedures in Annex C. The WGI values were derived from [WGI, 2015].

Table 21: Country production share, HHI and WGI for mining praseodymium

Country	2015		2020		2025		2030		WGI scaled
	share	HHI	share	HHI	share	HHI	share	HHI	
Australia	1.51		9.59		11.18		9.52		0.94
Brazil	0.20		0.00		1.37		3.19		0.53
Burundi	0.00		0.00		0.42		0.97		0.30
Canada	0.00		1.25		8.79		16.17		0.95
China	95.14		67.94		41.88		30.64		0.44
Germany	0.00		0.00		0.16		0.11		0.93
Greenland	0.00		5.14		11.03		8.83		0.89
Kenya	0.00		0.00		1.10		2.57		0.40
Kyrgyzstan	0.00		0.17		0.35		0.24		0.35
Madagascar	0.00		0.00		0.51		1.19		0.35
Malawi	0.00		0.00		0.52		1.22		0.44
Mozambique	0.00		0.00		0.17		0.27		0.41
Namibia	0.00		0.00		0.02		0.03		0.61
Russia	1.27		0.83		3.52		7.40		0.38
South Africa	0.00		0.77		3.14		3.71		0.60
Sweden	0.00		0.00		0.43		0.99		0.97
Tanzania	0.00		4.04		8.32		6.12		0.43
USA	1.72		8.95		6.29		6.25		0.84
Vietnam	0.16		1.32		0.80		0.56		0.43
Total	**100**	**9057**	**100**	**4835**	**100**	**2214**	**100**	**1536**	

Note: Production shares in 2015 are calculated based on 2015 data available from [MSA, 2016]. For consistency purposes, production allocated to Malaysia in that study was added up to Australia production. The production centre in Malaysia is known to be a processing plant of rare earths mined in Mount Weld, Australia. Production projections in 2020, 2025 and 2030 were obtained according to the procedures in Annex C. The WGI values were derived from [WGI, 2015].

Table 22: Country production share, HHI and WGI for mining dysprosium

Country	2015		2020		2025		2030		WGI scaled
	share	HHI	share	HHI	share	HHI	share	HHI	
Australia	1.55		16.49		5.71		4.49		0.94
Brazil	0.20		0.00		1.44		2.89		0.53
Burundi	0.00		0.00		0.00		0.00		0.30
Canada	0.00		7.83		17.90		17.68		0.95
China	95.10		55.57		27.60		16.80		0.44
Germany	0.00		0.00		0.02		0.01		0.93
Greenland	0.00		11.87		19.61		11.87		0.89
Kenya	0.00		0.00		0.88		1.76		0.40
Kyrgyzstan	0.00		1.18		1.95		1.17		0.35
Madagascar	0.00		0.00		0.89		1.78		0.35
Malawi	0.00		0.00		0.16		0.32		0.44
Mozambique	0.00		0.00		0.12		0.16		0.41
Namibia	0.00		0.00		0.77		1.07		0.61
Russia	1.27		0.74		2.10		3.69		0.38
South Africa	0.00		0.64		1.84		1.58		0.60
Sweden	0.00		0.00		1.97		3.94		0.97
Tanzania	0.00		0.60		0.99		0.60		0.43
USA	1.72		4.99		16.00		30.14		0.84
Vietnam	0.16		0.09		0.05		0.03		0.43
Total	**100**	**9051**	**100**	**3589**	**100**	**1776**	**100**	**1713**	

Note: Production shares in 2015 are calculated based on 2015 data available from [MSA, 2016]. For consistency purposes, production allocated to Malaysia in that study was added up to Australia production. The production centre in Malaysia is known to be a processing plant of rare earths mined in Mount Weld, Australia. Production projections in 2020, 2025 and 2030 were obtained according to the procedures in Annex C. The WGI values were derived from [WGI, 2015].

B.1.6 Indicator D1.4 Reserves depletion

Table 23: Data for calculating D1.4 reserves depletion for neodymium

Neodymium	2015	2020	2025	2030
Reserves REO (mio. tonnes)	130	129.9	129.7	129.3
Reserves Nd oxide (thousand tonnes)	20800	20780	20748	20696
Global demand (tonnes)	20320	32904	53283	86281
RDI (years)	**1024**	**632**	**389**	**240**

REO reserves are taken from [USGS, 2016]. Reserves for neodymium oxides were calculated as 16 % of the REO reserves [Gschneidner, 2012].

Table 24: Data for calculating D1.4 reserves depletion for praseodymium

Praseodymium	2015	2020	2025	2030
Reserves REO (mio. tonnes)	130	129.9	129.7	129.3
Reserves Pr oxide (thousand tonnes)	6500	6498	6495	6490
Global demand (tonnes)	6350	10266	16598	26835
RDI (years)	**1024**	**633**	**391**	**242**

Reserves for praseodymium oxides were calculated as 5 % of the REO reserves [Gschneidner, 2012].

Table 25: Data for calculating D1.4 reserves depletion for dysprosium

Dysprosium	2015	2020	2025	2030
Reserves REO (mio. tonnes)	130	129.9	129.7	129.3
Reserves Dy oxide (thousand tonnes)	1300	1300	1300	1300
Global demand (tonnes)	1270	2140	3606	6076
RDI (years)	**1024**	**607**	**360**	**214**

Reserves for dysprosium oxides were calculated as 1 % of the REO reserves [Gschneidner, 2012].

B.1.7 Indicator D1.5 Import reliance

Table 26: Import reliance on neodymium for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
EWEA low scenario	100	100	100	100
EWEA central scenario	100	100	100	100
EWEA high scenario	100	100	100	100
EC reference scenario	100	100	100	100
Scenario 1				
EWEA low scenario	100	100	97	95
EWEA central scenario	100	100	98	96
EWEA high scenario	100	100	98	97
EC reference scenario	100	100	97	94
Scenario 2				
EWEA low scenario	100	100	92	86
EWEA central scenario	100	100	93	86
EWEA high scenario	100	100	93	87
EC reference scenario	100	100	92	84
Scenario 3				
EWEA low scenario	100	98	62	27
EWEA central scenario	100	98	63	28
EWEA high scenario	100	98	63	29
EC reference scenario	100	98	62	26

Data used in the calculations of IR are given in Table 15 (EU demand) and Table 27 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 27: EU production, recycling and substitution of neodymium

Neodymium	**2015**	**2020**	**2025**	**2030**
EU production (tonnes)	0	0	349	994
EU recycling rate (%)	0	0	5	10
EU substitution rate (%)	0	2	30	58

EU production in 2015 is based on data available from [MSA, 2015]. Projections in 2020, 2025 and 2030 refer to mine capacities, obtained according to the procedures and references in Annex C. Recycling and substitution rates are based on the assumptions presented under Table 33 and Table 34.

Table 28: Import reliance on praseodymium for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
EWEA low scenario	100	100	100	100
EWEA central scenario	100	100	100	100
EWEA high scenario	100	100	100	100
EC reference scenario	100	100	100	100
Scenario 1				
EWEA low scenario	100	100	98	96
EWEA central scenario	100	100	98	96
EWEA high scenario	100	100	98	97
EC reference scenario	100	100	97	95

Scenario 2	2015	2020	2025	2030
EWEA low scenario	100	100	93	86
EWEA central scenario	100	100	93	87
EWEA high scenario	100	100	93	88
EC reference scenario	100	100	92	85
Scenario 3				
EWEA low scenario	100	98	63	28
EWEA central scenario	100	98	63	29
EWEA High scenario	100	98	63	30
EC reference scenario	100	98	62	27

Data used in the calculations of IR are given in Table 16 (EU demand) and Table 29 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 29: EU production, recycling and substitution of praseodymium

Praseodymium	2015	2020	2025	2030
EU production (tonnes)	0	0	96	261
EU recycling (%)	0	0	5	10
EU substitution (%)	0	2	30	58

Note: See Table 27 for information on the data sources.

Table 30: Import reliance on dysprosium for various scenarios (%)

Baseline	2015	2020	2025	2030
EWEA 2030 low scenario	100	100	100	100
EWEA 2030 central scenario	100	100	100	100
EWEA 2030 high scenario	100	100	100	100
EC reference scenario	100	100	100	100
Scenario 1				
EWEA low scenario	100	100	93	86
EWEA central scenario	100	100	95	88
EWEA high scenario	100	100	97	93
EC reference scenario	100	100	89	77
Scenario 2				
EWEA low scenario	100	100	88	77
EWEA central scenario	100	100	90	78
EWEA high scenario	100	100	92	83
EC reference scenario	100	100	84	67
Scenario 3				
EWEA low scenario	100	98	58	18
EWEA central scenario	100	98	60	20
EWEA high scenario	100	98	62	25
EC reference scenario	100	98	54	9

Data used in the calculations of IR are given in Table 17 (EU demand) and Table 31 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 31: EU production, recycling and substitution of dysprosium

Dysprosium	2015	2020	2025	2030
EU production (tonnes)	0	0	95	312
EU recycling rate (%)	0	0.5	5	10
EU substitution rate (%)	0	2	30	58

Note: See Table 27 for information on the data sources.

B.1.8 Indicator D1.6 Supply adequacy

Table 32: Nd, Pr, and Dy global demand and mining capacity

	2015	2020	2025	2030
Nd: Global demand all sectors (tonnes)	20320	33024	53671	87226
Nd: Global mine capacities (tonnes)	26464	33487	55931	80558
Nd: Capacities utilisation (%)	77	99	96	108
Pr: Global demand all sectors (tonnes)	6350	10266	16598	26835
Pr: Global mine capacities (tonnes)	7845	9982	16515	23604
Pr: Capacities utilisation (%)	81	103	101	114
Dy: Global demand all sectors (tonnes)	1270	2140	3606	6076
Dy: Global mine capacities (tonnes)	1365	2340	4739	7894
Dy: Capacities utilisation (%)	93	91	76	77

See Table 15, Table 16 and Table 17 for information on global demand data sources for Nd, Pr and Dy, respectively. Mine capacities in 2015, 2020, 2025 and 2030 were obtained following the procedures described in Annex C.

B.1.9 Indicator D1.7 Recycling

Table 33: Nd, Pr, Dy global recycling rates (%)

Materials	2015	2020	2025	2030
Nd	0	<1	7	30
Pr	0	<1	7	30
Dy	0	<1	7	30

It is very difficult to judge the future increase in the recycling rate of rare earths. The diffused nature of rare earths in end-use applications poses a significant challenge for their recycling. Currently, recycled Nd comes mostly from computer hard-disc drives (HDDs), even though HDDs do not represent the largest application of Nd. Within the NdFeB magnets for HDDs, the potential for closing the loop is significant: up to 57 % in 2017 is predicted as an achievable rate [Sprecher, 2014]. However, compared to the NdFeB production capacity, the recovery potential from HDDs is relatively small – in the range 1-3 %.

Nd recycling from magnets and other applications is forecast to achieve 40 % in the next 20 years [Dai, 2016].

The outcome of recycling of 500gr PM has been published, demonstrating the reuse of the entire alloy at relatively low energy and cost [Fraunhofer, 2015].

Several projects dedicated to permanent magnet recycling are either approved or under way in China [Roskill, 2015a].

For the current analysis, a gradual increase in the global recycling rate of up to 30 % is assumed as a more conservative approach.

At the EU level, a recycling rate of Nd, Pr and Dy of only 10 % is considered by 2030. There is currently no recycling of these three rare earths in the EU. The main future sources of these materials able to assure a sufficient material flow to justify opening new recycling facilities in the EU would be wind turbine generators and electric vehicle motors. However, up to 2030, most of the wind turbines will still be in operation (assuming a 30 years lifetime). As for the EV sector, vehicles sold before 2020 will become available for recycling by 2030 (assuming an average lifetime of 10 years), providing enough material for recycling: several million EV, resulting from the calculations.

It should be noted that the same recycling rates at global and EU level are also assumed for Nd, Pr and Dy in the EV sector.

B.1.10 Indicator D1.8 Substitution

Table 34: Nd, Pr, Dy global substitution rates (%)

Materials	2015	2020	2025	2030
Nd	0	2	30	58
Pr	0	2	30	58
Dy	0	2	30	58

Although rare earth substitution in PM is difficult to achieve, turbine generators and electric motors currently exist which do not use rare earths and are now produced commercially. Indeed, most of the wind turbines installed in the EU do not use PM generators and thus do not require rare earths. The same applies for electric motors; several EV models are currently using induction motors. Therefore, substituting a rare earth by using another technology is possible although it adversely affects the efficiency (in particular for a wind turbine). The development of new rare-earth-free electric motors is also being researched today.

PM is the major applications for Nd, Pr and Dy. Substitution solutions exist and new solutions might be commercialised within five to 10 years. This allows a relatively high substitution rate (around 60%) to be assumed for Nd, Pr and Dy. The same rates are assumed for rare earths in permanent magnets in both wind turbines and EV motors. However, future trends contemplate smaller, more compact products with greater efficiency, which is why the full replacement of the rare earths cannot be assumed within the 2030 time frame.

It should be noted that the same substitution rates are also assumed at both the global and EU level for Nd, Pr and Dy in the EV sector.

B.1.11 Indicator D2.1 Supply chain dependency

To perform the supply chain analysis, the main companies and their production/assembly capacity were identified for each step, as well as the location of their production sites. In addition, the production and assembly capacity were allocated to the production sites and aggregated at country level. This allowed for the derivation of the production/assembly capacity shares for each step of the supply chain. The data used for this assessment mainly stems from [FTI, 2015] and where relevant - additional references have been used.

Permanent magnets step: China leads the market with almost 55 % of the global market, followed by Japan (approx. 30 %) and Europe (approx. 15 %).

[FTI, 2015] source gives the capacity production of the major permanent magnet producers. It is assumed that the production takes place in the home country of the said companies. No capacity data could be retrieved for European manufacturers. Thus, the figures quoted there refer to the production level in 2014 [IndexBox, 2016].

Permanent magnet generators step: China leads the market with over 45 % of the global market, followed by Europe (approx. 30 %) and India (approx. 14 %).

Most of the capacities are retrieved from [FTI, 2015]. However, capacities are not always disaggregated among the various types of generators (e.g. DFIG, PMG, EESC, etc.). In such cases, it was assumed that 20 % – the approximate market share of PMG-based turbines in 2014 – of the overall capacity related to PMGs.

Additional references where found for Gamesa’s assembly capacity [Gamesa, 2015] and Siemens [WindPowerMonthly, 2011], while the capacity of ABB is not taken into account in Table 35. ABB seems to be leading the wind turbine generators sector, although the locations of ABB’s 17 factories could not be identified.

Further assembly capacity has been identified, but could not be quantified, in Brazil, Czech Republic, Germany, Italy, Japan, Korea and Portugal.

Disclaimer: FTI indicates an assembly capacity of > 14 000 MW/y for permanent magnet based generators. Applying the above-mentioned method gave a total figure of more than double (35 000MW/y).

Table 35: Country production share, HHI and WGI for relevant steps in the supply chain (Nd, Pr, Dy)

Country	2015		2020		2025		2030		WGI
	share	HHI	share	HHI	share	HHI	share	HHI	scaled
Step 1: Magnet alloys/powder									
China	83		83		83		83		0.44
Japan	10		10		10		10		0.89
USA	3		3		3		3		0.84
EU	1		1		1		1		1.00
Other	3		3		3		3		0.50
Total	**100**	**7064**	**100**	**7064**	**100**	**7064**	**100**	**7064**	
Step 2: Permanent magnets (PM)									
China	54		54		54		54		0.44
Japan	30		30		30		30		0.89
EU	15		15		15		15		1.00
Total	**100**	**4102**	**100**	**4102**	**100**	**4102**	**100**	**4102**	
Step 3: PM generators									
China	46		46		46		46		044
EU	27		27		27		27		1.00
India	14		14		14		14		0.47
Mexico	9		9		9		9		0.49
Serbia	3		3		3		3		0.56
USA	1		1		1		1		0.84
Total	**100**	**3111**	**100**	**3111**	**100**	**3111**	**100**	**3111**	
Step 4: Wind turbine assembly									
EU	30		30		30		30		1.00
Brazil	5		5		5		5		0.53
China	42		42		42		42		0.44
India	13		13		13		13		0.47
USA	10		10		10		10		0.84
Total	**100**	**2947**	**100**	**2947**	**100**	**2947**	**100**	**2947**	

The data are used to assess D2.1 indicator for Nd, Pr and Dy.

Wind turbine assembly step: China leads the market with over 40 % of the global market, followed by Europe (approx. 30 %), India and the USA (over 10 % each).

[FTI, 2015] provides the global turbine manufacturing capacity announced at the end of 2014 at the continental level. By using a textual description, this data could be further disaggregated by the origin of the OEMs (e.g. capacity per continental manufacturers per continent, such as European OEMs production in Europe, in America, in Asia, etc.). It should be noted though that only the main 15 OEMs are covered. The capacities have been complemented at country level based on a list of factories for most of the manufacturers [Acciona, 2016; ENERCON, 2016; SENVION, 2014; SENVION, 2016; SUZLON, 2016; Wobben, 2016]. References indicating assembly capacities have also been taken into consideration. When no capacity could be found, facilities located in the same region were assumed to have the same capacity.

Under the assumption that the assembly of a turbine requires the same effort, independent of its rated power, the capacities in MW have been converted into number of turbines. To this end, the rated power of the turbines produced in the facility has been used. 3MW has been assumed in cases where such information was not available.

Blades

Both the supply of and demand for CFCs are concentrated in Europe, the USA and Asia [CEMAC, 2016c]. Blades are produced in many countries around the globe, which is probably due to transport limitations. China leads the market with approximately 47 % of the global market, followed by Europe (approx. 25 %) and the USA (approx. 10 %).

Similarly to the shares in turbine assembly, most of the capacities are retrieved from [FTI, 2015] and re-arranged at country level, based on the location of the production facilities. Additional references may provide capacities in terms of units/blades. Under the assumption that the manufacture of a blade requires the same effort, independent of its rated power, the capacities in MW have been converted into capacity in the number of blades. To this end, the rated power of the turbines produced in the facility has been used. 3MW for three blades has been assumed where this information was not available.

Table 36: Country production share, HHI and WGI for relevant steps in the supply chain (CFC)

Country	2015		2020		2025		2030		WGI scaled
	share	HHI	share	HHI	share	HHI	share	HHI	
Step 1: Carbon fibre manufacturing									
Europe	27.7		27.5		27.5		27.5		1.00
USA	26.2		25.3		25.3		25.3		0.89
Asia (Japan and China)	44.7		42.0		42.0		42.0		0.67
Other countries	1.4		5.2		5.2		5.2		0.50
Total	**100**	**3455**	**100**	**3188**	**100**	**3188**	**100**	**3188**	
Step 2: Blades manufacturing									
Australia	0.3		0.3		0.3		0.3		0.94
Brazil	7.7		7.7		7.7		7.7		0.53
Canada	1.5		1.5		1.5		1.5		0.95
China	46.9		46.9		46.9		46.9		0.44
Europe	24.1		24.1		24.1		24.1		1.00
India	6.0		6.0		6.0		6.0		0.47
Mexico	1.1		1.1		1.1		1.1		0.49
South Korea	0.2		0.2		0.2		0.2		0.73
Turkey	2.2		2.2		2.2		2.2		0.52
USA	9.9		9.9		9.9		9.9		0.89
Total	**100**	**2988**	**100**	**2988**	**100**	**2988**	**100**	**2988**	
Step 3: Wind turbine assembly									
Europe	30.4		30.4		30.4		30.4		1
Brazil	5.0		5.0		5.0		5.0		0.53
China	41.7		41.7		41.7		41.7		0.44
India	12.5		12.5		12.5		12.5		0.47
USA	10.4		10.4		10.4		10.4		0.89
Total	**100**	**2947**	**100**	**2947**	**100**	**2947**	**100**	**2947**	

Table 37: Parameters for calculating D2.1 supply chain dependency for the wind energy sector (Nd, Pr, Dy)

	2015	2020	2025	2030
$A_{\text{step 1}}$	0.61	0.61	0.61	0.61
$B_{\text{step 1}}$	0.01	0.01	0.01	0.01
$D2.1_{\text{step 1}}$	0.31	0.31	0.31	0.31
$A_{\text{step 2}}$	0.82	0.82	0.82	0.82
$B_{\text{step 2}}$	0.15	0.15	0.15	0.15
$D2.1_{\text{step 2}}$	0.49	0.49	0.49	0.49
$A_{\text{step 3}}$	0.87	0.87	0.87	0.87
$B_{\text{step 3}}$	0.27	0.27	0.27	0.27
$D2.1_{\text{step 3}}$	0.57	0.57	0.57	0.57
$A_{\text{step 4}}$	0.89	0.89	0.89	0.89
$B_{\text{step 4}}$	0.30	0.30	0.30	0.30
$D2.1_{\text{step 4}}$	0.60	0.60	0.60	0.60
D2.1 (Nd, Pr, Dy)	**0.49**	**0.49**	**0.49**	**0.49**

Table 38: Parameters for calculating D2.1 supply chain dependency for the wind energy sector (CFC)

	2015	2020	2025	2030
$A_{\text{step 1}}$	0.93	0.93	0.93	0.93
$B_{\text{step 1}}$	0.28	0.25	0.25	0.25
$D2.1_{\text{step 1}}$	0.60	0.59	0.59	0.59
$A_{\text{step 2}}$	0.87	0.87	0.87	0.87
$B_{\text{step 2}}$	0.24	0.24	0.24	0.24
$D2.1_{\text{step 2}}$	0.56	0.56	0.56	0.56
$A_{\text{step 3}}$	0.89	0.89	0.89	0.89
$B_{\text{step 3}}$	0.30	0.30	0.30	0.30
$D2.1_{\text{step 3}}$	0.60	0.60	0.60	0.60
D2.1 (CFC)	**0.58**	**0.58**	**0.58**	**0.58**

B.1.12 Indicator D2.2 Purchasing potential

GDP per capita was obtained dividing the GDP by the population, using current data and forecasts from OECD [OECD, 2016a, 2016b, 2016c]. EPI (Environmental Performance Index) refers to the climate & energy indicator, retrieved from [EPI, 2016].

Table 39: Data for calculating D2.2 purchasing potential for non-EU countries

Non-EU countries	GDP per capita 2015 (USD)	GDP per capita 2030 (USD)	EPI
Australia	38075	49946	63
Brazil	10827	14890	56
Canada	38395	45047	75
China	9508	18102	75
India	3705	7561	67
Japan	32809	41834	59
Russia	17488	27063	84
South Korea	33332	49293	62
USA	47994	62717	81
Average	**12918**	**20038**	**-**

Table 40: Data for calculating D2.2 purchasing potential for EU countries

EU countries	GDP per capita 2015 (USD)	GDP per capita 2030 (USD)	EPI
Austria	37303	48225	79
Belgium	33127	42329	81
Czech Republic	24427	40693	91
Denmark	33341	42209	89
Estonia	20324	34486	77
Finland	31100	41996	90
France	31130	42379	80
Germany	36753	43616	78
Greece	20083	33503	70
Hungary	18110	25451	91
Ireland	37468	46041	91
Italy	25982	34067	79
Luxembourg	74993	94295	74
Netherlands	36531	51123	75
Poland	20068	28263	89
Portugal	21585	30246	91
Slovak Republic	22453	34686	91
Slovenia	24442	33979	82
Spain	26639	36232	82
Sweden	36595	49389	93
UK	34535	47097	85
Rest (1)	9252	9884	86
Average	**28495**	**38058**	-

Note: (1) Rest includes: Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Malta and Romania. The average EPI for these countries was used to scale their GDP per capita total.

B.1.13 Indicator D2.3 Material cost impact

Table 41: Parameters for calculating D2.3 material cost impact for wind power (Nd)

Neodymium	2015	2020	2025	2030
E (thousand USD/tonne)	71.2	108	148	148
F (tonne/MW)	0.03	0.11	0.22	0.35
G (thousand USD/MW)	1400	1400	1400	1400
D2.3 (Nd)	**1**	**0.99**	**0.98**	**0.96**

E (USD/tonne) is the Nd oxide price [Statista, 2016a]; since no price forecast is given for 2030, the same price is considered as for 2025.

F (tonne/MW) is the average Nd material intensity in wind: it is calculated by dividing the total demand for Nd by the total installed wind power – onshore and offshore – in 2015, 2020, 2025 and 2030 (indicator D1.1). Of course, the F values are similar for each deployment scenario.

G (USD/MW) is the turbine cost per MW [IRENA, 2012].

Table 42: Parameters for calculating D2.3 material cost impact for wind power (Pr)

Praseodymium	2015	2020	2025	2030
E (thousand USD/tonne)	121	123	119	119
F (tonne/MW)	0.01	0.04	0.07	0.12
G (thousand USD/MW)	1400	1400	1400	1400
D2.3 (Pr)	**1**	**1**	**0.99**	**0.99**

E (USD/tonne) is the Pr oxide price [Statista, 2016b]; since no price forecast is given for 2030, the same price is considered as for 2025.

F (tonne/MW) is the average Pr material intensity in wind: it is calculated by dividing the total demand for Pr by the total installed wind power – onshore and offshore – in 2015, 2020, 2025 and 2030 (indicator D1.1). Of course, the F values are similar for each deployment scenario.

G (USD/MW) is turbine cost per MW [IRENA, 2012].

Table 43: Parameters for calculating D2.3 material cost impact for wind power (Dy)

Dysprosium	**2015**	**2020**	**2025**	**2030**
E (thousand USD/tonne)	456	454	378	378
F (tonne/MW)	0.01	0.02	0.04	0.07
G (thousand USD/MW)	1400	1400	1400	1400
D2.3 (Dy)	**1**	**0.99**	**0.99**	**0.98**

E (USD/tonne) is the Dy oxide price [Statista, 2016c]; since no price forecast is given for 2030, the same price is considered as for 2025.

F (tonne/MW) is the average Dy material intensity in wind: it is calculated by dividing the total demand for Dy by the total installed wind power – onshore and offshore – in 2015, 2020, 2025 and 2030 (indicator D1.1). Of course, the F values are similar for each deployment scenario.

G (USD/MW) is turbine cost per MW [IRENA, 2012].

Calculating D2.3 materials cost impact for wind power (CFC)

D2.3 indicator for blades is calculated using data and information from [IRENA, 2012] and [CEMAC, 2016c]. A cost breakdown for wind turbine, based on typical onshore wind turbine is given in [IRENA, 2012]. The blades are representing about 22.2 % of the total turbine cost. The turbine cost is estimated to be on average 1400 USD/kW (grid connection, foundation, planning and miscellaneous excluded). The final cost of the blades would be then around 311 USD/kW. The materials represent around 75 % of the blades cost [CEMAC, 2016c] or around 233 USD/kW. The indicator D2.3 for blades is then calculated based on the numbers above: D2.3 = 0.83. The same D2.3 for blades is assumed until 2030.

B.2 Solar PV power

B.2.1 Deployment scenarios

During 2014, the solar PV power installed capacity in the EU was around 6.6 GW. This value has been used as a starting point for calculating material demand.

Four scenarios have been considered for the deployment of PV power in the EU until 2030 to calculate the future demand for materials:

1) **Solar power Europe 2030: low scenario** [SolarPower Europe, 2015]

2) **Solar power Europe 2030: high scenario** [SolarPower Europe, 2015]

3) **IEA PV Technology Roadmap: hi-ren scenario** [IEA, 2014]

4) **EU reference scenario** [EC, 2016^{a}]

Between 2000 and 2014, the installed solar capacity in the EU-28 was **86.6 GW** [SolarPower Europe, 2015].

Based on the above scenarios, the cumulative installed PV capacity in the EU by 2030 is calculated as follows:

Table 44: Cumulative installed PV capacity in the EU based on four different scenarios

Scenario	2020	2030
Solar power Europe 2030: low scenario capacity	110	284
Solar power Europe 2030: high scenario capacity	137	556
IEA PV Technology Roadmap: hi-ren scenario capacity	117	192
EU reference scenario capacity	119	165

Note: Capacity is given in GW.

B.2.2 Assumptions

Market shares for different PV technologies

The following market shares for the PV technologies being considered were assumed for EU demand calculations in 2015 (JRC experts' estimation):

Table 45: Market shares for different PV technologies in EU solar power

PV technology	Market share
Polycrystalline silicon PV	73 %
Monocrystalline silicon PV	23 %
Amorphous silicon thin-film PV	0.5 %
CIGS thin-film PV	3 %
CdTe thin-film PV	0.5 %

Polycrystalline and monocrystalline silicon PV are assessed together and denoted further as crystalline silicon (c-Si).

The same market shares for the EU are also assumed for 2030, based mainly on the assumption that a significant growth is not expected in the thin-film PV technology market share within this time frame (JRC experts' opinion). In fact, it is considered easier and less capital intensive to invest in different steps of the c-Si production supply chain, which is the dominant PV technology today, while the investments for thin-film are very intensive. Furthermore, such investments have to be implemented throughout the complete supply chain – from raw materials to final thin-film module production.

Demand for c-Si PV materials

Two materials were assessed for c-Si PV technology: silicon (Si) and silver (Ag). To estimate the Si demand in 2015 an average amount of **5 gr/Wp** is anticipated [ITRPV, 2016; JRC, 2016b]. An increase in material efficiency is considered for the future Si demand estimations as a consequence of the expected improvement in PV efficiency up to 2030. The amount of Si required per 1Wp is gradually reduced from 5 gr/Wp to 3.4 gr/Wp in 2030.

The demand for Ag is estimated based on the annual Ag consumption in 2014 and the amount of Ag required for photovoltaics in 2014 [WSS, 2015]. The amount of Ag required per 1Wp is gradually reduced from 0.04 g/Wp (2015) to 0.03 gr/Wp in 2030, due once again to the expected improvement in PV efficiency.

Demand for thin-film CIGS and CdTe materials (kg/MWp)

The amount of materials used in thin-film modules (per unit power) vary significantly in different studies. Therefore, the following procedure is applied in this analysis to assess the amount of materials required for a 1 MW power output:

The surface of a thin-film PV required to produce 1 MW of power output, referred to here as 'power specific surface' in MW/m^2 is calculated as follows:

$$Power\ specific\ surface\ = \frac{Output\ power * Efficieny}{Solar\ irradiance}$$

where the average 'solar irradiance' for the EU is considered to be 1000 W/m^2.

The 'power specific surface' for CIGS and CdTe PV modules was calculated to be 8333 MW/m^2 assuming average module efficiency of 12 %. The material mass (kg) required to produce 1 MW of power output, referred to here as 'material power specific mass', is calculated using the following formula:

$$Material\ power\ specific\ mass = Power\ specific\ surface * material\ density * specific\ material\ volume$$

The 'specific material volume' in m^3/m^2 is the volume corresponding to 1 square meter of PV thin-film module surface. For the specific volume calculations, a thin-film thickness of 2.5 μm is considered for both CIGS and CdTe modules.

The calculated material needs per unit power, according to the present thin-film efficiency (2015), are given in Table 46. An increase in the material efficiency (less material required for 1 MWp) is considered as a consequence of the foreseen improvement in PV thin-film efficiency until 2030. It is assumed that the thin-film efficiency will gradually reach 20 % by 2030. In this case, the power specific surface for CIGS and CdTe PV modules will be reduced to 5000 MW/m^2.

Therefore, the amount of the different materials required for manufacturing CIGS/CdTe thin-film modules needed to generate 1MWp power by 2030 will decrease, as summarised in Table 46.

Table 46: Materials required for 1 MWp power generated by CIGS and CdTe thin-film PV

Materials	Material density (kg/m^3)	Material power specific mass (kg/m^2)	Material fraction in cell (%)	Material requirement (kg/MWp)			
				2015	2020	2025	2030
Cu	8940	0.022	16.26	24	20	17	15
In	7310	0.018	28.08	34	29	24	21
Ga	5100	0.013	5.85	5	4	4	3
Se	4790	0.012	49.81	40	34	28	24
Cd	8650	0.022	47	46	39	32	27
Te	6240	0.016	53	52	44	37	31

The average fraction of the different elements in a thin-film cell, used to calculate the materials required for 1 MWp, has been taken from several scientific publications [Kavlak, 2014; Bruker, 2015]. The resulting materials efficiency values used in the present analysis are comparable to those presented in different publications [Woodhouse, 2013; Stamp, 2014; MIT, 2015].

B.2.3 Indicator D1.1 Material demand

Table 47: Data for calculating D1.1 material demand for indium

Indium	2015	2020	2025	2030
EU demand for CIGS (SolarPower Europe 2030: low scenario)	3.6	3.6	11.7	16
EU demand for CIGS (SolarPower Europe 2030: high scenario)	7.1	8.8	26.3	44.6
EU demand for CIGS (IEA PV Technology Roadmap: hi-ren scenario)	4.5	4.9	5.3	5.7
EU demand for CIGS (EU reference scenario)	7.8	4.3	2.9	3.2
EU demand, all sectors (SolarPower Europe 2030: low scenario)	138	184	253	339
EU demand, all sectors (SolarPower Europe 2030: high scenario)	142	189	268	368
EU demand, all sectors (IEA PV Technology Roadmap: hi-ren scenario)	139	185	247	329
EU demand, all sectors (EU reference scenario)	143	185	244	326
Global demand, all sectors	800	1071	1433	1918

Indium	**2015**	**2020**	**2025**	**2030**
D1.1.1 SolarPower Europe 2030: low scenario	0.005	0.004	0.01	0.01
D1.1.1 SolarPower Europe 2030: high scenario	0.009	0.009	0.02	0.03
D1.1.1 IEA PV Technology Roadmap: hi-ren scenario	0.001	0.001	0.004	0.003
D1.1.1 EU reference scenario	0.01	0.004	0.002	0.002
D1.1.2 SolarPower Europe 2030: low scenario	0.03	0.02	0.05	0.05
D1.1.2 SolarPower Europe 2030: high scenario	0.05	0.05	0.10	0.12
D1.1.2 IEA PV Technology Roadmap: hi-ren scenario	0.03	0.03	0.02	0.02
D1.1.2 EU reference scenario	0.05	0.02	0.01	0.01
D1.1.3 SolarPower Europe 2030: low scenario	0.18	0.18	0.19	0.19
D1.1.3 SolarPower Europe 2030: high scenario	0.19	0.19	0.20	0.20
D1.1.3 IEA PV Technology Roadmap: hi-ren scenario	0.18	0.18	0.18	0.18
D1.1.3 EU reference scenario	0.19	0.18	0.18	0.18

Note: Demand figures are given in tonnes.

The global demand for indium in 2014 is assumed to be 755 tonnes [USGS, 2016]. An annual growth rate of 6 % is assumed until 2030 based on historical data and information from [Eurostat, 2015]. The EU demand for In in 2014 is estimated using information from [MSA, 2015].

Table 48: Data for calculating D1.1 material demand for silver

Silver	**2015**	**2020**	**2025**	**2030**
EU demand for c-Si (SolarPower Europe 2030: low scenario)	141	158	554	823
EU demand for c-Si (SolarPower Europe 2030: high scenario)	281	381	1245	2309
EU demand for c-Si (IEA PV Technology Roadmap: hi-ren scenario)	179	212	251	297
EU demand for c-Si (EU reference scenario)	307	187	138	166
EU demand, all sectors (SolarPower Europe 2030: low scenario)	1947	2177	2810	3345
EU demand, all sectors (SolarPower Europe 2030: high scenario)	2088	2400	3501	4831
EU demand, all sectors (IEA PV Technology Roadmap: hi-ren scenario)	1986	2231	2507	2819
EU demand, all sectors (EU reference scenario)	2113	2206	2394	2687
Global demand, all sectors	27300	32424	38509	45737
D1.1.1 SolarPower Europe 2030: low scenario	0.01	0.01	0.01	0.02
D1.1.1 SolarPower Europe 2030: high scenario	0.01	0.01	0.03	0.05
D1.1.1 IEA PV Technology Roadmap: hi-ren scenario	0.01	0.01	0.01	0.01
D1.1.1 EU reference scenario	0.01	0.01	0.004	0.004
D1.1.2 SolarPower Europe 2030: low scenario	0.07	0.07	0.20	0.25
D1.1.2 SolarPower Europe 2030: high scenario	0.13	0.16	0.36	0.48
D1.1.2 IEA PV Technology Roadmap: hi-ren scenario	0.09	0.10	0.10	0.11
D1.1.2 EU reference scenario	0.15	0.09	0.06	0.06
D1.1.3 SolarPower Europe 2030: low scenario	0.07	0.07	0.07	0.07
D1.1.3 SolarPower Europe 2030: high scenario	0.08	0.07	0.09	0.11
D1.1.3 IEA PV Technology Roadmap: hi-ren scenario	0.07	0.07	0.07	0.06
D1.1.3 EU reference scenario	0.08	0.07	0.06	0.06

Note: Demand figures are given in tonnes.

The global demand for silver and its annual growth rate (2.25 %) until 2030 is estimated combining information from multiple sources: [Cross, 2009; Bullionvault, 2013; EUROSTAT, 2015].

The EU demand for silver in 2014 is calculated based on information from [MSA, 2015]. The EU demand for silver varies for 2015 according to the different deployment scenarios since 2014 has been used as a starting year for the analysis.

Table 49: Data for calculating D1.1 material demand for silicon

Silicon	2015	2020	2025	2030
EU demand for c-Si (SolarPower Europe 2030: low scenario)	16622	17742	59252	83718
EU demand for c-Si (SolarPower Europe 2030: high scenario)	33244	42854	133155	234962
EU demand for c-Si (IEA PV Technology Roadmap: hi-ren scenario)	21210	23867	26856	30220
EU demand for c-Si (EU reference scenario)	36288	21055	14778	16854
EU demand, all sectors (SolarPower Europe 2030: low scenario)(1)	599	723	913	1117
EU demand, all sectors (SolarPower Europe 2030: high scenario)(1)	615	748	987	1268
EU demand, all sectors (IEA PV Technology Roadmap: hi-ren scenario)(1)	603	729	880	1064
EU demand, all sectors (EU reference scenario)(1)	619	726	868	1050
Global demand, all sectors(1)	8019	9993	12453	15519
D1.1.1 Solar power Europe 2030: low scenario	0.002	0.002	0.01	0.01
D1.1.1 Solar power Europe 2030: high scenario	0.004	0.004	0.01	0.02
D1.1.1 IEA PV Technology Roadmap: hi-ren scenario	0.003	0.002	0.002	0.002
D1.1.1 EU reference scenario	0.001	0.002	0.001	0.001
D1.1.2 SolarPower Europe 2030: low scenario	0.03	0.02	0.06	0.07
D1.1.2 SolarPower Europe 2030: high scenario	0.05	0.06	0.13	0.19
D1.1.2 IEA PV Technology Roadmap: hi-ren scenario	0.04	0.03	0.03	0.03
D1.1.2 EU reference scenario	0.06	0.03	0.02	0.02
D1.1.3 SolarPower Europe 2030: low scenario	0.07	0.07	0.07	0.07
D1.1.3 SolarPower Europe 2030: high scenario	0.08	0.07	0.08	0.08
D1.1.3 IEA PV Technology Roadmap: hi-ren scenario	0.08	0.07	0.07	0.07
D1.1.3 EU reference scenario	0.08	0.07	0.07	0.07

Note: Demand figures are given in tonnes or (1) thousand tonnes for all sectors.

The global demand for silicon and its annual growth rate (3.9 %) until 2030 is estimated combining information from multiple sources: [Shah, 2011; ATKearney, 2012; Murthy, 2015; BP, 2016; Statista, 2016d; Statista, 2016e; ISE, 2016]. The EU demand for silicon in 2014 is calculated based on information from [BGS, 2016b]. The EU demand for silicon varies for 2015 according to the different deployment scenarios since 2014 has been used as a starting year for the analysis.

B.2.4 Indicator D1.2 Investment potential

Data for D1.2 calculation are given in Table 18 and Table 19.

B.2.5 Indicator D1.3 Stability of supply

Table 50: Country production share, HHI and WGI for mining indium from zinc ores

Country	2015		2020		2025		2030		WGI
	share	HHI	share	HHI	share	HHI	share	HHI	scaled
Albania	0.00		0.00		0.06		0.21		0.54
Argentina	0.30		0.25		0.30		0.20		0.45
Armenia	0.09		0.23		0.20		0.04		0.48
Australia	11.35		10.99		12.19		13.58		0.94
Bolivia	3.04		2.48		0.93		0.61		0.40
Bosnia and Herzegovina	0.05		0.04		0.04		0.04		0.49
Botswana	0.00		0.00		0.04		0.15		0.70
Brazil	1.14		0.96		1.06		1.36		0.53
Bulgaria	0.09		0.08		0.08		0.08		0.57
Burkina Faso	0.24		0.25		0.25		0.18		0.41
Burma	0.07		0.06		0.06		0.06		0.25

Country	2015		2020		2025		2030		WGI
	share	HHI	share	HHI	share	HHI	share	HHI	scaled
Canada	3.18		4.40		9.48		11.63		0.95
Chile	0.22		0.27		0.33		0.09		0.83
China	37.27		28.54		26.79		27.42		0.44
Colombia	0.00		0.01		0.05		0.03		0.48
Dem. Rep. Congo	0.09		0.08		0.60		1.87		0.17
Dominican Republic	0.00		0.07		0.02		0.07		0.49
Ecuador	0.00		0.00		0.04		0.13		0.39
Egypt	0.00		0.00		0.01		0.02		0.32
Eritrea	0.00		0.73		0.95		0.52		0.18
Ethiopia	0.00		0.00		0.01		0.05		0.35
Fiji	0.00		0.00		0.02		0.07		0.50
Finland	0.29		0.34		0.28		0.25		1.00
France	0.00		0.00		0.02		0.06		0.82
Germany	0.00		0.00		0.02		0.08		0.93
Greece	0.16		0.15		0.13		0.08		0.60
Greenland	0.00		0.41		1.37		1.40		0.89
Guatemala	0.01		0.14		0.14		0.04		0.40
Honduras	0.19		0.16		0.16		0.01		0.39
India	5.91		5.37		5.37		2.77		0.47
Indonesia	0.00		1.15		1.24		0.51		0.49
Iran	0.97		1.20		2.05		1.72		0.30
Ireland	2.44		1.68		1.07		1.77		0.92
Italy	0.00		0.03		0.21		0.51		0.66
Kazakhstan	2.69		3.17		2.96		1.89		0.43
Kenya	0.00		0.00		0.01		0.04		0.40
Korea, North	0.27		0.23		0.22		0.23		0.14
Korea, Republic of	0.01		0.01		0.01		0.01		0.73
Kosovo	0.05		0.04		0.04		0.05		0.46
Laos	0.02		0.02		0.02		0.02		0.38
Macedonia	0.22		0.02		0.02		0.02		0.58
Malaysia	0.00		0.01		0.00		0.00		0.67
Mexico	4.79		5.24		5.11		4.70		0.49
Mongolia	0.39		0.33		0.35		0.21		0.53
Montenegro	0.00		0.04		0.12		0.12		0.58
Morocco	0.34		0.22		0.18		0.03		0.48
Myanmar	0.00		0.13		0.15		0.06		0.25
Namibia	1.37		1.20		0.64		0.71		0.61
Nigeria	0.07		0.06		0.06		0.06		0.25
Oman	0.00		0.00		0.00		0.00		0.60
Pakistan	0.07		0.24		0.00		0.00		0.29
Papua New Guinea	0.00		0.02		0.01		0.02		0.42
Peru	10.07		8.65		9.46		9.34		0.49
Philippines	0.12		0.11		0.10		0.11		0.50
Poland	0.57		0.48		0.64		1.06		0.76
Portugal	0.40		0.82		0.68		0.38		0.78
Romania	0.00		0.02		0.01		0.03		0.59
Russia	1.42		7.46		3.70		2.75		0.38
Saudi Arabia	0.15		0.26		0.49		0.77		0.48
Serbia	0.00		0.00		0.00		0.00		0.56
South Africa	0.22		1.76		1.74		1.73		0.60
Spain	0.22		0.51		0.63		0.46		0.74
Sweden	1.31		1.38		1.53		1.95		0.97
Tajikistan	0.15		0.13		0.12		0.13		0.31
Thailand	0.22		0.19		0.20		0.25		0.47

Country	2015		2020		2025		2030		WGI scaled
	share	HHI	share	HHI	share	HHI	share	HHI	
Turkey	1.49		1.28		1.40		1.45		0.52
United Kingdom	0.00		0.00		0.02		0.08		0.90
USA	5.84		5.24		2.80		2.69		0.84
Uzbekistan	0.26		0.19		0.19		0.19		0.27
Vietnam	0.15		0.13		0.12		0.13		0.43
Yemen	0.00		0.26		0.25		0.26		0.18
Zambia	0.00		0.13		0.42		0.44		0.48
Total	**100**	**1755**	**100**	**1203**	**100**	**1153**	**100**	**1234**	

In data was derived assuming a fixed indium average content in zinc deposits; thus In data for the mine stage is proportional to zinc mine production, either current or forecasted. Production shares allocated to 2015 are based on 2013 zinc mine production as reported in [USGS, 2013]. The use of less updated data is intended to improve the level of disaggregation per country which in 2015 is rather poor. Production projections in 2020, 2025 and 2030 were obtained according to the procedures in Annex C.

Table 51: Country production share, HHI and WGI for refining indium

Country	2015		2020/2025/2030		WGI scaled
	Share	HHI	Share	HHI	
Belgium	3.3		4.7		0.9
Brazil	0.0		1.1		0.5
Canada	8.5		7.0		0.9
China	48.6		52.8		0.4
France	5.0		2.8		0.8
Germany	1.3		0.0		0.9
Japan	9.5		6.6		0.9
Korea, Rep. of	19.7		17.9		0.7
Peru	2.0		5.2		0.5
Russia	1.3		1.9		0.4
USA	0.7		0.0		0.8
Total	**100**	**2962**	**100**	**3263**	

Indium refinery production in 2015 was retrieved from [USGS, 2016]. Projections in 2020, 2025 and 2030 are based on existing refinery capacities in 2013 as identified in [By-Products, 2015].

Table 52: Country production share, HHI and WGI for mining silver

Country	2015		2020		2025		2030		WGI scaled
	share	HHI	share	HHI	share	HHI	share	HHI	
Argentina	3.91		3.95		4.76		6.47		0.45
Armenia	0.42		0.58		0.32		0.17		0.48
Australia	5.67		5.61		5.79		3.76		0.94
Azerbaijan	0.00		0.08		0.00		0.00		0.38
Bolivia	4.74		3.48		3.12		2.07		0.4
Botswana	0.02		0.33		0.44		0.50		0.7
Brazil	0.06		0.02		0.07		0.23		0.53
Bulgaria	0.07		0.11		0.03		0.07		0.57
Burkina Faso	0.05		0.04		0.04		0.04		0.41
Canada	1.38		3.55		5.50		7.62		0.95
Chile	5.46		7.58		8.01		7.67		0.83
China	12.30		10.40		9.73		9.41		0.44
Colombia	0.06		0.10		0.37		0.71		0.48
Dem. Rep. Congo	0.01		0.01		0.01		0.01		0.3
Dominican Republic	0.46		0.32		0.30		0.30		0.49

Country	2015		2020		2025		2030		WGI scaled
	share	HHI	share	HHI	share	HHI	share	HHI	
Ecuador	0.07		0.39		0.54		0.69		0.39
Eritrea	0.26		0.30		0.42		0.25		0.18
Ethiopia	0.01		0.01		0.01		0.01		0.35
Finland	0.01		0.19		0.17		0.00		1
France	0.00		0.00		0.03		0.03		0.82
Georgia	0.00		0.00		0.05		0.16		0.64
Ghana	0.01		0.01		0.01		0.01		0.54
Greece	0.11		0.38		0.35		0.43		0.6
Guatemala	3.12		2.47		2.33		1.17		0.4
Haiti	0.00		0.00		0.03		0.03		0.26
Honduras	0.12		0.12		0.00		0.00		0.39
India	1.35		1.80		1.75		1.92		0.47
Indonesia	1.11		1.42		1.32		1.60		0.49
Iran	0.37		0.29		0.29		0.30		0.3
Ireland	0.02		0.02		0.02		0.02		0.92
Italy	0.00		0.02		0.02		0.00		0.66
Japan	0.06		0.04		0.04		0.05		0.89
Kazakhstan	1.95		1.54		1.52		1.49		0.43
Kyrgyzstan	0.05		0.04		0.04		0.04		0.35
Laos	0.15		0.21		0.00		0.00		0.38
Macedonia	0.05		0.04		0.04		0.04		0.58
Mali	0.01		0.01		0.05		0.16		0.34
Mexico	21.37		18.92		20.23		17.64		0.49
Mongolia	0.29		0.28		0.33		0.34		0.53
Morocco	1.07		0.85		0.75		0.28		0.48
Myanmar	0.00		0.23		0.23		0.00		0.25
Namibia	0.00		0.14		0.00		0.00		0.61
New Zealand	0.03		0.03		0.03		0.03		1
Nicaragua	0.07		0.05		0.05		0.05		0.41
North Korea	0.09		0.07		0.07		0.07		0.14
Pakistan	0.01		0.01		0.01		0.01		0.29
Panama	0.00		0.14		0.14		0.14		0.58
Papua New Guinea	0.26		0.34		0.59		0.74		0.42
Peru	15.33		13.78		11.76		11.04		0.49
Philippines	0.10		0.02		0.02		0.00		0.5
Poland	4.68		3.70		3.91		4.58		0.76
Portugal	0.27		0.33		0.15		0.08		0.78
Romania	0.01		0.06		0.21		0.20		0.59
Russia	5.70		5.25		3.81		3.73		0.38
Saudi Arabia	0.08		0.06		0.06		0.06		0.48
Serbia	0.00		0.15		0.00		0.00		0.56
Slovakia	0.00		0.00		0.07		0.20		0.72
South Africa	0.12		0.10		0.10		0.10		0.6
Spain	0.15		0.43		0.22		0.07		0.74
Sweden	1.79		1.65		1.79		2.15		0.97
Tajikistan	0.01		0.01		0.01		0.01		0.31
Tanzania	0.05		0.13		0.00		0.00		0.43
Thailand	0.09		0.19		0.18		0.00		0.47
Turkey	0.73		0.65		0.67		0.82		0.52
Ukraine	0.00		0.14		0.09		0.00		0.35
USA	3.99		6.60		6.75		9.90		0.84
Uzbekistan	0.17		0.13		0.17		0.27		0.27
Venezuela	0.01		0.01		0.01		0.01		0.21
Zambia	0.06		0.04		0.04		0.05		0.48
Zimbabwe	0.01		0.01		0.01		0.01		0.22
Total	**100**	**1038**	**100**	**890**	**100**	**897**	**100**		

Silver mine production shares in 2015 are calculated based on 2015 data available in [WSS, 2016]. Production projections in 2020, 2025 and 2030 were obtained according to the procedures in Annex C.

Table 53: Country production share, HHI and WGI for refining silver

Country	2015		2020/2025/2030		WGI scaled
	Share	HHI	Share	HHI	
Asia	49.0		49.0		0.5
Europe	26.5		26.5		1.0
N. America	22.4		22.4		0.8
Other	2.1		2.1		0.5
Total	**100**	**3611**	**100**	**3611**	

Silver refinery production in 2015 was retrieved from [Manly, 2015]. The same shares are assumed in 2020, 2025 and 2030.

Table 54: Country production share, HHI and WGI for mining silicon

Country	2015		2020/2025/2030		WGI scaled
	Share	HHI	Share	HHI	
Bhutan	0.9		0.9		0.6
Brazil	1.9		1.9		0.5
Canada	0.6		0.6		0.9
China	68.6		68.6		0.4
France	1.6		1.6		0.8
Iceland	0.9		0.9		0.9
India	1.1		1.1		0.5
Norway	4.1		4.1		1
Other countries	4.7		4.7		0.5
Russia	8.5		8.5		0.4
South Africa	1		1		0.6
Ukraine	0.9		0.9		0.3
USA	5.1		5.1		0.8
Total	**100**	**4853**	**100**	**4853**	

Silicon mine production shares in 2015 are calculated based on data available at [Statista, 2016f]. The same shares are assumed in 2020, 2025 and 2030.

B.2.6 Indicator D1.4 Reserves depletion

Table 55: Data for calculating D1.4 reserves depletion for indium

Indium	2015	2020	2025	2030
Reserves (thousand tonnes)	12.4	7.89	1.85	-6.23
Global demand (tonnes)	800	1071	1433	1918
RDI (years)	**15**	**7**	**1**	**-3**

Note: the negative value of the reserves is an artefact due to the conservative assumption of "reserves depletion" scenario (see methodology).

Reserves of indium were retrieved from [Polinares, 2012].

Table 56: Data for calculating D1.4 reserves depletion for silver

Silver	2015	2020	2025	2030
Reserves (thousand tonnes)	570	424	250	43.2
Global demand (thousand tonnes)	27.3	32.4	38.5	45.7
RDI (years)	**21**	**13**	**6**	**1**

Silver reserves were retrieved from [USGS, 2016]. See Table 48 for information on global demand data sources.

Table 57: Data for calculating D1.4 reserves depletion for silicon

Silicon	**2015**	**2020**	**2025**	**2030**
Reserves (bn tonnes)	130.0	130.0	129.9	129.8
Global demand (thousand tonnes)	8019	9993	12453	15519
RDI (years)	**16211**	**13005**	**10431**	**8366**

Silicon reserves were retrieved from [USGS, 2016]. See Table 49 for information on global demand data sources.

B.2.7 Indicator D1.5 Import reliance

Table 58: Import reliance on indium for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
SolarPower Europe 2030: low scenario	48	61	72	79
SolarPower Europe 2030: high scenario	49	62	73	81
IEA PV Technology Roadmap: hi-ren scenario	48	61	71	78
EU reference scenario	50	61	70	78
Scenario 1				
SolarPower Europe 2030: low scenario	48	57	69	77
SolarPower Europe 2030: high scenario	49	58	71	79
IEA PV Technology Roadmap: hi-ren scenario	48	57	68	76
EU reference scenario	50	57	67	76
Scenario 2				
SolarPower Europe 2030: low scenario	48	57	66	71
SolarPower Europe 2030: high scenario	49	58	68	73
IEA PV Technology Roadmap: hi-ren scenario	48	57	65	70
EU reference scenario	50	57	64	70
Scenario 3				
SolarPower Europe 2030: low scenario	48	55	58	49
SolarPower Europe 2030: high scenario	49	57	60	55
IEA PV Technology Roadmap: hi-ren scenario	48	56	57	56
EU reference scenario	49	55	56	55

Data used in the calculations of IR are given in Table 47 (EU demand) and Table 59 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 59: EU production, recycling and substitution of indium

Indium	**2015**	**2020**	**2025**	**2030**
EU production (tonnes)	73	80	80	80
EU recycling rate (%)	0	0	3	6
EU substitution rate (%)	0	0	8	15

EU production in 2015 refers to refinery production as given in [USGS, 2016]. Projections in 2020, 2025 and 2030 are based on refinery capacities as identified in [By-Products, 2015]. Recycling and substitution rates are based on the assumptions presented under Table 65 and Table 66.

Table 60: Import reliance on silver for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
SolarPower Europe 2030: low scenario	8	18	36	47
SolarPower Europe 2030: high scenario	14	25	49	63
IEA PV Technology Roadmap: hi-ren scenario	10	20	29	37
EU reference scenario	15	19	25	33
Scenario 1				
SolarPower Europe 2030: low scenario	8	0	21	26
SolarPower Europe 2030: high scenario	14	9	36	49
IEA PV Technology Roadmap: hi-ren scenario	10	2	11	13
EU reference scenario	15	1	7	8
Scenario 2				
SolarPower Europe 2030: low scenario	8	0	17	22
SolarPower Europe 2030: high scenario	14	8	33	44
IEA PV Technology Roadmap: hi-ren scenario	10	1	7	8
EU reference scenario	15	0	3	4
Scenario 3				
SolarPower Europe 2030: low scenario	8	0	0	0
SolarPower Europe 2030: high scenario	14	6	8	0
IEA PV Technology Roadmap: hi-ren scenario	10	0	0	0
EU reference scenario	15	0	0	0

Data used in the calculations of IR are given in Table 48 (EU demand) and Table 61 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 61: EU production, recycling and substitution of silver

Silver	**2015**	**2020**	**2025**	**2030**
EU production (tonnes)	1789	2194	2233	2460
EU recycling rate (%)	0	<1	4	5
EU substitution rate (%)	0	<1	25	50

EU production in 2015 refers to mine production as given in [WSS, 2016]. Projections in 2020, 2025 and 2030 refer to mine capacities, obtained according to the procedures and references in Annex C. Recycling and substitution rates are based on the assumptions presented under Table 65 and Table 66.

Table 62: Import reliance on silicon for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
SolarPower Europe 2030: low scenario	78	82	86	88
SolarPower Europe 2030: high scenario	79	83	87	90
IEA PV Technology Roadmap: hi-ren scenario	78	82	85	88
EU reference scenario	79	82	85	88
Scenario 1				
SolarPower Europe 2030: low scenario	78	82	86	88
SolarPower Europe 2030: high scenario	79	83	87	90
IEA PV Technology Roadmap: hi-ren scenario	78	82	85	88
EU reference scenario	79	82	85	88
Scenario 2				
SolarPower Europe 2030: low scenario	78	82	86	88
SolarPower Europe 2030: high scenario	79	83	87	90
IEA PV Technology Roadmap: hi-ren scenario	78	82	85	88
EU reference scenario	79	82	85	88
Scenario 3				
SolarPower Europe 2030: low scenario	78	82	86	88
SolarPower Europe 2030: high scenario	79	83	87	90
IEA PV Technology Roadmap: hi-ren scenario	78	82	85	88
EU reference scenario	79	82	85	88

Data used in the calculations of IR are given in Table 49 (EU demand) and Table 63 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 63: EU production, recycling and substitution of silicon

Silicon	2015	2020	2025	2030
EU production (thousand tonnes)	130	130	130	130
EU recycling rate (%)	0	0	0	0
EU substitution rate (%)	0	0	0	0

EU production in 2015 refers to mine production as given in the [Statista, 2016f]. The same figures are assumed in 2020, 2025 and 2030. It is assumed that no recycling and substitution for Si will take place by 2030 as presented under Table 65 and Table 66.

B.2.8 Indicator D1.6 Supply adequacy

Table 64: In, Ag, Si global demand and mining capacity

	2015	2020	2025	2030
In: Global demand all sectors (tonnes)	800	1071	1433	1918
In: Global mine capacities (tonnes)	907	1040	1060	1016
In: Capacities utilisation (%)	88	103	135	189
Ag: Global demand all sectors (tonnes)	27300	32424	38509	45737
Ag: Global mine capacities (tonnes)	28796	31763	32098	31480
Ag: Capacities utilisation (%)	95	102	120	145
Si: Global demand all sectors (thousand tonnes)	8019	9993	12453	15519
Si: Global mine capacities (tonnes)	NA	NA	NA	NA
Si: Capacities utilisation (%)	NA	NA	NA	NA

See Table 47, Table 48 and Table 49 for information on global demand data sources for In, Ag and Si, respectively. Mine capacities in 2015, 2020, 2025 and 2030 were obtained following the procedures described in Annex C.

B.2.9 Indicator D1.7 Recycling

Table 65: In, Ag, Si global recycling rates (%)

Materials	2015	2020	2025	2030
In	0	2	13	20
Ag	0	1	4	5
Si	0	0	0	0

Indium

The major demand (around 70 %) for indium comes from the production of flat-panel displays where indium is used as transparent electrodes (indium tin oxide - ITO). The high prices of indium and the increasing demand from several more applications, such as the semiconductor industry, solar cells, photo-catalysts and light-emitting diodes, have provoked further interest in recycling indium.

In fact, the recycling of new scrap is currently the main source of indium globally: around 58 % of the indium supply [Hong, 2010].

Only 30 % of the indium is actually used in the ITO layer; the remaining 70 % is wasted during the sputtering process [Matthews, 2009]. More efficient recovery of the wasted indium from the sputtering chambers is one feasible way of increasing the recycling rate of In.

As regards the recycling of indium from old scrap (end-of-life applications), there is an upcoming issue concerning recycling the indium-containing components in electronic devices: large flat screens (primarily used for TV appliances and computer monitors); digital displays, digital picture frames, tablet PCs, smartphones, e-book readers and numerous other devices.

The current recycling rate of indium from flat-panel displays is < 1 %. Some large liquid-crystal display (LCD) producers have put effort into developing techniques for recycling indium from LCD. However, there is no established system to recycle it from WEEE in Europe [Zhang, 2015].

A study carried out for Germany has revealed 0 recycling rate of indium from electronic devices [Öko-institut, 2012].

As regards the recovery of indium from thin-film panels – an emerging application for In globally – any visible contribution to the recycling flows is not expected by 2030. Here, indium is used in minor quantities, accounting for only 0.02 % of the module weight [BINE, 2010]. Moreover, most of the installed thin-film PV will be still in use globally in 2030.

Therefore, for these calculations only a 20 % increase in the recycling of indium is assumed globally due to new scrap recycling potential as well as some initiatives being undertaken globally for recycling end-of-life products (displays, mobile phones and other devices using ITO).

For the EU, up to 6 % only is assumed as a reasonable recycling rate up to 2030. There is no production of flat-panel displays in Europe which could be the main source for recovering indium from production scrap. Therefore, in the near future, only the collection of electronic devices and recovery of indium from ITOs can be seen as potential sources of recycled indium in the EU.

Silver

Silver is already highly recycled globally. However, the methodology only takes into account the potential increase in material recycling rates from 2015 and beyond. Therefore, only new and emerging applications can make a tangible contribution to an eventual increase in the recycling rate.

The emerging application which can introduce higher recycling rates for silver is PV solar modules. However, the amount of silver (silver paste) is <1 % of the weight of the module. In addition, around 85 % of the installed PV capacity globally has been connected to the grid in the last five years.

Considering the lifetime of a PV module is 20 years or more, no tangible increase in recycling contribution should be expected before 2030. In addition, some of the old and less-efficient PV modules can be reused in spacious land areas where high efficiency is not required; the lifespan of such modules should be assumed as 30 years or more, according to various experts.

In the light of the above, only a 5 % increase in the recycling rate for silver is assumed both globally and in the EU until 2030.

B.2.10 Indicator D1.8 Substitution

Table 66: In, Ag, Si global substitution rates (%)

Materials	2015	2020	2025	2030
In	0	1	8	15
Ag	0	1	25	50
Si	0	0	0	0

Indium

As the result of the particular concern over the criticality of indium, significant efforts are being made by research and industry to find substitutes for indium in growing and emerging markets.

Possible substitutes for the material's main use – flat-panel displays – are aluminium-doped zinc oxide (AZO) and fluorine-doped tin oxide (FTO), both of which are produced on an industrial scale and at a lower cost. However, both AZO and FTO have a lower performance than ITO and therefore are not applied extensively. Indium remains the material of reference for transparent conductive oxide (TCO) coatings. Substitutes for TCO currently under development are ultra-thin metal films and zinc oxide-metal-zinc oxide multilayers, carbon nanotubes and metal nanowire films, graphene films, organic transparent conductors (PEDOT:PSS) and printed metal grids [CRM InnoNet, 2016]. Since the estimated time-to-market for these substitution options is up to 10 years, they cannot be considered as a feasible way to reduce the demand for In until 2030.

Another main use of indium is in optoelectronic windows. Substitution of indium is also possible here but only at the cost of reduced performance, specifically for heated windscreens and car lights. As for the current thin-film solar cell technologies, ITO alternatives already exist. It is expected that ITO substitution will be possible for the next-generation solar cells. The substitution of In in semiconductor applications is also possible, with the exception of optoelectronic devices (LEDs and laser diodes).

As concluded in the CRM InnoNet project [CRM InnoNet, 2016], indium can be substituted in most applications albeit sometimes at a higher cost. However, in its main application – flat panel displays – which accounts for 70 % of indium demand, substitution is not possible without a performance loss.

In our analysis, the potential for up to 15 % In substitution is considered by 2030.

Silver

Silver is used in solar panels and it is expected that demand for silver will continue to grow on a global scale. However, it is expensive and manufacturers are looking for alternative materials. In fact, silver can be easily substituted in solar panels – aluminium and copper are two materials that can replace silver in solar panels [Reddy, 2012].

Therefore, a substitution potential of around 50 % is assumed in the analysis.

B.2.11 Indicator D2.1 Supply chain dependency

Table 67: Country production share, HHI and WGI for relevant steps in the supply chain for CIGS PV (In)

Country	2015		2020		2025		2030		WGI
	share	HHI	share	HHI	share	HHI	share	HHI	scaled
Step 1: CIGS thin-film producers									
China	7		6		6		6		0.44
USA	4		4		4		4		0.89
Japan	79		81		81		81		0.89
EU	4		4		4		4		1.00
RoW	6		5		5		5		0.50
Total	**100**	**6322**	**100**	**6626**	**100**	**6626**	**100**	**6626**	

The data are used to evaluate D2.1 for In.

The CIGS thin-film manufacturing capacity used to calculate the shares comes from the JRC data compilation and analysis (private communication: courtesy of Arnulf Jaeger-Waldau JRC C.2).

Table 68: Parameters for calculating D2.1 supply chain dependency for CIGS PV (In)

Indium	**2015**	**2020**	**2025**	**2030**
$A_{step\ 1}$	0.92	0.92	0.92	0.92
$B_{step\ 1}$	0.04	0.04	0.04	0.04
$D2.1_{step\ 1}$	0.48	0.48	0.48	0.48
D2.1 (In)	**0.48**	**0.48**	**0.48**	**0.48**

Table 69: Country production share, HHI and WGI for relevant steps in the supply chain for c-Si PV (Si)

Country	**2015**		**2020**		**2025**		**2030**		**WGI scaled**
	share	**HHI**	**share**	**HHI**	**share**	**HHI**	**share**	**HHI**	
Step1: Solar-grade Si manufacturing									
China	50.9		50.9		50.9		50.9		0.44
USA	8.4		8.4		8.4		8.4		0.89
South Korea	18.3		18.3		18.3		18.3		0.84
Japan	2.4		2.4		2.4		2.4		0.89
Malaysia	1.9		1.9		1.9		1.9		0.50
Norway	4		4		4		4		0.98
EU	14		14		14		14		1
Total	**100**	**3218**	**100**	**3218**	**100**	**3218**	**100**	**3218**	
Step 2: c-Si cell manufacturing									
Japan	5.8		5.8		5.8		5.8		0.89
EU	2.0		2.0		2.0		2.0		1
Taiwan	14.4		14.4		14.4		14.4		0.81
China	66.1		66.1		66.1		66.1		0.44
USA	1.4		1.4		1.4		1.4		0.89
South Korea	2.7		2.7		2.7		2.7		0.73
India	0.3		0.3		0.3		0.3		0.47
Malaysia	4.6		4.6		4.6		4.6		0.67
Thailand	0.2		0.2		0.2		0.2		0.47
Vietnam	0.3		0.3		0.3		0.3		0.43
Other countries	2.3		2.3		2.3		2.3		0.5
Total	**100**	**4642**	**100**	**4642**	**100**	**4642**	**100**	**4642**	
Step 3: c-Si module manufacturing									
EU	21.3		6.6		6.6		6.6		1
Canada	2.3		8.7		8.7		8.7		0.95
China	32.4		46.0		46.0		46.0		0.44
Taiwan	13.6		1.6		1.6		1.6		0.81
Japan	16.4		-		-		-		0.89
Norway	1.3		-		-		-		0.98
USA	5.3		13.8		13.8		13.8		0.89
South Korea	1.0		4.1		4.1		4.1		0.73
India	6.3		10.5		10.5		10.5		0.47
Brazil	-		0.6		0.6		0.6		0.53
Thailand	-		0.7		0.7		0.7		0.47
Saudi Arabia	-		1.9		1.9		1.9		0.48
Vietnam	-		2.0		2.0		2.0		0.43
Malaysia	-		3.3		3.3		3.3		0.67
Ethiopia	-		0.1		0.1		0.1		0.35
Algeria	-		0.2		0.2		0.2		0.33
Total	**100**	**2033**	**100**	**2570**	**100**	**2570**	**100**	**2570**	

The data are used to evaluate D2.1 for Si.

The c-Si manufacturing capacities used to calculate the shares come from the JRC data compilation and analysis (private communication: courtesy of Arnulf Jaeger-Waldau JRC C.2). Data on new capacities for c-Si module manufacturing are taken from [PV-Tech, 2016]. The new capacities have been added to the existing (present) capacities in order to calculate the concentration of supply for the period 2020 to 2030.

Table 70: Parameters for calculating D2.1 supply chain dependency for c-Si PV (Si)

Silicon	**2015**	**2020**	**2025**	**2030**
$A_{\text{step 1}}$	0.85	0.85	0.85	0.85
$B_{\text{step 1}}$	0.14	0.14	0.14	0.14
$D2.1_{\text{step 1}}$	0.49	0.49	0.49	0.49
$A_{\text{step 2}}$	0.75	0.75	0.75	0.75
$B_{\text{step 2}}$	0.02	0.02	0.02	0.02
$D2.1_{\text{step 2}}$	0.39	0.39	0.39	0.39
$A_{\text{step 3}}$	0.93	0.87	0.87	0.87
$B_{\text{step 3}}$	0.21	0.07	0.07	0.07
$D2.1_{\text{step 3}}$	0.57	0.47	0.47	0.47
D2.1 (Si)	**0.48**	**0.45**	**0.45**	**0.45**

Table 71: Parameters for calculating D2.1 supply chain dependency for c-Si PV (Ag)

Silver	**2015**	**2020**	**2025**	**2030**
$A_{\text{step 1}}$	0.75	0.75	0.75	0.75
$B_{\text{step 1}}$	0.02	0.02	0.02	0.02
$D2.1_{\text{step 1}}$	0.39	0.39	0.39	0.39
$A_{\text{step 2}}$	0.93	0.87	0.87	0.87
$B_{\text{step 2}}$	0.21	0.07	0.07	0.07
$D2.1_{\text{step 2}}$	0.57	0.47	0.47	0.47
D2.1 (Ag)	**0.48**	**0.43**	**0.43**	**0.43**

Table 72: Country production share, HHI and WGI for relevant steps in the supply chain for c-Si PV (Ag)

Country	**2015**		**2020**		**2025**		**2030**		**WGI scaled**
	share	**HHI**	**share**	**HHI**	**share**	**HHI**	**share**	**HHI**	
Step 1: c-Si cell manufacturing									
Japan	5.8		5.8		5.8		5.8		0.89
EU	2.0		2.0		2.0		2.0		1
Taiwan	14.4		14.4		14.4		14.4		0.81
China	66.1		66.1		66.1		66.1		0.44
USA	1.4		1.4		1.4		1.4		0.89
South Korea	2.7		2.7		2.7		2.7		0.73
India	0.3		0.3		0.3		0.3		0.47
Malaysia	4.6		4.6		4.6		4.6		0.67
Thailand	0.2		0.2		0.2		0.2		0.47
Vietnam	0.3		0.3		0.3		0.3		0.43
Other countries	2.3		2.3		2.3		2.3		0.5
Total	**100**	**4642**	**100**	**4642**	**100**	**4642**	**100**	**4642**	

Country	2015		2020		2025		2030		WGI scaled
	share	HHI	share	HHI	share	HHI	share	HHI	
Step 2: c-Si module manufacturing									
EU	21.3		6.6		6.6		6.6		1
Canada	2.3		8.7		8.7		8.7		0.95
China	32.4		46.0		46.0		46.0		0.44
Taiwan	13.6		1.6		1.6		1.6		0.81
Japan	16.4								0.89
Norway	1.3								0.98
USA	5.3		13.8		13.8		13.8		0.89
South Korea	1.0		4.1		4.1		4.1		0.73
India	6.3		10.5		10.5		10.5		0.47
Brazil	-		0.6		0.6		0.6		0.53
Thailand	-		0.7		0.7		0.7		0.47
Saudi Arabia	-		1.9		1.9		1.9		0.48
Vietnam	-		2.0		2.0		2.0		0.43
Malaysia	-		3.3		3.3		3.3		0.67
Ethiopia	-		0.1		0.1		0.1		0.35
Algeria	-		0.2		0.2		0.2		0.33
Total	**100**	**2033**	**100**	**2570**	**100**	**2570**	**100**	**2570**	

The data are used to evaluate D2.1 for Ag.

B.2.12 Indicator D2.2 Purchasing potential

The data needed for Indicator D2.2 are given in Table 18, Table 19, Table 39 and Table 40.

B.2.13 Indicator D2.3 Material cost impact

Table 73: Parameters for calculating D2.3 material cost impact for CIGS PV (In)

Indium	2015	2020	2025	2030
E (USD/kg)	315	320	320	320
F (g/W)	0.03	0.03	0.02	0.02
G (USD/W)	1	0.7	0.6	0.4
D2.3 (In)	**0.99**	**0.99**	**0.99**	**0.98**

The data are used to calculate D2.3 for In.

E (USD/kg) is indium ingot price of 99.99 % purity (known as 4N) used for PV [Metalprices, 2016].

F (kg/W) is the indium material intensity (data taken from indicator D1.1).

The present and future technology/module specific costs for CIGS (USD/W) are taken from commercial sources [PVInsights, 2010; Greentech Media, 2015].

Table 74: Parameters for calculating D2.3 material cost impact for c-Si PV (Ag)

Silver	2015	2020	2025	2030
E (USD/kg)	564	564	564	564
F (g/W)	0.04	0.04	0.04	0.03
G (USD/W)	0.70	0.48	0.37	0.30
D2.3 (Ag)	**0.97**	**0.95**	**0.94**	**0.94**

The data are used to calculate D2.3 for Ag.

E (USD/kg) is the cost of Ag [WSS, 2016].

F (kg/W) is the Ag material intensity (data taken from indicator D1.1).

G (USD/W) represents the module cost evolution until 2030 calculated as the average between utility, commercial and residential systems [BNEF, 2016c].

Table 75: Parameters for calculating D2.3 material cost impact for c-Si PV (Si)

Silicon	**2015**	**2020**	**2025**	**2030**
E (USD/kg)	11.9	11.9	11.9	11.9
F (kg/W)	0.005	0.004	0.004	0.003
G (USD/W)	0.70	0.48	0.37	0.30
D2.3 (Si)	**0.92**	**0.89**	**0.87**	**0.87**

The data are used to calculate D2.3 for Si.

E (USD/kg) is the cost of Si metal [Statista, 2016d]; the cost is multiplied by a factor of 4.4 as 4.4 kg of metallurgical-grade Si is required to produce 1 kg of solar-grade Si [Odden, 2008].

F (kg/W) is the Si material intensity (data taken from indicator D1.1).

G (USD/W) represents the module cost evolution until 2030 calculated as the average between utility, commercial and residential systems [BNEF, 2016c].

B.3 Electric vehicles sector

B.3.1 Deployment scenarios

Three deployment scenarios have been considered to assess the demand for materials for EVs until 2030:

1) **European Roadmap Electrification of Road Transport 2nd edition** [ERERT, 2012];
2) **Tech 2** scenario proposed in Fuelling Europe's Future [CE, 2013];
3) **Tech 3** scenario proposed in Fuelling Europe's Future [CE, 2013].

The **ERERT** gives milestones for the penetration of BEVs and PHEVs in the EU by 2020 and 2025, namely: 5 million EVs on EU roads by 2020 and 15 million EVs by 2025. Since HEVs were not considered in the ERERT, AVICENNE ENERGY projections giving sales forecasts for HEVs until 2025 were used to make the calculations [AVICENNE, 2014c]. These projections are also in line with the Pike Research forecast up to 2020 [ElectricCarsReport, 2013], both giving around 27 % - 28 % CAGR for the HEVs European market until 2020.

The **Tech 2** scenario is derived from one of the scenarios used in the European Commission project 'EU Transport GHG: Routes to 2050'. It assumes a strong market penetration by HEVs: 20 % of new vehicles sales in 2020 and 42 % penetration in 2030.

The **Tech 3** scenario – deriving similarly from the European Commission project 'EU Transport GHG: Routes to 2050' – assumes a more rapid introduction rate for advanced EVs. The uptake rates of BEVs and PHEVs are in line with the 'EV breakthrough' scenario from CE Delft [CE Delft, 2011], a report for the European Commission studying possible EV deployment rates.

Detailed explanations on how the milestones and penetration rates envisaged in the three scenarios are used to calculate the demand for materials for EVs is given below.

ERERT: The ERERT gives common milestones for BEVs and PHEVs together. In 2015, around 60 % of the EVs registered in the EU were PHEVs and 40 % were BEVs. It is assumed that this proportion will be maintained for the future EV fleet until 2030. This is also consistent with the IEA's projections [IEA, 2011] for the OECD Europe: 70 % PHEV versus 30 % BEV is forecast for OECD Europe in 2030. The market shares for PHEVs and BEVs in 2050 are rather different: according to the IEA, the EV market will be dominated by BEVs; however, this time frame is out of the scope of this study.

To reach the first milestone of 5 million EVs by 2020, with 148 740 EVs having already been registered in the EU in 2015, an annual growth of 70 % must be achieved. This is not a surprising growth rate bearing in mind the trend over the last few years – from 2011 to 2013 – of doubling the number of the EVs each year [Mckinsey, 2014]. Furthermore, to reach the second milestone of 15 million vehicles on EU roads by 2025, no further increase in the annual production is actually required from 2020 onwards. The number of HEVs registered in the EU in 2015 [JATO, 2016] as well as the forecast for HEV sales until 2030 [AVICENNE, 2014c] is used in the ERERT deployment scenario. **Tech 2:** Projections for PHEV, BEV and HEV penetration rates proposed in the Tech 2 scenario are given as a percentage of new car registrations (Figure 70).

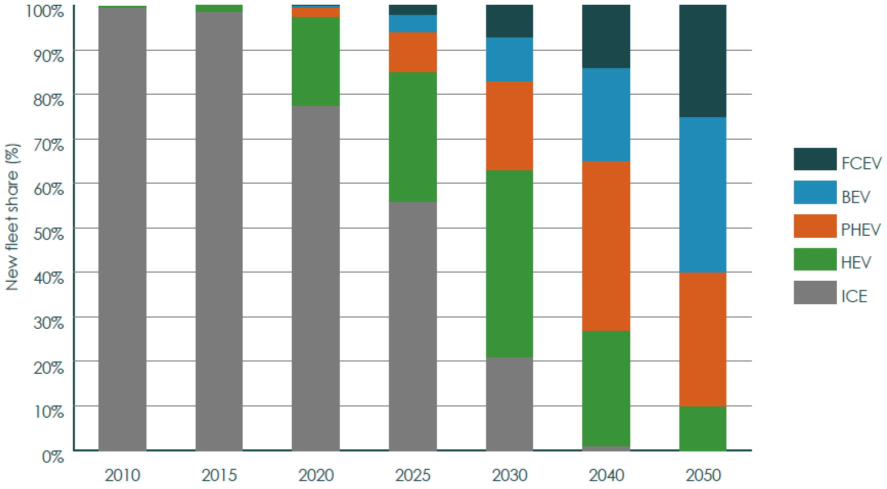

Figure 70: Tech 2 scenario [CE, 2013]

To estimate the number of new cars to be registered in the EU in 2020, 2025 and 2030, ACEA data have been used which give an estimation of the new cars registered per capita on average in the EU [ACEA, 2016]: on average, 27 new cars were registered in 2015 per 1000 inhabitants. The population statistics and forecast until 2030 is taken from the OECD database. This allows for an estimation of the total number of new cars to be registered in the EU in 2030, keeping the same ratio of 27 new cars per 1000 inhabitants.

The total number of new cars and the market shares given in Figure 70 for PHEVs, BEVs and HEVs are used to derive the number of PHEVs, BEVs and HEVs, respectively, until 2030 (see Table 76).

Table 76: Estimated numbers of PHEVs, BEVs and HEVs (Tech 2)

Number of cars	2015	2020	2025	2030
New cars (thousands)	-	11973	11986	11962
PHEV (% of new cars)	-	2	8.6	2
PHEVs (thousands)	90.0	239	1031	2392
BEV (% of new cars)	-	0.5	4	10
BEVs (thousands)	59.0	60.0	479	1196
HEV (% of new cars)	-	20	30	42
HEVs (thousands)	192	2395	3596	5024

Tech 3: The projections of PHEV, BEV and HEV penetration rates proposed in the Tech 3 scenario are given as a percentage of the new cars (see Figure 71).

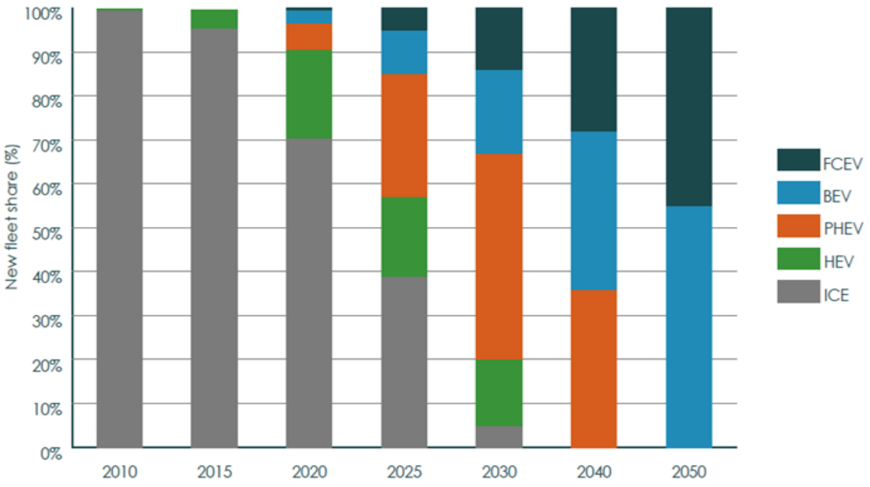

Figure 71: Tech 3 scenario [CE, 2013]

In a similar way to the Tech 2 scenario, population forecast and ACEA data are used to determine the number of new cars until 2030 [ACEA, 2016]. The total number of new cars and the market shares given in Figure 71 for PHEVs, BEVs and HEVs are used to derive the number of PHEVs, BEVs and HEVs, respectively (Table 77).

Table 77: Estimated numbers of PHEVs, BEVs and HEVs (Tech 3)

Number of cars	2015	2020	2025	2030
New cars (thousands)	-	11973	11986	11962
PHEV (% of new cars)	-	0.057	0.285	0.47
PHEVs (thousands)	90.0	682	3416	5622
BEV (% of new cars)	-	0.036	0.1	0.2
BEVs (thousands)	59	431	1199	2392
HEV (% of new cars)	-	0.2	0.18	0.15
HEVs (thousands)	192	2397	2158	1794

An overview of the three considered deployment scenarios is given in Table 78.

Table 78: PHEVs, BEVs and HEVs penetration scenarios: overview

Models	ERERT	Tech 2	Tech 3
PHEVs	5 million(1) EVs by 2020 15 million(1) EVs by 2025	2 %(2) in 2020 8.6 %(2) in 2025 20 %(2) in 2030	6 %(2) in 2020 29 %(2) in 2025 47 %(2) in 2030
BEVs		0.5 %(2) in 2020 4 %(2) in 2025 10 %(2) in 2030	4 %(2) in 2020 10 %(2) in 2025 20 %(2) in 2030
HEVs	CAGR (2015-2020) = 28 % CAGR (2020-2025) = 10 %	20 %(2) in 2020 30 %(2) in 2025 42 %(2) in 2030	20 %(2) in 2020 18 %(2) in 2025 15 %(2) in 2030

Note: (1) Cumulative number of EVs (both PHEVs and BEVs) on EU roads. (2) Percentage of new vehicles sales.

Comparison with global scenarios

The Paris Declaration on Electro-Mobility and Climate Change & Call to Action announced at COP21 (December, 2015) adopted a global target of 100 million electric cars by 2030 [UNFCCC, 2015]. The IEA's 2 Degree Scenario (2DS) establishes an even more challenging global deployment target for EVs: a stock of 140 million EVs (light duty) by 2030 [ETP, 2016]. The 4 Degree Scenario (4DS) is a more conservative setting with a target of just 24 million EVs by 2030. The Electric Vehicles Initiative (EVI) target set a figure of 20 million EVs on the road [IEA, 2013].

The scenarios above are compared to the three scenarios selected here to evaluate the demand for materials (see Figure 72).

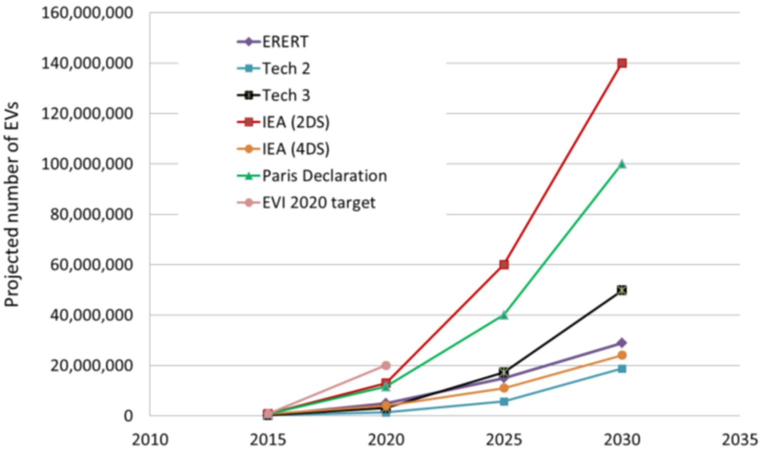

Figure 72: Comparison between existing global scenarios and the three EU scenarios selected here for EV deployment until 2030

The points on the graph correspond to EV stocks and not EV annual sales. It can be noted that the ERERT and Tech 2 selected in this study are aligned with the 4DS global scenario in terms of annual growth rates. However, the 4DS is a very conservative scenario which assumes less than 2.5 million EVs globally. The Tech 3 scenario is closer to the Paris Declaration in terms of growth rate. However, since it is too ambitious to expect that the EU might have half of the global EV stock, the Tech 3 scenario is considered as extreme for the EU.

B.3.2 Assumptions

Average lifetime of a battery

The average lifetime of a Li-ion battery varies according to the different types of EVs. It can range from five to 20 years depending on many factors, such as EV type, manufacturer, external factors, driving/charging patterns, etc. In our calculations, an average EV battery lifetime is assumed to be 10 years for PHEVs and BEVs [Smith, 2015]. This means that from 2025 onwards, the production of new batteries should also compensate for batteries reaching their end-of-life. Recycling will be feasible beyond 2025; a CAGR of 12.5 % will only be required to compensate for batteries collected for recycling between 2025 and 2030. Calculations show that around 150 000 batteries will be collected for recycling in 2025 and the number will progressively increase to above 2 million in 2030. If no recycling is done in the EU, around 5 million batteries will accumulate from PHEVs and BEVs alone.

Since the Tech 2 and Tech 3 scenarios forecast the number of PHEVs, BEVs and HEVs as a percentage of the new cars in 2020, 2025 and 2030 and not the cumulative number of cars in these years, the recycling of batteries should not be considered in the calculations.

Material efficiency

Lithium

Several industry research companies claim that, theoretically, 1 kg of Li is needed to enable a 6 kWh battery [MERIDIAN, 2010] or ≈ 167 g per kWh. Other references [ANL, 2009] indicate between 113 g and 246 g Li per kWh for various cathode types of batteries, all with a graphite anode, while a battery with a lithium titanate spinel anode has a high requirement of 423 g Li per kWh. The large scattering of these numbers illustrates the difficulty in quantifying how much Li should be considered per battery type/kWh/vehicle. Other factors to be considered when estimating realistic figures for Li content are: reduced battery capacity below the theoretical maximum, the discharge rate, cycle life capacity fade, electrochemical factors such as polarisation, internal resistance, electrolyte conductivity, separator conductivity, cation transport number, cation activity coefficient and order/disorder and particle size within the electrodes [MERIDIAN, 2010]. All these factors lead to a requirement for several times as much Li per kWh as the 'theoretical' quantity. Therefore, to be more realistic and conservative, according to this source it is advisable that around 3 kg of raw technical-grade lithium carbonate (or ≈ 564 g Li) per kWh battery capacity is considered. Assuming very high purity yields, optimistically the requirements can be reduced to 2 kg of lithium carbonate (or ≈ 376 g Li) per kWh. In this report, an average value of **286 g of Li per kWh** battery capacity is considered when calculating the demand for Li.

Plug-in hybrid electric vehicles (PHEVs)

Table 79: Estimated Li demand for PHEVs registered in the EU in 2015

PHEV models	EU sales (cars)	Battery capacity (kWh)	Li per vehicle (kg)	Li per model (kg)
Mitsubishi Outlander	28250	12	3.43	96954
VW Golf GTE	14834	8.8	2.52	37334
Audi A3 e-Tron	9851	8.8	2.52	24793
Volvo V60 PHEV	6328	11.2	3.20	20270
Volvo XC90	2818	9.2	2.63	7415
Mercedes C350e	5245	6.2	1.77	9300
BMW X5 40e	1472	9	2.57	3789
BMW i3Rex	4999	18.8	5.38	26879
BMW 225xe Active Tourer	263	7.7	2.20	579
VW Passat GTE	4730	9.9	2.83	13393
Others	10717	-	**2.59**(1)	27710
Total	**89507**			**268415**

Note: (1) The average Li demand to be used in the category 'Others' has been derived from Table 80.

PHEV sales per model were obtained from [EAFO, 2012; JRC, 2015b].

Table 80: Estimated Li demand for PHEVs, registered in the EU in 2014: 'Others' category

PHEV models: 'Others'	EU sales (cars)	Battery capacity (kWh)	Li per vehicle (kg)	Li per model (kg)
Porsche Cayenne S E-Hybrid	1486	11	3.15	4675
BMW i8	1116	7.1	2.03	2266
Toyota Prius PHEV	159	4.4	1.26	200
Mercedes S500 Plug-in Hybrid	141	8.7	2.49	351
Porsche Panamera S E-Hybrid	110	9.4	2.69	296
Total 'Others'	**3012**			**7788**

Sales numbers in 2014 differ from the eventual 2015 sales. However, the purpose of Table 80 was simply to determine the average amount of Li used per vehicle for models included in the category 'Others'. To do this, it is important that the relative shares of each model are similar in 2014 and 2015 (due to different battery capacities), which is the assumption here. It can be seen that 7788 kg of Li is required to manufacture 3012 PHEVs batteries (2014 data) [JRC, 2015b] leading to an average amount of Li of 2.59 kg per vehicle for the category 'Others'. This number is then used in Table 79.

The average content of Li required in a PHEV is calculated at **3 kg.** This number is used to calculate the future demand for Li in PHEVs.

Battery electric vehicles (BEVs)

Table 81: Estimated Li demand for BEVs registered in the EU in 2015

BEV models	**EU sales (cars)**	**Battery capacity (kWh)**	**Li per vehicle (kg)**	**Li per model (kg)**
Nissan LEAF	11896	30	8.58	102068
Tesla Model S[(1)]	10389	72.5	20.74	215416
VW e-Golf	2076	26.5	7.58	15734
Renault ZOE	16424	22	6.29	103340
BMW i3	3481	33	9.44	32854
VW e-UP	1397	18.7	5.35	7471
Kia Soul EV	4916	27	7.72	37961
Mercedes B-Class Electric	1288	28	8.01	10314
Peugeot iOn	870	16	4.58	3981
Citroën C-Zéro	1075	16	4.58	4919
Others	5421		**5.33**[(2)]	28913
Total	**59233**			**562972**

Note: (1) The Tesla S model is offered on the market with two battery capacities: 60 kWh and 85 kWh. To account for this, an average value of 72.5 kWh was used for the calculations thereby assuming an equal proportion of both battery capacities.
Note: (2) The average Li demand to be used in the category 'Others' has been derived from Table 82.

BEV sales per model were obtained from [EAFO, 2012; JRC, 2015b].

Table 82: Estimated BEVs registered in the EU in 2014: 'Others' category

BEV models: 'Others'	**Number of BEVs**	**Battery capacity (kWh)**	**Li per vehicle (kg)**	**Li per model (kg)**
Nissan e-NV200	1614	24	6.86	11078
Renault Kangoo ZE	1611	22	6.29	10136
Smart Fortwo ED	1132	17	4.86	5504
Renault Twizy	1138	6.1	1.74	1985
Bolloré Bluecar	229	30	8.58	1965
Mitsubishi i-MiEV	208	16.3	4.66	970
Total 'Others'	**5932**			**31639**

The 2014 sales [JRC, 2015b] were used to calculate the average content of Li required in BEV models pertinent to the category 'Others', namely 5.33 kg.

The average content of Li required in a BEV is calculated at **9.5 kg.** This number is used to estimate the future demand for Li in BEVs.

To summarise:

Average Li amount per PHEV = 3 kg

Average Li amount per BEV = 9.5 kg

Hybrid electric vehicles (HEVs)

A different approach was adopted to calculate the future demand for Li for the HEV market in the EU. Today, most of the HEV models are using the NiMH battery type; therefore these models should be excluded from the calculations.

Among the models registered in 2015, only the Mercedes C class model is using LIB. However, due to the global trend of switching to Li-ion technology in future, assumptions until 2030 have been made based on available commercial information. Toyota has announced its intentions to launch the Prius model in 2016 with two battery choices: NiMH and Li-ion. For the calculations, it is assumed that in 2016 only 25 % of the Toyota Prius will be produced with Li-ion batteries, in 2017 – 50 %, in 2018 – 75 %, and in 2019 – all Toyota Prius will have a Li-ion battery. The Lexus has announced that for the time being the NiMH will be the battery of choice. Therefore, it is assumed that only 35 % of Lexus cars might have a Li-ion battery in 2020, 90 % in 2025 and 100 % in 2030. Such Li-ion penetration rates are forecasted globally for the HEV sector.

Peugeot, on the other hand, will explore another propulsion technology by 2020: compressed air. Therefore, Peugeot models were not considered in the calculations of future EU demand for Li.

Table 83: Estimated Li demand for HEVs registered in the EU in 2015

HEV models	EU sales (cars)	Battery type	Battery capacity (kWh)	Li per model (kg)
Toyota Auris	72020	NiMH	1.43	0
Toyota Yaris	65457	NiMH	0.9	0
Lexus NX	14461	NiMH	1.3	0
Lexus CT	9230	NiMH	1.3	0
Lexus IS	6888	NiMH	1.6	0
Toyota Prius+	6522	NiMH	1.43	0
Toyota Prius	6249	NiMH	1.43	0
Mercedes C class	**4358**	**Li-ion**	**0.8**	**997**
Peugeot 508	3700	NiMH	1.1	0
Peugeot 3008	3051	NiMH	1.1	0
Total	**191936**			**997**

The HEVs sales per model for 2015 were obtained from [JATO, 2016].

Table 84: Projected sales of HEVs per model until 2030 (ERERT)

HEV models	2015	2020	2025	2030
Toyota Auris	72020	244866	403309	664274
Toyota Yaris	65457	222553	366559	603744
Lexus NX	14461	49167	80981	133381
Lexus CT	9230	31383	51689	85135
Lexus IS	6888	23421	38575	63536
Toyota Prius+	6522	22174	36522	60154
Toyota Prius	6249	21247	34995	57639
Mercedes C class	4358	14816	24403	40193
Peugeot 508	3700	12581	20721	34129
Peugeot 3008	3051	10375	17088	28145
Total	**191936**	**652583**	**1074842**	**1770328**

Table 85: Estimated number of HEVs using LIB per model until 2030 (ERERT)

HEV models	2015	2020	2025	2030
Toyota Auris		85703	362978	664274
Toyota Yaris		77894	329903	603744
Lexus NX		17208	72883	133381
Lexus CT		10984	46520	85135
Lexus IS		8197	34718	63536
Toyota Prius+		22174	36522	60154
Toyota Prius		21247	34995	57639
Mercedes C class	4358	14816	24403	40193
Peugeot 508				
Peugeot 3008				
Total	**4358**	**258223**	**942922**	**1708054**

Table 86: Estimated Li demand for HEVs until 2030 (ERERT)

HEV models	2015	2020	2025	2030
Toyota Auris		35051	148451	271675
Toyota Yaris		20050	84917	155404
Lexus NX		6398	27098	49591
Lexus CT		4084	17296	31653
Lexus IS		3751	15887	29074
Toyota Prius+		9069	14937	24602
Toyota Prius		8690	14312	23573
Mercedes C class	997	3390	5583	9196
Peugeot 508				
Peugeot 3008				
Li demand per year (kg)	**997**	**90482**	**328481**	**594767**

Table 87: Projected sales of HEVs per model until 2030 (Tech 2)

HEV models	2015	2020	2025	2030
Toyota Auris	72020	898542	1349255	1885197
Toyota Yaris	65457	816665	1226308	1713413
Lexus NX	14461	180420	270919	378531
Lexus CT	9230	115159	172924	241612
Lexus IS	6888	85943	129052	180313
Toyota Prius+	6522	81368	122182	170715
Toyota Prius	6249	77966	117074	163578
Mercedes C class	4358	54368	81639	114067
Peugeot 508	3700	46166	69323	96858
Peugeot 3008	3051	38070	57167	79874
Total	**191936**	**2394666**	**3595843**	**5024158**

Table 88: Estimated number of HEVs per model using LIB until 2030 (Tech 2)

HEV models	2015	2020	2025	2030
Toyota Auris		314490	1214330	1885197
Toyota Yaris		285833	1103677	1713413
Lexus NX		63147	243827	378531
Lexus CT		40306	155632	241612
Lexus IS		30080	116147	180313
Toyota Prius+		81368	122182	170715
Toyota Prius		77966	117074	163578
Mercedes C class	4358	54368	81639	114067
Peugeot 508				
Peugeot 3008				
Total	**4358**	**947556**	**3154508**	**4847425**

Table 89: Estimated Li demand for HEVs until 2030 (Tech 2)

HEV models	2015	2020	2025	2030
Toyota Auris		128620	496637	771008
Toyota Yaris		73573	284086	441033
Lexus NX		23478	90655	140738
Lexus CT		14986	57864	89831
Lexus IS		13765	53149	82511
Toyota Prius+		33278	49970	69819
Toyota Prius		31887	47881	66900
Mercedes C class	997	12439	18679	26098
Peugeot 508				
Peugeot 3008				
Li demand per year (kg)	**997**	**332025**	**1098921**	**1687938**

Table 90: Projected sales of HEVs per model until 2030 (Tech 3)

HEV models	2015	2020	2025	2030
Toyota Auris	72020	864001	778433	647403
Toyota Yaris	65457	785271	707500	588410
Lexus NX	14461	173484	156303	129993
Lexus CT	9230	110733	99766	82973
Lexus IS	6888	82639	74455	61922
Toyota Prius+	6522	78240	70491	58626
Toyota Prius	6249	74969	67544	56175
Mercedes C class	4358	52278	47100	39172
Peugeot 508	3700	44391	39995	33263
Peugeot 3008	3051	36607	32982	27430
Total	**191936**	**2302613**	**2074569**	**1725366**

Table 91: Estimated number of HEVs per model using LIB until 2030 (Tech 3)

HEV models	2015	2020	2025	2030
Toyota Auris		314490	728598	673285
Toyota Yaris		285833	662206	611933
Lexus NX		63147	146296	135190
Lexus CT		40306	93379	86290
Lexus IS		30080	69688	64398
Toyota Prius+		81368	73309	60970
Toyota Prius		77966	70245	58421
Mercedes C class	4358	54368	48983	40738
Peugeot 508				
Peugeot 3008				
Total	**4358**	**947556**	**1892705**	**1731223**

Table 92: Estimated Li demand for HEVs until 2030 (Tech 3)

HEV models	2015	2020	2025	2030
Toyota Auris		128620	297982	275360
Toyota Yaris		73573	170452	157512
Lexus NX		23478	54393	50264
Lexus CT		14986	34718	32083
Lexus IS		13765	31889	29468
Toyota Prius+		33278	29982	24935
Toyota Prius		31887	28729	23893
Mercedes C class	997	12439	11207	9321
Peugeot 508				
Peugeot 3008				
Li demand per year (kg)	**997**	**332025**	**659352**	**602835**

Cobalt

Once again, information on models registered in the EU in 2014/2015 has been used to estimate the demand for Co used in PHEVs, BEVs and HEVs until 2030. The different models use different LIB chemistries which means the Co content will differ – this should be taken into account when assessing the average amount of Co to be used for calculating future demand.

Information on the battery type and the corresponding Co content for PHEVs, BEVs and HEVs is given in the tables below.

Table 93: Estimated Co demand for PHEVs registered in the EU in 2015

PHEV models	EU sales (cars)	Battery capacity (kWh)	Battery type	Co density (g/Wh)	Co per vehicle (kg)	Co per model (kg)
Mitsubishi Outlander	28250	12	LMO	0	0	0
VW Golf GTE	14834	8.8	NMC	0.36	3.17	46994
Audi A3 e-Tron	9851	8.8	NMC	0.36	3.17	31208
Volvo V60 PHEV	6328	11.2	LMO(NMC) (1)	0.252	2.82	17860
Volvo XC90	2818	9.2	LMO(NMC) (1)	0.252	2.32	6533
Mercedes C350e	5245	6.2	NMC	0.36	2.23	11707
BMW X5 40e	1472	9	NMC	0.36	3.24	4769
BMW i3Rex	4999	18.8	NMC	0.36	6.77	33833
BMW 225xe Active Tourer	263	7.7	NMC	0.36	2.77	729
VW Passat GTE	4730	9.9	NMC	0.36	3.56	16858
Others	10717				**1.14**(2)	12268
Total	**89507**					**182760**

Note: (1) The LMO(NMC) type battery uses less Co.
Note: (2) The average Co demand to be used in the category 'Others' has been derived from Table 94.

Information on models registered in the EU in 2014 (Table 94) is used to calculate the average amount of Co per vehicle for the 'Others' category; consequently this is used in Table 93.

Table 94: Estimated Co demand for PHEVs registered in the EU in 2014: 'Others' category

PHEV models: 'Others'	EU sales (cars)	Battery capacity (kWh)	Battery type	Co density (g/Wh)	Co per vehicle (kg)	Co per model (kg)
Porsche Cayenne S E-Hybrid	1486	11	LFP	0	0	0
BMW i8	1116	7.1	NMC	0.36	2.56	2852
Toyota Prius PHEV	159	4.4	NCA	0.22	0.97	154
Mercedes S500 Plug-in Hybrid	141	8.7	NMC	0.36	3.13	442
Porsche Panamera S E-Hybrid	110	9.4	LFP	0	0	0
Total 'Others'	**3012**					**3448**

Similar approach is used to calculate the Co demand for BEVs (Table 95 and Table 96).

Table 95: Estimated Co demand for BEVs registered in the EU in 2015

BEV models	EU sales (cars)	Battery capacity (kWh)	Battery type	Co density (g/Wh)	Co per vehicle (kg)	Co per model (kg)
Nissan Leaf	11896	30	LMO(NMC)	0.252	7.56	89934
Tesla model S(1)	10389	72.5	NCA	0.22	15.95	165705
VW e-Golf	2076	26.5	LMO(NMC)	0.252	6.68	13864
Renault Zoe	16424	22	LMO	0	0.00	0
BMW i3	3481	33	LMO(NMC)	0.252	8.32	28948
VW e-UP	1397	18.7	LMO(NMC)	0.252	4.71	6583
Kia Soul EV	4916	27	Li metal polymer	0	0.00	0
Mercedes B-Class Electric	1288	28	NMC	0.36	10.08	12983
Peugeot iOn	870	16	LTO	0	0.00	0
Citroen C-Zero	1075	16	LTO	0	0.00	0
Others	5421				**2.81**(2)	15252
Total	**59233**					**333268**

Note: (1) The Tesla S model is offered on the market with two battery capacities: 60 kWh and 85 kWh. To account for this, an average value of 72.5 kWh was used for the calculations thereby assuming an equal proportion of both battery capacities.
Note: (2) The average Co demand to be used in the category 'Others' has been derived from Table 96.

Table 96: Estimated Co demand for BEVs registered in the EU in 2014: 'Others' category

BEV models: 'Others'	EU sales (cars)	Battery capacity (kWh)	Battery type	Co density (g/Wh)	Co per vehicle (kg)	Co per model (kg)
Nissan e-NV200	1614	24	LMO(NMC)	0.252	6.05	9761
Renault Kangoo ZE	1611	22	LMO	0	0.00	0
Smart Fortwo ED	1132	17	NMC	0.36	6.12	6928
Renault Twizy	1138	6.1	LMO	0	0.00	0
Bolloré Bluecar	229	30	Li metal polymer	0	0.00	0
Mitsubishi i-MiEV	208	16.3	LTO	0	0.00	0
Total 'Others'	**5932**					**16689**

The average amount of Co estimated from Table 93 to Table 96 for PHEVs and BEVs is as follows:

Average Co amount per PHEV = 2.04 kg

Average Co amount per BEV = 5.6 kg

The obtained values were used to assess the Co demand until 2030 for these two types EVs.

The demand for Co in HEVs has been calculated for the 3 different deployment scenarios similarly to the Li case. An average amount of **0.28 kg/kWh** is used for the purpose.

Information on the HEVs 2015 sales in the EU and sales projections until 2030 has already been given in Table 85.

Table 97: Estimated number of HEVs using LIB with Co per model until 2030 (ERERT)

HEV models	2015	2020	2025	2030
Toyota Auris		51422	217787	398564
Toyota Yaris		46736	197942	362246
Lexus NX		10325	43730	80028
Lexus CT		6590	27912	51081
Lexus IS		4918	20831	38121
Toyota Prius+		13304	21913	36092
Toyota Prius		12748	20997	34583
Mercedes C class	2615	8890	14642	24116
Peugeot 508				
Peugeot 3008				
Total	**2615**	**154934**	**565753**	**1024833**

Table 98: Estimated Co demand for HEVs until 2030 (ERERT)

HEV models	2015	2020	2025	2030
Toyota Auris		14398	60980	111598
Toyota Yaris		13086	55424	101429
Lexus NX		2891	12244	22408
Lexus CT		1845	7815	14303
Lexus IS		1377	5833	10674
Toyota Prius+		3725	6136	10106
Toyota Prius		3569	5879	9683
Mercedes C class	732	2489	4100	6752
Peugeot 508				
Peugeot 3008				
Co demand per year (kg)	**732**	**43382**	**158411**	**286953**

Table 99: Estimated number of HEVs using LIB with Co per model until 2030 (Tech 2)

HEV models	2015	2020	2025	2030
Toyota Auris		188694	728598	1131118
Toyota Yaris		171500	662206	1028048
Lexus NX		37888	146296	227119
Lexus CT		24183	93379	144967
Lexus IS		18048	69688	108188
Toyota Prius+		48821	73309	102429
Toyota Prius		46780	70245	98147
Mercedes C class	2615	32621	48983	68440
Peugeot 508				
Peugeot 3008				
Total	**2615**	**568534**	**1892705**	**2908455**

Table 100: Estimated Co demand for HEVs until 2030 (Tech 2)

HEV models	2015	2020	2025	2030
Toyota Auris		52834	204007	316713
Toyota Yaris		48020	185418	287853
Lexus NX		10609	40963	63593
Lexus CT		6771	26146	40591
Lexus IS		5053	19513	30293
Toyota Prius+		13670	20527	28680
Toyota Prius		13098	19668	27481
Mercedes C class	732	9134	13715	19163
Peugeot 508				
Peugeot 3008				
Co demand per year (kg)	**732**	**159189**	**529957**	**814367**

Table 101: Estimated number of HEVs using LIB with Co per model until 2030 (Tech 3)

HEV models	2015	2020	2025	2030
Toyota Auris		188694	437159	403971
Toyota Yaris		171500	397324	367160
Lexus NX		37888	87778	81114
Lexus CT		24183	56027	51774
Lexus IS		18048	41813	38639
Toyota Prius+		48821	43986	36582
Toyota Prius		46780	42147	35052
Mercedes C class	2615	32621	29390	24443
Peugeot 508				
Peugeot 3008				
Total	**2615**	**568534**	**1135623**	**1038734**

Table 102: Estimated Co demand for HEVs until 2030 (Tech 3)

HEV models	2015	2020	2025	2030
Toyota Auris		52834	122404	113112
Toyota Yaris		48020	111251	102805
Lexus NX		10609	24578	22712
Lexus CT		6771	15688	14497
Lexus IS		5053	11708	10819
Toyota Prius+		13670	12316	10243
Toyota Prius		13098	11801	9815
Mercedes C class	732	9134	8229	6844
Peugeot 508				
Peugeot 3008				
Co demand per year (kg)	**732**	**159189**	**317974**	**290846**

Graphite

To estimate the demand for graphite used in PHEVs, BEVs and HEVs until 2030, information on the models registered in the EU in 2014/2015 has been used.

Table 103: Estimated graphite demand for PHEVs registered in the EU in 2015

PHEV models	EU sales (cars)	Battery capacity (kWh)	C per vehicle (kg)	C per model (kg)
Mitsubishi Outlander	28250	12	34.44	972930
VW Golf GTE	14834	8.8	25.26	374648
Audi A3 e-Tron	9851	8.8	25.26	248797
Volvo V60 PHEV	6328	11.2	32.14	203407
Volvo XC90	2818	9.2	26.40	74406
Mercedes C350e	5245	6.2	17.79	93330
BMW X5 40e	1472	9	25.83	38022
BMW i3Rex	4999	18.8	53.96	269726
BMW 225xe Active Tourer	263	7.7	22.10	5812
VW Passat GTE	4730	9.9	28.41	134393
Others	10717		25.95(1)	278065
Total	**89507**			**2693536**

Note: (1) The average graphite demand to be used in the category 'Others' has been derived from Table 104.

The amount of natural graphite feedstock needed per kWh varies between 0.6 and 1.1 kg/kWh in different sources [TMR, 2014; AVICENNE, 2014c]. The amount of processed graphite (battery grade) is around three times less:

$$\frac{Natural\ graphite\ feedstock}{Processed\ graphite\ amount} = 3.3$$

Since the demand and supply figures used in D1.1 indicator refer to natural graphite, the amount of natural graphite (denoted as C) has been taken for calculating the demand for graphite for EVs. An average amount of **2.87 kg/kWh** and 2015 sales figures are used for calculating the demand for natural graphite in 2015.

Information on models sold in the EU in 2014 (Table 104) has been used to calculate the average amount of graphite per vehicle for the 'Others' category; consequently this is used in Table 103.

Table 104: Estimated graphite demand for PHEVs registered in the EU in 2014: 'Others' category

PHEV models: 'Others'	EU sales (cars)	Battery capacity (kWh)	C per vehicle (kg)	C per model (kg)
Porsche Cayenne S E-Hybrid	1486	11	31.57	46913
BMW i8	1116	7.1	20.38	22741
Toyota Prius PHEV	159	4.4	12.63	2008
Mercedes S500 Plug-in Hybrid	141	8.7	24.97	3521
Porsche Panamera S E-Hybrid	110	9.4	26.98	2968
Total 'Others'	**3012**			**78150**

Table 105: Estimated graphite demand for BEVs registered in the EU in 2015

BEV models	EU sales (cars)	Battery capacity (kWh)	C per vehicle (kg)	C per model (kg)
Nissan LEAF	11896	30	86.10	1024246
Tesla Model S(1)	10389	72.5	208.08	2161691
VW e-Golf	2076	26.5	76.06	157890
Renault ZOE	16424	22	63.14	1037011
BMW i3	3481	33	94.71	329686
VW e-UP	1397	18.7	53.67	74976
Kia Soul EV	4916	27	77.49	380941
Mercedes B-Class Electric	1288	28	80.36	103504
Peugeot iOn	870	16	45.92	39950
Citroën C-Zéro	1075	16	45.92	49364
Others	5421		53.52(2)	290142
Total	**59233**			**5649400**

Note: (1) The Tesla S model is offered on the market with two battery capacities: 60 kWh and 85 kWh. To account for this, an average value of 72.5 kWh was used for the calculations thereby assuming an equal proportion of both battery capacities.
Note: (2) The average graphite demand to be used in the category 'Others' has been derived from Table 106.

Information on models sold in the EU in 2014 (Table 106) has been used to calculate the average amount of graphite per vehicle (namely 53.52 kg) for the 'Others' category; consequently this is used in Table 105.

Table 106: Estimated graphite demand for BEVs registered in the EU in 2014: 'Others' category

BEV models: 'Others'	EU sales (cars)	Battery capacity (kWh)	C per vehicle (kg)	C per model (kg)
Nissan e-NV200	1614	24	68.88	111172
Renault Kangoo ZE	1611	22	63.14	101719
Smart Fortwo ED	1132	17	48.79	55230
Renault Twizy	1138	6.1	17.51	19923
Bolloré Bluecar	229	30	86.10	19717
Mitsubishi i-MiEV	208	16.3	46.78	9730
Total 'Others'	**5932**			**317491**

The information in Table 103 to Table 106 has been used to derive an average amount of natural graphite required per vehicle (PHEV and BEV) in order to calculate future demand until 2030 for these two types of EVs.

To estimate the demand for graphite for HEVs, a similar approach is taken as for lithium. The HEV models and number of cars per model using LIB has already been given in Table 85.

The demand for graphite according to the three deployment scenarios is presented in Table 107 to Table 109.

Table 107: Estimated graphite demand for HEVs until 2030 (ERERT)

HEV models	2015	2020	2025	2030
Toyota Auris		351735	1489699	2726247
Toyota Yaris		201199	852139	1559470
Lexus NX		64205	271926	497643
Lexus CT		40981	173567	317639
Lexus IS		37642	159424	291756
Toyota Prius+		91004	149889	246876
Toyota Prius		87200	143623	236555
Mercedes C class	10005	34018	56029	92283
Peugeot 508				
Peugeot 3008				
C demand per year (kg)	**10005**	**907983**	**3296296**	**5968469**

Table 108: Estimated graphite demand for HEVs until 2030 (Tech 2)

HEV models	2015	2020	2025	2030
Toyota Auris		1290697	4983731	7737037
Toyota Yaris		738306	2850798	4425746
Lexus NX		235601	909719	1412301
Lexus CT		150381	580661	901453
Lexus IS		138127	533347	827999
Toyota Prius+		333941	501448	700630
Toyota Prius		319981	480485	671339
Mercedes C class	10005	124828	187443	261897
Peugeot 508				
Peugeot 3008				
C demand per year (kg)	**10005**	**3331862**	**11027631**	**16938402**

Table 109: Estimated graphite demand for HEVs until 2030 (Tech 3)

HEV models	2015	2020	2025	2030
Toyota Auris		1290697	2990239	2763227
Toyota Yaris		738306	1710479	1580623
Lexus NX		235601	545831	504393
Lexus CT		150381	348397	321947
Lexus IS		138127	320008	295714
Toyota Prius+		333941	300869	250225
Toyota Prius		319981	288291	239764
Mercedes C class	10005	124828	112466	93535
Peugeot 508				
Peugeot 3008				
C demand per year (kg)	**10005**	**3331862**	**6616579**	**6049429**

Rare earths

To estimate the demand for Nd and Pr and Dy, respectively, in PHEVs, BEVs and HEVs until 2030, information on the models registered in the EU in 2014/2015 has been used. Not all EVs use a permanent magnet (PM) motor. Therefore, only those using PM have been taken into account when calculating the average demand for Nd, Pr and Dy per EV type.

The demand and supply figures used in D1.1 relate to Nd oxide; for reasons of comparison, the Nd metal demand is transformed into Nd oxide demand assuming that for every 1 kg of Nd metal used, around 1.17kg of Nd oxide feedstock is required. The same assumption has been made for the demand for Dy and Pr metal.

The Nd, Pr and Dy demand per vehicle is calculated as 22.65 %, 7.55 % and 7.5 % of the weight of the permanent magnet.

The weight of the permanent magnet is assumed at 1.5 kg for PHEVs and BEVs, and 0.63 kg for HEVs.

Neodymium

Table 110: Estimated Nd demand for PHEVs registered in the EU in 2015

PHEV models	EU sales (cars)	Motor type	Nd per model (kg)	Nd oxide per model (kg)
Mitsubishi Outlander	28250	PM	9598	11230
VW Golf GTE	14834	PM	5040	5897
Audi A3 e-Tron	9851	PM	3347	3916
Volvo V60 PHEV	6328	PM	2150	2515
Volvo XC90	2818	PM	957	1120
Mercedes C350e	5245	PM	1782	2085
BMW X5 40e	1472	PM	500	585
BMW i3Rex	4999	PM	1698	1987
BMW 225xe Active Tourer	263	PM	89	105
VW Passat GTE	4730	PM	1607	1880
Others	10717		3641(1)	4260
Total	**89507**		**30410**	**35580**

Note: (1) The average Nd demand to be used in the category 'Others' has been derived from Table 111.

Information on models sold in the EU in 2014 (Table 111) is used to calculate the average amount of Nd per vehicle for the 'Others' category; consequently this is used in Table 110.

Table 111: Estimated Nd demand for PHEVs registered in the EU in 2014: 'Others' category

PHEV models: 'Others'	EU sales (cars)	Motor type	Nd per model (kg)	Nd oxide per model (kg)
Porsche Cayenne S E-Hybrid	1486	PM	505	591
BMW i8	1116	PM	379	444
Toyota Prius PHEV	159	PM	54	63
Mercedes S500 Plug-in Hybrid	141	PM	48	56
Porsche Panamera S E-Hybrid	110	PM	37	44
Total 'Others'	**3012**		**1023**	**1197**

A similar approach is used to calculate the Nd demand for BEVs.

Table 112: Estimated Nd demand for BEVs registered in the EU in 2015

BEV models	EU sales (cars)	Motor type	Nd per model (kg)	Nd oxide per model (kg)
Nissan LEAF	11896	PM	4042	4729
Tesla Model S(1)	10389	Non-PM	0	0
VW e-Golf	2076	PM	705	825
Renault ZOE	16424	Non-PM	0	0
BMW i3(2)	3481	PM	355	415
VW e-UP	1397	PM	475	555
Kia Soul EV	4916	PM	1670	1954
Mercedes B-Class Electric	1288	PM	438	512
Peugeot iOn	870	PM	296	346
Citroën C-Zéro	1075	PM	365	427
Others	5421		745(3)	872
Total	**59233**		**9090**	**10635**

Note: (1) The Tesla S model is offered on the market with two battery capacities: 60 kWh and 85 kWh. To account for this, an average value of 72.5 kWh was used for the calculations thereby assuming an equal proportion of both battery capacities.

Note: (2) BMW i3 uses 30 % less PM, e.g. a PM weight of 0.45 kg.

Note: (3) The average Nd demand to be used in the category 'Others' has been derived from Table 113.

Table 113: Estimated Nd demand for BEVs registered in the EU in 2014: 'Others' category

BEV models: 'Others'	EU sales (cars)	Motor type	Nd per model (kg)	Nd oxide per model (kg)
Nissan e-NV200	1614	PM	548	642
Renault Kangoo ZE	1611	Non-PM	0	0
Smart Fortwo ED	1132	Non-PM	0	0
Renault Twizy	1138	Non-PM	0	0
Bolloré Bluecar	229	PM	78	91
Mitsubishi i-MiEV	208	PM	71	83
Total 'Others'	**5932**		**697**	**815**

Nd demand for HEVs in 2015 is presented in Table 114.

Table 114: Estimated Nd demand for HEVs registered in the EU in 2015

HEV models	EU sales (cars)	Motor type	Nd per model (kg)	Nd oxide per model (kg)
Toyota Auris	72020	PM	10277	12024
Toyota Yaris	65457	PM	9340	10928
Lexus NX	14461	PM	2063	2414
Lexus CT	9230	PM	1317	1541
Lexus IS	6888	PM	983	1150
Toyota Prius+	6522	PM	931	1089
Toyota Prius	6249	PM	892	1043
Mercedes C class	4358	PM	622	728
Peugeot 508	3700	PM	528	618
Peugeot 3008	3051	PM	435	509
Total	**191936**		**27388**	**32044**

Praseodymium

Table 115: Estimated Pr demand for PHEVs registered in the EU in 2015

PHEV models	EU sales (cars)	Motor type	Pr per model (kg)	Pr oxide per model (kg)
Mitsubishi Outlander	28250	PM	3199	3743
VW Golf GTE	14834	PM	1680	1966
Audi A3 e-Tron	9851	PM	1116	1305
Volvo V60 PHEV	6328	PM	717	838
Volvo XC90	2818	PM	319	373
Mercedes C350e	5245	PM	594	695
BMW X5 40e	1472	PM	167	195
BMW i3Rex	4999	PM	566	662
BMW 225xe Active Tourer	263	PM	30	35
VW Passat GTE	4730	PM	536	627
Others	10717		1214(1)	1420
Total	**89507**		**10137**	**11860**

Note: (1) The average Pr demand to be used in the category 'Others' has been derived from Table 116.

Table 116: Estimated Pr demand for PHEVs registered in the EU in 2014: ‘Others’ category

PHEV models: 'Others'	EU sales (cars)	Motor type	Pr per model (kg)	Pr oxide per model (kg)
Porsche Cayenne S E-Hybrid	1486	PM	168	197
BMW i8	1116	PM	126	148
Toyota Prius PHEV	159	PM	18	21
Mercedes S500 Plug-in Hybrid	141	PM	16	19
Porsche Panamera S E-Hybrid	110	PM	12	15
Total 'Others'	**3012**		**341**	**399**

Table 117: Estimated Pr demand for BEVs registered in the EU in 2015

BEV models	EU sales (cars)	Motor type	Pr per model (kg)	Pr oxide per model (kg)
Nissan LEAF	11896	PM	1347	1576
Tesla Model S(1)	10389	Non PM	0	0
VW e-Golf	2076	PM	235	275
Renault ZOE	16424	Non PM	0	0
BMW i3(2)	3481	PM	118	138
VW e-UP	1397	PM	158	185
Kia Soul EV	4916	PM	557	651
Mercedes B-Class Electric	1288	PM	146	171
Peugeot iOn	870	PM	99	115
Citroën C-Zéro	1075	PM	122	142
Others	5421		248(3)	291
Total	**59233**		**3030**	**3545**

Note: (1) The Tesla S model is offered on the market with two battery capacities: 60 kWh and 85 kWh. To account for this, an average value of 72.5 kWh was used for the calculations thereby assuming an equal proportion of both battery capacities.
Note: (2) BMW i3 uses 30 % less PM, e.g. a PM weight of 0.45 kg.
Note: (3) The average Pr demand to be used in the category 'Others' has been derived from Table 118.

Table 118: Estimated Pr demand for BEVs registered in the EU in 2014: 'Others' category

BEV models: 'Others'	EU sales (cars)	Motor type	Pr per model (kg)	Pr oxide per model (kg)
Nissan e-NV200	1614	PM	183	214
Renault Kangoo ZE	1611	Non PM	0	0
Smart Fortwo ED	1132	Non PM	0	0
Renault Twizy	1138	Non PM	0	0
Bolloré Bluecar	229	PM	26	30
Mitsubishi i-MiEV	208	PM	24	28
Total 'Others'	**5932**		**232**	**272**

Table 119: Estimated Pr demand for HEVs registered in the EU in 2015

HEV models	EU sales (cars)	Motor type	Pr per model (kg)	Pr oxide per model (kg)
Toyota Auris	72020	PM	3426	4008
Toyota Yaris	65457	PM	3113	3643
Lexus NX	14461	PM	688	805
Lexus CT	9230	PM	439	514
Lexus IS	6888	PM	328	383
Toyota Prius+	6522	PM	310	363
Toyota Prius	6249	PM	297	348
Mercedes C class	4358	PM	207	243
Peugeot 508	3700	PM	176	206
Peugeot 3008	3051	PM	145	170
Total	**191936**		**9129**	**10681**

Dysprosium

Table 120: Estimated Dy demand for PHEVs registered in the EU in 2015

PHEV models	EU sales (cars)	Motor type	Dy per model (kg)	Dy oxide per model (kg)
Mitsubishi Outlander	28250	PM	3178	3718
VW Golf GTE	14834	PM	1669	1953
Audi A3 e-Tron	9851	PM	1108	1297
Volvo V60 PHEV	6328	PM	712	833
Volvo XC90	2818	PM	317	371
Mercedes C350e	5245	PM	590	690
BMW X5 40e	1472	PM	166	194
BMW i3Rex	4999	PM	562	658
BMW 225xe Active Tourer	263	PM	30	35
VW Passat GTE	4730	PM	532	623
Others	10717	PM	1206(1)	1411
Total	**89507**		**10070**	**11781**

Note: (1) The average Dy demand to be used in the category 'Others' has been derived from Table 121.

Table 121: Estimated Dy demand for PHEVs registered in the EU in 2014: 'Others' category

PHEV models: 'Others'	EU sales (cars)	Motor type	Dy per model (kg)	Dy oxide per model (kg)
Porsche Cayenne S E-Hybrid	1486	PM	168	197
BMW i8	1116	PM	126	148
Toyota Prius PHEV	159	PM	18	21
Mercedes S500 Plug-in Hybrid	141	PM	16	19
Porsche Panamera S E-Hybrid	110	PM	12	15
Total 'Others'	**3012**		**341**	**399**

Table 122: Estimated Dy demand for BEVs registered in the EU in 2015

BEV models	EU sales (cars)	Motor type	Dy per model (kg)	Dy oxide per model (kg)
Nissan LEAF	11896	PM	1338	1566
Tesla Model S(1)	10389	Non PM	0	0
VW e-Golf	2076	PM	234	273
Renault ZOE	16424	Non PM	0	0
BMW i3(2)	3481	PM	117	137
VW e-UP	1397	PM	157	184
Kia Soul EV	4916	PM	553	647
Mercedes B-Class Electric	1288	PM	145	170
Peugeot iOn	870	PM	98	115
Citroën C-Zéro	1075	PM	121	141
Others	5421		247(3)	289
Total	**59233**		**3010**	**3522**

Note: (1) The Tesla S model is offered on the market with two battery capacities: 60 kWh and 85 kWh. To account for this, an average value of 72.5 kWh was used for the calculations thereby assuming an equal proportion of both battery capacities.
Note: (2) BMW i3 uses 30 % less PM, e.g. a PM weight of 0.45 kg.
Note: (3) The average Dy demand to be used in the category 'Others' has been derived from Table 123.

Table 123: Estimated Dy demand for BEVs registered in the EU in 2014: 'Others' category

BEV models: 'Others'	EU sales (cars)	Motor type	Dy per model (kg)	Dy oxide per model (kg)
Nissan e-NV200	1614	PM	182	212
Renault Kangoo ZE	1611	Non PM	0	0
Smart Fortwo ED	1132	Non PM	0	0
Renault Twizy	1138	Non PM	0	0
Bolloré Bluecar	229	PM	26	30
Mitsubishi i-MiEV	208	PM	23	27
Total 'Others'	**5932**		**231**	**270**

Table 124: Estimated Dy demand for HEVs registered in the EU in 2015

HEV models	EU sales (cars)	Motor type	Dy per model (kg)	Dy oxide per model (kg)
Toyota Auris	72020	PM	3403	3981
Toyota Yaris	65457	PM	3093	3619
Lexus NX	14461	PM	683	799
Lexus CT	9230	PM	436	510
Lexus IS	6888	PM	325	381
Toyota Prius+	6522	PM	308	361
Toyota Prius	6249	PM	295	345
Mercedes C class	4358	PM	206	241
Peugeot 508	3700	PM	175	205
Peugeot 3008	3051	PM	144	169
Total	**191936**		**9069**	**10611**

The average amount of Nd, Pr and Dy calculated using the information in Table 110 to Table 124 is presented in Table 125. These values have been used for estimating the demand for these three materials until 2030.

Table 125: Average amount of Nd, Dy and Pr per vehicle type used to calculate the Nd/Pr/Dy demand for PHEVs, BEVs and HEVs until 2030

Materials	PHEVs	BEVs	HEVs
Nd	0.398	0.180	0.167
Pr	0.133	0.060	0.056
Dy	0.132	0.059	0.055

Note: Average amount of materials per vehicle is in kilogrammes.

B.3.3 Indicator D1.1 Material demand

Li-ion battery

Table 126: Data for calculating D1.1 material demand for lithium

Lithium	2015	2020	2025	2030
EU demand for PHEV (ERERT)	0.27	3.81	3.71	6.92
EU demand for BEV (ERERT)	0.56	7.99	7.79	14.5
EU demand for HEV (ERERT)	0	0.09	0.33	0.7
EU demand for PHEV (Tech 2)	0.27	0.72	3.09	7.18
EU demand for BEV (Tech 2)	0.56	0.57	4.56	11.4
EU demand for HEV (Tech 2)	0	0.33	1.10	1.69
EU demand for PHEV (Tech 3)	0.27	2.05	10.2	16.7
EU demand for BEV (Tech 3)	0.56	4.10	11.4	22.8
EU demand for HEV (Tech 3)	0	0.33	0.66	0.60
EU demand, all sectors (ERERT)	8.00	20.8	23.0	36.2
EU demand, all sectors (Tech 2)	8.00	10.5	19.9	34.2
EU demand, all sectors (Tech 3)	8.00	15.4	33. 5	54.2
Global demand, all sectors	33.3	58.7	104	182
D1.1.1 ERERT	0.02	0.20	0.11	0.12
D1.1.1 Tech 2	0.02	0.03	0.08	0.11
D1.1.1 Tech 3	0.02	0.11	0.22	0.22
D1.1.2 ERERT	0.10	0.57	0.51	0.61
D1.1.2 Tech 2	0.10	0.15	0.44	0.59
D1.1.2 Tech 3	0.10	0.42	0.67	0.74
D1.1.3 ERERT	0.24	0.35	0.22	0.20
D1.1.3 Tech 2	0.24	0.18	0.19	0.19
D1.1.3 Tech 3	0.24	0.26	0.32	0.30

Note: Demand figures are given in thousand tonnes.

The global demand for Li and its annual growth rate (12 %) until 2030 was estimated combining information from multiple sources: [OROCOBRE, 2012; Roskill, 2013; USGS, 2016]. The EU demand for lithium was calculated based on information published by the European lithium company.

Table 127: Data for calculating D1.1 material demand for cobalt

Cobalt	2015	2020	2025	2030
EU demand for PHEV (ERERT)	0.18	2.60	2.52	4.72
EU demand for BEV (ERERT)	0.33	4.73	4.61	8.60
EU demand for HEV (ERERT)	0	0.04	0.16	0.36
EU demand for PHEV (Tech 2)	0.18	0.49	2.11	4.89
EU demand for BEV (Tech 2)	0.33	0.34	2.70	6.73
EU demand for HEV (Tech 2)	0	0.16	0.53	0.81
EU demand for PHEV (Tech 3)	0.18	1.39	7.00	11.5
EU demand for BEV (Tech 3)	0.33	2.43	6.74	13.5
EU demand for HEV (Tech 3)	0	0.16	0.32	0.29
EU demand, all sectors (ERERT)	19.8	32.7	40.7	57.7
EU demand, all sectors (Tech 2)	19.8	26.4	38.8	56.7
EU demand, all sectors (Tech 3)	19.8	29.4	47.5	69.5
Global demand, all sectors	123	159	206	267
D1.1.1 ERERT	0.004	0.05	0.04	0.05
D1.1.1 Tech 2	0.004	0.01	0.03	0.05
D1.1.1 Tech 3	0.004	0.03	0.07	0.09
D1.1.2 ERERT	0.03	0.23	0.18	0.24
D1.1.2 Tech 2	0.03	0.04	0.14	0.22
D1.1.2 Tech 3	0.03	0.14	0.30	0.36
D1.1.3 ERERT	0.16	0.21	0.20	0.22
D1.1.3 Tech 2	0.16	0.17	0.19	0.21
D1.1.3 Tech 3	0.16	0.18	0.23	0.26

Note: Demand figures are given in thousand tonnes.

The global and EU demand for Co and its annual growth rate (5 %) until 2030 was estimated combining information from multiple sources: [Roskill, 2014; CRU, 2015; Darton, 2016; Statista, 2016g]

Table 128: Data for calculating D1.1 material demand for graphite

Graphite	2015	2020	2025	2030
EU demand for PHEV (ERERT)	2.69	38.2	37.3	69.5
EU demand for BEV (ERERT)	5.64	80.2	78.1	146
EU demand for HEV (ERERT)	0.01	0.91	3.35	7.49
EU demand for PHEV (Tech 2)	2.69	7.21	31.0	72.0
EU demand for BEV (Tech 2)	5.65	5.71	45.7	114
EU demand for HEV (Tech 2)	0.01	333	11.0	16.9
EU demand for PHEV (Tech 3)	2.69	20.5	103	169
EU demand for BEV (Tech 3)	5.64	41.1	114	228
EU demand for HEV (Tech 3)	0.01	3.33	6.62	6.04
EU demand, all sectors (ERERT)	150	313	384	586
EU demand, all sectors (Tech 2)	150	210	353	566
EU demand, all sectors (Tech 3)	150	259	489	767
Global demand, all sectors	1157	1585	2172	2976
D1.1.1 ERERT	0.01	0.08	0.05	0.07
D1.1.1 Tech 2	0.01	0.01	0.04	0.07
D1.1.1 Tech 3	0.01	0.04	0.10	0.14
D1.1.2 ERERT	0.06	0.38	0.31	0.38
D1.1.2 Tech 2	0.06	0.08	0.25	0.36
D1.1.2 Tech 3	0.06	0.25	0.46	0.53
D1.1.3 ERERT	0.13	0.20	0.18	0.20
D1.1.3 Tech 2	0.13	0.13	0.16	0.19
D1.1.3 Tech 3	0.13	0.16	0.23	0.26

Note: Demand figures are given in thousand tonnes.

The global and EU demand for graphite and its annual growth rate (6.5 %) until 2030 was estimated combining information from multiple sources: [Roskill, 2014; ProGraphite, 2015; CRU, 2015; TMR, 2014; Statista, 2016h]

At present, around 55 % of batteries use natural graphite, 41 % synthetic graphite and around 4 % use amorphous graphite [ProGraphite, 2015]. Natural graphite has several advantages over synthetic graphite: lower price, higher energy density and higher power output – three important factors for the EV market. Therefore, it is expected that natural graphite will also prevail in the future. Since the future shares of natural and synthetic graphite cannot be forecast, a conservative assumption in the demand calculations is that all batteries will use natural graphite until 2030.

PM motors

Table 129: Data for calculating D1.1 material demand for neodymium

Neodymium	2015	2020	2025	2030
EU demand for PHEV (ERERT)	36	505	457	413
EU demand for BEV (ERERT)	11	151	136	123
EU demand for HEV (ERERT)	33	113	187	307
EU demand for PHEV (Tech 2)	36	95	410	951
EU demand for BEV (Tech 2)	11	11	86	215
EU demand for HEV (Tech 2)	33	416	624	872
EU demand for PHEV (Tech 3)	36	271	1358	2235
EU demand for BEV (Tech 3)	11	77	215	430
EU demand for HEV (Tech 3)	33	416	375	312
EU demand, all sectors (ERERT)(1)	3.50	10.8	14.0	21.4
EU demand, all sectors (Tech 2)(1)	3.50	10.5	14.3	22.7
EU demand, all sectors (Tech 3)(1)	3.50	10.8	15.2	23.6
Global demand, all sectors(1)	20.3	33.0	53.7	87.2
D1.1.1 ERERT	0.004	0.02	0.01	0.01
D1.1.1 Tech 2	0.004	0.02	0.02	0.02
D1.1.1 Tech 3	0.004	0.02	0.04	0.03
D1.1.2 ERERT	0.02	0.07	0.06	0.04
D1.1.2 Tech 2	0.02	0.05	0.08	0.09
D1.1.2 Tech 3	0.02	0.07	0.13	0.13
D1.1.3 ERERT	0.17	0.33	0.26	0.25
D1.1.3 Tech 2	0.17	0.32	0.27	0.26
D1.1.3 Tech 3	0.17	0.33	0.28	0.27

Note: Demand figures are given in tonnes or (1) thousand tonnes for all sectors.

Note: For Nd global demand in 2015 and until 2030 see notes in Table 15. The future EU demand – all sectors – differ for the two technologies: wind and EVs. The reason is that the wind demand has been considered when calculating the EU demand for the three EVs deployment scenarios, and vice versa. However, due to multiple scenarios considered for the wind technology, an average value has been taken into account as a wind demand in 2020, 2025 and 2030. The same point is valid also for the EVs.

Table 130: Data for calculating D1.1 material demand for praseodymium

Praseodymium	2015	2020	2025	2030
EU demand for PHEV (ERERT)	12	168	152	138
EU demand for BEV (ERERT)	4	50	45	41
EU demand for HEV (ERERT)	11	38	62	102
EU demand for PHEV (Tech 2)	12	32	137	317
EU demand for BEV (Tech 2)	4	4	29	72
EU demand for HEV (Tech 2)	11	139	208	291
EU demand for PHEV (Tech 3)	12	90	453	745
EU demand for BEV (Tech 3)	4	26	72	143
EU demand for HEV (Tech 3)	11	139	125	104
EU demand, all sectors (ERERT)	1095	3474	4449	6793
EU demand, all sectors (Tech 2)	1095	3391	4562	7191
EU demand, all sectors (Tech 3)	1095	3472	4838	7504
Global demand, all sectors(1)	6.35	10.3	16.6	26.8
D1.1.1 ERERT	0.004	0.02	0.02	0.01
D1.1.1 Tech 2	0.004	0.02	0.02	0.03
D1.1.1 Tech 3	0.004	0.02	0.04	0.04
D1.1.2 ERERT	0.02	0.07	0.06	0.04
D1.1.2 Tech 2	0.02	0.05	0.08	0.09
D1.1.2 Tech 3	0.02	0.07	0.13	0.13
D1.1.3 ERERT	0.17	0.34	0.27	0.25
D1.1.3 Tech 2	0.17	0.33	0.27	0.27
D1.1.3 Tech 3	0.17	0.34	0.29	0.28

Note: Demand figures are given in tonnes or (1) thousand tonnes for all sectors.

Note: For Pr global demand in 2015 and until 2030 see notes in Table 16. The future EU demand – all sectors – differ for the two technologies: wind and EVs (see explanation under Table 129).

Table 131: Data for calculating D1.1 material demand for dysprosium

Dysprosium	2015	2020	2025	2030
EU demand for PHEV (ERERT)	12	167	151	137
EU demand for BEV (ERERT)	4	50	45	41
EU demand for HEV (ERERT)	11	38	62	102
EU demand for PHEV (Tech 2)	12	32	136	315
EU demand for BEV (Tech 2)	4	4	29	71
EU demand for HEV (Tech 2)	11	138	207	289
EU demand for PHEV (Tech 3)	12	90	450	740
EU demand for BEV (Tech 3)	4	26	71	142
EU demand for HEV (Tech 3)	11	138	124	103
EU demand, all sectors (ERERT)	225	1479	1643	2384
EU demand, all sectors (Tech 2)	225	1396	1755	2780
EU demand, all sectors (Tech 3)	225	1477	2029	3090
Global demand, all sectors	1270	2140	3606	6076
D1.1.1 ERERT	0.02	0.12	0.07	0.05
D1.1.1 Tech 2	0.02	0.08	0.10	0.11
D1.1.1 Tech 3	0.02	0.12	0.18	0.16
D1.1.2 ERERT	0.12	0.17	0.16	0.12
D1.1.2 Tech 2	0.12	0.12	0.21	0.24
D1.1.2 Tech 3	0.12	0.17	0.32	0.32
D1.1.3 ERERT	0.17	0.69	0.46	0.39
D1.1.3 Tech 2	0.17	0.65	0.49	0.46
D1.1.3 Tech 3	0.17	0.69	0.56	0.51

Note: Demand figures are given in tonnes.

Note: For Dy global demand in 2015 and until 2030 see notes in Table 17. The future EU demand – all sectors – differ for the two technologies: wind and EVs (see explanation under Table 129).

B.3.4 Indicator D1.2 Investment potential

Data for D1.2 calculations are given in Table 18 and Table 19.

B.3.5 Indicator D1.3 Stability of supply

Table 132: Country production share, HHI and WGI for mining lithium

Country	2015		2020		2025		2030		WGI
	share	HHI	share	HHI	share	HHI	share	HHI	scaled
Argentina	11.4		13.3		14.1		14.1		0.4
Australia	40.2		30.8		30.1		24.9		0.9
Austria	0.0		0.0		0.3		0.8		0.9
Bolivia	0.0		5.4		4.3		3.5		0.4
Brazil	0.5		0.0		0.0		0.0		0.5
Canada	0.0		11.0		11.3		14.4		0.9
Chile	35.1		22.7		18.1		15.6		0.8
China	6.6		12.1		9.9		8.2		0.4
Czech Republic	0.0		0.0		0.8		2.3		0.8
Finland	0.0		0.0		0.4		1.1		1.0
Mexico	0.0		1.9		5.0		4.1		0.5
Peru	0.0		0.0		0.4		1.1		0.5
Portugal	0.9		0.5		0.4		0.4		0.8
Serbia	0.0		0.0		1.1		3.2		0.6
Spain	0.0		0.0		0.3		0.9		0.7
USA	2.6		1.4		2.9		5.0		0.8
Zimbabwe	2.7		0.9		0.7		0.6		0.2
Total	**100**	**3037**	**100**	**1942**	**100**	**1709**	**100**	**1410**	

Mine production shares in 2015 are calculated based on 2015 data available from [USGS, 2016]. Production projections in 2020, 2025 and 2030 were obtained according to the procedures in Annex C.

Table 133: Country production share, HHI and WGI for mining cobalt

Country	2015		2020		2025		2030		WGI
	share	HHI	share	HHI	share	HHI	share	HHI	scaled
Australia	4.9		4.9		7.9		11.3		0.94
Botswana	0.2		0.0		0.0		0.0		0.70
Brazil	2.1		1.1		0.9		0.9		0.53
Canada	5.1		4.0		4.3		3.6		0.95
China	5.9		5.2		4.6		0.5		0.44
Côte d'Ivoire	0.0		0.0		0.1		0.2		0.38
Cuba	3.4		5.0		4.4		4.2		0.43
Dem. Rep. Congo	51.3		55.2		49.9		46.5		0.30
Finland	1.7		1.7		1.5		1.6		1.00
Indonesia	0.3		0.9		2.8		2.6		0.49
Madagascar	2.9		3.5		3.1		3.0		0.35
Mexico	0.0		1.1		0.9		0.9		0.49
Morocco	1.1		0.4		0.0		0.0		0.48
New Caledonia	2.7		3.7		3.3		3.2		0.54
Norway	0.0		0.0		0.0		0.1		0.98
Papua New Guinea	1.7		2.1		2.4		3.4		0.42
Philippines	3.7		3.4		2.6		2.4		0.50
Russia	5.1		0.0		0.5		1.6		0.38
Serbia	0.0		0.2		0.0		0.0		0.56
Solomon Islands	0.0		0.0		0.1		0.3		0.45
South Africa	2.3		0.7		0.6		0.6		0.60
Tanzania	0.0		0.0		0.2		0.6		0.43
Tonga	0.0		0.0		2.8		9.0		0.57
Uganda	0.0		0.2		0.2		0.0		0.39
USA	0.6		0.6		1.1		1.3		0.84
Vietnam	0.2		0.0		0.0		0.0		0.43
Zambia	4.5		6.0		5.5		2.2		0.48
Zimbabwe	0.3		0.2		0.2		0.1		0.22
Total	**100**	**2820**	**100**	**3228**	**100**	**2694**	**100**	**2454**	

Mine production shares in 2015 are calculated based on 2015 data, available from [Statista, 2016g; Roskill, 2014]. Mine capacities projections in 2020, 2025 and 2030 were obtained according to the procedures in Annex C. It should be noted that the dataset used to normalise the data on capacities refers to the mine production in 2014 as given in [BGS, 2016a].

Table 134: Country production share, HHI and WGI for refining cobalt

Country	2015		2020/2025/2030		WGI
	Share	HHI	Share	HHI	scaled
Australia	5.3		4.3		0.94
Belgium	4.0		3.2		0.86
Brazil	1.3		1.1		0.53
Canada	4.0		4.6		0.95
China	43.6		35.6		0.44
Dem. Rep. Congo	10.1		15.8		0.3
Finland	9.9		8.1		1.0

Country	2015		2020/2025/2030		WGI scaled
	Share	HHI	Share	HHI	
France	0.3		0.2		0.82
India	0.7		0.5		0.47
Japan	2.0		4.1		0.89
Madagascar	3.7		3.0		0.35
Mexico	0.0		0.9		0.49
Morocco	1.3		1.1		0.48
New Caledonia	0.0		2.7		0.54
Norway	3.4		2.8		0.98
Russia	2.0		3.2		0.38
South Africa	1.2		0.9		0.6
South Korea	0.3		0.3		0.73
Uganda	0.7		0.5		0.39
UK	6.2		5.0		0.9
USA	0.0		0.8		0.94
Zambia	0.0		1.1		0.48
Total	**100**	**2243**	**100**	**1717**	

Cobalt refinery production in 2015 and refinery capacities in 2020 were retrieved from [Roskill, 2014]. The same shares are assumed in 2025 and 2030.

Table 135: Country production share, HHI and WGI for production of graphite

Country	2015		2020		2025		2030		WGI scaled
	share	HHI	share	HHI	share	HHI	share	HHI	
Australia	0.0		0.6		3.1		4.6		0.94
Austria	0.0		0.1		0.1		0.1		0.92
Brazil	6.7		4.2		3.0		0.9		0.53
Canada	2.5		5.0		7.3		8.8		0.95
China	65.6		49.6		36.2		30.0		0.44
Ethiopia	0.0		0.0		0.2		0.5		0.35
Germany	0.0		0.0		0.0		0.0		0.93
India	14.3		6.1		4.5		3.7		0.47
Indonesia	0.0		0.0		0.3		0.8		0.49
Madagascar	0.4		1.2		2.0		1.7		0.35
Malawi	0.0		0.0		1.0		2.8		0.44
Mexico	1.9		3.5		2.5		2.1		0.49
Mozambique	0.0		16.6		19.6		18.3		0.41
North Korea	2.5		1.2		0.9		0.7		0.14
Norway	0.7		0.5		0.4		0.3		0.98
Russia	1.3		0.8		0.6		0.5		0.38
South Korea	0.0		0.0		0.2		0.5		0.73
Sri Lanka	0.3		0.3		0.2		0.2		0.48
Sweden	0.0		1.7		2.4		4.2		0.97
Tanzania	0.0		3.4		10.7		13.8		0.43
Turkey	2.7		1.5		1.1		0.9		0.52
Ukraine	0.4		1.6		1.2		1.0		0.35
USA	0.0		0.0		0.9		2.4		0.84
Uzbekistan	0.0		1.6		1.2		1.0		0.27
Vietnam	0.0		0.2		0.1		0.1		0.43
Zimbabwe	0.6		0.2		0.2		0.1		0.22
Total	**100**	**4579**	**100**	**2850**	**100**	**1924**	**100**	**2295**	

Mine production shares in 2015 are calculated based on data available from [USGS, 2016 and WMD, 2016]. Mine capacities projections in 2020, 2025 and 2030 were obtained according to the procedures in Annex C. To be noted that the dataset used to normalise the data on capacities refers to the mine production in 2015 as given in [Statista 2016h].

Data for D1.3 indicator for Nd, Pr and Dy are given in Table 20, Table 21 and Table 22.

B.3.6 Indicator D1.4 Reserves depletion

Table 136: Data for calculating D1.4 reserves depletion for lithium

Lithium	**2015**	**2020**	**2025**	**2030**
Reserves (mio. tonnes)	14.0	13.8	13.4	12.8
Global demand (thousand tonnes)	33.3	58.7	104	182
RDI (years)	**420**	**235**	**130**	**70**

Lithium reserves were retrieved from [USGS, 2016]. See Table 126 for information on global demand data sources.

Table 137: Data for calculating D1.4 reserves depletion for cobalt

Cobalt	**2015**	**2020**	**2025**	**2030**
Reserves (mio. tonnes)	7.16	6.48	5.60	4.45
Global demand (thousand tonnes)	123	159	206	267
RDI (years)	**58**	**41**	**27**	**17**

Cobalt reserves were retrieved from [USGS, 2016]. See Table 127 for information on global demand data sources.

Table 138: Data for calculating D1.4 reserves depletion for graphite

Graphite	**2015**	**2020**	**2025**	**2030**
Reserves (mio. tonnes)	229	222	213	201
Global demand (thousand tonnes)	1157	1585	2172	2976
RDI (years)	**198**	**140**	**98**	**68**

Graphite reserves were retrieved from [USGS, 2016]. See Table 128 for information on global demand data sources.

Data for D1.4 indicator for Nd, Pr and Dy are given in Table 23, Table 24 and Table 25.

B.3.7 Indicator D1.5 Import reliance

Table 139: Import reliance on lithium for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
ERERT	96	99	99	99
Tech 2	96	97	98	99
Tech 3	96	98	99	99
Scenario 1				
ERERT	96	97	87	76
Tech 2	96	95	85	75
Tech 3	96	96	91	84
Scenario 2				
ERERT	96	96	82	61
Tech 2	96	93	80	60
Tech 3	96	95	86	69
Scenario 3				
ERERT	96	96	82	61
Tech 2	96	93	80	60
Tech 3	96	95	86	69

Data used in the calculations of IR are given in Table 126 (EU demand) and Table 140 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 140: EU production, recycling and substitution of lithium

Lithium	**2015**	**2020**	**2025**	**2030**
EU production (tonnes)	300	564	2974	8597
EU recycling rate (%)	0	1	5	15
EU substitution rate (%)	0	0	0	0

EU production in 2015 is based on data available from [USGS, 2016]. Projections in 2020, 2025 and 2030 refer to mine capacities, obtained according to the procedures and references in Annex C. Recycling and substitution rates are based on the assumptions presented under Table 152 and Table 153.

Table 141: Import reliance on cobalt for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
ERERT	89	94	95	96
Tech 2	89	92	95	96
Tech 3	89	93	96	97
Scenario 1				
ERERT	89	92	93	95
Tech 2	89	90	93	94
Tech 3	89	91	94	95
Scenario 2				
ERERT	87	77	58	55
Tech 2	87	75	57	55
Tech 3	87	76	59	56
Scenario 3				
ERERT	87	73	43	29
Tech 2	87	71	42	28
Tech 3	87	72	44	29

Data used in the calculations of IR are given in Table 127 (EU demand) and Table 142 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 142: EU production, recycling and substitution of cobalt

Cobalt	**2015**	**2020**	**2025**	**2030**
EU production (tonnes)	2104	2712	2772	2999
EU recycling rate (%)	0	15	35	40
EU substitution rate (%)	0	4	15	26

EU production in 2015 is based on data available from [Statista, 2016g]. Projections in 2020, 2025 and 2030 refer to mine capacities, obtained according to the procedures and references in Annex C. Recycling and substitution rates are based on the assumptions presented under Table 152 and Table 153.

Table 143: Import reliance on graphite for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
ERERT	99	99	99	100
Tech 2	99	99	99	100
Tech 3	99	99	99	100
Scenario 1				
ERERT	99	86	78	70
Tech 2	99	79	76	69
Tech 3	99	83	83	77
Scenario 2				
ERERT	00	85	73	61
Tech 2	00	79	72	60
Tech 3	00	82	78	68

Scenario 3	**2015**	**2020**	**2025**	**2030**
ERERT	100	71	45	23
Tech 2	100	64	43	22
Tech 3	100	68	50	30

Data used in the calculations of IR are given in Table 128 (EU demand) and Table 144 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 144: EU production, recycling and substitution of graphite

Graphite	**2015**	**2020**	**2025**	**2030**
EU production (tonnes)	517	43567	82875	174593
EU recycling rate (%)	0	1	5	9
EU substitution rate (%)	0	15	28	38

EU production in 2015 is based on data available from [USGS, 2016 and WMD, 2016]. Projections in 2020, 2025 and 2030 refer to mine capacities, obtained according to the procedures and references in Annex C. Recycling and substitution rates are based on the assumptions presented under Table 152 and Table 153.

Table 145: Import reliance on neodymium for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
ERERT	100	100	100	100
Tech 2	100	100	100	100
Tech 3	100	100	100	100
Scenario 1				
ERERT	100	100	98	95
Tech 2	100	100	98	96
Tech 3	100	100	98	96
Scenario 2				
ERERT	100	100	93	86
Tech 2	100	100	93	86
Tech 3	100	100	93	86
Scenario 3				
ERERT	100	98	63	28
Tech 2	100	98	63	28
Tech 3	100	98	63	28

Data used in the calculations of IR are given in Table 129 (EU demand) and Table 146 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 146: EU production, recycling and substitution of neodymium

Neodymium	**2015**	**2020**	**2025**	**2030**
EU production (tonnes)	0	0	349	994
EU recycling rate (%)	0	0	5	10
EU substitution rate (%)	0	2	30	58

Note: see Table 27.

Table 147: Import reliance on praseodymium for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
ERERT	100	100	100	100
Tech 2	100	100	100	100
Tech 3	100	100	100	100
Scenario 1				
ERERT	100	100	98	96
Tech 2	100	100	98	96
Tech 3	100	100	98	97
Scenario 2				
ERERT	100	100	93	87
Tech 2	100	100	93	87
Tech 3	100	100	93	87
Scenario 3				
ERERT	100	98	63	28
Tech 2	100	98	63	29
Tech 3	100	98	63	29

Data used in the calculations of IR are given in Table 130 (EU demand) and Table 148 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 148: EU production, recycling and substitution of praseodymium

Praseodymium	**2015**	**2020**	**2025**	**2030**
EU production (tonnes)	0	0	96	261
EU recycling rate (%)	0	0	5	10
EU substitution rate (%)	0	2	30	58

Note: see Table 29.

Table 149: Import reliance on dysprosium for various scenarios (%)

Baseline	**2015**	**2020**	**2025**	**2030**
ERERT	100	100	100	100
Tech 2	100	100	100	100
Tech 3	100	100	100	100
Scenario 1				
ERERT	100	100	94	87
Tech 2	100	100	95	89
Tech 3	100	100	95	90
Scenario 2				
ERERT	100	100	89	78
Tech 2	100	100	90	79
Tech 3	100	100	90	80
Scenario 3				
ERERT	100	98	59	19
Tech 2	100	98	60	21
Tech 3	100	98	60	22

Data used in the calculations of IR are given in Table 131 (EU demand) and Table 150 (EU production, recycling and substitution rates). See the table's notes for information on the data sources.

Table 150: EU production, recycling and substitution of dysprosium

Dysprosium	2015	2020	2025	2030
EU production (tonnes)	0	0	95	312
EU recycling rate (%)	0	0	5	10
EU substitution rate (%)	0	2	30	58

Note: see Table 31.

B.3.8 Indicator D1.6 Supply adequacy

Table 151: Li, Co and graphite global demand and mining capacity

	2015	2020	2025	2030
Li: Global demand all sectors (thousand tonnes)	33.3	58.7	104	182
Li: Global mine capacities (thousand tonnes)	81.3	103	133	160
Li: Capacities utilisation (%)	41	57	78	114
Co: Global demand all sectors (thousand tonnes)	123	159	206	267
Co: Global mine capacities (thousand tonnes)	241	160	180	189
Co: Capacities utilisation (%)	51	99	114	141
Graphite: Global demand all sectors (thousand tonnes)	1157	1585	2172	2976
Graphite: Global mine capacities (thousand tonnes)	1843	2446	3352	4039
Graphite: Capacities utilisation (%)	63	65	65	74

See Table 126, Table 127 and Table 128 for information on demand data sources for Li, Co and graphite, respectively. Mine capacities in 2015, 2020, 2025 and 2030 were obtained following the procedures described in Annex C.

See Table 32 for information on data sources for the rare earths (Nd, Pr and Dy).

B.3.9 Indicator D1.7 Recycling

Table 152: Li, Co, graphite global recycling rates (%)

Materials	2015	2020	2025	2030
Li	0	1	5	15
Co	0	15	35	40
Graphite	0	1	5	9

Data for D1.7 calculation for Nd, Pr and Dy are given in Table 33.

Lithium

Globally, the recycling rates of Li are close to zero due to its abundancy and low cost. The lithium–ion battery is the application which will drive future demand for lithium worldwide. However, lithium is only a small fraction of the battery weight and accounts for less than 3 % of the production cost. The recycling of Li-ion batteries is more valuable for recovering metals such as cobalt and nickel which have a higher price than lithium. Consequently, almost none of the lithium used in batteries for the consumer market is recycled.

Although lithium is 100 % recyclable, there is currently no economic driver for this. Recycled lithium costs five times the lithium extracted from brine. Specifically in the case of Li, LIB batteries will become the dominating application in the near future if no better substitute technology is found. Hence, secondary material flows are expected to arise from this particular end-use.

Currently, recycling companies do not have a business case to extract lithium from slag; likewise, equipment manufacturers could not remain competitive by buying higher-priced materials from recycling companies. With Li-ion technology is in its infancy, a lack of standardisation in battery chemistry, and ongoing research into different battery chemistries, currently there is no recycling infrastructure to explicitly recycle Li-ion batteries for automotive applications due to the very uncertain prospects for recycling companies. A few pilot plants exist at the demonstration stage, one of which is located in Belgium – Umicore's Hoboken plant.

For the time being, Li-ion is the dominant battery technology for the future EV market which will become a significant and steadily growing market. Therefore, in the longer term, it is expected that recycling will become the major source of Li supplies, assuring supply stability and preventing price fluctuations due to geopolitical or other factors, which will affect the car's purchase price. Other advantages of recycling include ecological paybacks and compliance with environmental laws. However, a significant number of batteries will only come through the waste stream for recycling after 2025, since the lifetime of a battery ranges from eight to 10 years. In light of the above, a recycling rate of around 15 % has been assumed for Li by 2030 [expert opinion: private communication]. An S-shape curve, with an onset after 2025, has been used to estimate the recycling rates in 2020, 2025 and 2030.

The same recycling rate has also been applied for the EU.

Cobalt

Sufficient data and information are available (courtesy of experts from UMICORE) regarding the recycling of Co, which enabled the use of the formula proposed in the methodology to estimate future recycling rates. In 2015, around 41 % of the cobalt used was for battery chemicals. This share is expected to increase by 2030: for the calculations, it has been assumed that 50 % of the Co will be used in batteries in 2030. No significant growth can be expected for the other applications of Co: super alloys, hard metals, ceramics/pigments, catalysis, magnets and a few other minor applications. Although the recovery rate of Co is rather high today – 95 % or more – the collection rate is only around 9 %. However, it is expected that the collection rate will increase in future, mainly due to the fact that the core use of Co will be in LIBs – automotive and energy storage. The spent batteries will be returned to the recycling premises as is the procedure today for lead-acid batteries. If we assume a 90 % collection rate by 2030 (which is not exaggerated considering the current collection rate of lead-acid batteries is around 99 %) the recycling rate from batteries can be estimated as the product of the above rates: 50 % x 90 % x 95 % = 43 %.

As regards non-battery applications, which will consume around half of the Co by 2030, a significant increase in collection rates is not expected (due mainly to the dispersive use of Co in these applications). If the collection rate rises to 15 % by 2030, the contribution expected from non-batteries applications will be: 50 % x 15 % x 95 % = 7 %.

A final recycling rate for Co of 43 % + 7 % = 50 % can be estimated using the methodology approach. The more conservative figure of a 40 % increase in the recycling rate has been taken for the calculations by 2030.

Graphite

The main increase in demand for graphite is expected to come from LIBs. However, the recycling of battery-grade flake graphite from spent LIBs is a challenge; the graphite is damaged and cannot be reused in batteries unless it is subjected to a special surface modification [Ghadi, 2014]. Apparently, this has yet to become a commercial solution.

Manufacturers can also use synthetic graphite – although this is more expensive it has better properties compared to natural graphite. These features do not provide so many opportunities for increasing the potential for recycling. Therefore, a graphite recycling rate of around 10 % is taken into account up to 2030 – both globally and in the EU.

B.3.10 Indicator D1.8 Substitution

D1.8 for Nd, Pr and Dy are assumed the same as for the wind sector.

Table 153: Li, Co, graphite global substitution rates (%)

Materials	2015	2020	2025	2030
Li	0	0	0	0
Co	0	4	15	26
Graphite	0	15	28	38

Data and information for the calculation of D1.8 for Nd, Pr and Dy is given in Table 34.

Lithium

A number of alternatives to Li-ion batteries, such as metal-air, lithium-sulphur, sodium-ion, magnesium-ion, and flow batteries are currently being explored for use in electric vehicles. Hydrogen fuel cells, aluminium-ion and graphene batteries are also recognised as potential future alternatives to Li-ion. All of these battery chemistries are at different development stages and, according to the experts, 15 to 20 years away.

The large technology companies and electric vehicles producers are aware of the limitations of current lithium-ion batteries and are investing heavily in battery chemistry research. However, before switching to another technology, the best replacement is being sought, which apparently is currently unavailable. Moreover, changes in production lines and manufacturing techniques are cost intensive. In a way, since this factor and existing deals with materials suppliers are hard to break, this will have a 'stabilising' effect on the lithium-ion technology until a proven substitute technology can be demonstrated.

In other end-use applications of lithium – glass and ceramics, lubricants, gas and air treatment, continuous casting, synthetic rubbers and plastics, and aluminium smelting – lithium can be substituted although the product’s performance will be reduced. The single application where Li cannot be substituted is pharmaceuticals, but this represents only about 2-3 % of Li use. Due to the limited performance resulting from Li substitution, it is logical to assume that no substitution will take place until there is abundant Li at a low price. The incentive for substitution will come with supply shortage and/or a substantial price increase.

For the time horizon under consideration – 2030 – no efforts are anticipated to substitute Li in its main applications and thus a substitution rate of 0 % has been applied in the calculations.

Cobalt

The substitution possibilities for Co are limited in most of its applications. However, substantial substitution results can be achieved for battery chemicals. Co is a major material in many new rechargeable batteries (up to 60 %), not only in electric cars but also in mobile phones and laptop computers. The future availability of Co is a matter of increasing concern for OEMs, which is expected to push forward the development of non- or low-cobalt-intensity batteries [CRU, 2015].

It is difficult to foresee how many batteries will contain less or no Co at all by 2030. The chemical composition of cathode materials varies depending on battery function and manufacturer. Various combinations of Ni, Mn and Al can be used to replace some of the Co, which will also lower the cost of the battery, an important factor for the automotive sector [Gaines, 2014]. Other materials are also mentioned as potential substitutes for the Co used in batteries. To reflect this, a substitution rate of around 26 % is assumed for Co until 2030.

Graphite

Today, more than 50 % of batteries use natural graphite. However, alternative substitutes for natural graphite do exist and can be applied in case of a supply shortage or price increase. Natural graphite can be substituted with synthetic graphite, amorphous carbon, or Si-Sn carbon composites [SGL Group, 2013]. Therefore, substitution can be a tangible mitigation measure to deal with graphite supply issues. Hence, a substitution rate of around 40 % has been considered for natural graphite up to 2030.

B.3.11 Indicator D2.1 Supply chain dependency

Two supply chains were analysed for EVs: one for LIBs and one for electric traction motors with permanent magnets. The results for the LIBs supply chain are used in the downstream dimension assessment of Li, Co and graphite materials, while the supply chain for electric motors is used in the assessment of Nd, Pr and Dy materials.

LIBs supply chain dependency

Table 154: Country production share, HHI and WGI for relevant steps in the supply chain

Country	2015		2020		2025		2030		WGI
	share	HHI	share	HHI	share	HHI	share	HHI	scaled
Step 1: LIB specific materials									
Step 1.1: Cathode material									
China	44		44		44		44		0.44
Japan	19		19		19		19		0.89
USA	0		0		0		0		0.84
Korea	8		8		8		8		0.73
EU	12		12		12		12		1.00
RoW	17		17		17		17		0.50
Total	**100**	**2794**	**100**	**2794**	**100**	**2794**	**100**	**2794**	
Step 1.2: Anode material									
China	71		71		71		71		0.44
Japan	26		26		26		26		0.89
USA	0		0		0		0		0.84
Korea	2		2		2		2		0.73
EU	0		0		0		0		1.00
RoW	1		1		1		1		0.50
Total	**100**	**5644**	**100**	**5644**	**100**	**5644**	**100**	**5644**	
Step 1.3: Electrolyte									
China	51		51		51		51		0.44
Japan	23		23		23		23		0.89
USA	5		5		5		5		0.84
Korea	8		8		8		8		0.73
EU	9		9		9		9		1.00
RoW	4		4		4		4		0.50
Total	**100**	**3316**	**100**	**3316**	**100**	**3316**	**100**	**3316**	

Country	**2015**		**2020**		**2025**		**2030**		**WGI scaled**
	share	**HHI**	**share**	**HHI**	**share**	**HHI**	**share**	**HHI**	
Step 1.4: Separator									
China	10		10		10		10		0.44
Japan	58		58		58		58		0.89
USA	14		14		14		14		0.84
Korea	12		12		12		12		0.73
EU	2		2		2		2		1.00
RoW	4		4		4		4		0.50
Total	**100**	**3824**	**100**	**3824**	**100**	**3824**	**100**	**3824**	
Step 2: Cell/module manufacturing									
China	26		23		33		33		0.44
Japan	31		10		9		9		0.89
USA	20		59		52		52		0.84
Korea	15		5		4		4		0.73
EU	0		0		0		0		1.00
RoW	8		3		2		2		0.50
Total	**100**	**2329**	**100**	**4184**	**100**	**3855**	**100**	**3855**	

The analysis is performed for two steps in the supply chain for which consistent information has been found: step 1 – LIB specific materials (processed materials); and step 2 – cell/module manufacturing.

The LIB-specific materials, namely cathode and anode materials, electrolyte and separator, are used to manufacture the electrodes; they are the key components of the battery cell. Cells, including other components, are assembled into battery packs to be integrated in the vehicles. Battery pack and cell/module manufacturing are assessed together since no information is available for companies performing only battery assembling/packaging activities as their main business. Thus, it is assumed that, in general, the companies producing the modules are the same as those indicated in the literature [Berger, 2011].

Data on LIB-specific materials were obtained from several sources: [AVICENNE, 2014a; AVICENNE, 2014b; CEMAC, 2015; CEMAC, 2016a; SNE Research data, 2016; Evonik, 2015].

In 2015, a high concentration of manufacturing capacity for LIB-specific materials was observed in Asia: China, Japan and Korea were hosting more than 90 % of the cathode and anode material, separator and electrolyte production [SNE Research data, 2016].

The concentration of supply until 2030 for the cell/module manufacturing step has been calculated using partially commissioned capacities, capacities under construction, and announced capacities [BNEF 2016c quoted in CEMAC, 2016b]. The capacities partially commissioned and under construction are taken into consideration for 2020 along with the announced one – from 2020 onwards. To calculate the shares for 2020, capacities existing in 2015 were added to the partially commissioned and under-construction capacities. The shares for 2025/2030 were calculated by adding the 'announced' capacities to the 2020 capacities. The Tesla gigafactory capacity of 35 GWh is included.

Table 155: Parameters for calculating D2.1 supply chain dependency for the electric vehicle sector (Li, Co, graphite)

	2015	2020	2025	2030
$A_{\text{step 1.1}}$	0.87	0.87	0.87	0.87
$B_{\text{step 1.1}}$	0.12	0.12	0.12	0.12
$D2.1_{\text{step 1.1}}$	0.50	0.50	0.50	0.50
$A_{\text{step 1.2}}$	0.71	0.71	0.71	0.71
$B_{\text{step 1.2}}$	0	0	0	0
$D2.1_{\text{step 1.2}}$	0.36	0.36	0.36	0.36
$A_{\text{step 1.3}}$	0.84	0.84	0.84	0.84
$B_{\text{step 1.3}}$	0.09	0.09	0.09	0.09
$D2.1_{\text{step 1.3}}$	0.47	0.47	0.47	0.47
$A_{\text{step 1.4}}$	0.95	0.95	0.95	0.95
$B_{\text{step 1.4}}$	0.02	0.02	0.02	0.02
$D2.1_{\text{step 1.4}}$	0.48	0.48	0.48	0.48
$A_{\text{step 2}}$	0.94	0.91	0.90	0.90
$B_{\text{step 2}}$	0	0	0	0
$D2.1_{\text{step 2}}$	0.47	0.46	0.45	0.45
D2.1 (Li, Co, C)	**0.46**	**0.45**	**0.45**	**0.45**

Note: The average between the four sub-steps has been taken to calculate the D2.1 for step 1 in the supply chain.

Electric motors supply chain dependency

Table 156: Country production share, HHI and WGI for relevant steps in the supply chain

Country	2015		2020		2025		2030		WGI
	share	HHI	share	HHI	share	HHI	share	HHI	scaled
Step 1: Permanent magnet manufacturing									
China	83.3		83.3		83.3		83.3		0.44
Japan	10.3		10.3		10.3		10.3		0.89
USA	2.6		2.6		2.6		2.6		0.84
EU	1.3		1.3		1.3		1.3		1
Other countries	2.6		2.6		2.6		2.6		0.50
Total	**100**	**7064**	**100**	**7064**	**100**	**7064**	**100**	**7064**	
Step 2: Electric motor manufacturing									
China	32.0		32.0		32.0		32.0		0.44
USA	28.0		28.0		28.0		28.0		0.84
UK	8.0		8.0		8.0		8.0		0.90
Japan	7.0		7.0		7.0		7.0		0.89
Taiwan	7.0		7.0		7.0		7.0		0.81
Canada	1.0		1.0		1.0		1.0		0.95
South Korea	2.0		2.0		2.0		2.0		0.73
Australia	0.8		0.8		0.8		0.8		0.94
Brazil	0.5		0.5		0.5		0.5		0.53
EU	14.0		14.0		14.0		14.0		1
Total	**100**	**2172**	**100**	**2172**	**100**	**2172**	**100**	**2172**	

Data used to calculate the concentration of supply for the permanent magnet manufacturing step were taken from [Benecki, 2011]. The concentration of supply for the second step was elaborated using data from [PR Newswire, 2011].

Table 157: Parameters for calculating D2.1 supply chain dependency for the electric vehicle sector (Nd, Pr, Dy)

	2015	2020	2025	2030
A $_{\text{step 1}}$	0.61	0.61	0.61	0.61
B $_{\text{step 1}}$	0.01	0.01	0.01	0.01
D2.1 $_{\text{step 1}}$	0.31	0.31	0.31	0.31
A $_{\text{step 2}}$	0.93	0.93	0.93	0.93
B $_{\text{step 2}}$	0.14	0.14	0.14	0.14
D2.1 $_{\text{step 2}}$	0.53	0.53	0.53	0.53
D2.1 (Nd, Pr, Dy)	**0.42**	**0.42**	**0.42**	**0.42**

B.3.12 Indicator D2.2 Purchasing potential

The data needed for D2.2 are given in Table 18, Table 19, Table 39 and Table 40.

B.3.13 Indicator D2.3 Material cost impact

Table 158: Parameters for calculating D2.3 material cost impact for EVs (Li)

Lithium	2015	2020	2025	2030
E (USD/kg)	8.50	9.54	10.70	12
F (kg/kWh)	0.286	0.286	0.286	0.286
G (USD/kWh)	369	246	185	123
D2.3 (Li)	**0.99**	**0.99**	**0.98**	**0.97**

E (USD/kg) is the price of lithium hydroxide. Both lithium carbonate and lithium hydroxide are used as a starting material in the production of batteries. Battery-grade lithium carbonate and lithium hydroxide are much more expensive than the technical-grade lithium used in ceramics, glass and other industrial applications. Telsa and other EV leaders have selected lithium hydroxide as a starting material for their batteries since it can provide better power density. Other auto manufacturers are using designs which can be easily switched from lithium carbonate to lithium hydroxide in the future. Since lithium hydroxide apparently has more potential and might be the car manufacturers' preferred option in the future, the price of lithium hydroxide is taken into consideration in the calculations of the D2.3 indicator. As to the future cost of lithium hydroxide, signumBOX forecasts the price will steadily increase, reaching 12 000 USD/t by 2031 [SNE Research data, 2016].

The prices of battery-grade lithium hydroxide fall in the range of 8375 USD/ton to 8700 USD/ton [SignumBOX, 2015]. In Korea and Japan, both known as high-quality battery producers, the price is even higher: battery-grade lithium hydroxide is sold between 8800 and 10 500 USD/ton. An average price of 8500 USD/ton has been taken for the calculations in 2015.

F (kg/kWh) is the Li material intensity in LIB (data taken from indicator D1.1).

G (USD/kWh) is the cost of the Li-ion cell. The current average price per cell (369 USD/kWh) was gathered from information from [CEMAC, 2016b]. There is a clear consensus between various research institutes and consultancies regarding the cost evolution of Li-ion packs: they all suggest a significant fall in the cost of batteries over the next 10 to 15 years [Muenzel, 2014]. The cost of Li-ion packs will drop from around 600 (average cost) USD/kWh in 2015 to around 400 USD/kWh in 2020, 300 USD/kWh in 2025 and 200 USD/kWh in 2030. It is logical to consider the same declining rate for Li-ion cells, too, namely:

2015 to 2020: CAGR = -7.8 %

2020 to 2025: CAGR = -5.6 %

2025 to 2030: CAGR = -7.8 %

When applying the same CAGR for the cost of the Li-ion cell, the cost is expected to fall to 123 USD/kWh, which has been taken for the calculations of D2.3 in 2030. Logically, the same G (USD/kWh) is also used in the analysis of Co and graphite.

Table 159: Parameters for calculating D2.3 material cost impact for EVs (Co)

Cobalt	**2015**	**2020**	**2025**	**2030**
E (USD/kg)	28.0	40.6	40.6	40.6
F (kg/kWh)	0.28	0.28	0.28	0.28
G (USD/kWh)	369	246	185	123
D2.3 (Co)	**0.98**	**0.95**	**0.94**	**0.91**

E (USD/kg) is the price of high-grade Co [eCobalt Solutions, 2016].

F (kg/kWh) is the average material intensity (average Co used per kWh) calculated within indicator D1.1.

G (USD/kWh) is the same as for Li, as described above.

Table 160: Parameters for calculating D2.3 material cost impact for EVs (graphite)

Graphite	**2015**	**2020**	**2025**	**2030**
E (USD/kg)	1.00	1.17	1.17	1.17
F (kg/W)	2.87	2.87	2.87	2.87
G (USD/W)	369	246	185	123
D2.3 (C)	**0.99**	**0.99**	**0.98**	**0.97**

E (USD/kg) is the price of natural graphite; the increase in prices by 2020 is forecast in [Statista, 2016h].

F (kg/kWh) is the average material intensity (average C used per kWh) calculated within indicator D1.1.

G (USD/kWh) is the same as for Li and Co, as described above.

A different approach is used to calculate D2.3 material cost impact for rare earths (Nd, Pr, Dy) required in EVs.

The three materials investigated – Nd, Pr and Dy – are always used in combination to manufacture permanent magnets. A different approach is used to estimate D2.3 for Nd, Pr and Dy: the impact of the cost of materials is estimated separately for the magnet and for the materials (Nd, Pr, Dy) contained in the magnets. The common D2.3 for Nd, Pr and Dy is then taken as the average between these two cost impact factors.

Magnet: the permanent magnet is around 53 % of the cost of the motor [US DOE, 2014]. This leads to D2.3 scoring (magnet related) of 0.47. This scoring is obtained as follows:

$$D2.3\ (magnet\ related) = \frac{Motor\ cost - Magnet\ cost}{Motor\ cost}$$

Materials for magnet: the combination of Nd, Pr and Dy accounts for more than 70 % of the permanent magnet cost [Widmer, 2015; Rahman, 2014]. This would lead to D2.3 scoring (material related) of 0.29. This scoring is obtained as:

$$D2.3(materials\ related) = \frac{Magnet\ cost - Materials\ cost}{Magnet\ cost}$$

The average value of **D2.3 = 0.38** is then used for the three materials – Nd, Pr and Dy.

Annex C. Methodology for data collection and aggregation on mine capacities

The following document provides an overview of the methodology and principles used to project trends in mine production through to 2030. It describes the practicalities of data collection, from the preparation of source data and assumptions made to fill gaps, to producing final aggregated results, presented in Annex B. Although the data collection followed a recursive routine, each material covered – Nd, Pr, Dy, Li, Co, C, In and Ag – has its own methodological issues which are discussed separately.

General methodological issues

Mine production capacities are the underlying data used to develop projections of future mine supply, to be used as inputs for the calculation of indicators D1.3, D1.5 (EU production) and D1.6.

The projections are based on current and announced annual production capacities (the nominal level of output based on plant design) of both operating mines and developing projects for which current information is available. For each mine/project (hereinafter also referred to as properties), idealised production profiles have been approximated using information published on resources and reserves.

The evolution of supply sources and capacities over time up to 2030 has been estimated assuming that current development-stage projects will reach production, adding capacities and new actors to the current list of suppliers. Given the nature of the mining industry and lead time for exploration/mining projects (10-15 years from discovery to production), the list of potential new suppliers is deterministic in that only the suppliers listed may be in the market e.g. [Poulizac, 2011].

While this assumption is legitimate, thereby allowing for a predictive analysis to be carried out supported by currently identified projects, market conditions are the primary driver of decisions to further develop exploration projects or move forward with committed and planned production centres. Projects must meet increasingly severe production-cost criteria in order to obtain financing for development. Therefore, estimates of potential future production are only reasonable under certain preconditions of growth in demand and rising prices.

In view of this, the analysis process implemented is rather simplistic as it allows all projects (including those with challenging economics) to start operating without considering the variables that companies must consider in turning reserves into profitable production.

Moreover, market conditions also make establishing the timing of the additional production capability extremely uncertain. Very often projects give an indication of planned production capacity without the start year. To make allowance for this and also delays in the delivery of mine projects, fixed development time frames have been applied to the projects at various stages of development.

Data sources

The SNL Metals & Mining database [SNL, 2016] (hereby referred to as SNL) was used as the main source of data on production capacities and resources. SNL integrates a large volume of data, comprising comprehensive and updated resource extraction and exploration data for mines and projects targeting several material categories. This data set gathers information from a variety of sources, most commonly from companies' annual reports and other public documents. Access to the online database was allowed under a DG-GROW-JRC agreement.

SNL provides a list of all properties that include a specific commodity ranked by total contained reserves and resources. Data can be filtered by geography (country), development stage, activity status and property type. In addition to the above criteria, information on each project includes: owner, all commodities at the project, control risk ratings and total *in-situ* value. For each operation, a property profile is provided giving details on development studies, geology, significant drill results, a detailed breakdown of the project's resources and reserves, the year production started or is projected to start, estimated and projected annual production capacity including, in some cases, operating costs, recovery rates and mill-head grades.

While resources and reserves for the list of properties, including breakdowns by target, activity status and stage of development, could be retrieved from the database in one single Excel file, capacities had to be compiled on a project-by-project basis from individual property profiles.

As regards the development stage, SNL breaks down the mining development phases into three top-level stages, defined as follows:

- Early-stage (includes grassroots, exploration, target outline): a project without a defined resource estimate;
- Late-stage (split into reserves development and feasibility, started or completed): a project with a defined resource that has not yet reached a production decision;
- Mine-stage (includes pre-production, further breakdown into construction planned and started, and production stage including the following phases: operating, satellite, expansion, limited production and residual production): a project that has made a decision to move forward with production or is actively producing.

The following indicators are used for the activity status: active; temporarily on hold; on hold awaiting financing; on hold awaiting higher commodity prices; under litigation; inactive; or care and maintenance.

Resources are presented as reported by profiled companies in a given year and include reserves. Resources and reserves are given as mineralisation in-place with no recovery factors applied to quantify total tonnes.

The average annual capacity of an operation may refer to an initial capacity, an expanded capacity, or the operation's average life-of-mine capacity. It is estimated using optimal cut-off grades based on the characteristics of reserves and market conditions.

SNL provides comprehensive coverage of most commodities targeted in this study. However, the data on rare earths is provided in aggregated form which implies the need to integrate a number of other data sets. The TMR Advanced Projects Index [TMR, 2016] was used as the source of ore grade statistics and relative distribution of in-situ rare earth oxides, to disaggregate the SNL resources and reserves information. Since these data do not cover all SNL listed projects, we have used additional sources such as company data to obtain rare earths distributions.

Roskill reports covering cobalt and graphite [Roskill, 2014; Roskill, 2015b] were used to address gaps in the data on capacity provided by SNL.

Moreover, in the case of indium, which is extracted during the refining of zinc concentrates, mine capacities are not available. Its assessment required a different strategy which involved the screening of the primary product and performing the assumptions described below.

Data assembly

Data collection took place over a three-month period between June and August 2016. The compilation process of resources and capacities from the source data followed specific steps and guidelines, described below.

- Projects reviewed fall into the above-described stages of: reserves development, prefeasibility/scoping, feasibility (either started or completed), pre-production, including construction planned and started and production, including operating, satellite, expansion and limited production categories. Early-stage projects were excluded from the analysis.
- Only active operations and projects *temporarily on hold* that have been delayed due to poor market conditions or suspended for technical, labour, environmental or political reasons were included. Properties stated as under care and maintenance were also included. Inactive operations were excluded from the analysis.
- Projects for which information on resources and reserves is not available (as a result, for instance, of the company involved not having or not releasing the data) were excluded from the analysis.
- The most recent year's resources and reserves calculated for the property were used to filter late-stage developing properties (feasibility and reserves development), as follows:
    - Cobalt, graphite and lithium: properties in which the most recent resources and reserves assessment/reporting was before 2012 were excluded;
    - Rare earths: no filter was applied based on resources and reserves reporting;
    - Silver: properties with resources and reserves assessment and reporting prior to 2013 were excluded;
    - Zinc: properties with resources and reserves assessment and reporting previous to 2011 were excluded;
    - This was intentional to suppress projects that have not undergone recent development work. No filter was applied to mine-stage projects.
- Regarding data collection on production capacities, an effort was made to screen all properties meeting the criteria set out above. However, in the cases of silver and zinc, the very high number of properties in the final lists made data collection less feasible, thus the screening of production capacities was carried out on shortened property lists obtained by introducing thresholds based on the amount of metal in resources and reserves:
    - Zinc: only properties containing Zn above 1 000 000 t were screened;
    - Silver: properties with over 100 000 000 oz Ag and those with <100 000 000 oz Ag in resources and reserves but having Ag as the primary commodity were traced.
    - For the rest, capacities were estimated by applying a statistical correlation between annual known capacities (of screened projects) and total contained metal in resources and reserves, as described below.
- For projects which, although screened, production capacity was not available, the following procedures applied: for graphite and cobalt, data was taken from the Roskill reports when available. Where these numbers were not available, production allocated to previous years, as provided in SNL, were considered instead. If no such data was available, capacities were derived statistically (described below).
- For the rare earths, resources and reserves of each individual rare earth in the deposit were derived using rare earth oxides distribution profiles provided in [TMR, 2016]. In some cases, information available from SNL was used. In cases where the previous data were not available, rare earth contents were collected from [Roskill, 2015a] or approximated using average REO distributions attributable to the predominant REE-bearing mineral in the deposit. In the few cases where these numbers were not available, the properties concerned were excluded from the analysis. Production capacities for Nd, Pr and Dy were then derived using the SNL overall reported capacities adjusted to disaggregated resources and reserves.

Statistical correlations used to handle missing data

As the result of data availability issues for all materials and the impracticalities of a comprehensive screening of the SNL database for zinc and silver, some data on production capacities was derived statistically.

The approach described in [Cox, 1981] was used to fill gaps in the data. The invoked procedure is based on the assumption that the total metal contained in deposits and their annual production is log-normally distributed – large deposits produce relatively less metal per tonne of metal contained annually than medium and small deposits – and a high correlation between the two can be observed. This correlation was used by the authors for a rough prediction of the potential copper production from undeveloped deposits in the US.

For the purposes of this analysis, annual production capacities of properties for which information are available were compared with resources and reserves. Both variables were first transformed by taking the natural logarithms; regression equations relating them were obtained and used in the prediction of missing capacities data. Different improvements in the correlation coefficients were tested by eliminating outliers in the data (Figure 73).

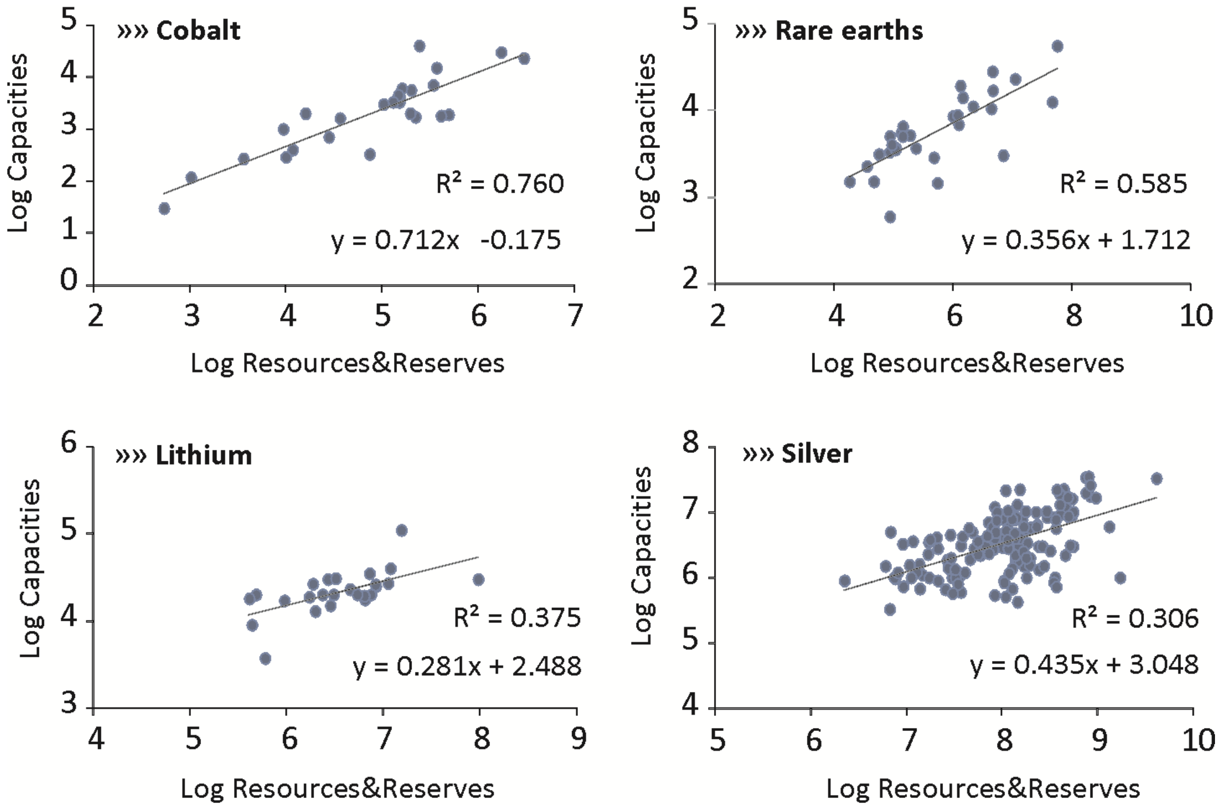

Figure 73: Examples of linear regressions expressed as the logarithms of production capacities and resources and reserves, for cobalt, rare earths, lithium and silver.

While for cobalt the correlation coefficient for the data sample is 0.8, for other materials regression equations relating log annual capacity to log resources and reserves are much less significant statistically, showing correlation coefficients between 0.3 and 0.6. In these cases, the statistical simulation has serious limitations, reflecting a high variability in ore grades and ore/waste ratios between properties.

Life-of-mine forecasts

To develop projections of future mine supply, idealised production profiles to 2030 were approximated for each property. Life-of-mine forecast profiles were modelled using a declining resources method to estimate the number of years of production the reported resources and reserves could theoretically support at full capacity. A depletion date for each mine was determined dividing resources and reserves by annual capacity. For operating mines, supply is assumed to have occurred from the date resources and reserves were reported – these deductions were applied when calculating the remaining years of production.

Moreover, as planned production capacities are rarely attained quickly after start-up, capacity profiles of mines expected to come online in the future were calculated assuming a production up trajectory over the first two years (30 % in the first year and 70 % in the second year), each mine reaching full capacity in the third year. To account for a decline in production near end-of-life, a ramping down trajectory of the same magnitude and rate was applied whenever mine closure was anticipated before 2030.

Since no distinction is made between reserves and resources, to calculate the remaining years of production, resources and reserves figures were adjusted by a factor of 75 %. This conversion rate is assumed to be reasonable between resources and reserves, and used for example by SNL to assess strategies for copper reserves replacement [SNL, 2014].

Moreover, to account for the losses occurring at nearly every stage of mining and processing, throughout the analysis, calculations of remaining years of production assumed average recovery rates of material held in the resources (Table 161).

Despite the use of optimisation procedures, the analysis is constrained by several assumptions:

- Production profiles were established under the assumption that capacity will remain the same as reported throughout the mine-life. However, a drop in ore grades, commodity price fluctuations, or seasonal slowdowns are likely causes of capacity oscillations;
- Events such as strikes, plant failures and other factors can lead to unforeseeable production stoppages;
- Expansions at the mine site aimed at increasing production and/or extending mine-life are likely to occur throughout the mine's life, if market conditions are favourable. Other factors that can be expected to increase production are technical developments and improvements in mining configuration, processing and metallurgical performance;
- To calculate the remaining years of production it was assumed that each year production equals capacity. However, since mines normally do not run at full capacity for cost-efficiency reasons, mine production rarely matches production capabilities and therefore a longer life time is foreseeable;
- Although reports of mineral resources must satisfy the requirement that there are reasonable prospects for eventual economic extraction, it should not be assumed that such upgrading will always occur [JORC Code, 2012];
- Mine-processing recovery rates applied to downgrading resources and reserves figures are average values that do not reflect the variability of losses between properties and therefore do not allow for reliable estimates. In addition to aspects related to the intrinsic ore mineralogy and the complexity of metal recovery, increasing concentrate treatment and refining costs, extraction methods also introduce differential losses, which are higher for underground mining methods.

Table 161: Average mine-processing recovery rates and respective data sources. For cobalt, recoveries, refer to the downstream refinery process from nickel and copper concentrates

Commodity	Recovery rate	Data source
Cobalt	83 %	[Oakdene Hollins & Fraunhofer ISI, 2013] *Note: 83 % is an average recovery value from nickel and copper operations*
Graphite	85 %	[USGS, 2015]
Lithium	45 % (brines), 50 % (pegmatites, hectorites and jadarites)	[Yaksic, 2009] *Note: The type of deposit was allocated in accordance with the property's group of commodities*
Rare earths	50 %	[USGS, 2013] *Note: 50% are ceiling rates for ion adsorption clay deposits*
Silver	90 %	[Infomine, 2008]
Zinc	87 %	[USGS, 2000]

Establishing start-up dates for developing projects

The stages in the life cycle of a mine have different development time frames which also depend on the project scale, commodity and geography.

For the pre-production stage, typical development time frames will be around one year. For developments prior to the decision to build a mine, the best-case scenario will be four years (Figure 74).

According to [SNL, 2015], a pre-feasibility study prepared with suitable resources identified (after around six years of initial and advanced exploration), can take two years to produce. When reflecting a positive outcome for the project, the pre-feasibility study will then be developed further into a feasibility study, which takes an average of two years to prepare. The permitting and financing stage should take about three years while construction of a mine is likely to take at least two years.

To overcome the fact that projects very often do not have an indication of the start year, the previous criteria were used to fix the date when it may be anticipated that a new property in a given development stage can begin commercial production, as follows:

- Mines currently under construction are expected to come on-line in 2018 (two years from the current date);
- Projects at the feasibility stage are expected to come on-stream in 2020 (four years from now);
- Supply from pre-feasibility and reserves development-stage projects should not be expected to be available at the project site until 2025 (nine years from now).

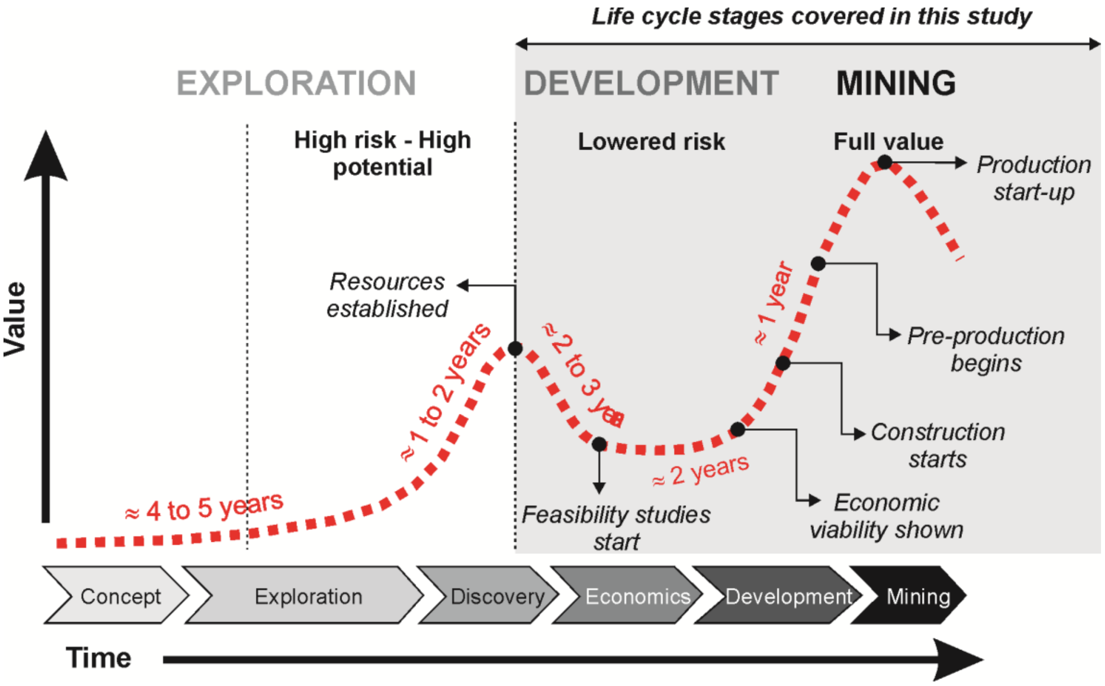

Figure 74: Development time frames over the life cycle of a mine project, adapted from [Sykes, 2012]

These time frames can be further constrained by delays during the development period, which can be expected, especially in less favourable market conditions. Uncertainties and challenges in raising investment for mine development – due to generally increasing mining costs combined with uncertainties associated with market prices – are a major source of delays in setting up new operations. Developments are normally brought into line with materials prices picking up, while some delayed projects may be reactivated by the appropriate market signals.

Other unexpected factors, such as geopolitical events, labour disruptions, permitting issues and various technical challenges (e.g. mining engineering and metallurgical problems) can also stall or put the development of planned and prospective mines on hold.

On the other hand, depending on the project's economics, it is reasonable to expect that at least some projects with less challenging economics will take fewer years than the fixed time frames to come into production.

Indium calculations

Indium is a by-product of zinc-metal-refining operations; about 99 % is produced from zinc ores [By-products, 2015].

The degree to which both zinc mine production and indium refinery production are related was evaluated using USGS historical data (1999-2013). By applying a linear regression, a correlation coefficient of 0.96 was obtained. The resultant equation was used to calculate indium production capacities up to 2030, based on zinc data collected as described.

This relation entails an average production of 60 g of indium per tonne of zinc produced and ultimately reflects an average indium content of 134 ppm in sphalerite ores, assuming they have a zinc content of 67 % [Schwarz-Schampera, 2002], and that a typical metallurgical recovery efficiency of 30 % is achieved [Oakdene Hollins & Fraunhofer, 2013].

Final adjustments

The data collected on capacities were aggregated per country to be used in D1.3, while totals in each year were estimated to produce results for D1.6.

A final adjustment was made to the capacities data by comparing it with available production statistics for 2015, for which references are presented in the relevant tables in annex B. In cases where production in 2015 in a given country was estimated to be higher than the aggregated total capacity for all SNL-covered properties, data was normalised by summing the remaining difference with the assembled capacities data up to 2030. This is designed to account for projects that might not have been covered, for which information was not available or that were excluded during the compilation exercise, but are, in fact, producing operations. However, we are aware that this introduces additional volumes that can also result from mines that were recently divested, stockpiling, and artisanal or other kinds of informal mining.

Furthermore, it was realised that in the case of graphite there was a large discrepancy between the SNL inventory and Roskill data sets. Many projects highlighted by Roskill were not covered by SNL. These operations were identified and the capacities allocated to them were added to the country's total up to 2030.

Final remarks

For the methodology, it is important to note that there is great uncertainty surrounding the further development of some projects, especially those in the reserves development and pre-feasibility stages. To date, these remain ‘works in progress’ without consideration of all the factors that determine the economics of an ore body. Therefore, there is no guarantee that they will prove to be feasible. It is also reasonable to expect that many of these projects will only go forward under strengthening market conditions while others may become unprofitable due to changes in material prices and production costs. New resources that are close to production with low estimated costs are more likely to be developed. For this and other reasons, there is no assurance that the indicated levels of production will be attained.

On the other hand, it is also reasonable to expect additional capacities offered by some current early-stage projects (exploration stage), that have not been taken into account. Up to 2030, it is likely that at least some will be developed and enter into operation within less constrained timeframes.

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