Supplementary material

Methodology

The EU resilience to supply of raw materials and components downstream is evaluated along two independent dimensions, called hereafter upstream and downstream dimension.

Dimensions

1.1 Upstream dimension (D1)

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.

1.2 Downstream dimension (D2)

The downstream dimension (D2) comprises four 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.
- D2.4 estimates how much exactly of the EU demand can be covered by domestic production for each supply chain step.

More details for each individual indicator are given in section 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 analyses were performed.

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

Dimension 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 and the expected global demand evolution in the given timeframe. 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 = (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 =(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.

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:

$$D1.2 = \frac{\sum_{i=1}^{28}\left(GDP_{EU_i} * \left(1 - EPI_{EU_i}/100\right)\right)}{\sum_{j=1}^{9}\left(GDP_{non-EU_j} * \left(1 - EPI_{non-EU_j}/100\right)\right) + \sum_{i=1}^{28}\left(GDP_{EU_i} * \left(1 - EPI_{EU_i}/100\right)\right)}$$

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.[1] 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:

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

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

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 $_{mining}$ and D1.3 $_{refining}$ 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.

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.

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= (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

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

The available material for recycling in the EU – ‘Recycled material $_{\mathrm{EU}}$’ – is estimated using the proposed formula further in the document (see indicator D1.7). In addition, the average lifetime of the products (end-use applications) is also taken into account to calculate the so-called ‘old scrap’ or material available for recycling each year, e.g. a laptop has shorter lifetime than a car. The ‘Substituted material $_{\mathrm{EU}}$’ is calculated simply by multiplying the substitution rate defined within indicator D1.8 (see further in the document) and the 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:

$D1.5=1-I\mathrm{R}$

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.

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.[2] 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 % utilization 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.[2] 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=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.

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 economic 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).

$$D1.7(2030) = \sum_{i} Material\ share_{i} * (CR\ new\ scrap * RR\ new\ scrap + CR\ old\ scrap * RR\ old\ scrap)_{i}$$

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.

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 analyzed 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.

Dimension 2

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):

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

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

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'*.

$$D2.1i = \overline{A_i * B_i}$$

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.

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
$$C = \frac{\sum_{i=1}^{28}\left(GDP_{EU_i} * \left(EPI_{EU_i}/100\right)\right)}{\sum_{j=1}^{9}\left(GDP_{non-EU_j} * \left(EPI_{non-EU_j}/100\right)\right) + \sum_{i=1}^{28}\left(GDP_{EU_i} * \left(EPI_{EU_i}/100\right)\right)}$$

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

The average GDP per capita for the EU is calculated as the ratio of the total EU GDP (EPI scaled) and total EU population. The same applies for the average GDP per capita for non-EU countries. 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 utilized. 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.

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 recognized 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 labor, 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).

D2.4 downstream supply adequacy

D2.4 indicator measures an eventual supply-demand misbalance at each step of the supply chain. It is given by the ratio between the EU share of the global supply for each step of the supply chain (see parameter B from D2.1 'Supply chain dependency' indicator) and the EU demand for a given technology as a fraction of the global demand (sub-indicator D1.1.1 of the 'Material demand' indicator). If the ratio is higher or equal to 1, the 'Downstream supply adequacy' indicator is assumed equal to 1 since the EU can satisfy its demand only by domestic production. If the ratio is less than 1, the obtained value is assigned also to the indicator D2.4.

The following formula is used to calculate D2.4i indicator for a step 'i' of the supply chain:

$$D2.4_i = \frac{B_i}{D1.1.1}$$

The final D2.4 indicator is the average between D2.4i calculated for each step.

$$D2.4 = \overline{D2.4_i}$$

Indicators 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 (30 %:20 %:20 %:30%) of its four constituent indicators. More weight is given to D2.1 and D2.4 indicators to reflect their higher importance to the downstream problematic. Dimensions are expected to evolve with time. The D1 and D2 values per material can be presented for different points of time: 2015, 2020, 2025 and 2030 in our case. 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. The upstream (D1) and downstream (D2) dimensions represent the 'X' and 'Y' axis respectively of the so-called materials' resilience chart (Figure 1).

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 ($D1*D2 \geq 0.45$), 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 along the supply chain – anticipated as medium EU resilience.
- Materials positioned below the red line ($D1*D2 \leq 0.3$) represent a high likelihood of supply shortages along the supply chain – 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.

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%.

Indicators' estimation for lithium used in LIBs for EVs to be deployed in the EU until 2030 under ERERT scenario

D1.1 Material demand

Data required for D1.1 indicator:

a) EU demand for Li in LIB automotive sector: current data and future demand forecast till 2030

b) EU demand for Li in all sectors: current data and future demand forecast till 2030

c) Global demand for Li: current data and future demand forecast till 2030

To calculate the EU demand for Li in LIBs - current and future - we need to know:

- o Vehicle types registered in the EU in 2015 requiring Li for the battery
- o Number of vehicles per type and model registered within EU in 2015
- o Li requirements per vehicle type and model
- o Forecasted penetration rates per vehicle type within EU till 2030

The following electric vehicle types are considered here: Battery Electrical Vehicles (BEVs), and Plug-In Hybrid Electric Vehicles (PHEVs). The 2015 sales figures of the BEVs and PHEVs in the EU are taken from the European Alternative Fuel Observatory.[3] (Table 3 & Table 4). Additional information regarding BEV/PHEV models registered in the EU within the category "Others" is obtained from a JRC Report.[4] The screened literature gives indicative figures regarding the Li content per vehicle though very large scatter is observed: 4 to 40 kg per BEV and 1 to 10kg per PHEV.[5-7] Such scatter can be explained by the different storage capacity of the batteries used in different models even though belonging to the same vehicle type – BEV or PHEV. Taking simply the average of these values per vehicle type would introduce large uncertainty when estimating Li demand. To make more precise estimation, the Li required per unit battery storage capacity (kWh) is used further: 286 g of Li per kWh battery capacity is considered. The reasoning of choosing this number can be found in. Because of the significant difference in the quantity of Li used in PHEV and BEV, these two types of EVs are treated individually. Moreover, the different models have diverse battery capacities and therefore varying Li requirements which would require also knowing the number of cars sold per each model.

Plug-in hybrid electrical vehicles (PHEVs)

Table 1 below gives the number of PHEVs per model sold in the EU in 2015, the battery capacity of each model, the Li amount required per vehicle as well as the total Li required for the PHEVs sold in 2015. PHEV sales per model were obtained from.[3] The category 'Others' includes Porsche Cayenne S E-Hybrid, BMW i8, Toyota Prius PHEV, Mercedes S500 Plug-in, Porsche Panamera S E-Hybrid. The 2014 sales data (due to unavailability of 2015 sales data) for these models are taken from another source[4] with the aim to determine the average amount of Li required per vehicle to be used in the category "Others" of Table 1. Details of 'Others' PHEV models are given in Table 2 below. It can be seen that 7788kg of Li is required to manufacture 3012 PHEVs batteries (2014 data) leading to an average amount of Li of 2.59kg per vehicle for the category 'Others'. This number is then used in Table 1 above. The average content of Li required in a PHEV is calculated at 3kg (derived from Table 1). This number is used to estimate the future EU demand for Li in PHEVs until 2030.

Battery Electrical Vehicles (BEVs)

Table 3 below gives the number of BEVs per model registered in the EU in 2015, the battery capacity of each model, the Li amount required per vehicle as well as the total Li required for the BEVs sold in 2015 in the EU.

BEV sales per model were obtained from.[3] The category 'Others' includes Nissan e-NV200, Renault Kangoo ZE, Smart Fortwo ED, Renault Twizy, Bollore Bluecar, Mitshubishi i-MiEV. As for the PHEVs, the 2014 sales data for these models are taken from the same source[4] in order to determine the average amount of Li required per vehicle to be used in the category "Others" of Table 3. Details of 'Others' BEV models are given in Table 4 below. The 2014 sales[4] were used to calculate the average content of Li required in BEV models pertinent to the category 'Others', namely 5.33kg. The average content of Li required in a BEV is calculated at 9.5kg. This number is used to estimate the future demand for Li in BEVs.

To summarise:

1. Average Li amount per PHEV = 3kg
2. Average Li amount per BEV = 9.5kg

Assuming that supply equals demand, the global demand in 2015 can be considered to be 33330 tonnes being the actual 2015 global supply of Li (Table 5). The global demand for Li and its annual growth rate (12 %) until 2030 was estimated combining information from multiple sources:[6,8,9] The EU demand for lithium was calculated based on information published by the European lithium company. An overview of the values required for the D1.1 sub-indicators calculation is given in Table 6. The following ratios representing D1.1.1, D1.1.2 and D1.1.3 sub-indicators are calculated using the data from Table 6:

D1.1.1 = (a) / (c)

D1.1.2 = (a) / (b)

D1.1.3 = (b) / (c)

The final D1.1 is calculated as the weighted average of the three sub-indicators.

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

Further, Table 7 is presenting an overview of the D1.1 indicator and sub indicators.

D1.2 Investment potential

D1.2 is calculated for 2015 and 2030 using 2015 GDP data and 2030 projections from the Organization for Economic Co-operation and Development's database. For the years 2020 and 2025, a linear data interpolation is 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. Data used for the calculation of D1.2 indicator are given in Table 8 & Table 9. Mine production shares in 2015 are calculated based on 2015 data available from.[9] As for the refining stage of lithium, refining is done only for lithium obtained from minerals. Nowadays most of the lithium is obtained from brines. Brine purification is done in brine treating facilities normally in close vicinity to the production sites which should not introduce change in the concentration of supply. Therefore, stability of supply for the refining stage of Li is considered to be the same as for the mining stage.

D1.4 Reserves depletion

Lithium reserves for 2015 were retrieved from.[9] Apparently, even assuming that no transformation of resources into reserves will happen in the period 2015-2030, still there will be enough reserves to meet the global demand, although in 15 years the availability will drop more than 4 times: in 2015 reserves would be available for 420 years while in 2030 the time to depletion will become 70 years. For our purposes however, this is enough to say that geological availability of Li is not an obstacle for the deployment of the EVs vehicles globally and therefore it scores 1 for the whole period 2015-2030.

$D1.4_{(2015/2020/2025/2030)} = 1$

D1.5 Import reliance

The data required for D1.5 indicator calculation are given in Table 14. The calculations of D1.5 are based on information of present and future Li domestic production (info available in D1.3), Li usage in different sectors (see D1.1) and estimated EU recycling rates until 2030. The EU recycling rates are supposed to be the same as the global one (see D1.7), however it is expected that recycling will begin in the EU only in 2025 onwards while globally some recycling is expected already in 2020. The potential recycled flows of lithium in the EU are calculated following the assumption that batteries are the major application from where lithium could be recovered. Two main streams of batteries are considered: batteries from consumer electronics and automotive batteries. The EU demand for these two streams is already assessed within D1.1 indicator. The available flows for recycling in 2020, 2025 and 2030 are then assessed assuming 3 years average lifetime for a battery of consumer electronic product and 10 years lifetime for an automotive battery. Further, the collection rate for electronics is anticipated to increase from the current level of 47 %[10] to 90 % in 2030. High collection rate of automotive batteries (around 90 %) is logically to be expected based on present data of lead-acid batteries. The lithium recovery rate for lithium for both streams is assumed to be 85 %. As a result, the final recycling rate for consumer electronics batteries is expected to change from around 40 % to 77 % due to higher collection rates expected in future, while the recycling rate for automotive batteries will be constant – 77 %.

D1.6 Upstream supply adequacy

The data required for D1.6 indicator estimation are presented in Table 15 below.

D1.7 Recycling

Globally, the recycling rates of Li are close to zero due to its abundance and low cost. Nowadays, recycling of Li-ion batteries is more valuable for recovering metals such as cobalt and nickel being more highly priced than lithium. The recycling companies do not have business case to extract lithium from slag; neither the equipment manufacturers would be competitive to buy higher price materials from recycling companies. With Li-ion technology is in its infancy, lack of standardisation in battery chemistries and on going research on different battery chemistries, currently there is no recycling infrastructure to recycle explicitly automotive Li-ion batteries due to very uncertain prospective for the recycling companies. However, lithium–ion battery is the application which is expected to drive the future lithium demand worldwide. Hence, secondary materials flows is expected to arise from this particular end-use. Lithium has strong potential for recycling development - demonstrated recycling efficiency of between 80-90%.[11] Yet its secondary production is not being realized yet because of its uncompetitive price. However, three factors can become a strong push for the lithium recycling globally. The first factor is the steadily increasing demand for Li-ion batteries, not only for the automotive sector but also for stationary applications. The second factor is the recent increase in the lithium prices globally and prospects for even further increase. Finally, the third factor is the necessity to deal with the millions of waste batteries in the horizon of stringent environmental laws. The following reasoning has been applied to estimate the global recycling rates for lithium by 2030 (then assumed also for the EU):

Currently (2015 data) around 40 % of Li is used in batteries and around 60 % - in other end-use applications such as glass and ceramics, lubricant greases, cement production etc.[8] An average annual growth rate of 9 % and 3 % are assumed for batteries and non-batteries applications based on information of numerous sources and studies. This will translate the market share for batteries to almost 60 % in 2030, while the non-battery applications will have reduced share of only 40 %. Conservatively no recycling of lithium is supposed to happen from non-battery application. As for the Li-ion batteries recycling in the timeframe 2030, assuming collection rates to be 90% and the recycling process efficiency to be 85% this would result in an end-of-life recycling rate of 77%. According to the proposed methodology, the final recycling rate for lithium is estimated to be 46 %. In the light of the above, it is assumed that substantial recycling of lithium will occur only beyond 2025 when significant amount of batteries will come through the waste stream for recycling, having in mind 10 years lifespan of an electrical car. Indicator D1.7 for the period 2015 - 2030 is given in Table 16.

D1.8 Substitution

The big technology companies and electric vehicles producers are aware of the limitations of current lithium-ion batteries and invest heavily in battery chemistry research. However, before switching to another technology, the best replacement is sought, which apparently today is not available. Moreover, change in production lines and manufacturing techniques are cost intensive. This and the existing deals with materials suppliers being hard to break are ‘stabilising’ in a sense the lithium-ion technology until a proven substitute technology is demonstrated.

In the other end-use applications of lithium – glass & ceramics, lubricates, gas & air treatment, continuous casting, synthetic rubbers & plastics, aluminium smelting – lithium can be substituted although the performance of the product will be reduced. The single application where Li is not substitutable is pharmaceuticals, but it represents only about 2-3 % of the 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 low price. The incentive for substitution will come when there is shortage of Li supply and the price increases substantially. From the analysis performed within indicator D1.1, it can be deduced that some supply shortages might occur beyond 2020 when demand for Li may drastically increase due to high material request from the battery sector – mainly automotive. This can trigger some substitution activities also in the other sectors where substitutes are available. However, no feasible effect of substitution is really anticipated in the considered timeframe, therefore:

D1.8 $_{\mathbf{2015/2020/2025/2030}}$ **= 0**

D2.1 Supply chain dependency

The data /parameters required for the calculation of D2.1 indicator for different steps of the supply chain are presented in Table 17 & Table 18. 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. Step 1 consists of 4 sub-steps (1.1 to 1.4) related to different processed materials being key components of the LIB cells, namely cathode /anode materials, electrolyte and separator. 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.[12] Data on LIB-specific materials were obtained from several sources:[13–16] 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.[17] 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.[18] 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.

D2.2 Purchasing potential

The data needed for the claculation of D2.2 indicator are presented in Table 8 & Table 9.

D2.3 Materials cost impact

For the case of LIB, lithium carbonate and lithium hydroxide are used as starting material for the batteries production. 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 having designs which can be easily switched from lithium carbonate to lithium hydroxide in the future. Since lithium hydroxide has apparently more potential and might be the preferred option in future by the auto manufacturers, the price of lithium hydroxide is considered further in the calculations of D2.3 indicator.

The prices of battery grade lithium hydroxide are in the range of 8,375 USD/ton to 8,700 USD/ton.[19] In Korea and Japan, both known as high quality battery producers, the price is even higher: battery grade lithium hydroxide is sold between 8,800 and 10,500 USD/ton. For the purpose of the D2.3 indicator, the Li hydroxide price is considered. An average price of 8,500 USD/ton is taken for the calculations in 2015. The following data are used to calculated D2.3 indicator:a) Cost of Li hydroxide (per kg): 8.5 USD/kg b) Amount of Li (kg) used in 1 kWh: 0.286 kg/kWh

c) Final component cost (per kWh): 369 USD/kWh*

*The cell cost varies between 333 and 395 USD/kWh[18] depending on the manufacturer/country (different labour, energy cost etc.). An average of 369 USD/kWh is therefore considered for D2.3 calculations.

D2.3 = (369 – 8.5*0.286)/369 = 0.99

Or **D2.3** $_{\mathbf{2015}}$ **= 0.99** is considered for the 2015 polar chart. To calculate the future material cost impact, we need to know how the Li hydroxide cost and the cell/pack cost will evolve till 2030. There is a clear consensus between various research institutes and consultancies regarding the cost evolution of Li ion batteries: all of them suggest a significant fall in battery cost over the next 10 to 15 years.[19] 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 drop rate also for the Li-ion cells, namely:

2015 to 2020: CAGR = -7.8 %

2020 to 2025: CAGR = -5.6 %

2025 to 2030: CAGR = -7.8 %

Applying the same CAGR for Li-ion cell cost, a cost forecast can be obtained till 2030 (Table 18). While the battery cost is supposed to drop in order to become more attractive for the consumer, the Li hydroxide cost is most probably destined to increase due to rapidly increasing demand expected to occur in the next years, according to Nemaska Lithium and other sources.[20] This might make the material contribution to the final battery cost more feasible. As for the future Li hydroxide price, the forecast is that the price will steadily increase reaching 12,000 USD/t by 2031. An average price of 12,000 USD/

ton is taken into account for the calculations in 2030. By calculating the flat CAGR 2015 - 2030, the Li hydroxide price can be deduced also for 2020 and 2025. Li-ion cell and Li hydroxide forecasted price evolution till 2030 is shown in Table 29. The estimated D2.3 for 2015, 2020, 2025 and 2030 (assuming similar material efficiency) are presented in Table 20 below: apparently, even though the price of the raw material is believed to increase and the price of the final product (battery cell) is projected to decrease Li cost will not become a critical factor for the deployment of EVs (assuming the above cost increase for Li hydroxide commodity).

D2.4 Downstream supply adequacy

The data required for D2.4 estimation are already presented in relation to other 2 indicators: D1.1 and D2.1. The derived D2.4 indicator for the period 2015 – 2030 is presented in Table 21 below:

Indicators overview

An overview of the indicators along the upstream and downstream dimensions as well as final resilience score is given below (Table 22). To exemplify the potential of the studied mitigation measures on the overall resilience according to the proposed methodology, the resilience score is given individually for the cases where: 1) only recycling is taking place; 2) only the EU Li production is increased but no recycling occurs and 3) both more lithium is mined in the EU and recycling practices are in place by 2030.[21–26]