MinFuture

D5.2 Testing of the Framework

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1 Introduction

Through the MinFuture project a framework for MFA methodology was developed, see Deliverable 5.1. The framework consists of 7 components (Systems, data, uncertainty, models and scenarios, visualisations, indicators and strategy and decision support) that enables the development of robust MFAs. Systems forms the foundation of all MFAs and works as the founding component in the MinFuture pyramid. The components included in the framework are hierarchically linked, meaning that the robustness of the components on the upper levels are dependent on the robustness of the components on the lower levels. This framework is meant as a tool for the continued development of the monitoring of the physical economy (PE). In addition to the framework, the project has developed guidelines for how to develop these seven components meant to be used by MFA practitioners.

The goal of this Deliverable is to apply the MinFuture project and to inform MFA practitioners and decision makers about the most effective ways to systematically improve the knowledge base of MFA for informing strategies and policy. The purpose of this testing is to illustrate through case studies how the framework can be applied to best inform policy and decision making.

This report is presenting the outcomes of several individual initiatives throughout the project and the layout of the report is as follows, we first briefly introduce the framework, more information regarding the framework can be found in D5.1. We then further show the status of five of the seven components in the framework for aluminium, cobalt, lithium and neodymium. This tasked is aimed to show the status of each materials as well as to show for which material and components more effort should be spent. We then showcase two case studies related to the two bottom layers of the pyramid, systems and data with a case study on cobalt and aluminium respectively. We then present the outcome of the three task forces established by the MinFuture project, International trade, mineral resources and reserves and anthropogenic stocks. The last part of this report will be looking at the policy context of monitoring of the physical economy.

2 MinFuture framework

The MinFuture pyramid includes essential MFA components used in the monitoring of physical flows and stocks of materials. These include: systems, data, uncertainty, models and scenarios, visualisation, indicators, and strategy support. The pyramid components are organised using a hierarchical order, because the robustness of components found in the upper level is impacted by the robustness of components found in the lower levels. The MinFuture framework provides an assessment of these seven components to support MFA practitioners in their work.

Robust strategies for sustainable resource management depend on a solid understanding of the physical economy – the anthropogenic stocks and flows of matter and energy. MinFuture provides a framework for the description and monitoring of the physical economy using Material Flow Analysis (MFA). It distinguishes seven components, which are organised in a hierarchical structure (pyramid).

SYSTEMS

Importance and challenges:

Systems describe where materials are located (stocks) and where they are moving (flows), without quantities.

The knowledge about systems of the physical economy is often highly fragmented, particularly for minor metals, critical raw materials and for end-of-life management.

Key messages:

- Monitoring the system of the physical economy on various scales (site, company, region, country, global) is indispensable for effective resource management and emissions control.

Read more: https://minfuture.eu/theme/systems

DATA

Importance and challenges:

Data about the physical economy tend to be highly fragmented or lacking entirely.

The reference points of data collected are often unclear (described in words only), which results in ambiguous meaning and misinterpretation of the data.

Key messages:

- Reporting data with their system context ("coordinates") adds clarity and robustness and facilitates data harmonisation.
- Government authorities should consider describing their data with metadata about the system location of the measurements.

→ Monitor systems, not isolated flows

Read more: https://minfuture.eu/theme/data

MODELS & SCENARIOS

Importance and challenges:

Models are mathematical representations of material cycles and their drivers. They are used to forecast resource demand and supply and to test strategies under different conditions.

The robustness of models is usually limited by a lack of robust data and system understanding.

Key messages:

- Adding mass and energy balance constraints to resource and emission models enhances the robustness of forecasts.
- Improving system understanding and data quality is the most effective way to improve the quality of forecasts.

Read more: https://minfuture.eu/theme/models-and-scenarios

UNCERTAINTY

Importance and challenges:

A model can never perfectly represent a natural system.

Uncertainties in MFAs are caused by data paucity and errors in system definitions:

Ignoring uncertainty can result in wrong interpretations of the results.

Key messages:

- Uncertainty analysis makes uncertainties transparent and enables users to identify the strengths and weaknesses of the model.
- Systematically evaluating uncertainty enhances the robustness of results and interpretations.

Read more: https://minfuture.eu/theme/uncertainty

INDICATORS

Importance and challenges:

Indicators are used to measure the performance of a system or to capture the essence of a system with numbers.

Indicators are often poorly defined.

Strategies to enhance the indicator performance often cause in problem shifts.

Key messages:

- The definition of indicators (or indicator sets) can be enhanced through an explicit system definition.
- This adds clarity to the definition and facilitates a robust selection of indicators that capture potential problem shifts.

Read more: https://minfuture.eu/theme/indicators

VISUALISATIONS

Importance and challenges:

Visualisations are used to capture the essence of complex systems using images, and to communicate the results in an effective way.

The systems analysed tend to include several dimensions, which are difficult to communicate in words.

Key messages:

- Visualisations can capture multiple dimensions, which adds clarity and transparency, and provide interpretations of complex systems.
- Visualisations can be strengthened by integrating different modes of communication (images, words, and numbers).

Read more: https://minfuture.eu/theme/visuasilations

STRATEGY & DECISION SUPPORT

Importance and challenges:

Strategies for resource management tend to be ineffective and shift problems if they are not based on a robust system understanding.

Strategies for monitoring individual aspects of the physical economy tend to be expensive and of limited use for resource strategies if they are not based on an explicit system definition.

Key messages:

- Improving the robustness of the system understanding and the data is the most critical aspect for improving resource strategies.
- MFAs can inform strategies for monitoring the physical economy by providing a language for integrating data and for identifying key points for measurements.

Read more: https://minfuture.eu/theme/strategy-and-decision-support

3 Status of the seven components for different materials

The aim of this task was to establish the MFA knowledge base for a selected set of raw materials. This is a highly important task as it is important to showcase to policy and decision makers what we know and even more importantly, what we do not know about the different materials. As MFAs can be used as a policy and strategy development tool it is of high importance that policy makers and strategists are aware of the status MFA for the materials of interest. This way efforts can be spent more efficiently and directly relate this to the materials that are of high importance for the EU, such as the critical raw materials. An additional aspect of this work is to help in the priority setting for future research. For instance, for which materials do we know the least, and for which components are more efforts needed.

The framework developed by the MinFuture project serves as guidelines for MFA practitioners to be able to conduct more robust MFAs. For the abovementioned purpose, the framework was used as a basis for scoring the currently published papers on the selected materials and give component scores across the four MinFuture dimensions (stages, international trade, layers and time). The results are presented as 'traffic light' pyramids for the four metals.

The following metals were assessed as a starting point, aluminium, cobalt, lithium and neodymium. For the purpose of this task we will first go through the overall methodology and then the methodology for the single components followed by results and a conclusion. The criteria for testing are still under development and will be presented in an upcoming publication. This will also be expanded to include more materials.

3.1 Methodology

As the aim was to establish the knowledge base, a literature review was performed for all of the different metals that aimed to find the available MFAs that was conducted on those materials. We selected only the papers that aimed at establishing a full material cycle (the whole economy). This meant that studies in which a specific technology or a sector was assessed was excluded from our scope. For the minor metals this meant that several studies were excluded such as battery studies for lithium and cobalt (Asari and Sakai 2013; Ziemann et al. 2018; Schmidt, Buchert, and Schebek 2016). The number of studies is presented in Table 1, for an overview of the studies see Annex A: Papers assessed.

Table 1 Numbers of papers assessed per metal

	Number of studies assessed
Aluminium	25
Lithium	4
Cobalt	9
Neodymium	7

The materials were tested using a scoring matrix so that each component was divided into the four MinFuture dimensions (stages, international trade, layers and time), for more information regarding the components and dimensions, see Deliverable 5.1 MinFuture framework. In addition, an "other" category was used in some cases to assess aspects that were not directly related to the dimensions, see example in Table 2 below.

Table 2: Scoring matrix

		DIMENSIONS				
COMPONENTS		**Stages**	**International Trade**	**Layers**	**Time**	**Other**
	Systems	S.S	S.I	S.L		S.O
	Data	D.S	D.I	D.L	D.T	D.O
	Models	M.S	M.I	M.L		M.O
	Uncertainty	U.S	U.I	U.L	U.T	U.O
	Visualisation	V.S	V.I	V.L	V.T	V.O
	Indicators					
	Strategy and decision support					

Data on all publications was collected using the scoring matrix. For each criteria, points were assigned between 0 to 10, with 0 being the worst and 10 the "best" value for a criteria. In theory the maximum knowledge is infinite, but as aluminium was the metal that had the largest number of studies, the scores are somewhat relative to aluminium and the results for aluminium enabled us to develop the scores. As a result, the knowledge brought by the study can be mapped on finite, discrete scales on each dimension further called the "knowledge table".

An Excel Macro was developed that uses a loop function compiling the score from all studies. For each study, a cursor of knowledge will be placed on each of the axis of the dimensions depending on the value of the criteria for this study. These cursors will define a multidimensional shape whose area represents the knowledge brought by this specific study.

The sum of the scores of the individual studies was plotted on a multidimensional "summary table" using the same approach as the individual studies, with one axis per dimension and scales from 0 to 10 on each axis, See graph 1 in Figure 1. The summary table was filled up with Boolean values. The volume represented by the study's knowledge table will set the corresponding volume in the summary table at "True" and define the colour of the cell. In the case that the value in the cell is already "true" due to a previously plotted study, nothing happens to the cell, making sure that we do not double count in any dimension.

In the end, the summary table will be filled with "true" values delimitating a multidimensional discrete volume of knowledge, and with "False" values indicating the areas for further research. The "True" values on the example are represented by all the orange cells. The score for the component will be the number of cells set to "True". This score has to be relativized to the total number of cells in the table, in order to get a number between 0 and 1. If we have 4 dimensions with scales from 0 to 10, the total number of cells is 11^4 = 14641. This may vary as different components can have different numbers of dimensions depending on the component.

This way of scoring will give scores between 0 and 1 for each of the dimension, we call these our **intermediate component** scores. Following this, scores of the different components can be linked together by multiplying them by the lower components of the Pyramid, making these our **final component** scores. As an example, the final score for data, uncertainty and models are multiplied with the score for systems showing the linkage between systems and data. And the score for visualisation is linked to the score of models and scenarios and the uncertainty score by adding the two together and multiplying this with the intermediate score of visualisations.

The process of attributing points by sorting criteria into ranges of values is important to ease the calculation of the volume, because we use cells (discrete numbers) instead of continuous numbers. The resolution can be varied depending on the scale chosen (from 0,001 to 1, from 1 to 1000).

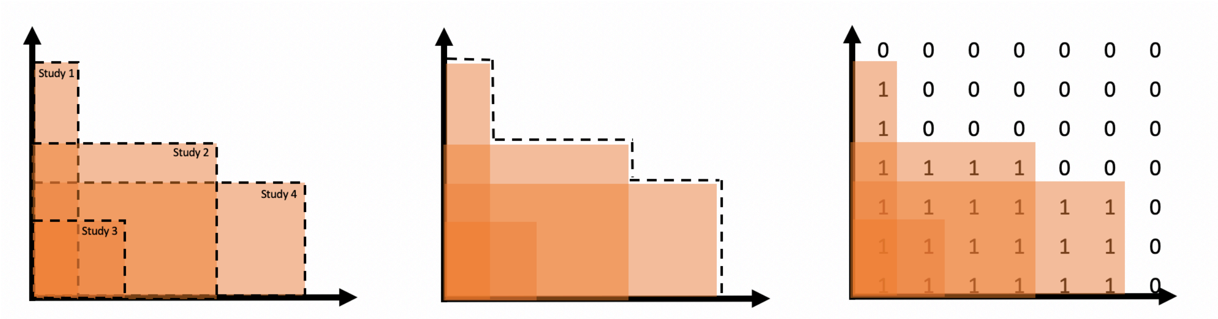

Figure 1: Scoring system, exemplified in two dimensions

3.1.1 Systems

Criteria's assessed:

	STAGES	INTERNATIONAL TRADE	LAYERS	TIME	OTHER
SYSTEMS	**S.S.1:** Number of processes	**S.I.1:** Number of regions **S.I.2:** Number of trade flows	**S.L.1:** Number of layers	N.A.	

Systems does not have a time dimension since systems do not depend on time. As for stages, the flowcharts presented in the papers was used as a basis for counting the number of processes that were included. For 5.3 Anthropogenic stocks, we used the number of flows into use and the number out from use was divided by two to reflect the level of detail of the stock. The number of processes is used as a proxy for how well the system was described. This has several limitations as the metals assessed have very different processing routes that for some require several steps and for other fewer steps are needed which might skew the overall scores for some metals the same is applicable for the use phase.

For trade the number of trade flows included in the flowchart or described in the study was counted individually. Further on for trade the number of countries or world regions that were studied was also counted as individual entities, no difference was made if the study was on a national, regional or global level.

If we are able to track one substance or element consistently throughout the systems in the study this counts as one layer. Not many studies deal with layers in MFA, this is especially the case for studies in which the whole economy was assessed, which are the scope of the papers tested. When looking at MFAs that aim to understand a specific technology or that just investigates the in-use stock of vehicles for instance, it is more common to introduce layers.

3.1.2 Data

Criteria's assessed:

	STAGES	INTERNATIONAL TRADE	LAYERS	TIME	OTHER
DATA	**D.S.1:** percentage of flows populated with data	**D.I.1:** percentage of trade flows populated with data	**D.L.1:** Number of layers with data	**D.T.1:** Number of years	**D.O.1:** Publicly available data

With regards to the data, the flowchart and the information found in the papers was assessed according to the criteria's described above. The majority of publications presented a flowchart or a Sankey diagram which was quantified, for the studies who did not, information from the paper was used. Systems can be produced without data, and knowledge is added through quantifying those systems. The aim of this exercise was to see how far it is currently possible to quantify the published systems.

For stages, used the number of flows quantified divided by the number of flows presented in the flowcharts. The same method was used for looking at trade flows. As for layers we looked at how many layers in each study was quantified.

The data component is dependent on time, here the number of years quantified in the individual studies were counted. In the other category we looked at if the data used in the study was publicly available by going through the study and the list of references, this was quantified by 1 for yes and 0 for no.

3.1.3 Uncertainty

Criteria's assessed:

	STAGES	INTERNATIONAL TRADE	LAYERS	TIME	OTHER
UNCERTAINTY	**U.S.1:** Systematic errors	**U.I.1:** Uncertainty in trade data	**D.L.1:** Uncertainty in layers	**D.T.1:** Uncertainty in lifetime	**U.O.1:** Random errors **U.O.2:** Data reconciliation **U.O.3:** Sensitivity analysis **U.O.4:** Error propagation

To develop the criteria for uncertainty, MinFuture Deliverable 3.3 on uncertainty was used. For all uncertainty categories, yes and no questions were asked as it was challenging to find a quantitative measure on uncertainty. For stages we asked if the study dealt with systematic errors. We went through all of the studies and looked at whether or not this was discussed. Here, some studies might have done some of these measures, but if they were not mentioned in the study, we were not able to capture this.

For the trade dimension, we looked at if the study discussed uncertainty in trade data. The same was done for the layers dimension. As for time we looked at if the study had discussed any uncertainty related to the lifetime of products, this is mainly relevant if the study included an in-use stock.

For uncertainty we also used the others category, since it was not possible to assess certain aspects of uncertainty within the already defined dimensions. The following questions were asked, (1) Does the study deal with random errors? (2) does the study perform a data reconciliation (3) Does the study perform a sensitivity analysis? (4) Does the study perform an error propagation.

All criteria for uncertainty were yes and no questions, for which the studies received points after how many of the aspects related to uncertainty that they had discussed in the studies.

3.1.4 Models and scenarios

Criteria's assessed:

	STAGES	INTERNATIONAL TRADE	LAYERS	TIME	OTHER
MODELS & SCENARIOS	**M.S.1:** No mathematical model **M.S.2:** Quasi stationary model **M.S.3:** Dynamic model	**M.I.1:** No mathematical model implicating trade **M.I.2:** Quasi stationary model implicating trade **M.I.3:** Dynamic model implicating trade	**M.I.1:** No mathematical model implicating layers **M.I.2:** Quasi stationary model implicating layers **M.I.3:** Dynamic model implicating layers	N.A.	

For models and scenarios, we looked at what type of model that was presented in the study and asked yes and no questions that gave points towards the final score. Here, having a dynamic model would give the study the best score. This reflects the fact that dynamic models can be more useful and provide more insights than what a mass-balance model or a quasi-stationary model are able to provide. As for stages, we looked at whether or not they had a mathematical model, with this we mean if the study was only quantified by mass balance (no mathematical model) for a year using no parameters. If this was the case, the study got the lowest possible score. In a quasi-stationary model which implies that the flows do not change over time, but the stocks might. (Brunner and Rechberger 2004). As for dynamic models, both stocks and flows change over time, such models are often the most comprehensive and are highly data intensive. The same criteria were used for the international trade dimension and the layers dimensions, here is was assessed whether or not the model included trade or layers respectively. For models and scenarios, the time dimension was not used.

3.1.5 Visualisations

Criteria's assessed:

	STAGES	INTERNATIONAL TRADE	LAYERS	TRADE	OTHER
VISUALISATIONS	**V.S.1:** Visualisation of stages	**V.I.1:** Visualisation of trade	**V.L.1:** Visualisation of layers	**V.T.1:** Visualisation of time	**V.O.1:** Number of dimensions visualised at the same time.

The visualisations in the studies were assessed and we looked at which dimensions they visualised together with how many of the dimensions were visualised in the same visualisation as out "other" criteria. The aim of this task was to assess how the majority of results were presented in MFA studies. Nearly all studied included a visualisation of stages, often through a flowchart or a Sankey diagram in which the processes, stocks and flows were presented. These visualisations were also used as a basis for evaluating the bottom two components of the pyramid, systems and data. The same procedure was used for trade, layers and time, the visualisations presented in the studies were assessed and were given scores based on yes or no if the dimensions were visualised.

3.1.6 Indicators

Most publications on material cycles does not include specific indicators other than for instance recycling rates which is the most commonly used. For indicators and policy and decision support we have to look at who is using this type of information generated by MFA and for which purpose. For indicators that means that we need to look to industry associations such as the international aluminium institute, the cobalt institute and other institutes and associations that make use of indicators to say something regarding the performance of the metals. Here it is very challenging to make use of the dimensions as the challenges each metal were facing often were material specific. Indicators are often used by policy and decision makers which may not have an interest in the underlying system. However, it is important being able to communicate the fact that good indicators must be based on a good system understanding and that they are dependent on all the underlying components of the pyramid.

Indictors were assessed in Deliverable 3.1 Modelling approaches and indicators that were published before the framework was developed. Here indicators from publications and reports were collected and assessed by the MinFuture partners. The indicators were sorted after type such as criticality indicators, material stocks and flow indicators, end of life, collection and recycling indictors, environmental indicators and emissions indicators to name a few. Further it was considered which life cycle stage the indicators considered, the units and a general description of the indicator. For more information regarding this, please see Deliverable 3.1.

For this testing, we have not yet developed criteria for indicators since we for this deliverable chose to mainly look at the publications. Although, in the upcoming publication criteria for indicators will be included.

3.1.7 Strategy and decision support

MFAs are typically developed to address two fundamental questions: (i) How well do we understand the physical system, and how can we improve our understanding of the system most effectively? (ii) What are challenges related to the real-world system analysed, and how can we control the system most effectively to reach certain goals? Whilst the first relate more to methodology, the second question aims at intervening and changing the system. For the purpose of this task, establishing the MFA knowledge base, the second aspect is more relevant as this task is aimed at informing decision makers and priority setting for future research.

As for indicators, for strategy and decision support, we need to go beyond the results of the publications when we aim to test the framework. For this reason, we did not develop criteria for this component in this report, but as with indicators this will be included in an upcoming publication.

3.2 Preliminary results

3.2.1 Aluminium

Aluminium comes out with the best score both in absolute and relative terms. This is in many cases reflect by the number and diversity of studies published on aluminium. In our example this is also the study that has been studied for the longest time and it is the metal that is used the most in terms of weight in our economy from our selected metals. On average aluminium systems contains 9 processes and the processing of aluminium is well known. 18 of the 25 studies assessed includes trade and the geographical scale spans from 1 to 66 entities that trade with each other. Majority of the studies are able to quantify the entire cycle with an average of 91% of flows quantified indicting that the availability of data is quite good for aluminium. When it comes to models and scenarios 9 studies does not present a mathematical model, 9 includes a quasi-stationary model and 8 models are dynamic which gives a yellow in the relative score, since dynamic models are valued higher in this scoring systems. In both absolute and relative terms, the score for uncertainty is yellow as some studies not even mention the term uncertainty in the study. If they do, mainly random errors are discussed in 13 of the 25 studies. Data reconciliation is done in 7 of the studies and sensitivity analysis is done in 9 of the studies. Only 6 studies perform any sort of error reconciliation. The relative scores are for model and uncertainty given by the multiplication of the actual score times the score of data making both components depending on the data. For visualisations the relative score is depended on the combined score of models and uncertainty. Since it is the model and the underlying uncertainty in these models that are visualised. Nevertheless, aluminium is the metal that comes out the best on all components.

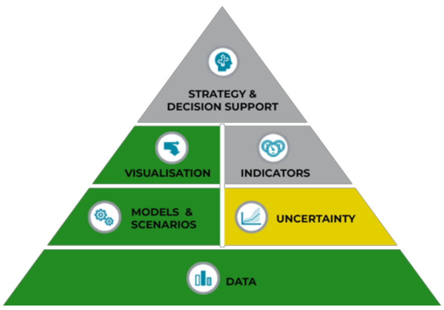

Figure 3: Intermediate component scores aluminium.

Figure 2: Final component scores aluminium.

3.2.2 Cobalt

In total 9 studies were assessed for cobalt. Both for the intermediate and the final component score systems are yellow. The average number of processes in the studies are 7, but the span is much smaller than for aluminium, from one to eleven processes. Several studies on cobalt were excluded due to the fact they did not consider the entire economy such as studies on electric vehicles and batteries which is one of the main uses of cobalt. All of the studies on cobalt includes trade, which might be a consequence of the highly globalised supply chain of cobalt. However, the number of entities included in the trade is quite a lot lower that what was the case for aluminium the maximum entities that were trading was 14, whilst for aluminium this was 66. As for the quantification of flows, cobalt scores lower when compared to aluminium with an average of 74% of flows being quantified. When looking at the studies, the most frequent lack of data occurs in the in-use and end-of-life stages. Most studies only cover one year with the exemption of Zeng & Li, 2015, that covers 22 years for China. This study is also the only study that uses a dynamic model whilst the rest of the studies are either quasi-stationary (4 studies) or does not include a mathematical model (4 studies). As the final component represents when the components are dependent on each other, the red results upwards in the pyramid reflects the poor system understanding and data availability for cobalt. This if further explored in part 4 where a case study on cobalt and data was undertaken. For cobalt 3 studies look at random errors, for any of our other criteria for uncertainty none of the studies assesses these, resulting in the colour red for both the intermediate and the absolute score. As for visualisations, for cobalt they are quite good with some studies having multidimensional visualisation including 3 dimensions, resulting in green in the intermediate score, whilst for the final score this is red due to the dependency on models and scenarios and uncertainty.

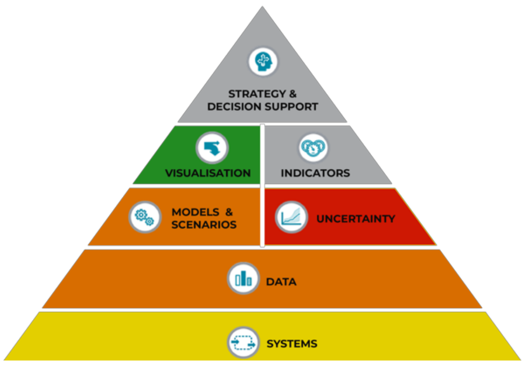

Figure 5: Intermediate component score cobalt

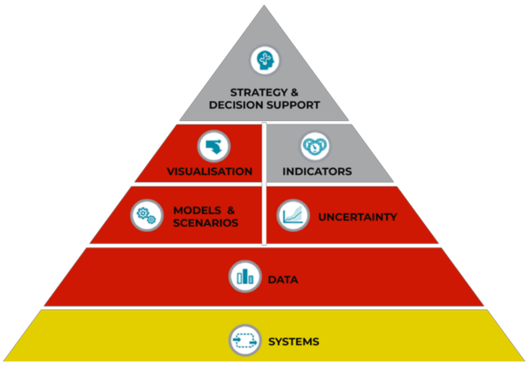

Figure 4: Final component score cobalt.

3.2.3 Lithium

The final component score pyramid for lithium looks the same as for cobalt, but their intermediate components scores differs some. Lithium had the least amount of studies assessed with only four, as several of MFA publications on lithium relates to products or technology (Ziemann et al. 2018; Chang et al. 2009). Even though the average number of processes are rather high with 31, the total number of cases outweigh this in the final score for lithium. The highest level of disaggregation is in the refining/production and manufacturing stages since lithium has a rather complex refining process with several chemical lithium compounds produced. Only one of the assessed studies did not include trade, the remainder has an average of 84 trade flows included. When it comes to data, lithium is metal that has the least amount of flows populated with data with an average of only 31% flows populated. This has a vast impact on the scores for the components above data in the final component score as they are dependent on the score for data. One of the models on lithium is dynamic, while the remaining three are quasi stationary models. None of the studies on lithium either discuss or perform any type of uncertainty analysis, giving lithium the lowest score of all metals for uncertainty. As for visualisations, the maximum number of dimensions visualised at the same time are two.

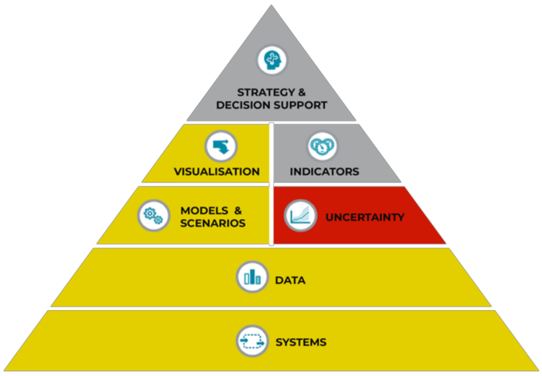

Figure 7: Intermediate component score lithium

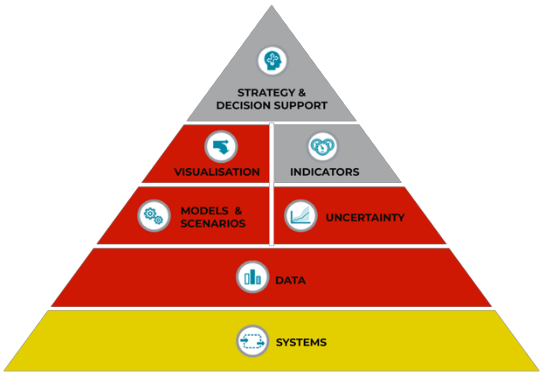

Figure 6: Final component score lithium

3.2.4 Neodymium

All metals currently assessed with the exception of aluminium revives a yellow score for the system component. For neodymium the average number of processes are 10, and only three of the seven studies include trade. Two of the studies include layers, Peiró, Méndez, and Ayres (2013) include 22 layers in their model and Swain et al. (2015) includes 9. As for data, the average of flows populated with data is 86%, this comes mainly from the fact that Nansai et al. (2014) is only looking at the trade flows to and from markets along the value chain and not the flows between processing stages. As for models and scenarios, none of the models are dynamic, four of the studies include no mathematical model and three are quasi-stationary. Only one of the seven studies looks at uncertainty and only one of the studies visualize more than one dimension. For the final component score this means that the poor scores in data and systems translate up the pyramid leaving the top three components red.

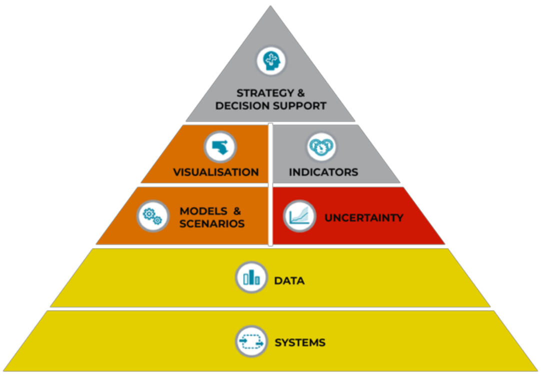

Figure 8: Intermediate component score neodymium

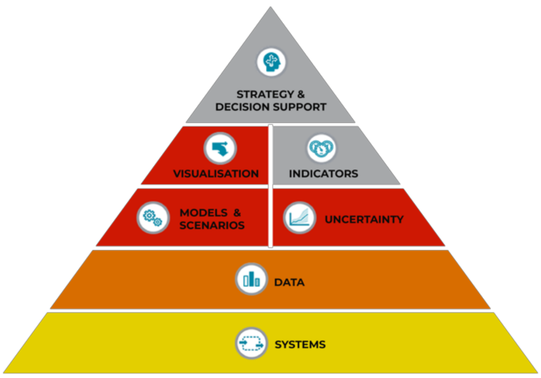

Figure 9: Final component score neodymium

3.3 Conclusions

As our testing has shown, the metal with the largest knowledge base of the four selected metals is aluminium. This is enforced by the number and diversity of the publications found that aims at developing a cycle in which the entire economy is monitored. From the three remaining metals only cobalt and neodymium (rare earths) are categorized as a critical raw materials (European Commission 2017). The common denominator for these three minerals are they all play a vital part in green energy technology and their use will probably increase in the future (Nansai et al. 2014). Therefore, mapping and understanding their supply chain is of high importance, as they might play an important role in our economy. The results of our testing show that in order to be able to monitor the flows and stocks of cobalt, lithium and neodymium we need further efforts already on the system level, before efforts are spent in the upper levels of the pyramid. As the components are linked hierarchically linked one first needs to have systematic efforts towards increasing our system understanding.

For many of the minor metals, the availability of data represents a large challenge. When compiling global cycles, we are dependent on the use of trade data either from UN Statistics COMTRADE or Eurostat's Comext. For the minor metals their supply chain is often lumped together in the way that one code covers several processing stages which does not allow for further disaggregation.

For all metals tested, further work on uncertainty is highly required. As neither of the metals are able to score green. This shows that MFA practitioners need to improve the work on uncertainty, it is also of high importance to communicate this uncertainty to strategy and decision makers.

To be able to develop robust models and scenarios, a good understanding of the system and the availability of data is central. In total 10 of the models assessed were dynamic, 19 quasi-stationary and 17 were mass-balance models. More work is needed in the development of dynamic models, and although the usefulness is higher for dynamic models, they are significantly more data intensive. According to the framework developed, the data availability of the minor metals is something that needs to be overcome first.

This exercise has shown us that more work is needed to be done, especially on the two bottom layers of the pyramid. In the following chapter in this report an exercise for cobalt was undertaken showing from a data provider perspective the challenges we are facing when placing data into systems.

4 Mapping data to systems – A testing exercise using existing data and systems

4.1 The cobalt system.

A cobalt system was drafted during the MinFuture project to explore issues around the development of systems for minor metals. A system describes the different processes and transformation stages of materials. It represents a map of material flows and stocks and it defines the coordinates of measured and non-measured physical data. A system is sufficiently explicit when it characterises well reality and replicates a commodity supply chain. Systems represent the foundation of material flow analysis and they are of fundamental importance to physical accounting. The MinFuture MFA framework defines systems as the first component of an MFA. The system (Figure 10) shows the different stages in the cobalt cycle starting from different ore deposit types through extraction and processing routes to various cobalt uses.

The system diagram used for this correlation exercise was dated 16 June 2018. The cobalt system has already undergone several iterations during the project life and it is still work in progress, as many uncertainties with processes taking place exist.

4.1.1 The cobalt data

Once a system is in place, then the availability of physical data can be investigated. Physical data are attributed to the system to develop mass balance consistent models. The second tier of the MinFuture pyramid therefore is data. This document describes an attempt to correlate to the cobalt system data, and its associated metadata, which are collected by the British Geological Survey (BGS) for mined and refined cobalt production. The aim of this testing exercise is to check the applicability of the developed cobalt system, but also to explore whether existing data from one of the very limited global mineral data providers are developed with the right system definitions in mind. These data are extracted from the World Mineral Statistics database (T. J. Brown, Idoine, et al. 2018) and this correlation was carried out by country for the year 2016. The mine production data are sourced from companies, government ministries, central banks, statistics offices, geological surveys and the USGS, with any remaining gaps filled by BGS estimates. Data for refined cobalt production are primarily sourced from the Cobalt Institute, government ministries and companies. Many of the same sources also contain metadata which can be used to correlate the data to the system diagram. In some cases, data or metadata are limited or inconsistent (e.g. different reported production figures for a single country and year) and as a consequence the uncertainty associated with these data is increased.

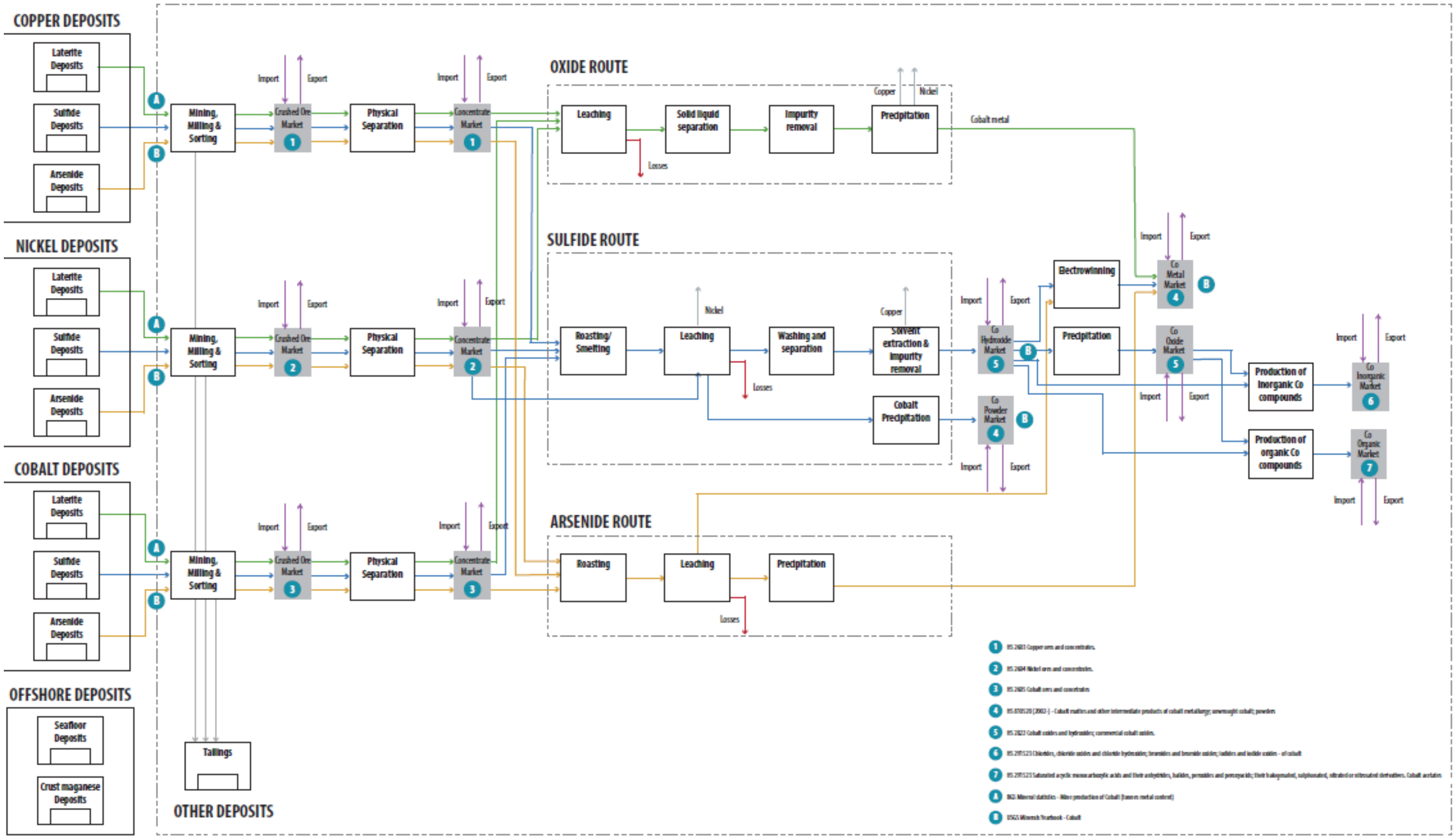

Figure 10: The cobalt system.

4.1.2 The cobalt system from the data perspective

The points numbered [1] to [7] on the diagram, relate to points at which the cobalt form has been identified as the equivalent to that specified by the codes and descriptions used in the Harmonised System (HS), i.e. the codes typically used for trade statistics.

During the correlation exercise, it was noticed that there are difficulties regarding the interpretation of the reported figures due to uncertainties surrounding how production data match the descriptions specified by the HS codes. Often these are because a company just reports a cobalt figure but does not specifically state whether it is ore or concentrate, or because the final product is not identified (e.g. oxide, hydroxide, etc.). It is usually assumed that mined cobalt corresponds to the cobalt concentrate market because it is more expensive to ship raw ore in an unconcentrated state. The majority of BGS data for mine production match the corresponding HS codes of Crushed Ore and Concentrate Market, shown on the roadmap diagram as points [1], [2], or [3] depending on the ore deposit type, respectively.

Uncertainties regarding refined cobalt production emerge i) due to different reported production figures from the various sources and ii) due to the difficulty in attributing the production to the various product markets. For example, it is not possible to assign the BGS refined cobalt figures to any one point, e.g. [4], [5], [6] or [7] in the diagram (due to insufficient metadata) but figures are a combination of all the points. The correlation exercise is illustrated in more detail later in this document through the provision of specific country examples.

The major processes throughout the cobalt life cycle are shown in the system. These processes can be divided into three stages: mining, physical processing and chemical processing including final metallurgical and chemical products. Recycling and waste management have not yet been considered in this correlation exercise as it is hard to trace the flow of in-use products and the waste stream inside and across countries. Also, reliable metadata for robust estimation are not available. Therefore, stages of product use and recycling/waste management are not covered in the presented version.

On the system diagram, at the resource mining stage, four groups of deposits containing cobalt resources are shown: copper deposits, nickel deposits, cobalt deposits and offshore deposits. Within each group three sub-groups are shown (laterite, sulphide and arsenide) because the downstream processing varies as a result of chemical composition, however not all these sub-groups correlate with currently exploited deposit types. Cobalt is mined either as a by-product or a main product and then processed physically and chemically. Currently, the main sources of cobalt are nickel-cobalt laterites (e.g. Goro, New Caledonia), sediment-hosted stratiform copper-cobalt sulphide deposits (e.g. Central African Copper Belt, DRC), magmatic nickel-copper (with cobalt-platinum group element) sulphide deposits (e.g. Sudbury, Canada) and cobalt arsenide deposits (e.g. Bou Azzer, Morocco). Deposit types differ in their cobalt grade from 0.13 to 0.22 % in nickel-cobalt laterites, from 0.01 to 0.21 % in magmatic nickel-copper deposits, from 0.1 to 1.1 % in sediment-hosted stratiform copper-cobalt deposits, and up to 1% in the hydrothermal Bou Azzer deposit, Morocco (Hitzman, Bookstrom, Slack, & Zientek, 2017.). Offshore deposits consist of ferro-manganese nodules and crusts, which are enriched in nickel, copper, cobalt and a range of other metals, but these are not currently extracted commercially.

The physical processing stage includes mining, milling and sorting of the ore, as well the physical separation. Generally speaking, these steps are conducted at the mining site. Production figures at this stage usually refer to "mined cobalt" or "finished cobalt" (meaning finished by the mine, not necessarily a pure cobalt product). BGS data are attributed to

"Crushed Ore Market" or "Concentrate Market" both identified by HS codes as points [1], [2] and [3] on the diagram, depending on the ore deposit type.

When considering data for mined cobalt, there is often a considerable difference between the cobalt quantity in the ore that is raised and the amount of cobalt that is actually recovered. The metadata collected with the mine production figures are rarely sufficient to enable the compiler to be certain whether the data represent 'recoverable' cobalt or simply the cobalt that is present. In other words, it depends on whether the measurement of the mined cobalt is carried out when the raw ore enters the initial beneficiation stages or when the concentrated materials leave the mine.

As the majority of cobalt is mined as a by-product of another metal, e.g. nickel or copper, the initial metal extraction processes are often designed to maximise the recovery of the major metal rather than the by-product. Thus the recovery rate for cobalt will often be lower than for the copper or nickel and the unrecovered cobalt will end up in tailings (T. J. Brown, Gunn, et al. 2018; Mudd et al. 2013). Furthermore, if the ore that is raised is immediately processed into certain forms, e.g. ferro-nickel or nickel-pig-iron, the cobalt that may still be present is effectively 'lost' and unrecoverable. This is because these forms are directly used, e.g. in the production of stainless steel, without further steps to separate the cobalt. Even if the subsequent products are later recycled, generally it will be to further types of the same material, e.g. to more stainless steel, without any processing steps to enable the cobalt to be extracted first. Indeed, there is no incentive to do so because such processing would incur a financial cost and the presence of a small amount of cobalt is usually beneficial to the properties of the material.

On the system diagram, three different routes are separated in the chemical processing stage: oxide route, sulphide route and arsenide route. These are distinguished due to the individual processing techniques, i.e. whether the ore is primarily processed by leaching, roasting and/or smelting, and finally extracted by solvent extraction or precipitation, etc. After cobalt precipitation, impurity removal and/or electrowinning, the final cobalt markets are defined as: Co Metal Market and Co Powder Market (which have the same HS code; shown as point [4]), Co Hydroxide and Co Oxide Market (again with the same HS code; shown as point [5]), Co Inorganic (shown as point [6]) and Co Organic Market (shown as point [7]). The wide range of metallurgical and chemical products includes (among others): cobalt cathodes, cobalt powder, cobalt sulphate, cobalt oxide, cobalt hydroxide, cobalt carbonate and cobalt chloride. These basic chemical compounds are then used to produce many derivatives for manufacturing batteries, superalloys, catalysts, ceramics, etc.

One of the most significant uncertainties in the data for refined cobalt is the risk of double-counting because some of the 'products' identified can either be used directly or used as an intermediate material which is further processed into different cobalt products. If this further refining happens in a different country, the figures can show refined cobalt products from both countries. Careful consideration of any available metadata can sometimes enable the position to be established but if metadata is limited or absent it can be difficult to be certain that no intermediate products are included in the total. A further difficulty is due to cobalt being a by-product and therefore its movement is sometimes 'hidden' within shipments of nickel or copper concentrates or intermediate products such mattes.

Trade data for cobalt is further confused by the combination of different forms into single HS trade codes. For example, cobalt "mattes and other intermediate products of cobalt metallurgy" is combined with "unwrought cobalt and cobalt powders" in HS code 81052000. The cobalt content of the former is likely to be approximately 20% cobalt while the latter is closer to 100% cobalt (European Commission, 2017b). This is of particular importance when attempting to track global flows of cobalt because the majority of the material shipped from the DRC is an intermediate product.

4.1.3 Country examples

4.1.3.1 Canada

In 2016 mine production amounted to 7,148 t contained cobalt, reported by a Government Ministry as "cobalt mine production". However, the Government Ministry reports two series of figures: a higher series described as "mine production" and a lower series described as "recoverable cobalt in concentrate shipped". The difference between these two series in 2016 was more than 3000 tonnes of cobalt and the reasons behind such a large difference are unclear. It may be that one is 'production' while the other is 'sales' (although this would leave a significant quantity 'on stock' somewhere), or it could be that large quantities of cobalt are 'lost' during processing. Alternatively, the lower series could be only the cobalt contained within concentrates and does not include the cobalt exported from Canada in other forms (i.e. matte or refined metal).

The producing companies in Canada are: Vale, Glencore, Canadian Royalties Inc and North American Palladium. Vale is operating a number of mines at Sudbury, plus the Voisey's Bay and Thompson mines; Glencore has the Raglan mine and two Sudbury mining operations; Canadian Royalties Inc has a mine at Nunavik; and North American Palladium is operating the Lac des Iles mine. On the Glencore website it lists production in 2016 of 805 t of cobalt in concentrate at Raglan Mine and 505 t of cobalt in concentrate from their Sudbury operations. In its Annual Report, Vale lists production of 882 t of contained cobalt from its Sudbury operations, 700 t from Thompson and 887 t at Voisey's Bay. Canadian Royalties Inc is a privately-owned company (a subsidiary of a Chinese firm) and does not report any data. North American Palladium, as the name suggests, is focussed on the extraction of platinum group metals and does not report cobalt because it is a by-product that does not occur in large enough quantities for it to receive any payable credits. Consequently, it is impossible to compile a complete set of data on a mine by mine basis to check against the Government Ministry figures.

The Canadian deposits are classified as magmatic nickel-copper (with cobalt-platinum group elements) sulphide deposits, thus the mine production data fit to number [2] in the diagram.

In 2016, refined cobalt production was reported by the Government Ministry as 6,302 t. In contrast, the Cobalt Institute reports 5,544 t refined cobalt for 2016. The difference is unexplained. Producing companies are Sheritt (through a joint venture (JV)), Vale and Glencore.

Concentrate from Glencore's three mines is sent to its Sudbury smelter where it is cast into matte, which is subsequently shipped to Norway for refining into pure metal. Glencore's website reports 2,537 t of cobalt-in-matte were produced in 2016, so its Sudbury smelter is also processing concentrates from other mines (which may include Glencore's other global mining operations and/or third party mining operations in Canada or elsewhere). It is believed that this material is not included in either figure reported above because it is an intermediate product that is further refined elsewhere.

Concentrates from Vale's Canadian mines are processed at Vale–owned smelters in Thompson, Sudbury or Long Harbour (the first of these is in the process of being closed) and cobalt is refined at Vale plants in Port Colborne and Long Harbour (all in Canada; the latter commenced in 2017). The Port Colborne refinery produced 1,851 t of refined cobalt metal in 2016 and the Vale annual report also refers to cobalt being contained in nickel concentrates shipped elsewhere for processing.

The Sherritt JV operates a refinery at Fort Saskatchewan where it processes mixed nickel-cobalt sulphides imported from mines in Cuba. In the company's annual report, it reports

3,694 t of 'finished cobalt' from the Fort Site (of which 50% is attributed to Sherritt under the JV). This 'finished cobalt' is described in other documents on the Sherritt website as 'cobalt powder and briquettes'.

Based on the available information, the 'refined cobalt' data is likely to fit primarily to point number [4] on the roadmap diagram but it is possible the higher figure from the Government Ministry includes cobalt in other forms that relate to numbers [5] to [7].

4.1.3.2 China

Cobalt mine production in 2016 was reported in the Yearbook of Nonferrous Metals Industry of China as 9,293 t cobalt contained in concentrate. The number of currently operating cobalt mines in China is unknown, but the majority of deposits are: (a) magmatic nickel-copper-cobalt sulphide; (b) hydrothermal and volcanogenic cobalt polymetallic; (c) stratabound sediment-hosted copper-cobalt; and (d) lateritic nickel-copper deposits. One identified mine is the volcanogenic massive sulphide (VMS) Deerni copper-cobalt (-zinc) deposit operated by ZiJin Mining, but there are also other mines including those operated by the Jinchuan Group. The data for mined cobalt production is probably a combination of numbers [1] and [2] in the roadmap diagram-

Refined cobalt production in 2016 was reported by the Cobalt Institute to be 45,046 t contained cobalt, excluding the plants operated by Umicore. The main operating companies are: Huayou Cobalt Co, Shenzhen Green Eco-manufacture Hi-tech Co, Jiangsu Cobalt Nickel Metal Co, and Umicore. The latter operates a number of different plants in China, typically through joint ventures, including Jiangmen Chancsun Umicore (JCU) and Ganzhou Yi Hao Umicore Industries Co Ltd (GYHU). However, Umicore's cobalt production is not generally separated between individual countries and its production in China is therefore usually shown under Belgium, where the company has its headquarters.

Huayou Cobalt refers to its main products as cobalt tetroxide, cobalt oxide, cobalt carbonate, cobalt hydroxide, cobalt oxalate, cobalt sulphate and cobalt monoxide, thus data for this company (if they were available) would likely fit to numbers [5] and [6] in the diagram.

Shenzhen Green Eco-manufacture Hi-tech Co reports a detailed list of annual production referring to 1,500 t ultra-fine cobalt powder, 3,000 t cobalt carbonate, 3,000 t cobalt oxalate, 500 t cobalt oxide, 1,000 t cobalt sulphate, 2,000 t cobalt chloride (11,000 t refined cobalt). Therefore, these data would fit to numbers [4[, [5], [6] in the diagram.

Jiangsu Cobalt Nickel Metal Co refers to cobalt cathodes and cobalt salt series including cobalt oxide, cobalt carbonate, cobalt chloride and cobalt sulphate. As a result, data for this company (if there were available) would probably match numbers [5] and [6] in the diagram.

The Umicore website says that the GYHU plant (Ganzhou Yi Hao Umicore Industries Co Ltd) produces "first class cobalt salts and oxides". The Umicore website also refers to cobalt sulphate, cobalt oxalate, cobalt carbonate, cobalt hydroxide, cobalt chloride, cobalt trioxide. Therefore, data for this company (if they were available) would probably match numbers [5], [6] and [7] in the diagram.

As demonstrated above, it is often difficult to separate figures for refined cobalt production into individual products, with only one Chinese company reporting figures to this level of detail. Therefore, separating data between points [4] to [7] on the diagram is very difficult.

4.1.3.3 Democratic Republic of Congo

Mined cobalt production in the Democratic Republic of Congo (DRC), as reported by the Central Bank, achieved 68,822 t contained cobalt in 2016. However, the Central Bank's bulletin just refers to "cobalt" and provides no further detail. In the DRC at least 14 industrial mines plus many artisanal mines are active. The largest mines, in terms of cobalt output, are believed to be Mutanda (owned by Glencore) and Tenke Fungurume (recently purchased by China Molybdenum Co Ltd from Freeport McMoRan) but there are many others including Luiswishi (Zhejiang Huayou Cobalt Co Ltd), Boss (Eurasian Natural Resources) and Big Hill (Groupe Forrest International SA) (Al Barazi et al. 2017). Ore deposits with economic cobalt resources are stratiform sediment-hosted copper sulfide deposits, and it is therefore assumed that the mine production data fit to diagram number [1] (Crushed Ore and Concentrate Market of Copper Deposits).

The refined production in the DRC amounted to 400 t cobalt in 2016 (as reported by the Cobalt Institute). However, a significant proportion of the cobalt mined in the DRC is exported as an intermediate product for further refining elsewhere and is, therefore, not included in this figure.

Only a limited amount of information is available regarding the processing technologies used by the mining companies operating in DRC or regarding the products they export. For example, the Glencore website refers to the production of cobalt hydroxide at its Mutanda mine and similarly China Molybdenum's Annual Report refers to cobalt hydroxide from Tenke Fungurume. Elsewhere, Katanga Mining Limited (65% owned by Glencore), which operates the Kamoto/KOV mines in DRC, announced the successful commissioning of the first part of the "Whole Ore Leach Project" (WOL Project[1]) in December 2017. Elsewhere, the Katanga website refers to roasting, leaching, purification and electro-winning but does not indicate the purity of the cobalt product, thus it is unclear whether this is a refined or intermediate form. Production review reports of Katanga Mining Limited refer only to "finished cobalt" without any further details of what form this actually takes.

Consequently, the data for 'refined cobalt' probably fit to the Co Metal and Hydroxide Markets, indicated by numbers [4] and [5] in the diagram. However, the significant proportion of the cobalt hydroxide production in DRC is likely to be an intermediate and excluded from the published 'refined cobalt' figure.

4.1.3.4 Finland

The mining sector in Finland produced 2,308 t contained cobalt, as reported by the Geological Survey of Finland (GTK) in 2016. There are three operational mines where the ore contains cobalt, these are Sotkamo (operated by Terrafame, previously Talvivaara), Kylylahti and Kevitsa (both operated by Boliden). The Sotkamo deposit is a metamorphosed black shale-hosted nickel-copper-cobalt-zinc sulphide deposit. Kylylahti is a hydrothermal volcanogenic copper-nickel-zinc-cobalt-gold-silver sulphide deposit. Kevitsa is a magmatic copper-nickel-cobalt-PGM sulphide deposit.

At all three mines, cobalt is extracted as a by-product of both copper and nickel. Boliden report that Kylylahti produces a concentrate containing copper, gold, zinc and silver which is sent to its own smelters in Harjavalta and Kokkola (both in Finland) but does not report what happens to the cobalt. At Kevitsa, Boliden report that the mine's main output is a metal concentrate containing nickel, copper, gold, platinum and palladium, which is

[1] http://www.katangamining.com/~/media/Files/K/Katanga-mining-v2/reports-and-presentations/2015-06-investor-presentation.pdf

supplied to the Harjavalta Smelter and to external customers; again there is no indication of what happens to the cobalt. The geological survey of Finland has indicated that the cobalt from Boliden's mines remains in the residual material resulting from processing and this is currently 'stored' and not further refined. Terrafame reports that the main product from the Sotkamo mine is a nickel-cobalt sulphide precipitate, which is delivered to its customers for further processing. The possibility of further processing on site is under consideration. The production of cobalt from the Finnish mines would match to number [1] and [2] on the diagram.

Refined cobalt is produced in Finland, primarily from imported materials, by Freeport Cobalt at its Kokkola Cobalt Refinery. In 2016 refined cobalt production as reported by the GTK amounted to 12,393 t contained cobalt, whereas the Cobalt Institute reported 11,187 t refined cobalt. The Freeport Cobalt website lists a wide range of cobalt products including acetate, carbonate, hydroxide, oxide, sulphate and several different types of cobalt powder without reporting specific numbers. As a result, the refined cobalt data would fit to diagram numbers [4], [5], [6] and [7].

4.1.4 Cobalt case study conclusions

The application of the diagram has shown that the allocation of data for mined and refined cobalt production to single HS codes is somewhat difficult to achieve. At first, the initial differentiation between copper deposits, nickel deposits and cobalt deposits is difficult to apply in some cases, e.g. there are no known cobalt-laterite deposits, and it is unclear where hydrothermal and volcanogenic deposit types fit. It is also not clear whether both copper sulphide and nickel sulphide deposits mean "magmatic" deposits. Currently there is only one deposit where cobalt is extracted as main commodity, and this is a cobalt-arsenide deposit at Bou Azzer in Morocco, whereas all others are mining cobalt as by-product. Therefore, a strict separation termed as "Cobalt Deposits" is perhaps not appropriate. Further, new exploration projects also concentrate on other deposit types like Mississippi Valley type, Iron-Oxide-Copper-Gold (IOCG), black-shale hosted and Five-element vein deposits, but it is not clear where these would fit in the diagram. It might be better to maintain a geological classification into 1) stratiform sediment-hosted copper-cobalt deposits, 2) magmatic nickel-copper deposits, 3) lateritic nickel deposits and 4) other deposit types including VMS, IOCG etc.

For the refined cobalt production is it difficult to allocate the available data to single HS codes, e.g. Cobalt Metal Market, Powder Market, Inorganic or Organic Market. This is because it is generally not possible to clearly identify how much cobalt goes into the production of hydroxide, oxide, powder, inorganic or organic cobalt products. Company websites usually refer to more than one product but only report one figure. Finally, secondary resources (recycling) are currently missing in the diagram, while tailings are listed but data availability for cobalt amounts in tailings is very limited or does not exist.

Another question would be what is meant by the term "other deposits" on the diagram, which is positioned next to "tailings"? Other deposits are not necessarily resources such as tailings. Ideally, material flow analysis for cobalt life cycles would quantify how much raw material is produced from primary sources (mining) and how much is produced from secondary sources.

The analysis presented in this document required substantial background research. Some of this information are stored as metadata in the World Mineral Statistics database, but often metadata information do not accompany the reported figures and therefore additional research to build up sufficient contextual information of the data provided is undertaken by BGS. This is time consuming and increases the uncertainty of the data reported, as in many cases assumptions need to be made. The testing exercise undertaken was highly valuable. It provided an opportunity to challenge the cobalt reported figures, to enhance our understanding and to provide an analysis of the gaps and uncertainties that exist with the cobalt data. Similar uncertainties are expected to exist with the data reported from other global providers, which at the moment are not explicit.

4.2 The aluminium system

The basic aluminium system has been developed in earlier projects prior to MinFuture commencing and consequently the processes and transformation stages of aluminium (from bauxite ore, to alumina, to aluminium metal and recycling) are fairly well understood. Aluminium is the second most commonly used metal in society, after iron, and it therefore provides an interesting contrast to the situation with 'minor metals' such as cobalt. As with the cobalt case study, systems are a representation of reality demonstrating how materials flow through the commodity supply chain. They represent the foundation of material flow analysis and they are of fundamental importance to physical accounting. The MinFuture MFA framework defines systems as the first component of an MFA. The system for aluminium (Figure 11) shows the different stages in the aluminium life cycle including recycling. This system was published by Liu and Müller (2013a) and is included here with the permission of the authors. The points contained in highlighted square brackets on Figure 11, e.g. [1], represent the processes taken into consideration in this case study. Further explanation of the other processes can be accessed through the original paper.

4.2.1 The aluminium data

As with cobalt, once a system is in place the physical availability of data can be investigated. This text describes an initial attempt to correlate data collected by the BGS, with its associated metadata, to the above system. BGS collects global production figures for mined bauxite (the main ore of aluminium), refined alumina (calcined aluminium oxide produced primarily from bauxite and forming the main intermediate used to produce metal) and primary aluminium metal. BGS does not routinely collect data relating to secondary sources of aluminium, including recycling. The data referred to in this text are extracted from the World Mineral Statistics database (and published in (Brown et al. 2018) and this correlation was carried out by country for the year 2016. The data for bauxite and alumina are sourced from government ministries, statistical agencies, companies, in-country trade associations, geological surveys, central banks or chambers of mines, with data gaps filled by estimates. Data for primary aluminium are sourced from the same kinds of organisations but with a higher proportion of company reported data. Many of these data sources also contain metadata which can be used to provide a greater understanding of the system. However, in other cases this metadata may be limited or inconsistent and as a consequence the uncertainties associated with these data are increased.

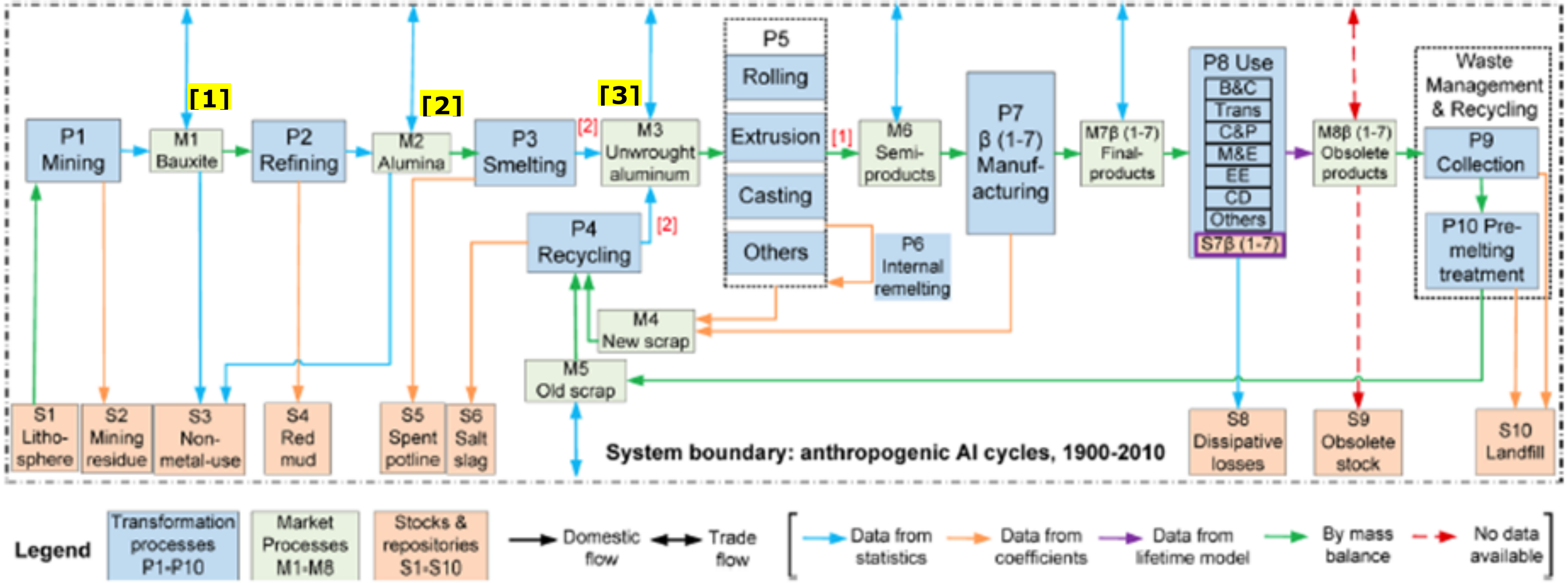

Figure 11: The aluminium system (Liu and Müller, 2013) with highlighted reference points in square brackets added.

4.2.2 The aluminium system from the data perspective

4.2.2.1 Bauxite

Deposits of bauxite are generally categorised into two groups: 'karst bauxite' (i.e. those overlying carbonate rocks) and 'lateritic bauxite' (i.e. those overlying other types of rocks) but the majority of the world's production comes from the latter group. Both these deposit groups are known as 'residual deposits' because they are formed by intense and sustained weathering processes, usually in tropical or sub-tropical locations, which removes the more mobile elements. If the original source rock was suitable, i.e. contained the necessary elements, this residual deposit may be formed of bauxite. Bauxite is actually a heterogeneous material consisting of three aluminium bearing minerals (gibbsite, boehmite and diaspore) together with varying quantities of silica, iron oxide and other elements.

In terms of the defined aluminium system, and in contrast to the system for cobalt, the differences in minerals or deposit types are not distinguished and all of the mined bauxite is shown in a single box (see point [1], Figure 11). This is a good thing because usually the available data also does not separate different types of bauxite deposit, nor does the data distinguish between the different aluminium-bearing minerals contained within bauxite. All of the BGS data for mine production of bauxite should, therefore, correlate to point [1] in the above diagram. Nevertheless, there are some important points that need to be considered.

In contrast to most types of metal ores, virtually all reported figures for bauxite are reported as 'gross weight' and do not identify the grade or quantity of aluminium metal contained. This is an important point for any organisation attempting a 'mass balance' study. Between 2 and 4 tonnes of bauxite are required to produce one tonne of alumina and the precise quantity within this range will vary from country to country.

Whilst the majority (85–90%) of the bauxite mined in the World is used to produce aluminium metal, a proportion (10–15%) is also used for other, non-metallurgical purposes such as abrasives, refractories, cements and chemicals either directly as bauxite or after refining to alumina (Hill and Sehnke 2006; Patricia Plunkert 2003). This is shown on the system diagram, Figure 1, by the blue arrows leading from boxes 'M1' and 'M2' to box 'S3'. The percentage figures noted above are often quoted but no precise quantity figures are available from any known source and it is likely that these will vary a little from year to year.

4.2.2.2 Alumina

Alumina is refined from bauxite using the Bayer process, which involves crushing and milling, desilication (if levels of silica are considered high), digestion in hot caustic soda, clarification and settling, cooling and precipitation, classification and finally calcination. For a more detailed description of the process, please see the IAI's dedicated web pages (International Aluminium Institute 2016).

Prior to the final calcination step in the process, the material is in the form of 'alumina hydrate', which has a chemical formula of Al(OH)3 whereas the calcined form of alumina (also known as 'aluminium oxide') has a chemical formula of Al2O3. It is the latter form that is used to produce aluminium metal. However, often production data are published as 'alumina hydrate' rather than calcined alumina and a conversion is therefore required to ensure consistency in global totals. In some cases, individual refinery plants appear to sell both forms and it can be difficult to establish how much of each is contained within the production data. Both the BGS and the USGS attempt to publish either reported 'alumina' or the calcined equivalent of any reported 'alumina hydrate' but this represents one of the most significant uncertainties associated with the published figures.

With regards to the system diagram, the data collected by BGS should all relate to point [2], however the diagram does not break down the refining stage into its component steps so the production of ‘alumina hydrate’ would be contained within the box ‘P2’. There is nowhere on the diagram for ‘alumina hydrate’ material that is sold on the market.

The data published by BGS also relate only to alumina produced from bauxite. The production of secondary aluminium from recycling processes can result in the formation of salt slags from which alumina-rich materials may be derived. These are not included in the published data. Also, a very small amount (<1%) of alumina is produced from nepheline syenite rather than bauxite and further research is ongoing that may eventually lead to the production of alumina from other sources.

Flows of alumina are further complicated by a range of non-metallurgical uses, such as refractory products, abrasives or ceramics, and also by “specialty” uses in chemical applications or pharmaceuticals where high purity is required.

4.2.3 Country examples

There are 56 countries worldwide that produce one or more of bauxite, alumina and primary aluminium metal, but only 15 of those produce all three stages of the aluminium system (Cv Table 3)

Cv Table 3: Countries that include all three stages of bauxite, alumina and aluminium metal production

Australia	Greece	Saudi Arabia
Bosnia & Herzegovina	India	Russia
Brazil	Indonesia	Turkey
China	Iran	USA
France	Kazakhstan	Venezuela

Of the 10 countries that host two of these three stages of the aluminium system, four do not have mine production of bauxite, four do not have alumina refining and two do not have aluminium smelting (Table 4).

Table 4: Countries with only two stages on the aluminium system; grey: countries with alumina refining and aluminium metal production; blue: countries with bauxite production and aluminium metal refining; green: countries with mine production and alumina refining

Canada	Romania	Ghana	Montenegro	Jamaica
Germany	Spain	Malaysia	Mozambique	Vietnam

With regards to the first group of four countries, it could be simply because bauxite does not occur within those countries for geological reasons, or that available and economic resources have been depleted. The second group of four countries are more difficult to explain because it would appear that the mining of bauxite and smelting of aluminium are operating independently of each other. Of the remaining two countries, it is believed that there is an aluminium smelter under construction in Vietnam, which will complete the vertical integration of the three stages in that country.

A further 31 countries only have one of these three stages of the aluminium system. Of these 10 countries only had mine production of bauxite in 2016 (Croatia, Dominican Republic, Fiji, Guinea, Guyana, Hungary, Pakistan, Sierra Leone, Solomon Islands and Tanzania). Some of countries, e.g. Hungary, were alumina producers in the recent past but these plants have closed. A few others are considering the possibility of building alumina refineries in future. Only three countries (Ireland, Japan, Ukraine) have just the alumina refining stage without either bauxite mining or alumina smelting operations and of these Japan was an aluminium producer in the very recent past. Another 18 countries have a primary aluminium smelter without hosting the earlier stages (Argentina, Azerbaijan, Bahrain, Cameroon, Egypt, Iceland, Netherlands, New Zealand, Norway, Oman, Qatar, Slovakia, Slovenia, South Africa, Sweden, Tajikistan, United Arab Emirates and United Kingdom). In some cases, this position has arisen due to the plentiful availability of energy, which lowers the cost of electricity and hence lowers the cost of energy intensive aluminium production. This is certainly the case with Iceland, which has significant quantities of geothermal power due to its geological location.

The scope of this study is to provide critical insight into the data available in order to highlight some of the difficulties and uncertainties that exist with them. Considering the large number of producers available, only a small number of countries is selected for this analysis.

4.2.3.1 China

China is the largest producer of primary aluminium in the world, with an output of nearly 32 million tonnes in 2016 or 54% of the global total. It is also the world's largest producer of alumina, with an output of nearly 61 million tonnes in 2016 or 51% of the global total. However, it is not the largest producer of bauxite — it is second behind Australia, with an estimated output of 68 million tonnes or 24% of the global total in 2016. China does not mine enough bauxite within its own borders to support its high levels of alumina and aluminium production and is therefore a major importer of bauxite.

The origin of China's imports of bauxite in recent years is interesting (Figure 12). For many years China was dependent on imports of bauxite from Indonesia, but in 2014 Indonesia brought in an export ban with the intention of encouraging the development of its own domestic downstream value-added processes (i.e. alumina refining). China then switched to importing significant quantities of bauxite from Malaysia, as well as continuing to increase its imports from Australia. However, the authorities in Malaysia became concerned about the dramatic increase in bauxite mining in their country and took steps to limit its exports of bauxite too. China has therefore switched its source of bauxite imports again and in 2017 it imported a significant proportion of its bauxite requirements from Guinea, where Chinese companies have also invested in a mine. These events are clearly reflected in the import data (see Figure 12).

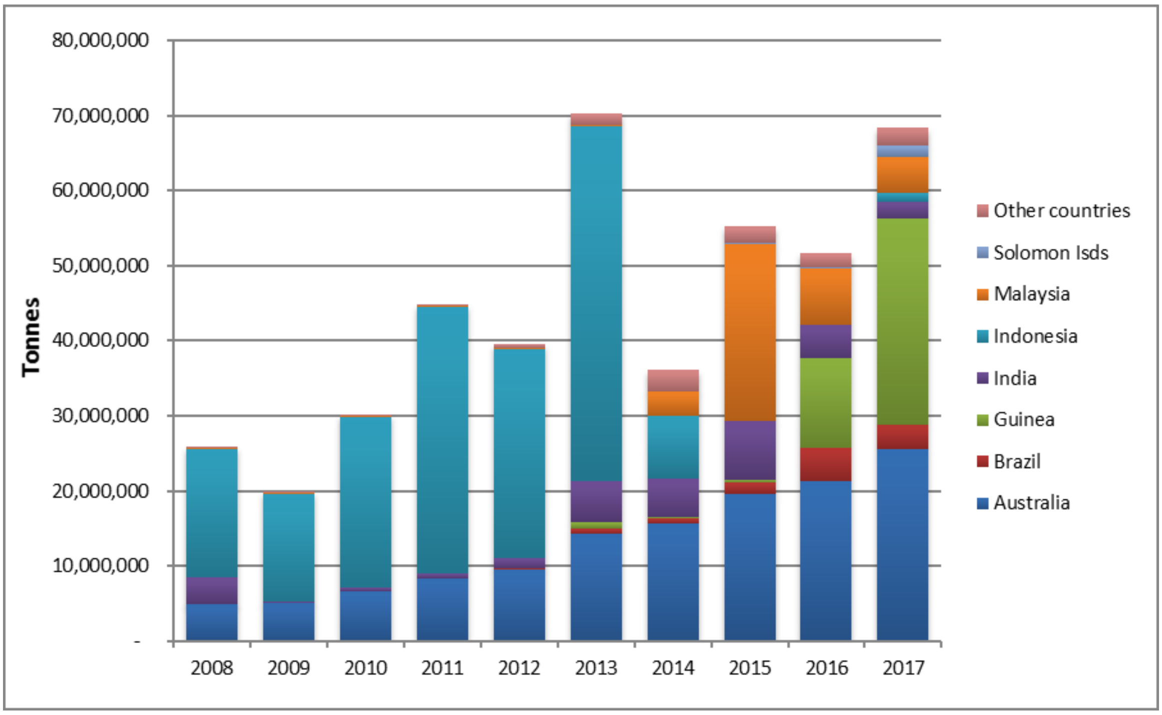

Figure 12: Origin of China's imports of bauxite 2009 to 2017 (data from UN Comtrade)

China's production of alumina and aluminium are reported by the National Bureau of Statistics of China (NBSC) as "aluminium oxide" and "output of electrolyzed aluminium" respectively, on a monthly basis through the data section of their website. These monthly figures are subsequently updated by an annual publication entitled "The Yearbook of Nonferrous Metals Industry of China" albeit with a two-year time lag and only in printed form. The updated figures also appear in the "China Statistical Yearbook" published by the NBSC on their website, again with a two-year time lag.

Unfortunately, the production of bauxite is not recorded in the same monthly statistics, nor in the "China Statistical Yearbook", but it does appear in the "The Yearbook of Nonferrous Metals Industry of China". Consequently, the most recent completed year has to be estimated initially and subsequently replaced when the actual figure is released. This estimation is done based on: the quantity of alumina produced, the amounts of imports and exports of bauxite, and expert opinion on how many tonnes of Chinese-sourced bauxite is required for each tonne of alumina produced.

The detail of the numbers of companies, plants and mines operating within China is difficult to obtain because the text of "The Yearbook of Nonferrous Metals Industry of China" is written in the Chinese language. Only on the statistical tables is there an English translation. This is indicative of a whole different aspect of complexity involved in compiling these data. The Aluminium Corporation of China Ltd (Chalco) is believed to be the largest bauxite, alumina and aluminium producing company in China but there are many others of varying sizes. Although Chalco does publish some financial information on its website there are no details of the numbers or locations of mines or plants that it operates. Chalco is part owned by the confusingly named Aluminum Corporation of China (Chinalco) but this parent company is state-owned and consequently publishes even less information, particularly on the english language version of its website.

4.2.3.2 Guinea

Guinea is one of the ten countries that mined bauxite in 2016 but without any alumina refining or aluminium smelting carried out within its borders. It has the largest known resources of any country in the world, according to the USGS, with an estimated 7.4 billion tonnes (approximately a quarter of global total) (Bray 2018). There are a number of bauxite mines in Guinea, currently operated by four companies:

- La Société Minière de Boké (SMB) [part owned by a Chinese aluminium company via subsidiaries];
- La Compagnie des Bauxites de Guinée (CBG) [jointly owned by Alcoa, Rio Tinto, Dadco and the Guinean Government];
- Compagnie Des Bauxites De Kindia (CBK) [wholly owned by Rusal]; and
- Alufer Mining Limited (which started in September 2018).

A number of other bauxite mines are also under construction or proposed, including one owned by the Guinea Alumina Corp (GAC) [a wholly owned subsidiary of Emirates Global Aluminium from the UAE] and another owned by Société des Bauxites de Guinée (SBG) [a subsidiary of Metal Corp Group, headquartered in Luxembourg]. Some of the projects that are under construction or are proposed include the construction of alumina refineries.

Bauxite mining in Guinea has expanded rapidly in recent years, largely due to SMB commencing production and exports in 2015, and this is expected to continue as other mines commence or ramp up production. Unfortunately there are also to serious concerns surrounding human rights, land ownership laws, environmental protection and the country's governance (Human Rights Watch 2018).

Data published by BGS is obtained from the statistics office in Guinea, which is believed to include all producers, and does not subsequently make any adjustments for moisture content. However, other compilers of production data, that attempt to obtain individual company figures, can run into difficulties because some of the companies report their production output as 'dry' while others record it as 'wet'. Because the figures are quoted in tonnes, the moisture content of the material can make a significant difference to its weight. According to international safety standards, bauxite should have a moisture content of less than 10% before shipping due to the risk of liquefaction in transit (which could cause a ship to capsize; IMO, 2017). CBG has reported in the past that its bauxite was dried from a typical moisture content of 12.5% to less than 7% prior to shipping. There is no information relating to moisture content of other bauxite mines in Guinea, nor indeed regarding this issue for other bauxite producing countries around the world.

4.2.3.3 Argentina

From the list of countries that only have the primary aluminium production without the earlier stages, Argentina provides a good example. Argentina has just one aluminium smelter located in Puerto Madryn, operated by Aluar which commenced production in 1974. It has a capacity of 460,000 tonnes per year through 784 electrolytic tanks and most of the plant's output passes through an integrated casthouse. It also employs more than 2,200 people and uses electricity from its own hydroelectric power plant.

Production data for this plant have been provided directly by the company for many years, via a simple exchange of e-mails. However, two separate series of figures are provided: "hot metal" and "pure ingots, slabs, bars and alloys". The latter, by this description, is believed to be the casthouse production but occasionally this series is reported simply as "production" which can lead to confusion. In the case of Argentina, the difference between the two series is relatively small (Figure 13) and it could be argued that it will not have a significant impact on the global total of aluminium production. However, a similar confusion for other countries also occurs, potentially with a larger effect on the total.

For 2016 and 2017, no response has yet been received from the company but in the meantime, figures can be obtained from the company's quarterly and annual reports. However, the description used for production in these reports is not the same as that provided previously by the company. The reports describe it in Spanish as "Volumen de producción (en electrólisis)", which translates to "Production volume (in electrolysis)". It is believed this is the same as the 'hot metal' production but the sum of four quarters does not match the annual figures for 2013, 2014 and 2015 for either of the two series (Figure 13). This is a representative example of the issues that can be experienced by data compiler, which leads to increased uncertainty attached to the figures.

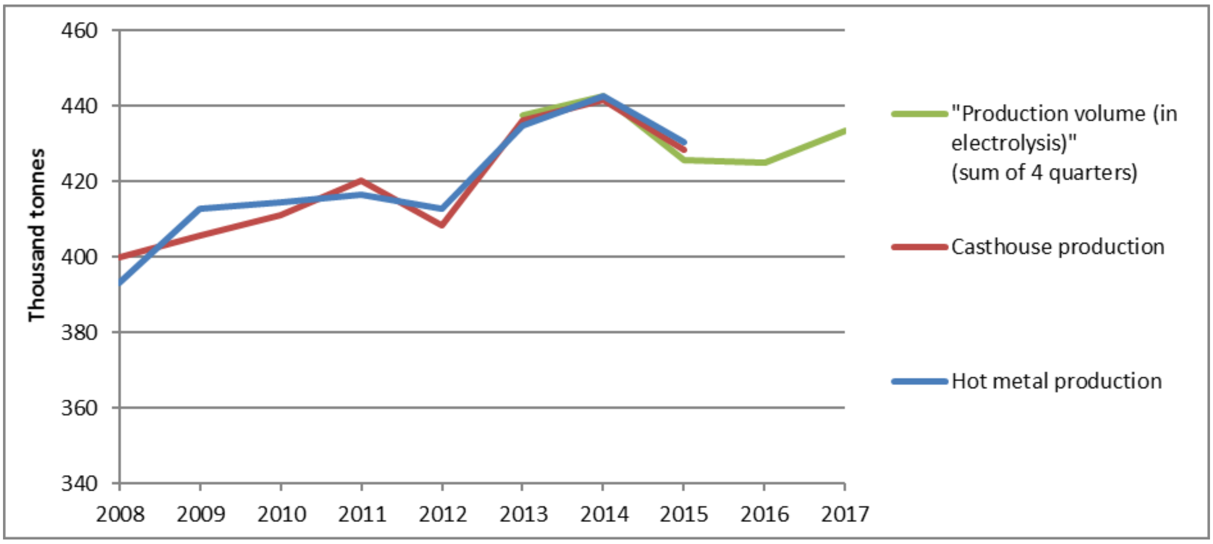

Figure 13: Aluminium production in Argentina, figures reported by Aluar (note: vertical axis in this diagram does not start at zero)

An additional layer of complexity is added when compiling data for Aluar using its quarterly and annual reports because the company operates according to a fiscal year ending in June. Hence the need to sum data from four quarters in order to obtain calendar year figures.

All of Argentina's primary aluminium production is fed by imported alumina, primarily from Brazil and Australia. Although some of the company's output is sold as 'hot metal' or is formed into finished aluminium shapes, the majority of its sales are in the form of ingots, slabs or bars.

4.2.3.4 India

India was the 5th largest bauxite mining country in the world in 2016 and it was also the 4th largest global producer of both alumina and aluminium. Although India operates to a fiscal year ending in March each year, it is generally quite difficult to convert all of its data into calendar years and consequently within BGS publications, Indian data are shown with a footnote that reads "years ending 31 March of the year following that stated". This means that for '2016' the Indian data is actually for the year ending 31 March 2017. However, despite this, India does publish extensive mineral production data on both a monthly and annual basis, albeit with a few weeks' time delay on the monthly releases and often as much as two years' time lag for the annual data.

According to the "Indian Minerals Yearbook", India had 157 bauxite mines in 2016/17, operated by 10 "principle producers", which are mining a total of more than 24.6 million tonnes of bauxite from eight of India's 36 states/territories (Chhattisgarh, Gujarat, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, Odisha and Tamil Nadu). Of the total bauxite mined, approximately 17.8 million tonnes (72%) was used for alumina and aluminium while the remaining 6.9 million tonnes (28%) was used for cement, abrasives, refractories and chemicals. The text of the Yearbook also describes how many of the country's bauxite mines are small and the entire workings are carried out "manually" or in a "semi-mechanised" way. Only a few mines, which are part of integrated alumina/aluminium businesses, are described as "mechanised" (Indian Bureau of Mines, 2018).

From the 10 principle bauxite mining companies, only two also operate alumina refineries and aluminium smelters: National Aluminium Co Ltd (1 of each) and Hindalco Industries Ltd (3 refineries and 4 smelters). In addition, Vedanta Aluminium Co Ltd operates 1 of each plant and Bharat Aluminium Co Ltd also operates a smelter. According to the Yearbook, India's five alumina refineries produced nearly 4.6 million tonnes of alumina in 2016/17 while its seven smelters produced nearly 2.9 million tonnes of primary aluminium (Indian Bureau of Mines, 2018). Whilst the Yearbook does include information describing the various links and material flows between its bauxite mines, alumina refineries and aluminium smelters it is not always possible to easily match the various names and producers. Some time would be required to cross-check these descriptions with company information to do this satisfactorily. There are also various developments described in the Yearbook with new plants planned or under construction.

In addition, India exports and imports both bauxite and alumina, with exports of bauxite amounting to 2.9 million tonnes in 2016 compared to imports of 1.5 million tonnes. In contrast exports of alumina were only slightly higher than imports at 1.4 million tonnes and 1.3 million tonnes respectively. The majority of India's exports of bauxite were shipped to China, while the majority of its imported bauxite came from Guinea, which raises the question of whether some of these flows were just transiting the country. The four largest export destinations for India's alumina were the United Arab Emirates, China, Egypt and Iran (together amounting to 87% of India's exports of alumina), while 77% of India's imports of alumina came from Australia.

4.2.4 Aluminium case study conclusions

Although a larger number of studies have been carried out on the 'major' metals (e.g. aluminium, copper, lead, zinc, etc.) rather than the 'minor' metals (e.g. cobalt), which means that the flows of materials are better understood, there remains uncertainty in the published figures that data users may not be aware of. The levels of uncertainty will also vary from country to country and year to year. This text has sought to present a few of the issues encountered regularly by data compilers as an illustration of the uncertainties involved. However, this is not a comprehensive list of the potential issues that can occur, nor does it describe all of the methods used to address them.

The material flows of the bauxite, alumina and aluminium system are complex, both within a single country between bauxite mines, alumina refineries and aluminium smelters and also internationally between countries. There are both metallurgical and non-metallurgical uses for bauxite and alumina and these distinctions are not generally made in the reporting of production data. The example of India suggests that this is an area which could benefit from further investigation into the data sources. However, it does seem to be clear that once the material enters the non-metallurgical route it generally does not return to the metallurgical processes and vice versa.

Although the ‘system diagram’ (Figure 11) represents ‘transformational processes’ and ‘market processes’ as single boxes, in reality each of these may cover a number of different physical processes. These are often contained within a single plant but in other cases they may be conducted at multiple plants in different locations. Consequently, the resolution achieved in this diagram is not sufficient to be exactly precise when identifying the specific point to which the available data relates. However, for many countries the available metadata for each production figure is not sufficient to identify this precise point either and some assumptions have to be made.

Collecting data for downstream processes, e.g. extruding, rolling or fabricating, could be even more complicated than the upstream processes of mining, refining and smelting. BGS has never attempted to collect data for these downstream processes and although many figures are known to be published it is unclear whether these would be comprehensive enough for global totals.

4.3 Mapping data to systems – summary conclusions

In order to move forward with the reporting of data in a system context, several changes need to be implemented that will be commodity specific, but also country specific. Based on the two case studies the following summary conclusions can be drawn:

- In order to enable providers to report data with a system context, it is essential that the system, which includes the different stages and processes within a material cycle is accompanied by an additional layer illustrating the different material forms across the transformation stages. Most of the metadata available on reported figures describe material forms rather than processes. Wrong assumptions and false mapping of data to systems could be avoided therefore if the system also included a layer of material forms.

- Ultimately systems, such as the one available for cobalt and aluminium will be required to cover the periodic table including construction minerals, industrial minerals, biotic commodities and so on. This is essential if the vision is to change the way data is reported and to move away from monitoring single datasets to monitoring systems, for the benefit of understanding the physical economy.

- It is essential that consistent and comprehensive metadata accompany all datasets. These should be requested during data reporting and become available together with the data.

5 Critical areas for further development in material flow analysis

5.1 International trade

In the context of MinFuture, trade is a dimension linking raw material supply and use. Although there is mining in Europe, the EU depends critically on the supply of raw materials from regions outside of Europe (e.g. UNEP, 2016). This holds particularly true for metals and for fossil energy carriers.

The trade dimension allows us to understand raw material dependencies, and the interlinkages between countries around the world. The EU, along with other developed countries, relies on the supply of raw materials from international markets. Understanding the global nature of raw materials value chains, requires a good understanding of how the EU material cycles are linked to other regions/countries by international trade.

5.1.1 Classification systems

Being able to analyse international trade relies on the availability and quality of the available trade data. Trade data is collected by almost every country for taxation purposes and are some of the most comprehensive long-term datasets that currently exists. Within the MinFuture project we have mainly looked at the United Nations Comtrade database and European database Comext hosted by Eurostat. Currently, 3 main trade classifications exist the **Harmonized Commodity Description and Coding System** (HS), **Standard**

International Trade Classification (SITC) and the **Combined Nomenclature** (CN). Although the systems were developed for the same purpose, tracking the import and export of goods, they differ in terms of time and disaggregation levels as shown in Table 5.

Table 5: Classification systems in trade statistics.

	SITC	HS	CN
Starting year	1962	1988	1987
Current version	Rev. 4	2017 (updated every 5 years)	2018 (updated annually)
Transition tables to production statistics[1]	Yes (SITC Rev. 3 → ISIC Rev. 3)	Yes (HS 2007 → CPA 2008)	Yes (CN 2018 → CPA 2.1; CN 2017 → PRODCOM 2017/CPA 2008)[1]
Number of reporting countries in 2015 (IMP/EXP)	SITC 1: 146/147 SITC4: 150/149	HS 12: 140/139	(not comparable)

As trade statistics are collected for taxation purposes and not for the tracking of materials through the economy, it can be a challenge for MFA practitioners to utilize trade data. A first hurdle is the units collected since it is the monetary flows that are tracked most consistently and not the physical flows. In addition, assumptions must be made on the material composition of products since it is only the products themselves that are tracked. The next challenge comes from the fact that the level of disaggregation needed to consistently track materials through the economy is not reflected in trade statistics as these data are not collected with a system perspective in mind. Several data points along the supply chain is lumped together not allowing for sufficient disaggregation such as mineral ores and concentrates, or products and scraps which for many of the minor metals are collected within the same codes.

Nevertheless, the overall data availability for trade is quite good compared to other areas. There is a clear need for further disaggregation of the classification systems. Further reading on this topic can be done in the working paper on trade developed by IFEU.

5.1.2 Suggestions for further development

Trade data are indispensable for monitoring global flows of materials. Trade statistics subdivide trade flows by materials and steps of processing (raw material/semi-processed/final good). There are different classification systems with different purposes and differentiations of traded products. UN Comtrade provides global trade data for 220 countries/areas covering several decades and different classifications. This is a good starting point for material flow analysis.

Looking forward and acknowledging the need for a deeper and complete monitoring of abiotic mineral trade it is advisable to choose one or two classification systems and further develop it/them in terms of required disaggregation by materials or material contents. We suggest working with the HS-classification at a global level as it is the most common and most differentiated classification system globally. For longer time series (starting earlier than 1988), however, the SITC classification is the only classification that can be used. For trade with EU partners, we further suggest using the CN classification from Comext as much as possible as the level of disaggregation is higher than in HS.

With respect to materials, we suggest working with the European list of critical materials. We suggest a further differentiation of the homogeneous product groups, so that each critical material can be monitored as:

- raw material (ore, concentrate, but also as by-product),
- as slag and waste
- as semi-processed material (bars, wires, etc.) and,
- as far as possible, as part in a final article.

We further suggest including a new unit in trade statistics: metal content. Currently, there are several additional units such as m^3 for timber or karat for diamonds. The additional unit metal content could be introduced, in a first step with regard to ores and concentrates and in following steps with regard to waste, scrap and slags. According to our knowledge, several reporters already provide this information to international trade statistics internally. This shows that an implementation is feasible.

The analysis has shown that mismatches in bilateral trade data are the normal case - and matching bilateral trade data is the exception. There are several reasons why bilateral trade data do not match. Nevertheless, the magnitude of the deviations is alarming.

In order to improve the quality of bilateral trade data, especially the physical values, the reasons for mismatches should systematically be addressed, e.g. by

- rising awareness for the political need of complete and good information on physical trade flows
- regular and systematic checking by statistical bodies, including e.g. support for less advanced statistical bodies in developing countries,

- regular and systematic comparison and checking of trade data by international bodies which are gathering information (UN Comtrade), and the
- development of standards for gap filling, error correction and balancing of bilateral trade data with respect to monetary and physical data.

As the scientific community has only a limited influence on the procedures for trade statistics, in the short-term common guidelines could be developed on how to cope with data gaps and publicly available lists of materials for a large number of (representative) products could be created.

5.2 Mineral resources and reserves

5.2.1 Global challenge

Exploration is a key stage in the supply chain of raw materials. Without exploration, there would be no mining and no raw materials to feed the supply chain. Exploration includes several processes and stages of feasibility studies prior to mine production. Currently there is no mass-balance consistent method for integrating exploration and the dynamic nature of geological knowledge into MFA models needed to monitor the physical economy. The reason, and main challenge addressed by the resources and reserves task force, is the lack of a conceptual framework and data available to convey information about the geological stock of mineral commodities.

The overarching question, 'what is the geological stock of any commodity' has been of primary interest to geologists, but sustainability practitioners, economists and even sociologists increasingly pose the same question. The shift in focus of our societies towards sustainable consumption and production, resource management, security of supply, the use of clean energy, resource traceability and the circular economy are among the reasons why this question has gathered momentum and is increasingly important in policy development, decision-making and research. The fact that a simple and concise answer cannot be provided is another reason why this subject remains open to debate. Discussions over resource depletion and scarcity have intensified over the years with mentions in media and scientific publications, but they are poorly supported by underpinning data or geological knowledge (see Resource and reserve estimates have traditionally been used to reduce risk in mining and to find and report new economically exploitable resources through exploration projects. The use of mineral resources and reserves data to assess the depletion of finite resources on earth is relatively new, and common reporting systems and standards are not designed for this. This has as a result the development of a variety of studies on resource scarcity and 'peak minerals' that are misinterpreting mineral resources and reserves data. The geological community however states that geological resource availability is not an issue.

Box 1 and Box 2).

Many of the drivers of change in the society request not just to understand the present situation within a single stage in a material's cycle, but to follow a holistic approach and to forecast the future demand for resources and their availability. Better forecasts therefore are needed to identifying future supply issues and the role of primary raw materials to satisfy future demand. These would then provide quantitative evidence to calculate the contribution of resources from primary and secondary sources for future supply and support informed decision-making. For the foreseeable future however, mining and quarrying will remain the primary source of mineral raw materials. Thus, a better understanding of the future supply of primary mineral raw materials is important.

Resource and reserve estimates have traditionally been used to reduce risk in mining and to find and report new economically exploitable resources through exploration projects. The use of mineral resources and reserves data to assess the depletion of finite resources on earth is relatively new, and common reporting systems and standards are not designed for this. This has as a result the development of a variety of studies on resource scarcity and 'peak minerals' that are misinterpreting mineral resources and reserves data. The geological community however states that geological resource availability is not an issue.

Box 1: Copper resources and resource depletion

According to Ragnarsdottir and Sverdrup (2015) scarcity issues with copper may become available by 2050. USGS estimated identified resources and undiscovered resources for two major types of copper deposits. They concluded that identified resources equate to approximately 100 times the present annual mined production and undiscovered resources to 150 times. Kesler and Wilkinson (2008) conclude that there are mineable copper resources in the earth's crust for 5500 years. Schodde (2017) looks at the problem from an economic side and suggests that sufficient copper supply on short and medium terms purely depends on the amount of money put into new exploration.

Box 2: Phosphate rock and resource depletion.

During recent years, several studies have raised warnings about phosphate rock depletion, ranging from 60 to 300 years (Cordell and White 2011) or phosphate peak scenarios within this century (Ragnarsdottir and Sverdrup (2015). A review of studies from the past 20 years revealed significant confusion and misinterpretations of the mineral resources and reserves data used. However, according to USGS, who presented the following statement in the 2017 Mineral Commodity Summaries "World resources of phosphate rock are more than 300 billion tons. There are no imminent shortages of phosphate rock" (Jasinski 2017).

The transformation of our societies is multi-layered. Aspirations such as the circular economy and the low carbon economy aim to ensure that growth and technological improvement continue, but with minimum negative impacts to the environment and humans. From the mineral resources perspective however, this is a major challenge. as ore grades for most metals are in decline, which means that deeper mines may be needed, marine minerals may be exploited and mine waste volumes will grow. At the same time new technology and in particular the shift to clean energy demands for more metals to be supplied. Other important issues, including urbanisation and preservation of the natural environment, as well as competing demand for land use suggest that opportunities for new mining projects are more 'constrained' that they used to be in the past. Enhancing our knowledge about known and undiscovered in-ground geological resources, and monitoring their change over time, is essential.

5.2.2 Data challenge

A key challenge of scenario forecasting is the lack of understanding of the purpose and limitations of reported resources and reserves data, as well as inconsistencies associated with using and combining different datasets. (T. Brown and Petavratzi 2015) address this by raising questions such as 'what are resources and what are reserves, and how do you compare different datasets, standards and modern versus historical data?'.

Another major issue is overall lack of data, either due to confidentiality, gaps in the reporting or due to non-existent data (T. Brown and Petavratzi 2015). The latter is related to the purposes behind the generation of mineral resources and reserves data, which is neither designed for land use planning nor useful for understanding potential issues with resource depletion. Instead, the main objective of resources estimates is for junior exploration companies to attract investment for their projects.

Resources and reserves estimates are influenced by multiple factors, including market prices, technology development and social acceptance for mining. Their valuation is periodically reviewed and updated on a case-by-case basis given new observations and measurements. Estimates therefore change dynamically over time and at best tell us something about the current potentially exploitable quantities and about the rate at which resources and reserves were increasing (or decreasing) historically, but nothing about the stocks in the ground or the share of stocks that may become available to future generations.

Methods for estimating **undiscovered resources** have been developed (Singer and Menzie 2010; Johnson et al. 2014) and some studies have been produced primarily by geological surveys and also addressed in a European Innovation Project.[2] However, these

remain only case specific, focusing for instance on specific deposit types or locations. For a pan-European dataset of undiscovered resources to be developed, additional investment and policy initiatives are required to provide the right motivation and conditions.

Concerning **historical data**, mostly available by geological surveys, there are significant data gaps and harmonization problems. The European project Minerals4EU provided the first attempt to collect European resources and reserves data that are available through the European Minerals Yearbook. Brown and Petavratzi (2015) concluded: "The most significant issue for resources and reserves data is the absence of a single system of reporting that is common across all European countries" and, that data gaps are significant. Only "14 countries [out of 33] indicated that data collation takes place on a statutory (i.e. compulsory) basis either annually or more frequently".

5.2.3 Terminology challenge

A common understanding and definition of the terms resources and reserves is required

Resources are a concentration of a mineral commodity that may become of potential economic interest (Figure 14). Reserves are part of the resource, which has been fully geologically evaluated and is commercially and legally mineable with current technology. Mineral resources convert to mineral reserves because of several 'modifying factors'. Both terms are dynamic, but resources are closer to reflecting part of the stocks in the ground. If a mining company goes bankrupt, their reserves will be downgraded to resources, since they cannot be realistically produced.

Using reserves estimates as a measure for global geological stocks is incorrect, since reserves are nothing more than an economic term used to describe the part of resources made ready for production. A mine may have a policy of having a reserve horizon of 12 years for example. This does not mean that the mine will close in 12 years, but that it is economically viable within such a horizon. The investments needed for turning resources into reserves are large, and it is economically wiser to spread such costs over time. Most mines have a resource base that is much larger than reserves, and some confidence that these resources in time can be developed to reserves.

[2] https://eitrawmaterials.eu/project/map/.

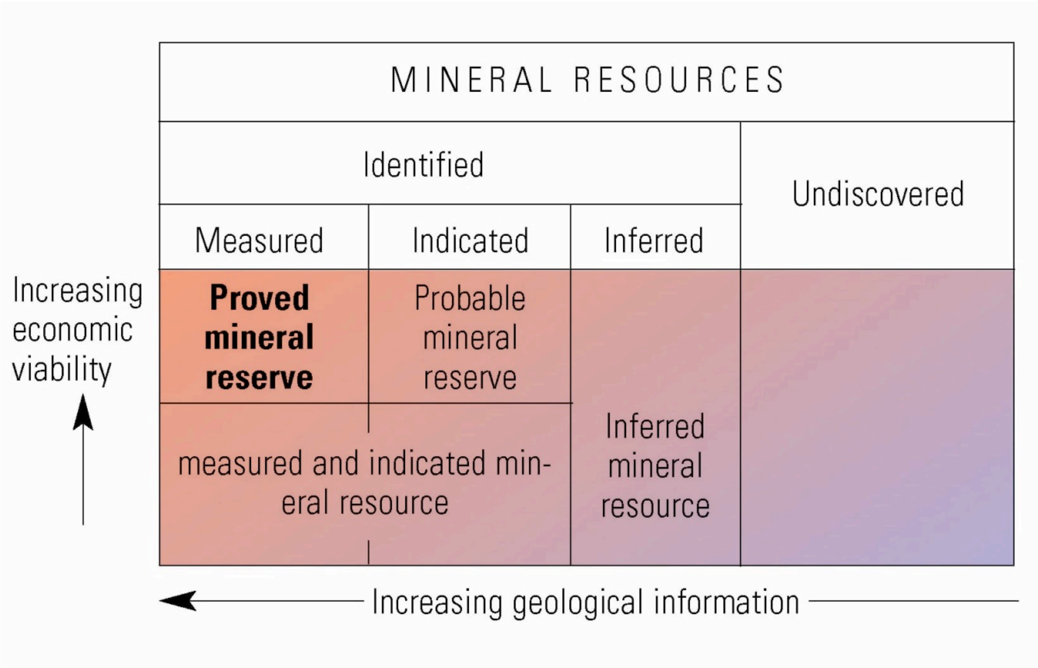

Figure 14: Classification of mineral resources and reserves

Resources are divided in several categories, reflecting the level of geological confidence on the figures. The level of confidence associated with a measured resource is higher than an indicated (Figure 14). Resources may also include crude estimates on exploration targets and exploration results, and as described above, statistical probabilities of undiscovered resources. The latter can further be divided in conventional resources (those geological types of mineral resources that are produced) and unconventional (new types of mineral resources never produced before). In the future, we will most likely have to develop a range of unconventional resources; due to increasing needs for traditional metals (e.g. sea-floor resources) and those in the periodic table that have not used in the past (e.g. technology metals).

Thus, one may consider various categories of resources as a chain of knowledge, moving from "none", or "crustal abundance" of a particular mineral raw material, to measured resources, and finally reserves in operating mines (Figure 15). A consensus, however, on terminology as well as a framework that explains the different terms of the knowledge chain and identifies the best one to characterise the geological stock for use in MFA, LCA and other sustainability studies is currently missing.

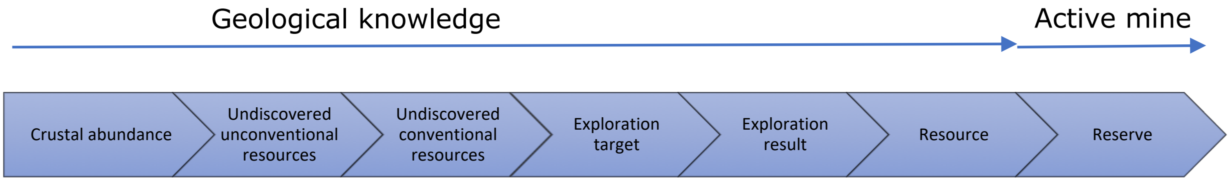

Figure 15: Knowledge chain" from crustal abundance to reserves

5.2.4 The challenge of data reporting

During the last 30 years, reporting standards for resources and reserves have evolved, from a range of national standards to international ones. The JORC (1989), PERC (2001), and other CRIRSCO aligned (2002) standards have been born by the need for standardized reporting of mineral exploration projects to the stock market. They are strongly linked to metal resources, since there are few industrial minerals (with some exceptions), aggregate and natural stone producers needing such kind of reporting procedures. A family-owned metallic mine does neither need to do such reporting, unless there are national legislations requiring it.

The majority of mineral resources data in Europe are historic or follow the rules of national systems of reporting. They are not therefore reported according to modern standards, with the exception of most operating metallic ore mines and metallic ore exploration companies. In addition, it is not straightforward to transpose such data into modern international standards. In the case of systems used for reporting to the stock market (CRIRSCO template), a so-called "competent person" on a specific commodity will be needed in each case. Resource categories such as the undiscovered resources are not within the remit of existing systems of reporting and therefore such data are not available.

The UNFC standard (2009) unlike other standards, is a three-dimensional system that consist of an axis defining the geological knowledge (G-axis) and two other axes that relate to project advancement (F-axis) and socio-economic aspects (E-axis). UNFC does not combine resources and reserves along one axis – since reserves are considered as resources that are advanced along the two other axes. The geological knowledge axis (G) in UNFC reflects better the stocks in the ground and can accommodate a whole range of resources from undiscovered to reserves. Other aspects such as mine waste and tailings can be represented too. Bridging documents between UNFC and CRIRSCO exist that allow mineral resources and reserves data to be transposed between the two systems.

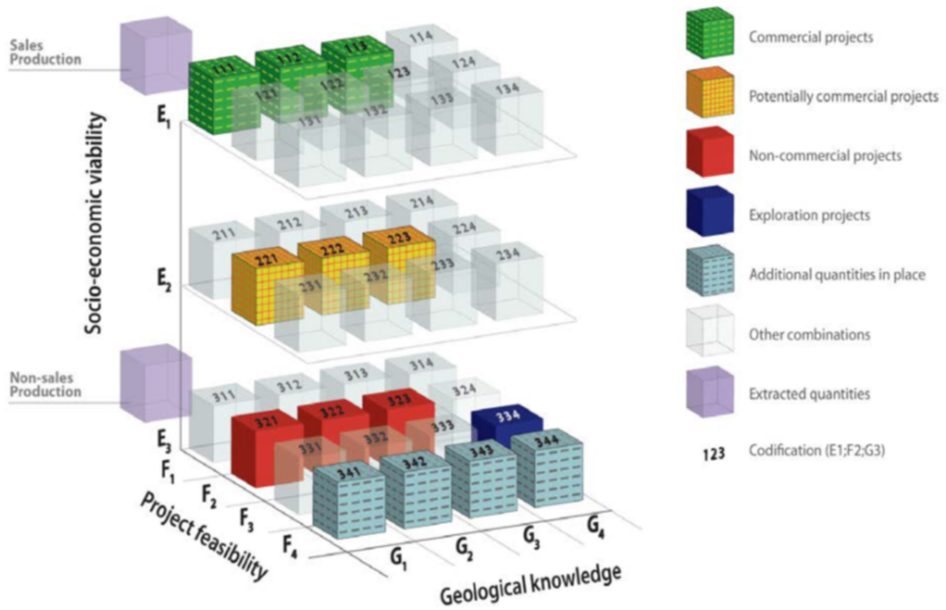

Figure 16: The three axes of the UNFC reporting system (UN 2014)

5.2.5 Ways forward

Given that there is consensus for the need of harmonised mineral resources and reserves data, the way forward should address terminology, reporting standards, reporting procedures and data gaps. Many of the recommendations below have also been raised in the past (T. Brown and Petavratzi 2015; Parker et al. 2015).

Agree on the common use of terminology for mineral resources and reserves. This will enable the consistent use of terms under different circumstances, which could eliminate the misinterpretation of data or assumptions made on resource depletions due to data gaps (e.g. on undiscovered resources).

Agree on systems of reporting for mineral resources and reserves. The industry commonly uses commercial standards for reporting mineral resources and reserves. There should be no needs to change that. For the purposes of reporting data however at national or international level, and in order to allow comparisons to be made or data to be combined together, standardisation and harmonisation procedures should be introduced. The use of a reporting framework such as UNFC could provide these conditions, without this implying that its use should be endorsed to everyone, but that data provided can easily transpose to it.

Agree on procedures to tackle issues with data reporting and classification. No matter the standard or reporting procedures chosen to produce mineral resources and reserves data, there are several challenges to overcome. These include uncertainties around the classification and terminology used for different commodities (e.g. for non-metallic minerals), the differences in approaches followed to deal with historic data, unconventional resources and ore grade, interdependencies between commodities (for example, primary ore and by-products) and others.

Closing the data gap. This will require long-term effort, investment and cross collaboration of scientists, industry and governments beyond the national geographical boundaries, if envisioning the development of a pan-European or international, harmonised dataset. The data gaps are many and with different origins, for example, geographic due to missing countries in existing data, statistical due to non-reporting or geological, owed to fragmented and insufficient knowledge about specific resources. As pointed out by Brown and Petavratzi (2015) "The benefits of central collation of data should be demonstrated and publicised to all countries" and "There can be no compulsion for a sovereign state to change its national laws, therefore other ideas for encouraging central collation should be explored".

Closing the geological data gap is the biggest challenge of all the aforementioned. Geological data depend on exploration activities undertaken by private enterprises and pre-exploration mapping carried out by geological surveys and research institutes. With few exceptions, government funding (across Europe) for mineral resources characterisation and mapping is very low, which means that data gaps remain, and geological databases are not enhanced with more and better data. It is important to realize that even if we manage to harmonise reporting and figures, the data will not be better than they already are, unless we invest in collecting new data. An important first step for approaching the above points could be the establishment of an expert group at EU or international level that will be working towards this direction and will attempt to address the challenges mentioned above.

5.3 Anthropogenic stocks

The anthropogenic material stocks consist of materials and products staying in the techno-sphere over a certain period of time. The anthropogenic material stocks could be categorised into mobile stock (e.g. consumer durables, machinery, and electronic equipment) and built environment stock (buildings and infrastructure) (Brattebø et al. 2009).The latter refers to "the aggregated stocks and structures of built environment in a city". The built environment stocks play multiple roles in the socioeconomic metabolism of our society (Stefan Pauliuk and Müller 2014)

- The built environment stocks constitute the majority of anthropogenic material stocks in terms of the mass, thereby providing an extensive reservoir of secondary raw materials. Measures such as urban mining, smart construction waste management and decarbonisation strategies can be supported by understanding better issues around the quantity, quality, temporal changes and location of built environment stocks.
- The built environment stocks are important contributors in material and energy cycles, but also of environmental impacts associated with these cycles. Understanding the historical patterns of built environment stocks in industrialised countries could provide essential knowledge for benchmarking similar stock development in developing countries.
- The built environment stocks shape the physical fabric of a city and to a large extent determine the temporal dynamics of socioeconomic metabolism of a city. The built environment stocks can stay in use for decades or even centuries and thus might cause technological lock-in hindering a city to switch to be more material- and energy-efficient.
- The built environment stocks are the physical representation of services that our society rely on. They provide a complementary perspective of human wealth in addition to flow-based affluence measures.

5.3.1 Status and challenges

System and data

First and foremost, the definition of built environment stock is not adequately explicit. For example, "hibernating stock" is not always distinguished from "5.3 Anthropogenic stock", because the terminology used is not consistent. (Kapur and Graedel 2006) define the 5.3 Anthropogenic stock as "social stock" or "employed stock", while Daigo's definition of "5.3 Anthropogenic stock" refers to the combination of obsolete stock and 5.3 Anthropogenic stock (Daigo et al. 2015). The inconsistencies in the built environment stock definition hinders comparisons between studies.

The categorisation of built environment stock also appears to vary significantly. For example, building typology in different countries is based on national classification and specification systems, which makes it difficult to compare material use in buildings across countries in a transparent way.

The state-of-the-art of the characterisation of built environment stocks is mostly still staying at a national level, although there were some efforts at the region and city levels. Note worthily, there is a clear tendency to characterise the built environment stocks at a more spatially refined level (e.g., neighbourhood scale or building level), in order to better understand the location of built environment stocks.

Indicators

The object and unit of the measurement of built environment stock are not consistently used in different studies. The variety of materials used differs widely from one specific building material to a comprehensive list of building materials. Metals and bulk construction materials are the two most studied material groups. Studies on built environment stocks typically use mass-related indicators (e.g., mass/capita or mass/m^2) to present their characterisation. Occasionally, built environment stocks are quantified in terms of physical dimensions such as volume of buildings, floor area of buildings, and length of roads.

Models & scenarios

Models developed for the characterisation of built environment stocks are generally grouped into the top-down or bottom-up approach. In some cases, a hybrid approach that uses bottom-up results to calibrate top-down models or a GIS-assisted approach is used to help improve the characterisation or to obtain a refined resolution.

The top-down approach usually uses the mass balance principle and lifetime distribution, which is particularly efficient in obtaining an overview of the stock dynamics over a long period of time. The most significant shortcoming of the top-down approach is its lack of spatial and sectoral resolutions because shipment or apparent consumption data are normally available on the global and national level.

The bottom-up approach uses information directly derived from stock inventory data and thereby could theoretically generate more accurate estimates than the top-down approach. In addition, the bottom-up approach could improve the understanding of quality, building compositions, and location of built environment stocks. Due to extensive data needs, the bottom-up approach is applied in a limited amount of areas currently.

Several auxiliary approaches were recently developed to overcome the shortcomings of traditional top-down or bottom-up approaches. For example, the nighttime lights (NTL) data could be used to extrapolate built environment stocks of countries or regions where statistical data are lacking in a low cost, high spatial resolution and high efficiency manner (Rauch 2009; Takahashi et al. 2010; Liang et al. 2017; Yu et al. 2018). When additional bottom-up data are available, estimates (especially uncertainties) in the top-down approach could be improved by bottom-up data. Another newly developed alternative approach is using monetary data in Input-output tables to estimate physical stocks, which demonstrates great potentials to harness the rich monetary data in economic statistics (Wei-Qiang Chen and Graedel 2015; W. Chen, Shi, and Qian 2010; Jiang et al. 2017; S Pauliuk, Wood, and Hertwich 2015).

5.3.2 Ways forward

System, data, and indicators

Data availability and transparency are the crucial factors hindering a refined understanding of built environment stocks. To improve the data availability and transparency, architects and civil engineers should be more involved in dialogues of system definitions and material intensities. Collaborations with architects and civil engineers internationally could also help improve cross-contextual comparability and transferability of material-related information, because they fundamentally rely on a consistent system definition. In addition, the fruitful outcomes from studies focusing on energy efficiency of buildings could be harnessed to derive material-related information. Urban planners (e.g., municipal authorities) could provide valuable information or centralised data sources of built environment stocks, such as construction, renovation and demolition information, spatial data, historical data.

Collaborations with local authorities should be strengthened via multilateral dialogues, which also include architects, civil engineers, and waste managers.

Models & scenarios

To support the sustainable transformation of built environment at the urban level, a spatially refined characterisation of built environment stocks is urgently needed. In light of the limitations of the current characterisation approaches, several critical recommendations on approaches are proposed here:

- Building archetypes (or reference buildings) should be developed to represent certain types of buildings, in order to efficiently derive average material intensity coefficients for different types of buildings.
- Auxiliary information (e.g., building typology, lifetime, location, geometry, and general material use information) from GIS-based data sources should be integrated into the bottom-up approaches. Data sharing and harmonization should also be developed, as data used to quantify built environment stocks are usually from multiple sources and reported in inconsistent formats.

5.4 Critical Raw Materials

Even the issue on Critical Raw Materials was not a separate task force in MinFuture, during the project appeared several challenging issues which are related to materials and especially metals considered critical by some countries or communities.

5.4.1 CRM concept

Definitions of which raw materials are considered 'critical' vary across organisations and across time as well as across different criteria, scope and priorities employed in criticality methodologies. In the latter years and in the face of indications of growing protectionism in some important mineral exporting countries (e.g., China, Indonesia) there has been a growing interest in the issue of 'critical raw materials' (CRMs), i.e. materials of high economic importance for the socio-industrial metabolism but whose global supply may be at risk due to protectionist (free trade-distorting) measures, with little or no substitutes available. Methodologies and studies have been developed to identify CRMs in the USA (35 minerals), India and the EU (27 minerals). Even though criteria and results differ, a common feature is the identification of several specialty or high-tech metals among the 'critical' ones such as gallium, germanium or niobium (Annex B: Official CRMs according to classifications by different governments). Another commonality concerns the fact that raw materials criticality seems to be more relevant from an economic and a geopolitical perspective, than from a physical constraint perspective (Barteková and Kemp 2016).

In comparison to bulk metals often not considered critical (such as iron, copper or nickel), CRMs are produced and traded under special conditions. An important specificity of CRMs lies in that **many are not made available as crude raw materials, but in refined – often alloyed – products**, with specifications aimed for certain industry products. For instance, in the case of beryllium, the EU entirely depends on imports of processed and semi-finished products, mainly under the form of beryllium master alloys and alloys and beryllium metal. The European industry uses these processed materials to manufacture finished products. However, others are provided in the form of (imported or domestically produced) ores and concentrates (e.g. tungsten) (Murguía and Tiess 2017).

Another particular feature of **CRMs is that** while some are extracted as the primary extraction target of a mine or quarry operation (bauxite, borates, limestone, chromium, coking coal, fluorspar, magnesite, tungsten, phosphate rock, tin, potash, silicon metal), others (cobalt, gallium, germanium, indium, molybdenum, rare earth elements) are extracted as by-products[3] of minor importance in economic terms, **i.e. as a companion metal to another carrier (or host) element (or metal)**. The latter occurs because CRMs are geologically closely connected to certain major metal deposits, and their extraction depends heavily on the host metal. For instance, gallium occurs in very small concentrations in ores of other metals and most gallium production results from processing bauxite and zinc ores. Other typical examples are germanium and indium which are typically associated with lead-zinc ores or cobalt and PGMs which are found together with nickel (Murguía and Tiess 2017).

The market dynamics and economics of production of by-products are often quite different to primary products, since their production is largely driven by demand for the primary metal. Their production as minor components of much larger principal metals means that they may have only a negligible impact on the profits of diversified miners. Consequently, many producers of the principal metals may consider them 'non-core'(Chapman et al. 2013) to their business practice. For these reasons price volatility is often much greater for by-products than for base metals and their physical accounting may not be as accurate and detailed as the target metals.

5.4.2 Status and challenges

Despite their 'specialty', per-country statistics cover well the annual mine production of most CRMs. Given its comprehensive scope, USGS´s Mineral Commodity Summaries covers *per-country* mine production and reserves data for all U.S.-defined CRMs (except for uranium) and for almost all 27 EU-defined CRMs (except for production of natural rubber, no production data on hafnium, no reserves data for gallium, germanium, indium, magnesium or scandium). The BGS is actively involved in research focused on identifying CRMs, assessing risks to supply disruption and improving understanding of the Earth processes that produce deposits of the critical metals. The BGS World Mineral Production book provides production statistics complimentary to the Mineral Commodity Summaries, but lacks to provide data on some EU-defined CRMs such as coking coal, hafnium, helium, natural rubber and scandium. Yet, when figures are compared between USGS and BGS, there exist differences between world annual production numbers which varies between smaller to larger ones, rendering difficult to know which source is the correct one. At the same time, USGS and BGS information does not cover annual recycling production of CRMs.

In relation to trade data, we need for first acknowledge that the HS system is often revised (amended) by the WCO´s Customs Co-operation Council in light of new needs imposed by the changes in technology and patterns of international trade. For instance, in its last revision in 2017, environmental and social issues of global concern (broached by the FAO) featured as the major HS 2017 amendments, e.g. in fisheries to improve monitoring of endangered species. Examples from such last modification of relevance to MFA studies are:

- **Technological progress**: modification of the structured nomenclature of headings 87.02, 87.03 and 87.11 to reflect the technological changes in the automotive industry (hybrid, plug-in hybrid and all-electric vehicles).

[3] Some CRMs like PGMs are often called co-products (and not by-products) as they are co-elements of carrier metals who have their own production infrastructure. Yet, to simplify matters, we call all minor metals produced with carrier metals by-products as the only CRM who qualifies as co-product are PGMs (other materials often termed co-products are gold, silver, molybdenum, lead and zinc, see wheel of metal linkages in **Error! Reference source not found.**).

- **Technological progress**: Amendment of the text and the structured nomenclature of heading 85.39 for light-emitting diode (LED) lamps

Despite such improvements, the level of detail regarding trade statistics is a major limitation for trade flow analysis of CRMs. Under UN Comtrade´s HS, many CRMs such as niobium, indium, gallium, hafnium, niobium or tantalum are only reported in association with other substances, i.e. grouped, which enables a per-element analysis of trade flows. For instance, niobium, tantalum and vanadium are all reported together in Chapter 26 under the code '2615' (Niobium, tantalum, vanadium or zirconium ores and concentrates, same as beryllium, chromium, germanium, vanadium, gallium, hafnium, indium, niobium (columbium), rhenium and thallium; all reported together under code '8112'. Such article asks the reporting of all those metals, including waste and scrap all together.

As argued by (Glöser-Chahoud et al. 2016), the same is true for specific substances from element groups such as specific Rare Earth Elements (REEs) or Platinum Group Metals (PGMs) for which only platinum and palladium are reported separately.

Eurostat statistics do not generally report on the use of individual critical raw materials (CRMs) as identified for the European Union[4]. However, some of the Eurostat data could be particularly useful for studying the use of CRMs in parts of the European supply chain. Unfortunately, the material classification does not reach the level of detail required to identify extraction & trade of all minerals respectively CRMs individually. Most metallic minerals are listed under aggregate indicators like 'other non-ferrous metals' or 'precious metals', which again mixes the non-critical materials like silver, in one category with critical materials like PGMs. Thus, in its current state, it becomes impossible to study the flows of non-energetic minerals individually.

Relevant indicator sets like the resource efficiency scoreboard[5], but also the material flow accounts[6], present data on aggregated material use. This is exemplified by the lead-indicator on resource productivity, which is expressed in Euro of GDP per kg of domestic material consumption (DMC), which sums all consumed materials, critical or not. Such aggregated data on the use of materials limits the value for CRM research.

5.4.3 Ways forward

For the mineral extraction, the most relevant data are those provided by USGS and BGS. The highly detailed production & trade databases like PRODCOM or the combined set of trade & production statistics in the EUROPROMS database[7] could be used as a basis for analysis of the European (C)RM use. Potentially, such product-oriented databases could be combined with CRM use & content like developed in the PROSUM project for example[8].

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[4] European Commission. (2014).

[5] Eurostat. (2017). Europroms. Retrieved from http://ec.europa.eu/eurostat/web/prodcom/overview/europroms

[6] Eurostat. (2016b). Material flow accounts - flows in raw material equivalents. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Material_flow_accounts_-_flows_in_raw_material_equivalents#Material_flow_indicators_in_RME_compared_to_EW-MFA_indicators

[7] Eurostat. (2017). Europroms. Retrieved from http://ec.europa.eu/eurostat/web/prodcom/overview/europroms

[8] Huisman, J., et al. (2016).

A different part of the supply chain is addressed by the Eurostat Environmental Data Centre on Waste, which provides an important set of tables related to the generation, management and recycling of wastes[9]. Of particular interest are the tables on key waste streams (referenced under env_wasst), which cover a selection of relevant CMR contained in product groups such as batteries, end-of-life vehicles and waste electrical and electronic equipment (WEEE). For each of these product groups the database contains details on the annual sales, the weight of the generated wastes as well as the recycling, thus providing a rather complete view on the three product categories responsible for a large share of demand & use of CRMs in Europe.

Finally, there is the Raw Materials Information System (RMIS) hosted at the JRC[10]. The RMIS currently combines data from two main sources, being the background report to the 2014 CRM list and a more recent report on Raw Material System Analysis[11], but the platform will also host the data produced in the update of the EU CRM list, for which the methodology was recently published[12]. Linking the data available in the RMIS platform to complement the Eurostat tables mentioned above, could be a first step towards a more comprehensive knowledge base at the level of detail required to assess specific CRMs.

At the global scale, however, the availability, quality, reliability and comparability of data on many of the CRMs still represents a big gap. The potential improvement will depend on, among others, how the level of aggregation in the globally used products classifications will be further developed and to what extent there will be a progress in the system understanding of physical economy flows.

[9] Eurostat. (2017). Main objectives of the Environmental Data Centre on Waste. Retrieved from http://ec.europa.eu/eurostat/web/waste/overview

[10] http://rmis.jrc.ec.europa.eu/

[11] BIO by Deloitte, 2015.

[12] European Commission, 2017c.

6 Policy context of monitoring the physical economy

This chapter summarizes the understanding of monitoring the physical economy from the perspective of policy and legal frameworks at global and EU level. What is the background of data collection, who has the institutional mandate to provide any amendments and what are the gaps, challenges and possibilities to improvements in this respect.

There is a lot to be explored and investigated, especially with regards to the roles of national statistic offices, but also Eurostat, the World customs organisation (WCO) and UN. The work we do can help refine further our information flow models and add another dimension to it, as well as provide useful recommendations.

6.1 Global context

6.1.1 Global players in commodity statistics

The main current global players in mineral commodity statistics of relevance for global MFA studies are for production data the IEA (only energy minerals), the USGS and the BGS, and for trade data the UN Comtrade and the World Custom Organization (WCO). Of European importance are PRODCOM and COMEXT both of which are analysed in the next section (6.2 EU context). Each of these organisations was created with a mandate to respond to challenges faced by their parent institutions within a certain context and historical time.

The **BGS,** is the UK´s principal supplier of national capability in geoscience. From an international MFA perspective, the BGS manages the **World Mineral Statistics dataset** which began collecting data in 1913 and covers the majority of economically important mineral commodities (over 70 commodities). The information contained in the dataset, and associated publications, is compiled from a wide range of sources: home and overseas government departments, national statistical offices, specialist commodity authorities, company reports, and a network of contacts throughout the world. It contains **mineral production** data by commodity and country and contains **import and export** data for a large number of the commodities for the majority of the 20th century. Data from 1970 onwards can be downloaded as an excel sheet.

The **USGS Energy and Minerals Mission Area** conducts research and assessments that focus on the location, quantity, and quality of mineral and energy resources, including the economic and environmental effects of resource extraction and use. The core mission of the minerals information activity within the USGS is to collect, analyse, and disseminate information on the domestic and international supply of and demand for minerals and materials essential to the U.S. economy (Sibley 2009).

The USGS annually prepares and publishes two landmark publications widely employed and internationally acknowledged as main sources for international analysis:

- **Minerals Yearbook**: reviews the mineral and material industries of the US and foreign countries, contains statistical data on materials and minerals, and includes information on economic and technical trends. It includes chapters on approximately 90 commodities and over 175 countries. For those countries, each report includes sections on government policies and programs, environmental issues, trade and production data, industry structure and ownership, commodity sector developments, infrastructure, and a summary outlook.

- **Mineral Commodities Summary**: covers non-energy mineral industry data. At US level data sheets contain information on the domestic industry structure, government programs, tariffs, recycling and 5-year salient statistics for over 90 individual minerals and materials. At international level (global context to frame US data) data sheets for each mineral provide a global overview including world mine production and reserves of the largest-producing countries (per-country data), world resources and substitutes available (general overview).

In 1947 was the birth year of the nowadays-called **World Customs Organisation (WCO)** when 13 Governments represented in the Committee for European Economic Co-operation set up a Study Group to examine the possibility of establishing one or more Customs Unions between the various European countries. The Study Group decided to establish two Committees: An Economic Committee which later evolved into the Organisation for Economic Co-operation and Development (OECD), and a Customs Committee which later became the Customs Co-operation Council (CCC). In 1994, the CCC adopted the working name WCO.

The WCO´s work has been instrumental in many areas covering the development of international conventions, instruments, and tools on topics such as commodity classification, valuation, rules of origin, collection of customs revenue, supply chain security, international trade facilitation, customs enforcement activities, among others. It is of high importance for international MFA studies as the **WCO is in charge of maintaining the international Harmonized Commodity Description and Coding System (HS system).**

Greater trade liberalisation in the second half of the 20th century shaped the development of indicators related to production and trade (tariffs, non-tariff mechanisms). The leading international organisation, the United Nations, created in the early 1960s and under mandate of the United Nations Statistics Division (UNSD), the **United Nations International Trade Statistics Database (UN Comtrade).** Such database stands as one of the most comprehensive (contains over 4 billion records) and most frequently used trade statistics database available. It provides annual international trade statistics in monetary and physical (volumetric) units by commodity dating as far back as 1962 (annual trade) and monthly data since 2010.

Over 200 reporter countries/areas provide the UNSD with their annual international trade statistics data detailed by commodities/service categories and partner countries. These data are subsequently transformed into the UNSD standard format with consistent coding and valuation using the processing system. All commodity values are converted from national currency into US dollars using exchange rates supplied by the reporter countries or derived from monthly market rates and volume of trade. Quantities, when provided with the reporter country data and when possible, are converted into metric units.

UN Comtrade utilizes three distinct trade classification systems: the Harmonized Commodity Description and Coding System (HS), the Standard International Trade Classification (SITC), and Broad Economic Categories (BEC). Commodities are classified according to SITC (Rev.1 from 1962, Rev.2 from 1976, Rev.3 from 1988 and Rev. 4 from 2006), the Harmonized System (HS) (from 1988 with revisions in 1996, 2002, 2007, 2012 and 2017) and Broad Economic Categories (BEC). Of those, the HS system is the most commonly used by governments for international trade data reporting and trade policymaking.

There are some other global players who have a role in dealing with statistical data about mineral resources. We should not forget the ones from the area of energy resources. However, as energy minerals were not in the main focus of MinFuture, they are described in the Annex C.

6.1.2 Systems understanding, data collection and limitations

When collecting *per-country* data either on commodity production or trade for their international datasets, the global players rely on their partner countries´ statistical offices and other partner data suppliers such as companies. Such partners collect data based on how they have historically understood and currently understand their national economic system (socio-industrial metabolism), i.e. which inputs and outputs are worth recording to monitor the status and evolution of their national economy (or of their companies, governments). In consequence, material flows worth measuring, and monitoring are in general primarily conditioned by the economic importance of such flows.

Production data (mineral extraction, waste from extraction, waste generation)

As consequence, regarding mineral commodity production data, both USGS and BGS collect per-country data on used extraction (ore extracted or net metal content, depending on the mineral) and also on mineral reserves (only USGS). The availability of data on mine production and reserves reflects the prevailing system understanding in the companies and associations of the sector which are the data creators, i.e. are the ones monitoring and measuring material flows at mine sites.

Yet, under such systems understanding (hidden) **flows of unused materials (extraction and processing waste[13]) are generally not recorded.** Likewise, and following a linear productive thinking (design for discarding and not for recycling), flows of recycled/re-used minerals are also not collected.

With regards to **waste statistics** (not only mining waste but other waste streams such as municipal, industrial, hazardous and non-hazardous waste), MFA experts argue that their definition and coverage across countries varies considerably which indicates that comparison of waste indicators needs careful interpretation. Similar problems exist for recycling flows, only accounted for in some countries (Moriguchi and Hashimoto 2016).

International trade

At the international level, the Harmonized System (HS) for classifying goods is a six-digit code system. The HS is used by more than 200 countries and economies as a basis for their Customs tariffs and for the collection of international trade statistic. Up to the HS-6 digit level, all countries classify products in the same way (a few exceptions exist where some countries apply old versions of the HS).

The HS system employed by UN Comtrade, despite improvements, reflects its historical creation process. The Harmonized System was first implemented in 1988 and is maintained and updated by the World Customs Organization (WCO). The system was originally designed to organize tariff collection and traditional products like textile and clothing which are thus over-represented in terms of number of subheadings compared to newer products in machinery, vehicles and instruments (Arun, 2016) .

As shown in the graph below the UN Comtrade data is requested to official partners (countries), it is pre-processed (transformed from national data to the input format required by the internal processing system, among other tasks) and then commodities are normalised/harmonised according to standard codes.

[13] Extraction waste refers to rock/soil excavated and moved for construction, gangue, overburden, interburden. Processing waste refers to tailings.

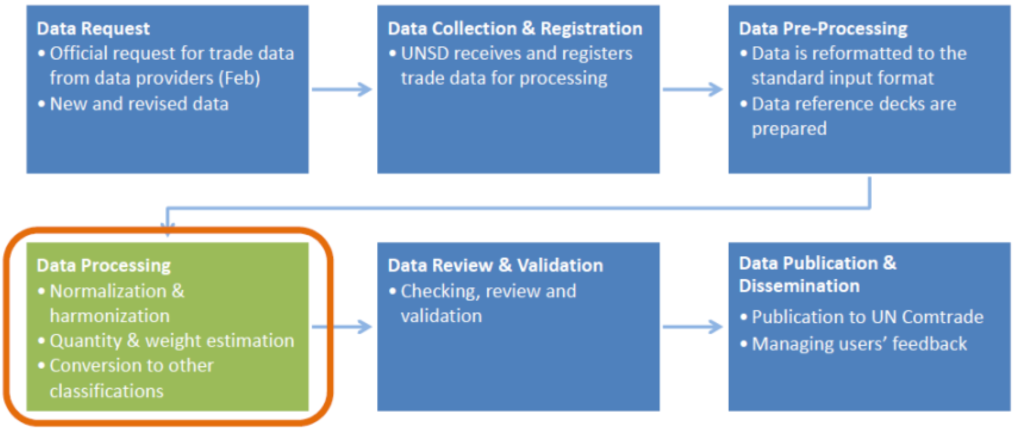

Figure 17: UN Comtrade. Data request, processing & publication procedure (UNSD, 2017)

UN Comtrade provides large amounts of data that need to be processed algorithms or routines suitable to the lead research question. One useful approach is **Chatham House´s Resource Trade Database (CHTRD)** which reorganizes data around natural resources. As the International Merchandise Trade Statistics and HS systems contain all types of traded goods - including manufactured goods - analysing natural resource trade flows in UN Comtrade typically requires amalgamating a variety of HS codes. The difficulty of this varies: products that have a long history of being traded extensively are captured in greater detail than products that are traded less frequently.

For example, there is a single HS code associated with rare earth elements, but several hundred codes assigned to steel and steel products. The CHRTD overcomes this problem by selecting over 1,350 HS codes that are identifiable as raw materials or relatively undifferentiated intermediate products and grouping them by resource type. For example, copper ores and concentrates, intermediate copper products such as mattes, bars or wires and copper scrap are classified into a single 'copper' category, enabling global copper trade to be tracked at different stages of the value chain. (Chatham House, 2018).

A closer examination of HS Chapters 25-27 and 72-83 shows that recycling is expected to be collected and informed by partners as most metals have a code for "waste and scrap".

6.1.3 New global initiatives for monitoring of the physical economy

Despite the work of existing global, regional and national players in collecting commodity statistics, there still remain many gaps in the face of the emerging challenges. Various international initiatives have appeared over the years, which indicates that there exists international political will to join efforts and overcome difficulties. We now provide a summary of three leading initiatives that may act as a source of inspiration for policy-motivated initiatives for the challenges identified in the MinFuture project.

JODI (cooperation & harmonisation of oil data)

The IEA has an important role in the harmonisation of international energy statistics. Yet, despite the work of IEA and others, in the late 1990s Energy Ministers identified the lack of transparent and reliable oil statistics as a key contributor to oil price volatility urging a global response to greater transparency. Six international organisations - APEC, Eurostat, IEA, OLADE, OPEC and the UNSD - took up the challenge and in April 2001 launched the

Joint Oil Data Exercise (JODI). The primary goal was not to build a database, but to raise awareness among oil market players about the need for more transparency in oil market data. After pilot test exercises, at the 8th International Energy Forum in Osaka in 2002, Ministers reaffirmed their political support, and with that mandate the six organisations obtained agreement from their Member Countries to make the Exercise a permanent reporting mechanism.

As the scale of the Initiative and global interest in it continued to grow, it was clear that the information had to be made available in a compatible form which led to the creation of the JODI-Oil World Database. In 2014 the JODI-Gas World Database was opened to the public. Nowadays partner organisations are the Asia Pacific Economic Cooperation (APEC), Eurostat, Gas Exporting Countries Forum (GECF), IEA, Latin American Energy Organization (OLADE), Organization of the Petroleum Exporting Countries (OPEC) and the United Nations Statistics Division (UNSD).

The information made available at JODI is also supported by the work of International Energy Statistics (InterEnerStat) meetings held since 2005. In 2015 participants agreed on the importance of improving data and consistency of reporting of final energy use data (and activity data) to support the development of energy efficiency indicators; the topic was resumed in the latest meeting in Paris (October 2018).

IRP´s Global Material Flows Database

The International Resource Panel (IRP) was launched by the United Nations Environment Programme (UN Environment) in 2007 to build and share the knowledge needed to improve our use of resources worldwide. The Panel consists of eminent scientists, highly skilled in resource management issues. Their reports distil the latest scientific, technical and socio-economic findings around global resource use. They provide advice and connections between policymakers, industry and the community on ways to improve global and local resource management.

In response to the lack of a harmonised global reference dataset on material extraction and trade, the IRP took the initiative of asking a consortium to put together a global database on material flows. The result was the creation of a global database on material flows and resource productivity produced as part of a collaborative effort by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia, the Vienna University of Economics and Business (WU Vienna), Austria, the Institute of Social Ecology Vienna (SEC), Austria, the University of Nagoya, Japan, and University of Sydney’s Integrated Sustainability Analysis (ISA), Australia.

The database reports material extraction, trade, material footprints and material intensity.

The database is the most comprehensive one on global material extraction currently available, covering (in its 2017 version) 191 countries, nearly 300 different raw materials for the time period of 1970 to 2017, made available in a detail of 13 aggregated material categories (Lutter 2018). Data from this database are used by academics around the world, integrated into several multi-regional input-output databases such as EXIOBASE and WIOD and regularly featured in reports by international organisations, such as UNEP, OECD and the EEA.

Global E-Waste Statistics Partnership

Since the 1990s, the worldwide use of information and communications technology (ICT) equipment and other electronic equipment is growing. Consequently, there is a growing amount of equipment that becomes waste after its time in use. With ever-increasing technological innovation and rapidly increasing sales, electronic waste or e-waste has become one of the fastest-growing waste streams. This is a challenge for waste management, as many electronic products contain both hazardous and valuable materials, including many CRMs.

In order to understand the dynamics of this complex waste stream, a framework is needed to capture e-waste's most essential features. Currently, there is too much discrepancy between official/governmental data and academic data. Only a few countries have a uniform measurement system for waste electrical and electronic equipment (e-waste or WEEE). However, there is already substantial data available for both developed and less-developed countries that relate to e-waste statistics. All available data could feed into such a system, preferably linking to statistical classifications and existing frameworks. Such a harmonised framework and measurement would help to interpret e-waste-related data and to compile e-waste statistics that are comparable between countries worldwide (Forti, Baldés, and Kuehr 2018).

The Partnership on Measuring ICT for Development established a Task Group on Measuring E-Waste (TGEW) in 2013 to support the compilation of reliable data on e-waste as a basis for political decision making and further action on the environmentally sound management of used and end-of-life ICT equipment. The immediate objective of the task group has been met, by developing e-waste statistics framework based on internationally defined indicators that have been verified with experts in the field. The first edition of the guidelines was published in January 2015. Next to the methodological work, the first Global E-waste Monitor was published in 2015 and received great media exposure in over 70 countries. Between 2015 and 2017, United Nations University joined forces with the United Nations Economic Commission for Europe (UNECE), the Organisation for Economic Co-operation and Development (OECD) and the United Nations Statistics Division (UNSD) to improve the global data coverage.

In order to improve comparability between countries, a **sound measurement framework** (called the UNU-KEYs) (see (Wang et al. 2012) was proposed that integrates available statistical data and non-statistical data sources into e-waste statistics. The framework captures the most important elements of e-waste and is relevant to all countries that aim to gather data and compile statistics on e-waste. The methods have been applied successfully for the first Global E-waste Monitor published by the United Nations University, the second Global E-waste Monitor published by the Global E-waste Statistics Partnership, and two regional e-waste monitors co-authored by the United Nations University (Forti et al., 2018). The goal of the international guidelines published by the Partnership on Measuring ICT for Development is to help countries produce e-waste statistics that are internationally comparable and of relevance for national and international policy-making. Harmonising the measurement framework and indicators will be a substantial step towards reaching an integrated and comparable global measurement framework for e-waste.

The UNU-KEYS are constructed such that product groups share comparable average weights, material compositions, end-of-life characteristics and life-time distributions. This makes the system very useful for compiling e-waste statistics. UNU-KEYs is compatible with UN Comtrade data on e-waste and the WEEE Directive. UNU-KEYs encompasses all possible EEE (about 900 products, clustered into 660 main product types). Here, the system closely follows the harmonised statistical coding of the international trade codes, the Harmonised System (HS).

6.1.4 Ways forward

The current policy context seems keen on embracing newly developing technologies (e.g., data mining, big data, etc.) to deal with the increasingly volumes of data available on production, trade, consumption, etc. to orientate policies addressing global challenges such as climate change crisis, the on-going biodiversity crisis, increasing inequality leading to more unequal over-consumption and under- consumption patterns, digitalisation,mounting streams of e-waste, etc. However, few initiatives are actually focusing on the need to devote a higher degree of attention towards the underlying and historically-formed systems which are the basis for the data being collected. Thus, we believe that, just like the 1973 oil crisis triggered the creation of the IEA, the current global situation could trigger the promotion of more globally coordinated actions for coordinating the monitoring of national system and the discussion on system harmonisation opportunities and progressive data-collection harmonisation mechanisms.

From the institutional side, such coordination could be overtaken by an international agency (e.g. International Materials Agency) with the mandate of collaborating with the existing initiatives (such as JODI, IRP´s Global Material Flow Database, etc.) and institutions in the monitoring of systems, data collection (including focus on metadata) and opportunities to modify how systems are monitored to include data currently not being collected, or collected in too aggregated or in fragmented ways (not inter-operable data).

Current national accounting systems for statistics on raw materials are based on companies´ own accounting systems which are mostly based on decades of linear thinking. Even though recent pushes to promote the circular economies approach are gaining in strength, still no or little information is available on flows or stocks of unused extraction (mine waste, e-waste, and other waste), recycled materials and consumption patterns. One of key initiatives could be to support modifications in systems monitoring (production, trade, waste, recycling) towards a progressive inclusion of those non-captured flows, including a major focus on CRMs (e.g. for trade data to disaggregate codes in the HS and capture separately the trade flows of low-volume but high economic and industrial importance minerals).

At the same time, such institution should promote, as a transition, the further development and usage by national governments, companies and other bodies of guidelines or methods (e.g., UNU-KEYs for e-waste, Chatham House Resource Trade Database for mine production) which orientate as to how to monitor policy-relevant physical flows using existing data such as UN Comtrade or USGS.

Finally, another important role where much needs be done is in the communication stage, for policy-makers and the public. Here improvements in simple and customizable visualisation techniques (maps of value chains, of stocks and flows of production, trade, waste and recycling among countries, etc.) should not be disregarded.

6.2 EU context

6.2.1 EUROSTAT - role, mandate, legal and policy background

The need for European statistics was already recognized in the Treaty of Paris (Art. 46 and 47) signed on 18 April 1951 which established the European Coal and Steel Community. The first statistical report was issued in 1953 and contained statistics on the structure, production and external trade of the coal and steel sector in the founding Member States. One of the important first steps of the functioning of the Statistics Division was harmonisation of common methodologies which got under way in collaboration with national statisticians (De Michelis and Chantraine, 2003).

The Eurostat is since 1958 one of the Directorates-General of the European Commission. It is based in Luxembourg. Eurostat's key role is to supply with data other European Institutions and in the support of the Community policies. The publicly available data serves also to national governments, businesses or media. Eurostat is headed by a Director

General and a Deputy Director General and consists of seven Directorates[14] responsible for different sectors of Eurostat activities.

According to the Regulation No. 223/2009 on European statistics (the so-called 'Statistical Law') the Eurostat is the statistical authority of the Union. Eurostat co-ordinates statistical activities at Union level and more particularly inside the Commission, ensures consistency and quality of the data in the way that it should aim to minimize the reporting burden. The roles, rules of functioning of the Eurostat, statistical principles and responsibilities are defined by the Decision on Eurostat (2012/504/EU) adopted by the European Commission on 17 September 2012. The document also makes reference to the European Statistics Code of Practice which is the standard for developing, producing and disseminating European statistics.

The last amendment of the Statistical Law, the Regulation (EU) 759/2015 in particular, the Article 5a define the competencies of Heads of National Statistical Institutes (NSIs), i.e. requires that they have the sole responsibility for coordinating all activities at national level for European statistics (deciding on processes, methods, standards and procedures, on the content and timing for all European statistics).

The information about the updates in the legislation in force related to all kinds of statistics is available at the Eurostat web page.[15]

The cooperation, comparability and reliability of statistics is ensured by the activities of the European Statistical System (ESS)[16]. The ESS is the partnership between the Eurostat, and the national statistical institutes (NSIs) and other national authorities including the EFTA countries. At the heart of the ESS is the European Statistical System Committee (ESSC) chaired by Eurostat. Its role is to lead the harmonisation of statistics in close cooperation with the national statistical authorities. Among others the Committee is responsible for setting priorities and development of Statistical Programme, issues concerning data confidentiality and any other question with respect of methodology, arising from the establishment or implementation of statistical programme, etc[17].

6.2.2 EUROSTAT and physical economy data

The European statistics on physical economy are primarily secured by statistics on industrial production (PRODCOM) and international trade in goods statistics (ITGS). Statistics focused particularly on material flows, is the statistic on Economy-wide Material Flow Accounts (EW-MFA) which combines data from the previously mentioned two statistical surveys and from other sources.

Production of manufactured goods (PRODCOM)

Prodcom (from French PRODuction COMmunautaire) provides data on structure of industrial production of industrial enterprises and exceptionally non-industrial enterprises with a significant share of industrial activity or producing special products. Mining, quarrying and

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[14] (1. Resources, 2. Methodology; Dissemination; Cooperation in the European Statistical System 3. Macro-economic statistics 4. Government finance statistics (GFS) and quality 5. Sectoral and regional statistics 6. Social statistics 7. Business and trade statistics) https://ec.europa.eu/eurostat/documents/10186/758154/Organisation-chart_EN.pdf

[15] https://ec.europa.eu/eurostat/web/european-statistical-system/legislation-in-force

[16] https://ec.europa.eu/eurostat/web/european-statistical-system/overview

[17] https://ec.europa.eu/eurostat/web/european-statistical-system/ess-governance-bodies/essc

manufacturing match sections B and C of the Statistical Classification of Economy Activity in the European Union (NACE 2)[18]. The survey was established by legal act (EEC) No 3924/91 of 19 December 1991 with the last update provided by the Commission regulation (EU) No 2119/2017 of 22 November 2017[19].

The purpose of the statistics is to report the amount of each product in the Prodcom List, in the reporting country during the reference period. This means that Prodcom statistics relate to products and are therefore not strictly comparable with activity-based statistics such as Structural Business Statistics. The NACE codes on which Prodcom codes are based merely serve to identify the enterprises that should be surveyed in order to determine the amount of production of the product.

The PRODCOM list is an annually revised classification whose implementation date is always the first of January and limit of operational life is the 31st of December. The List consists of about 3900 products. The 8-digit codes used are based on the 6-digit CPA headings and hence the 4-digit NACE rev 1.1. From 2008 onwards the Prodcom code is linked to CPA 2008 and NACE Rev. 2. The link to NACE enables the National Statistical Institutes to use the Business Register to identify the enterprises likely to be manufacturing the product. The Prodcom codes normally relate to one or more Combined Nomenclature (CN) headings, thus enabling external trade data to be related to production data[20].

Prodcom data are collected by the National Statistical Institutes (NSIs) among enterprises annually. Some countries conduct more frequent surveys to satisfy national requirements. Data are collected through statistical survey, together with any other sources or use of estimates, if needed. Some countries survey only a sample of the enterprises in the target population and then gross-up the results. There is one Prodcom coordinator in each reporting country in charge of transmission of these data. All organisations and providers are defined in eDAMIS[21]. Several plausibility checks are applied (by the National Statistical Institutes and Eurostat) to Prodcom data. Eurostat consults the NSIs in case of errors or anomalies[22]. Eurostat also keep the metadata about how the data are collected and processed at national level.[23]

International trade in goods (COMEXT database)

Comext is a statistical database on trade of goods managed by Eurostat which focuses on the size and the evolution of imports and exports. Statistics relating to the international trade represent an important source of data for many decision makers of the public and private sectors on national or international levels.

ITGS (international trade in good statistics) are based on the data collected by customs authorities on trade transactions between countries. Customs declarations are used for

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[18] https://ec.europa.eu/eurostat/statistics-explained/index.php/Industrial_production_statistics_introduced_-_PRODCOM

[19] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1408095659344&uri=CELEX:52009DC0404

[20] http://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=DSP_GEN_DESC_VIEW_NOHDR&StrNom=PRD_2017&StrLanguageCode=EN

[21] The EDAMIS (Electronic Dataflow Administration and Management Information System) is Eurostat's principal system for data exchange with the Member States.

[22] https://ec.europa.eu/eurostat/cache/metadata/en/prom_esms.htm#data_rev1537281218503

[23] https://ec.europa.eu/eurostat/cache/metadata/en/prom_esms.htm

statistical purposes as the basic data source which provides detailed information on exports and imports of goods with a geographical breakdown. The trade statistics are one of the eldest ones in the Community (The first piece of EU legislation on ITGS was adopted in 1975). By the removal of customs formalities between Member States due to the launch of Single Market on 1 January 1993, the subsequent loss of trade statistics data sources required the establishment of a new data collection system Intrastat[24]. Since then ITGS are based on two data collection systems: Extrastat and Intrastat while each of them runs under separate legislative framework.

Statistics relating to the trading of goods by the Community and its Member States with non-member countries are based on Regulation (EC) No 471/2009 of the European Parliament and of the Council and implementing regulations -Commission Regulation (EC) No 92/2010 and Commission Regulation (EC) No 113/2010. Statistics relating to the trading of goods between Members States are based on Regulation (EC) No 638/2004 of the European Parliament and of the Council, and its implementing Commission Regulation (EC) No 1982/2004.

Extrastat data on trade in goods with non-EU countries are collected by customs authorities and are based on the records of trade transactions in customs declarations, whereas Intrastat data are directly collected from intra-EU trade operators once a month[25].

The Combined Nomenclature (CN) is applied for the detailed data whereas the Standard International Trade Classification (SITC) or the Broad Economic Categories (BEC) is used for aggregated data. The Geonomenclature is classifying the countries for international trade purposes.[26] The for different classifications used are usually published conversion tables.

As acknowledged by Eurostat[27], discrepancies may exist between EU and national data due to the application of different concepts and definitions. Nevertheless, it should be kept in mind that data revisions may also alter the comparability of European and national data, at least for a transitional period. According to the EU legislation, revised data should be communicated to Eurostat within one month each time a revision occurs at national level. The metadata about data collection and processing of trade statistics are available on Eurostat[28].

EW-MFA and environmental accounts

Economy-wide material flow accounts (EW-MFA) is one of the modules included in Regulation (EU) No. 691/2011 on European environmental economic accounts. It contributes directly to the Union's policy priorities on circular economy, green growth, and resource productivity by providing important information and statistical indicators on material use. EW-MFA are a statistical accounting framework describing the physical interaction of the (EU) economy with the natural environment and the rest of the world economy in terms of flows of materials.

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[24] https://ec.europa.eu/eurostat/web/international-trade-in-goods/overview

[25] https://ec.europa.eu/eurostat/web/international-trade-in-goods/overview

[26] https://ec.europa.eu/eurostat/cache/metadata/EN/ei_et_esms.htm

[27] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_trade_statistics_-_background#Data_collection

[28] For detailed information about ITGS statistics at national level see the link here: https://ec.europa.eu/eurostat/web/international-trade-in-goods/methodology/eu-and-national-metadata

Regulation (EU) No. 691/2011[29] created a legal obligation for EU Member States to report the Economy-wide material flow accounts (EW-MFA) data to Eurostat. With other words: Economy-wide material flow accounts (EW-MFA) is one of the modules included in Regulation (EU) No. 691/2011 on European environmental economic accounts. (Only) Domestic extraction of (selected) materials and physical trade are covered in the regulation and for mandatory reporting in the EW-MFA questionnaire. The EW-MFA questionnaire includes further voluntary components, namely domestic processed output (DPO). The general purpose of EW-MFA is to describe the interaction of the domestic economy with the natural environment and the rest of the world economy in terms of flows of materials (excluding water and air). EW-MFA is a statistical framework conceptually embedded in environmental-economic accounts and **fully compatible with concepts, principles, and classifications of national accounts** – thus enabling a wide range of integrated analyses of environmental, energy and economic issues e.g. through environmental-economic modelling.

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The Eurostat Environmental accounts as described in Eurostat´s website[30], consist of a database on material flows and resource productivity, with a table reference of 'env_mrp' and in particular the Material Flow Accounts referenced under 'env_ac_mfa'. This dataset set contains imports exports as well as domestic production data for a wide selection of (grouped) materials, covering multiple years for each EU member state with a good quality (validation procedures are in place to guarantee consistency & plausibility).

In order to facilitate compiling extended material flow accounts at the country level, Eurostat has published the 'Country RME tool', accompanied by the 'Handbook country RME tool' and a file with input data. This tool allows the user to estimate country-level estimates of flows in raw material equivalents (RME), such as imports and exports in RME, raw material input (RMI) and raw material consumption (RMC).

Waste generation and management monitoring

Eurostat produces annual data on waste generation and management, except for the data based on the Regulation on waste statistics which is collected every second year. All data are available on Eurostat's database and are used to produce indicators[31] for monitoring the progress in achieving Sustainable Development Goals (SDG´s), Resource efficiency and

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[29] Regulation (EC) No 223/2009 of the European Parliament and of the Council of 11 March 2009 on European statistics and repealing Regulation (EC, Euratom) No 1101/2008 of the European Parliament and of the Council on the transmission of data subject to statistical confidentiality to the Statistical Office of the European Communities, Council Regulation (EC) No 322/97 on Community Statistics, and Council Decision 89/382/EEC, Euratom establishing a Committee on the Statistical Programmes of the European Communities

[30] Eurostat. (2016a). Environmental accounts - establishing the links between the environment and the economy. Accessed on August 10, 2017, from http://ec.europa.eu/eurostat/statistics-explained/index.php/Environmental_accounts_-_establishing_the_links_between_the_environment_and_the_economy

[31] https://ec.europa.eu/eurostat/web/waste/indicators

Circular Economy targets. The statistical reporting obligations and EU policies on wastes are supported by legislative framework:[32]

- **Data reporting on quantity, hazardousness and shipments of waste**
  Waste Statistics Regulation (Regulation (EC) No 2150/2002)
  Waste Shipments Regulation (Regulation (EC) No 1013/2006)

- **Data reporting obligations – monitoring compliance with targets**
  Waste Framework Directive (Directive 2008/98/EC)
  Packaging and packaging waste Directive (Directive 94/62/EC)
  End of Life Vehicles (Directive 2000/53/EC)
  Directive Waste Electrical and Electronic Equipment (Directive 2012/19/EU)
  Directive Batteries Directive (Directive 2006/66/EC)

- **Joint data collection with OECD**
  Municipal waste

The categories of waste are according to the Waste Statistics Regulation are breakdown i) according to their source based on NACE rev.2 economic activities; and ii) in waste categories on the basis of the statistical European Waste Classification (EWCStat), which is a substance-oriented nomenclature (European Commission, 2013).

6.2.3 Challenges, gaps and limitations

First of all, it is important to keep in mind that physical economy is an extremely complex and dynamic system. Thus, any monitoring, analysis and evaluation methodology will be always a very limited one. However, as the need for a high-quality information is of utmost importance for decision-making, the official statistics should aim to achieve the highest level of approximation to the reality as possible. It must be acknowledged that the Eurostat provides world-class statistics in the area of production and trade in goods as well as in waste statistics which are continuously improved.

In this section we provide a brief overview of gaps and limitations which represents the challenges which are connected to the MinFuture call for better "system understanding".

Inconsistency in definitions

One of the basic problems could be a misunderstanding of concepts. Definitions challenge was one of the task forces of the MinFuture. Discussions showed that same terms are used in different context (type of statistical survey, historical understanding, country, etc.) Therefore, a clear definition of concepts must be always provided together with the indication of relevant step in the value chain they represent.

Classifications and nomenclatures

There exists numerous classification and nomenclatures of products at different levels (global, EU, national) for different types of statistical surveys. For the data compilation and material flow analysis it could represent several obstacles:

- Aggregated data and level of detail – several types of materials are grouped together which makes impossible to identify material flow for some minor metals including some critical raw materials (CRMs)

[32] https://ec.europa.eu/eurostat/web/waste

- Unclear the material composition and step in the value chain - Ores and concentrates are in most of the statistics reported together. The total volume of such categories has an unclear composition and content of valuable material (especially in case of metals)
- Comparability of different statistics – there exist conversion tables[33] between different nomenclatures, however, they usually only include respective corresponding codes for each product and no other additional information is provided. Analysis of longer time-series is also becoming time-consuming as the conversion tables are available for different revisions of the same nomenclature.

Completeness and accuracy of data

The relevance of data is depending on several factors related to the methodology of the data collection. These are among others:

- Statistical unit selection and statistical population – Some of the statistics might be selective and not covering all relevant enterprises, e.g. the small and medium sized enterprises are usually not surveyed or misrepresented in order to minimize the administrative burden. The key is the threshold for reporting obligation.
- Data estimation – is related to statistical population, in the case of selective statistics, the data for not surveyed enterprises might be estimated. Estimation could be also used in the case of late or no responses. The quality of data depends on the estimation method.
- Confidentiality – the completeness of data is impacted by confidentiality, the data could be far away from the reality, if the significant amount of data is not disclosed.

Waste flows

While statistics on manufactured products and trade statistics has already relatively long tradition and they are well established even globally, the waste statistics do not have this tradition and therefore, they are still under dynamic development. Wastes have its important place in the material flows as they represent the stocks in the environment that could be returned to the life-cycle (which is the objective of Circular economy). However, the system how this is happening in practice is still not very well explored. On the other hand, it represents the gap where further research might be oriented.

6.2.4 EU and MS policies and MFA requirements for the future

The reason behind every data collection is clearly defined by the pyramidal structure of the MinFuture common framework. Based on the knowledge of the system, supported by credible and sufficient data with manageable uncertainty, we are able to create models, scenarios, calculate indicators and provide reliable visualizations. However, such effort would be pointless if it would not lead to necessary evaluation and consequent decisions.

In the practice, such interrelations usually work in the reverse mode. The policy and decision-makers might as: "How could the MFA support me in achieving specific objectives? Which information (indicators, data, etc.) do I need to prepare a realistic strategy and to make a decision?" As described in the Deliverable 5.1 (Petavratzi, et al., 2018) MFA results cannot provide directly a meaningful strategy, but they could support to identify or describe

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33 http://ec.europa.eu/eurostat/ramon/relations/index.cfm?TargetUrl=LST_REL&StrLanguageCode=EN&IntCurrentPage=4

problems, test alternative strategies for their mitigation or to identify potential business opportunities related to the physical economy. While the relevance of MFA results is always limited by the system definition chosen.

In the EU were, especially in the last decade, defined several policy objectives focused on material use in physical economy and related economic and environmental targets which have led to diverse initiatives, action plans, strategies, communications and directives. To name a few:

- Resource Efficient Europe and Circular Economy[34] policies
- Low carbon economy and Paris Agreement targets[35]
- Waste management Directives[36]
- EU policy on Critical Raw Materials[37]
- Raw Materials Initiative Strategic Implementation Plan[38]
- National mineral and environmental policies

MFA could serve not only for monitoring the effectiveness of such policies, moreover, based on system understanding principle it could help to (re-)define indicators, provide interpretations of models and scenarios and its uncertainty, advice on data gaps and data requirements, system challenges etc. This kind of cooperation would lead to mutual benefits: improvement in the quality of policies and better-informed decision making in one hand and better understanding of physical economy on the other hand.

The MinFuture project is calling for more cooperation between monitoring of physical economy and decision-making. The lack of connection between raw materials policies, material flows analysis and related data collection was identified especially at national level already in MICA project (Hamadová, et al., 2017). The findings on EU level about Eurostat (described in section 6.2.2 and 6.2.3) are also indicating gaps and challenges in data compilation from European statistics like PRODCOM, International trade in goods, or EW-MFA where is not sufficient compatibility and harmonisation between different nomenclatures and details of classifications in different types of products and raw materials.

The highest emphasis in the MinFuture project is given to the need to "report under system understanding". It means that the reliability of data is conditioned by the availability of sufficient metadata or "coordinates" about why, how, where, by whom the data were collected and what is their real meaning (which point in the value chain the number actually represent). In the best case the monitoring of physical economy could work under similar rules as an INSPIRE. The clear messages and recommendations of the project should be, therefore addressed to competent authorities (i.e. at EU level the ESS Committee).

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[34] i.e. Roadmap to a Resource Efficient Europe (COM/2011/0571); Towards a circular economy: A zero waste programme for Europe (COM/2011/0571); Closing the loop - An EU action plan for the Circular Economy (COM/2015/614)

[35] A Roadmap for moving to a competitive low carbon economy in 2050 (COM/2011/112)

[36] Waste Framework Directive 2008/98/EC; WEEE Directive 2012/19/EU; End-of-life Vehicles Directive 2000/53/EC, Batteries Directive 2006/66/EC

[37] http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

[38] ec.europa.eu. (2018). STRATEGIC IMPLEMENTATION PLAN (SIP) - European Commission. [online] Available at: https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/content/strategic-implementation-plan-sip-0#Read%20EIP%20docs [Accessed 8 Nov. 2018].

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Annex A: Papers assessed

Metal	Author	Title	Geographic scale
Aluminium	(G Liu and Müller 2013b)	Mapping the global journey of anthropogenic aluminium : a trade-linked multilevel material flow analysis	World
Aluminium	(G Liu and Müller 2013a)	Centennial Evolution of Aluminum In-Use Stocks on Our Aluminized Planet	World
Aluminium	(W.-Q. Chen and Graedel 2012)	Dynamic analysis of aluminum stocks and flows in the United States: 1900-2009	USA
Aluminium	(Gang Liu, Bangs, and Müller 2011)	Unearthing potentials for decarbonizing the U.S. aluminum cycle	USA
Aluminium	(Plunkert 2006)	Aluminum recycling in the United states in 2000	USA
Aluminium	(W. Chen, Shi, and Qian 2010)	Substance flow analysis of aluminium in mainland China for 2001, 2004 and 2007: Exploring its initial sources, eventual sinks and the pathways linking them	China
Aluminium	(Dahlström K, Ekins P, He J, Davis J 2004)	Iron, steel and aluminium in the UK: material flows and their economic dimensions	UK
Aluminium	(Martchek 2006)	Modelling More Sustainable Aluminium	World
Aluminium	(Cullen and Allwood 2013)	Mapping the global flow of aluminum: From liquid aluminum to end-use goods	World
Aluminium	(Bertram et al. 2017)	A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products	World
Aluminium	(Buchner et al. 2014)	In-depth analysis of aluminium flows in Austria as a basis to increase resource efficiency	Austria
Aluminium	(Ding, Yang, and Liu 2016)	Substance flow analysis of aluminum industry in mainland China	China
Aluminium	(Ciacci et al. 2013)	Historical evolution of anthropogenic aluminum stocks and flows in Italy	Italy
Aluminium	(Sevigné-Itoiz et al. 2014)	Environmental consequences of recycling aluminum old scrap in a global market	Spain
Aluminium	(Rauch and Pacyna 2009)	Earth's global Ag, Al, Cr, Cu, Fe, Ni, Pb, and Zn cycles	World
Aluminium	(Sverdrup, Ragnarsdottir, and Koca 2015)	Aluminium for the future: Modelling the global production, market supply, demand, price and long term development of the global reserves	World
Aluminium	(Müller, Liu, and Bangs 2013)	Stock Dynamics and Emission Pathways of the Global Aluminum Cycle	World
Aluminium	(Amicarelli, Lagioia, and de Marco 2004)	Aluminium industrial metabolism, a commodity science contribution	Italy
Aluminium	(Menzie et al. 2010)	The global flow of aluminum from 2006 through 2025	World
Aluminium	(Lassen and Hansen 2000)	Paradigm for Substance Flow Analyses	Denmark
Aluminium	(International Alumnium Institute 2006)	Aluminium for Future Generations - Sustainability Update 2006	World
Aluminium	(IAI 2007)	Aluminium for Future Generations - 2007 update	World
Aluminium	(IAI 2008)	Aluminium for Future Generations - 2008 update	World
Aluminium	(IAI 2009a)	Aluminium for Future Generations - 2009 update	World
Aluminium	(IAI 2009b)	Global Aluminium Industry Sustainability Scorecard 2009	World

Cobalt	(Schmidt, Buchert, and Schebek 2016)	Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries	World
Cobalt	(Harper, Kavlak, and Graedel 2012)	Tracking the Metal of the Goblins: Cobalt's Cycle of Use	World, USA, China, Japan
Cobalt	(Shedd 1993)	The material flow of Cobalt in the United States	USA
Cobalt	(Yan et al. 2015)	Analysis of Cobalt Substance Flow through China in Year of 2012	China
Cobalt	(Andersen, Hansen, and Poulsen 1984)	Forbrug og forurening med arsen, chrom, cobalt og nikkel	Denmark
Cobalt	(Murakami et al. 2004)	Material Flow Accounting for Metals in Japan	Japan
Cobalt	(Groat 2003)	Flow Studies for Recycling Metal Commodities in the United States - Cobalt Recycling in the United States in 1998	USA
Cobalt	(Nansai et al. 2014b)	Global Flows of Critical Metals Necessary for Low-Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum	World
Cobalt	(Zeng and Li 2015)	On the sustainability of cobalt utilization in China	China
Neodymium	(Nansai et al. 2014b)	Global Flows of Critical Metals Necessary for Low-Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum	World
Neodymium	(Du and Graedel 2011a)	Global in-use stocks of the rare earth elements: a first estimate	World
Neodymium	(Du and Graedel 2011b)	Uncovering the global life cycles of the rare earth elements.	World
Neodymium	(Peiró, Méndez, and Ayres 2013a)	Material flow analysis of scarce metals: sources, functions, end-uses and aspects for future supply.	World
Neodymium	(Wenjuan Chen et al. 2018)	Substance flow analysis of neodymium based on the generalized entropy in China	China
Neodymium	(Swain et al. 2015)	Materials flow analysis of neodymium, status of rare earth metal in the Republic of Korea	South Korea
Neodymium	(Busch et al. 2014)	Managing Critical Materials with a Technology-Specific Stocks and Flows Model	UK
Lithium	(Sun et al. 2018)	Global Lithium Flow 1994–2015: Implications for Improving Resource Efficiency and Security	World
Lithium	(Ziemann, Weil, and Schebek 2012)	Tracing the fate of lithium—The development of a material flow model	World
Lithium	(Hao et al. 2017)	Material Flow analysis of lithium in China	China
Lithium	(Sun et al. 2017)	Tracing global lithium flow: A trade-linked material flow analysis	World

Annex B: Official CRMs according to classifications by different governments

Mineral	Considered critical by			
	EU (2017)	USA (2018)	India (2011)	India (2030)
Aluminium (bauxite)		X		
Antimony	X	X		
Arsenic		X		
Barium			X	
Barite	X	X		
Beryllium	X	X		X
Bismuth	X	X		
Borate	X		X	
Cesium		X		
Chromium		X	X	X
Cobalt	X	X	X	
Coking coal	X			
Flourspar	X	X		
Gallium	X	X		
Germanium	X	X		X
Graphite (natural)	X	X	X	X
Hafnium	X	X		
Helium	X	X		
Indium	X	X		
Limestone			X	X
Lithium		X	X	
Magnesium	X	X		
Manganese		X		
Molybdenum			X	
Natural rubber	X			
Niobium	X	X	X	X
PGMs	X	X		
Phosphate rock	X		X	
Phosphorus	X			

Mineral	Considered critical by			
	EU (2017)	USA (2018)	India (2011)	India (2030)
Potash		X	X	
Rare earth elements group	X	X	X (light REE only)	X
Rhenium		X		X
Rubidium		X		
Scandium	X	X		
Silicon metal	X		X	X
Strontium		X	X	X
Tantalum	X	X		X
Tellurium		X		
Tin		X		
Titanium		X		
Tungsten	X	X		
Uranium		X		
Vanadium	X	X	X	
Zirconium		X		X

Source: self-elaboration based on (Deloitte et al. 2017; DST 2016; "Final List of Critical Minerals 2018" 2018). Note: for India considers only minerals located in Zone-I (most critical)

Annex C: Global players in statistics for energy sector

Following WW II, the second half of the 20th century was characterised by a period of rapid economic growth with rapidly industrialising oil-based economies. In 1968 the **Organization of Arab Petroleum Exporting Countries** (**OAPEC**)[39] was created as a regional inter-governmental organization between the three governments of the Kingdom of Saudi Arabia, the State of Kuwait and the (then) Kingdom of Libya. Some of the main goals of the OAPEC were (and are) the cooperation of the members in various forms of economic activity in the petroleum industry and the determination of ways and means of safeguarding the legitimate interests of its member countries in such industry. The OAPEC was created in 1968, one year after the 1967 oil embargo in response to the Six-Day War (between Israel and Egypt, Jordan and Syria).

The year 1973 was a turning point for the OAPEC and the major oil-importing countries as it was the year of the Yom Kippur War when a coalition of Arab states led by Egypt and Syria attempted to recover Arab territory occupied by Israel (supported by the US) following the 1967 Yom Kippur War. In October 1973 OAPEC members proclaimed an oil embargo (until March 1974) at those countries perceived as supporting Israel during the Yom Kippur War which led to an "oil crisis" as oil prices, especially US oil prices, increased significantly and shortages took place, e.g., of importance in the US. Regardless of the success or failure of the oil embargo itself, the oil embargo changed the nature of energy supply security policy in the western world towards increased exploration, alternative energy research and energy efficiency measures.

At the same time, **the oil crisis of 1973 led to the formation of the International Energy Agency (IEA)**, which nowadays stands out as the most important multilateral organization for energy-importing countries and one of the best-equipped multilateral energy forums (Van de Graaf 2012). The IEA serves to coordinate the energy policies of its 30 member countries, all drawn from the Organization for Economic Cooperation and Development (OECD). The IEA was established by mandate of the OECD Council in the context of the previously mentioned oil crisis in which many OECD countries found themselves inadequately equipped with the information and organization necessary to meet the challenge of ensuring a stable oil supply. Thus, at the time of its foundation the IEA´s primary mission was to coordinate emergency measures in times of oil crises, i.e. energy security (supply security) and other questions of energy policy co-operation among Member countries. While these remain key aspects of its work, the IEA has evolved and expanded over the decades towards other complementary issues such as long-term policy, information "transparency", energy and the environment, research and development and international energy relations.

In the context of the MinFuture project, the IEA appears as main global player in the provision of statistics and data on global and per-country energy production, consumption, trade flows (gas), energy balances, efficiency, prices, markets, CO2 emissions, among others. High-quality and harmonised data on international energy statistics is of high relevance modelling and orientation of policy-makers, e.g.:

39 Not to be confused with the Organisation of Petroleum Exporting Countries (OPEC) created in 1970.

- IEA Member countries have an obligation to hold 90 days of oil stocks (net imports/consumption) and thus need reliable and timely data on oil stocks (reserves, stockpiled) and flows (imports, domestic consumption, etc.)

- EU Member countries under the Renewables Energy Directive (2009/28/EC) have an obligation to achieve a minimum share of electricity consumption based on renewable sources, thus they need reliable data on renewable energy generation, CO2 emissions, etc.

The IEA collects data on national energy statistics via:

- **OECD countries**: via 5 harmonised annual questionnaires (coal, oil, natural gas, electricity and heat and renewables) from official sources on <u>mandatory basis</u>

- **Non-OECD countries** (aprox. 150 countries)
    - Questionnaires or national formats from official sources on a <u>voluntary basis</u>
    - From secondary sources if needed (utilities, associations, trade reports; etc.)