Deliverable 4.2: Estimation of composition and lifetimes

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1. Introduction

The new European Green Deal calls for the transition to a low-carbon and circular economy and for ensuring the security of supply for critical raw materials. To achieve these goals, the European and other economies worldwide need to fundamentally change the ways in which they extract and use natural resources, thereby reducing greenhouse gas emissions and waste. The first step in this change is the development of a robust information base regarding the current and future demands for natural resources, their routes across the globe and their disposition after they are not required anymore in their current functions. This information base should include data on economic aspects linked to physical stocks and flows of materials and products, covering the complete value chain of different raw materials. Various existing databases provide information on economic or physical aspects of separate stages of the value chain but fall short of a holistic portrayal of the physical base of the global economy. New projects addressing resource-efficiency often contain specific objectives and make use of different methodologies and classification systems, resulting in scattered data. This also hampers the application of the gathered data in forward-looking models capable of projecting future material flows and stocks and their environmental implications, as well as economic implications of resource supply issues.

The objective of the PANORAMA project is thus to gather data from a wide range of currently available data sources and, through a data harmonization process, eventually provide a database that contains relevant physical and economic information on important materials throughout their complete value chain. The first step towards the development of a complete and harmonized database was an assessment of the different aggregated data sources available and the types of data provided. Following this, an overview of the missing data was compiled, which guided the selection of possible additional data sources for gap filling. These steps were carried out in Work Package 3 (data harvesting) and are described in Deliverable 3.1 of the PANORAMA project. The availability of data was additionally clustered and mapped along the stages of the anthropogenic material cycle at the beginning of Work Package 4 (data processing). This step is described in Deliverable 4.1 of the PANORAMA project.

The work described in this deliverable relates to the collection and processing of composition and lifetime data, as well as information on end-of-life (EoL) characteristics of the products in the anthropogenic material cycle. Due to the vast amounts of data to be collected and potential data gaps, an approach was chosen that keeps the workload of Work Package 4 manageable. A total of 16 elements/substances were selected based on criteria relating to proliferation and criticality. They are summarised in Table 1.

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Table 1. List of elements considered in PANORAMA

Element	Inclusion criteria
Aluminium (Al)	Volumes, variety of uses
Cerium (Ce)	Critical according to EU CRM list[1]
Cobalt (Co)	Critical according to EU CRM list
Copper (Cu)	Volumes, variety of uses
Dysprosium (Dy)	Critical according to EU CRM list
Germanium (Ge)	Critical according to EU CRM list
Indium (In)	Critical according to EU CRM list
Iron (Fe)	Volumes, variety of uses
Lanthanum (La)	Critical according to EU CRM list
Natural Graphite[2]	Critical according to EU CRM list
Niobium (Nb)	Critical according to EU CRM list
Neodymium (Nd)	Critical according to EU CRM list
Palladium (Pd)	Critical according to EU CRM list
Platinum (Pt)	Critical according to EU CRM list
Tantalum (Ta)	Critical according to EU CRM list
Tungsten (W)	Critical according to EU CRM list

After an initial focus on these substances for the data collection, a commodity-based approach was eventually chosen to achieve complete coverage. The range of commodities to be included is based on the complete list of six-digit codes from the 2017 version of the international Harmonized Commodity Description and Coding System (short: Harmonized System or HS), which was developed by the World Customs Organisation (WCO) way of classifying international trade flows. The HS is used by international organisations, governments and the private sector for tax purposes, trade policies, economic research or monitoring of the global flow of goods. Regarding the latter, it is also the classification used in the United Nations Commodity Trade Statistics Database (UN Comtrade). The HS integrates well with other economic classification systems, as summarised in Figure 1. The complete HS 2017 list contains 5388 commodities ranging from live animals to works of art and can be viewed on the web pages of the WCO[3] or UN Comtrade.[4]

[1] COM(2017) 490 final

[2] For simplicity, we adopted the element symbol for carbon (C) to describe natural graphite in PANORAMA. However, we acknowledge that this is only one of the forms in which elementary carbon appears.

[3] http://www.wcoomd.org/en/topics/nomenclature/instrument-and-tools/hs-nomenclature-2017-edition/hs-nomenclature-2017-edition.aspx

[4] https://unstats.un.org/unsd/tradekb/Knowledgebase/50018/Harmonized-Commodity-Description-and-Coding-Systems-HS

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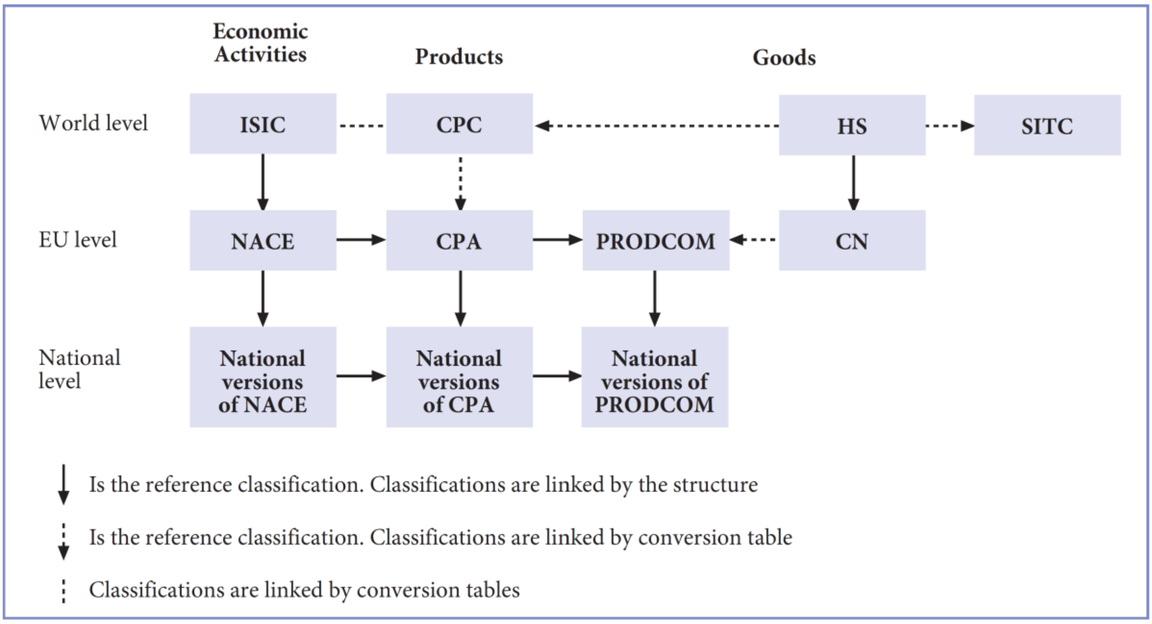

Figure 1. The international system of economic classifications (Eurostat 2008)

For the collection of composition data, a binary dataset developed by TNO was used, which indicated the presumed presence of the 16 selected elements in the list of 5388 commodities (TNO 2015). For the collection of lifetime data, the 5388 commodities were characterised as intermediate goods, capital goods or different types of household consumption products. Lifetime data was then collected only for finished products, i.e. excluding intermediate goods, since their lifetimes generally determine the fixation of the elements in anthropogenic stocks. For the EoL characteristics, mainly for waste electrical and electronic equipment (WEEE), data is collected for formally collected and recycled waste, and recycling efficiencies for selected elements in WEEE. More information on the data collection methodology and data coverage is provided in the chapters below.

The report is structured as follows. In Chapter 2, the data collection methodology is described, including metadata and data quality assessment. The consortium partners have extensive experience in WEEE; therefore, emphasis is given to WEEE in the case of lifetimes and EoL characteristics. Chapter 3 describes data coverage and provides a characterisation of the data for the 16 selected elements in terms of different characteristics, along with data quality scores. Chapter 4**Error! Reference source not found.** closes with a brief conclusion.

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2. Data collection methodology

2.1 Compositions

Product composition data is reported in various forms and can be found in a variety of publications, including databases, scientific reports, journal articles and specialized web pages. Most of the data is, however, not reported in the logic of the 5388 commodities based on the list of six-digit HS 2017 codes and does not cover the full range of the 16 elements selected for the PANORAMA project, which are summarised in Table 1. The partners of the consortium therefore initially employed several approaches to collecting composition and lifetime data, including element-based approaches, which use a given element as the starting point for finding all applications containing that element and the respective concentrations (as well as the respective lifetimes of these applications). To consolidate and monitor these data collection efforts and to get an overview of the coverage, a data coverage sheet was developed. The actual composition data points were reported in a separate dataset, both of which are the primary components of this deliverable. They are described in the following sections.

Tracking of data collection

The coverage sheet consists of a table with the 5388 HS 2017-denoted commodities in rows and the 16 elements in columns. The sheet was initially filled with binary information developed by TNO on the potential presence of a given element in a commodity. To develop the underlying dataset, TNO used the following criterion: if the presence of an element in a commodity cannot be definitively ruled out, it is assumed to be present (TNO 2015). The respective cells in the coverage sheet were labelled with an “X”. Additional datasets were consulted to check whether composition data was already available for commodity/element combinations. The consulted datasets are:

- ProSUM (Huisman et al., 2017): consulted for several element contents in electronics
- Nansai et al. (2014): consulted for Co, Nd and Pt
- A pre-existing dataset developed by Fraunhofer ISI for copper (cf. Soulier et al. 2018)
- Deetman et al. (2017): consulted for Ta
- Passarini et al. (2018), a technical report by the Joint Research Centre of the European Commission (EC-JRC): consulted for Al, Cu and Fe
- Other studies are available in the literature reporting products compositions and the content of several elements in different commodities.

For the subsequent data collection, the nomenclature summarised in Table 2 was adopted.

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Table 2. Nomenclature of data coverage sheet

Symbol	Explanation
X	Element is assumed to be present based on the TNO dataset
X 0	Research within PANORAMA has ruled out presence of element in commodity
X -	Content of element in commodity could not be established, but presence is not ruled out
X G	Element assumed to be present and content has been found within PANORAMA
X P	Element assumed to be present and content reported in Huisman et al. (2017)
X N	Element assumed to be present and content reported in Nansai et al. (2014)
X F	Element assumed to be present and content reported in Soulier et al. (2018)
X D	Element assumed to be present and content reported in Deetman et al. (2017)
X J	Element assumed to be present and content reported in Passarini et al. (2018) - JRC
G	Element not assumed to be present but content has been found within PANORAMA
P	Element not assumed to be present but content reported in Huisman et al. (2017)
N	Element not assumed to be present but content reported in Nansai et al. (2014)
F	Element not assumed to be present but content reported in Soulier et al. (2018)
D	Element not assumed to be present but content reported in Deetman et al. (2017)
J	Element not assumed to be present but content reported in Passarini et al. (2018) - JRC

Combinations of the above letters were also possible. For instance, some data points were reported in more than one source (e.g. in Soulier et al. (2018) and Huisman et al. (2017), leading to the combination “F P”). Figure 2 provides an exemplary screenshot of the tracking sheet for a range of commodities and elements.

HS17	DescriptionDescriptionDescriptionDescriptionDescriptionDescription	Co	In	C	Nb	W	Cu
850511	Magnets; permanent magnets and articles intended to become permanent magı	X N G					X G
850519	Magnets; permanent magnets and articles intended to become permanent magı	X G					X 0
850520	Magnets; electro-magnetic couplings, clutches and brakes	X G					X G
850590	Magnets; electro-magnets, holding devices and parts n.e.c. in heading no. 8505	X G				X 0	X F
850610	Cells and batteries; primary, manganese dioxide	X -					X G
850630	Cells and batteries; primary, mercuric oxide	X -					X G
850640	Cells and batteries; primary, silver oxide	X -					X G
850650	Cells and batteries; primary, lithiumCells and batteries; primary, lithium	X N P G	P		P	P	X P
850660	Cells and batteries; primary, air-zincCells and batteries; primary, air-zinc	X P G	P		P	P	X P
850680	Cells and batteries; primary, (other than manganese dioxide, mercuric oxide, sil	X -		X 0			X G
850690	Cells and batteries; primary, parts thereof	X G		X G			X G
850710	Electric accumulators; lead-acid, of a kind used for starting piston engines, incluc	X P	P		P	P	X P
850720	Electric accumulators; lead-acid, (other than for starting piston engines), includi	X P	P		P	P	X P
850730	Electric accumulators; nickel-cadmium, including separators, whether or not rec	X P G	P		P	P	X P
850740	Electric accumulators; nickel-iron, including separators, whether or not rectangu	X -					X G

Figure 2. Screenshot of composition coverage sheet

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The single "X" entries were used to identify commodity/element combinations for which values had to be found either through original research or matching with existing commodity-level data that had already been researched by one of the PANORAMA partners but not yet matched with the respective HS codes. The data coverage sheet contains a summary table at the bottom indicating the coverage of each element for the list of commodities based on the number of products in which a given element is assumed to be present ("X") and the number of commodities for which composition data has been provided (see Figure 3). It also lists the number of additional data points that exist beyond those labelled as present by the TNO dataset, i.e. all cells containing the above letters without the "X".

	Co	In	C	Nb	W	Cu	Ge	Ta	Pd	Pt	Ce	La	Nd	Dy	Al	Fe
Element present	307	107	195	131	247	1347	84	142	202	192	292	306	279	194	1384	1843
Covered	307	107	195	131	247	1347	84	142	202	192	292	306	279	194	1384	1843
Left	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Additional	333	202	0	210	205	55	200	212	179	264	158	164	244	172	210	225
Coverage	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 3. Summary table of coverage sheet

Reporting of collected data

To determine the compositions of the relevant commodities, more than 300 individual sources were consulted. As stated above, these sources include databases, scientific reports, journal articles and specialized web pages. All sources are reported alongside the composition data in a dedicated dataset, which contains individual sheets for each of the 16 considered elements. The dataset also contains a range of meta information for each data point and comprises six sections (cf. Figure 4).

Meta information element - component	Meta information component - product	Content element - component	Content component - product	Commodity weight and source of concentration data	Meta information concentration data

Figure 4. Schematic illustration of the structure of composition dataset

The first two sections are constructed identically and provide information on:

- the type of commodity covered (element, material, component or product),
- the classification system in which it is listed (since not all data points were found in the HS 2017 classification),
- the respective classification code,
- the commodity name and description and

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- the source in which the classification code was found.

The next two sections are also identical and provide information on:

- a possible lower limit of the element content in a given commodity,
- a possible higher limit of the element content,
- a unique content or the average of the lower and higher limit and
- the unit in which the content is reported (e.g. weight percent or decimal points).

The dataset was originally designed to contain two of these sections each to allow for a cascade-like portrayal of element contents in commodities. It was conceived in such a way because information may be found on the content of a given element in a certain component (e.g. copper in a printed circuit board, PCB), which is then related to a final product (e.g. a computer). For example, if copper makes up 5% of the weight of the PCB and the PCB makes up 5% of the weight of the computer, then the weight content of copper in the computer is at least 0.25% (plus additional copper contained in other components, such as wires). However, in the final dataset, element contents are provided directly, so that each of the listed commodities is assigned a value for the respective element content without having to perform additional calculations based on the element to-component-to-product relationships. All element contents are thus provided either as weight fractions (wf) or weight percentages (wt.%) of the respective commodity.

The fifth section of the dataset contains a column in which the weight of the respective commodity can be reported. With the help of this column, additional data points from the literature that are reported as weight per unit (e.g. grams of copper per computer) could be related to the commodity weight and thus transformed into weight fractions or percentages. This section also contains detailed information on the source(s) of the concentration data and commodity weight.

The sixth section finally contains information on:

- the year to which the concentration data refers,
- the country to which the concentration data refers,
- the type of source (e.g. database, scientific report etc.),
- the way the concentration data was generated (e.g. through lab experiments, models etc.),
- a score for the data quality,
- a mnemonic code for the choice of the data quality score or free text explanations and

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- additional comments on researched data, including used assumptions, calculations performed etc.

The latter category is relatively broad since the HS-system encompasses a wide range of commodity types, ranging from ores and basic products to complex machines and installations. In addition, the differentiation between these commodities or commodity groups is often not aligned with a composition logic. For example, to determine the copper content of the commodity group of ball bearings (HS 2017 code 848210), it did not suffice to determine the copper content of ball bearings made from copper alloys because this group also contains ball bearings made from steel. Therefore, the share of copper alloy-based bearings within the wider group had to be determined as well. Since no direct information on this share was available, the additional assumption had to be made that the share is similar to that of ceramic bearings, as they are used in similar applications. The copper content of all ball bearings in group 848210 is thus the copper content in copper alloy-based bearings multiplied by the market share of copper alloy-based bearings within the wider group. Similarly, the cobalt content in battery applications can be significantly different between different chemistries within the same battery category. Lithium-ion batteries are good examples, where the cobalt content ranges from less than 10 wt.% (nickel-manganese-cobalt, NMC 811 chemistry) to 60 wt.% (lithium-cobalt-oxide, LCO chemistry), but all chemistries are grouped under the same HS 2017 code (850650).

A screenshot of the dataset for the case of cobalt is provided in Figure 5.

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Type of commodity - y	Classification system - y	Code - y	Commodity name (description) - y	Source of classification code - y	Lower limit (range) - x	Higher limit (range) - x	Content (average or unique value) - x	Unit - x	Lower limit (range) - y	Higher limit (range) - y	Content (average or unique value) - y	Unit - y	Weight of product (when reported)	Unit	Source of content and product weight	Year of concentration data	Country of concentration data	Type of source	Concentration data generation	Data quality score	Data quality score comments	Other comments
Material		260200	Manganese nodules a	HSCodeandDescription - Excel			2.50	wt.%							Cobalt Institute (2019)	Not available	Global	Website	Not availabl	2	Experts	
Material		260200	Manganese nodules a	HSCodeandDe	1	2.5		wt.%							British Geological Surv	2009	Global	Geologica	Survey	2		
Material		260300	Copper ores and conc	Nansai et al 2014 & HS1996 to HS2017 Conversion A			2.00	wt.%							Nansai, K., Nakajima, I	2005	Global	Peer-revie	Estimations	3	A. Data from estimat	
Material		260300	Sediment hosted	HSCodeandDe	0.1	0.4		wt.%							Cobalt Institute (2019)	Not available	Global	Website	Not availabl	2	Experts	
Material		260300	Sediment hosted	HSCodeandDe	0.1	0.4		wt.%							British Geological Surv	2009	Global	Geologica	Survey	2		
Material		260300 / 2605	Sulfide ores - Chaloco	HSCodeandDe	0.5	3		wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		260300 / 2605	Sulfide ores - Copper-	HSCodeandDescription - Excel			3.50	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		260300 / 2605	Sulfide Ores - after flc	HSCodeandDe	0.23	0.31		wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		260300 / 2605	Sulfide Ores - concent	HSCodeandDe	0.7	0.82		wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		260400	Nickel sulfide ores an	HSCodeandDescription - Excel			0.40	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		260400	Nickel concentrate &	HSCodeandDescription - Excel			0.09	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material		260400	Nickel ore	HSCodeandDescription - Excel			0.10	wt.%							Sun, X., Hao, H., Liu, Z.	2019	Global	Peer-revie	Estimated	3	A. Data from estimat	
Material		260400	Nickel ores and conce	Nansai et al 2014 & HS1996 to HS2017 Conversion A			0.18	wt.%							Nansai, K., Nakajima, I	2005	Global	Peer-revie	Estimations	3	A. Data from estimat	
Material		260500	Cobalt ores and conce	HSCodeandDe	5	10		wt.%							Darton Commodities L	2018	Global	Commodi	Market revie	2	Experts	
Material		260500	Cobalt concentrate &	HSCodeandDescription - Excel			7.60	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material		260500	Cobalt ores and conce	Nansai et al 2014 & HS1996 to HS2017 Conversion A			6.50	wt.%							Nansai, K., Nakajima, I	2005	Global	Peer-revie	Estimations	3	A. Data from estimat	
Material		260500	Cobalt-rich ores after	HSCodeandDe	10	15		wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		260500	Cobalt-rich ores after	HSCodeandDe	0.2	0.6		wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		260500	Cobalt ore	HSCodeandDescription - Excel			15.00	wt.%							Sun, X., Hao, H., Liu, Z.	2019	Global	Peer-revie	Estimated	3	A. Data from estimat	
Material		262011 / 2620	Slag	HSCodeandDe	0.2	1		wt.%							Jones et al. 1996 Recov	1996	South Africa	Internatio	Experimenta	3	A. Data from experin	
Material		262011 / 2620	Slag	HSCodeandDescription - Excel			0.49	wt.%							Bulut, G. (2006) Recove	2005	Turkey	Peer-revie	Experimenta	3	A. Data from experin	
Material		262060 / 2617	Arsenide Ores -prima	HSCodeandDescription - Excel			2.00	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		262060 / 2617	Arsenide Ores - conce	HSCodeandDe	13	14		wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		261790 / 2603	Oxide Ores - concentr	HSCodeandDe	2	3		wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		261790 / 2603	Hydrothermal/volcan	HSCodeandDescription - Excel			0.10	wt.%							Cobalt Institute (2019)	Not available	Global	Website	Not availabl	2	Experts	
Material		261790 / 2603	Hydrothermal/volcan	HSCodeandDescription - Excel			0.10	wt.%							British Geological Surv	2009	Global	Geologica	Survey	2		
Material		261790 / 2604	Laterite	HSCodeandDe	0.05	0.15		wt.%							Cobalt Institute (2019)	Not available	Global	Website	Not availabl	2	Experts	
Material		261790 / 2604	Laterite	HSCodeandDe	0.05	0.15		wt.%							British Geological Surv	2009	Global	Geologica	Survey	2		
Material		261790 / 2603	Magmatic sulphide	HSCodeandDescription - Excel			0.10	wt.%							Cobalt Institute (2019)	Not available	Global	Website	Not availabl	2	Experts	
Material		261790 / 2603	Magmatic sulphide	HSCodeandDescription - Excel			0.10	wt.%							British Geological Surv	2009	Global	Geologica	Survey	2		
Material		810520	Cobalt,unwrought,ma	Nansai et al 2014 & HS1996 to HS2017 Conversion A			6.50	wt.%							Nansai, K., Nakajima, I	2005	Global	Peer-revie	Estimations	3	A. Data from estimat	
Material		711100	Base metals,silver o g	Nansai et al 2014 & HS1996 to HS2017 Conversion A			0.0039	wt.%							Nansai, K., Nakajima, I	2005	Global	Peer-revie	Estimations	3	A. Data from estimat	
Material		810520	Hydrometallurgical in	HSCodeandDescription - Excel			20.00	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material		810520 / 8105	Cobalt metal	HSCodeandDescription - Excel			99.00	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material		282200	Cobalt oxide and hydr	HSCodeandDescription - Excel			32.90	wt.%							Sun, X., Hao, H., Liu, Z.	2019	Global	Peer-revie	Estimated	3	A. Data from estimat	
Material		283329	Cobalt(III) sulfate hex	HSCodeandDescription - Excel			20.98	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		283699	Cobalt(II) carbonate -	HSCodeandDescription - Excel			49.57	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		283699	Cobalt carbonate	HSCodeandDescription - Excel			49.60	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material		291529	Cobalt(II) acetate - Co	HSCodeandDescription - Excel			23.68	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		282200	Cobalt oxides and hyc	Nansai et al 2014 & HS1996 to HS2017 Conversion A			73.44	wt.%							Nansai, K., Nakajima, I	2005	Global	Peer-revie	Estimations	3	A. Data from estimat	
Material		282200	Other cobalt oxides a	HSCodeandDescription - Excel			67.50	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material		282200	Cobalt oxide - gray co	HSCodeandDescription - Excel			78.66	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		282200	Cobalt oxide - black c	HSCodeandDescription - Excel			73.44	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		282200	Tricobalt tetraoxide ((	HSCodeandDescription - Excel			65.00	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material		282200	Cobalt(II) Hydroxide -	HSCodeandDescription - Excel			64.43	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		282540	Nickel oxide	HSCodeandDe	0	1.5		wt.%							Vale 2013 Nickel Oxide	2013	Japan, New Cale	Industry re	Experimenta	3	A. Data from experin	
Material		282739	Cobalt chloride	HSCodeandDescription - Excel			45.40	wt.%							Sun, X., Hao, H., Liu, Z.	2019	Global	Peer-revie	Estimated	3	A. Data from estimat	
Material		282739	Cobalt chloride	HSCodeandDescription - Excel			45.40	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material		282739	Cobalt chloride	Nansai et al 2014 & HS1996 to HS2017 Conversion A			45.74	wt.%							Nansai, K., Nakajima, I	2005	Global	Peer-revie	Estimations	3	A. Data from estimat	
Material		282739	Cobalt(II) chloride he	HSCodeandDescription - Excel			24.79	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		291711	Cobalt(II) oxalate dihy	HSCodeandDescription - Excel			32.23	wt.%							Donaldson, J.D., Beyer	2012	Global	Book chap	Collected fr	2	A. Reliable sources (	
Material		291711	Cobalt oxalate	HSCodeandDescription - Excel			40.00	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material / component		850650 / 8506	Cathode NMC532	HSCodeandDescription - Excel			18.24	wt.%							Bobba, S., Mathieux, F	2011, 2013, 2016	Europe	Peer-revie	Collected fr	3	A. Data from other sc	
Material / component		850650 / 8506	Cathode NMC622	HSCodeandDescription - Excel			12.16	wt.%							Bobba, S., Mathieux, F	2011, 2013, 2016	Europe	Peer-revie	Collected fr	3	A. Data from other sc	
Material / component		850650 / 8506	CathodeNMC811	HSCodeandDescription - Excel			6.06	wt.%							Bobba, S., Mathieux, F	2011, 2013, 2016	Europe	Peer-revie	Collected fr	3	A. Data from other sc	
Material / component		282520 / 8506	Lithium cobalt oxides	HSCodeandDescription - Excel			60.00	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	
Material / component		282520 / 8506	Lithium Cobalt Oxide	HSCodeandDescription - Excel			60.20	wt.%							Sun, X., Hao, H., Liu, Z.	2019	Global	Peer-revie	Estimated	3	A. Data from estimat	
Material / component		282520 / 8506	Lithium Nickel Manga	HSCodeandDe	10	30	12.20	wt.%							Alves Dias, P., Blagoev	2016 / 2018	Global	JRC report	Reported by	2		
Material / component		282520 / 8506	Lithium cobalt nickel	HSCodeandDescription - Excel			12.20	wt.%							Sun, X., Hao, H., Liu, Z.	2019	Global	Peer-revie	Estimated	3	A. Data from estimat	
Material / component		282520 / 8506	Lithium cobalt nickel	HSCodeandDescription - Excel			20.40	wt.%							Sun, X., Hao, H., Liu, Z.	2019	Global	Peer-revie	Estimated	3	A. Data from estimat	
Material / component		282520 / 8506	Lithium Nickel Manga	HSCodeandDe	10	15		wt.%							Alves Dias, P., Blagoev	2016 / 2018	Global	JRC report	Reported by	2		
Material / component		282520 / 8506	Lithium nickel cobalt	HSCodeandDescription - Excel			9.20	wt.%							Sun, X., Hao, H., Liu, Z.	2019	Global	Peer-revie	Estimated	3	A. Data from estimat	
Material / component		850650 / 8506	Ternary anode materi	HSCodeandDescription - Excel			14.40	wt.%							Chen, Z., Zhang, L., Xu,	1994 - 2016	China	Peer-revie	Industry rep	2	Experts	

Figure 5. Screenshot of composition dataset for cobalt

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Data quality assessment

For several commodities, significantly different composition values have been reported in the literature, and in many cases, it is not immediately clear which value is the most reliable one. A reason for the difference in reported composition of products is the fact that the studies or reports communicating these values were developed based on different methodologies, product technologies or geographical/temporal representations. For instance, the composition data reported by a battery manufacturer will, in most cases, be different from the composition data reported by a battery recycler, considering that the manufacturer will report the content of each element added to the battery, whereas the recycler reports how much element was recovered from a battery that reached its end-of-life. Taking into account that recycling processes are not 100% efficient in recovering all the elements contained in the product, or that losses of the material may occur at the use-phase, the data reported by a manufacturer may be a better indicator of product compositions. However, if data from the manufacturing phase was not available, composition data from recycling was considered, along with a quality score to indicate that the data point may not be well suited for the purpose of the analysis. A simplified data quality assessment (DQA) framework was developed to evaluate the representativeness and reliability of the composition data. The DQA consisted of scores assigned to each data point taking into account the criteria listed below:

The initial DQA score per data point is either:

- 1 for metal articles/primary forms/extraction or
- 2 for original data from manufactures/reliable studies/etc.

An additional unit (+1) was added to the initial DQA score considering the following criteria:

A. +1 if data came from recycling/experimental sources
B. +1 if the original source already used market share to adjust the contents
C. +1 if the person who collected the data adjusted the contents based on market shares
D. +1 if it was unclear/vague whether the content was reported for the whole product or only parts of it (components)
E. +2 if the content of similar technology/application was taken
F. +1 if data source was older than the year 2000
G. +1 if data was reported according to the HS 4-digit level (less than 3 sub-headings)
H. +2 if data was reported according to the HS 4-digit level (more or equivalent to 3 sub-headings)
I. +1 if additional assumptions were made either by the authors/source of data or by the person collecting the data, including any assumption not previously listed.

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For each commodity/HS code for which content of a given element was collected, the uncertainty or DQA score was determined (1 to 5). The derived score was assigned to the data point in the composition dataset, along with the mnemonic code specifying which criteria were used (i.e. 'CDE'). If the total score after application of the DQA framework listed above was higher than 5, the data point was assigned a DQA score of 5. A default score of 2 was assumed for cases when the element content of a given product could not be determined or its presence could not be confirmed (content value of 0).

2.2 Lifetimes

Product lifetime is an important parameter for a dynamic (material flow) system as it portrays the current and historical societal metabolism. In PANORAMA, lifetimes have been studied for various commodities and applications. Several partly contrasting definitions of lifetimes, which are sometimes also referred to as lifespans, exist. Murakami et al. (2010) define the main product "life" terminologies in the following way:

- **Product age** is defined as the period from the beginning of a product's life to the present (or the time of interest).
- **Residential time** is defined as the duration of the existence of the goods in question, such as materials or elements in our society, regardless of whether the goods still function.
- **Service lifespan** is defined in terms of goods or parts, not in terms of the owners. It denotes the length of the period in which the goods function and are in use, including the duration of distribution for the next use.
- **Possession span** indicates how long a consumer possesses the goods in question.
- **Duration of use** indicates how long a consumer uses the goods in question. Because it is defined for one owner, the duration of use is different from the service lifespan. The difference between possession span and duration in use is the "dead-storage period", which is also referred to as "hibernation". Thus, the product in question is not in use during this period, it may not be included in the service lifespan of the product.

Within the context and model requirements of the PANORAMA project, none of the existing framings entirely fit our needs. Indeed, as we aim to use product lifetime values to model the annual waste flows generated by industries and final consumers, we need the lifetimes until the moment when a product is discarded (irrespective of how many users owned it previously). This fits best with the "duration in use of parts", which is an ancillary term used by Murakami et al. (2010) and matches the definition of product lifetime of den Hollander et al. (2017). It is schematically illustrated in Figure 6.

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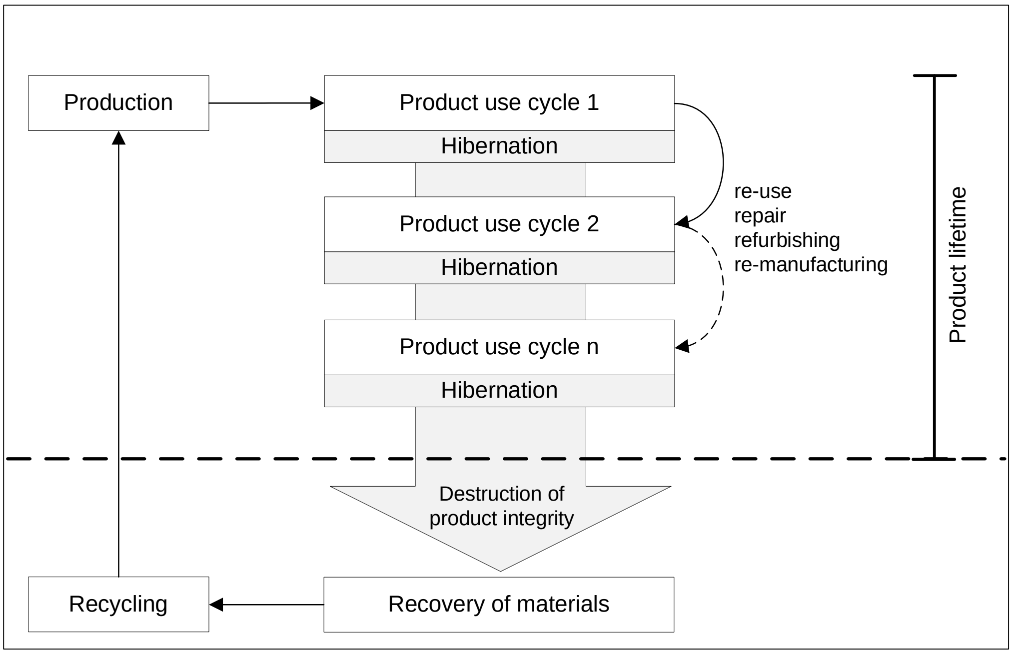

Figure 6. Schematic illustration of product lifetime; source: Glöser-Chahoud et al. (2019)

To obtain lifetimes according to the above definition for the 5388 commodities, the manual collection from existing sources is thus complemented by primary data harvesting using the newly developed product lifetimes information system within PANORAMA. The data collection in each case is described in the sections below.

Existing sources

To direct the research on product lifetimes within existing sources, a coverage sheet similar to that used for composition data was designed. So far, approximately 50 individual sources have been scanned for product lifetimes. Figure 7 provides a screenshot of the coverage sheet, where for each HS code, the sum of the elements confirmed as being present in the commodity (out of the 16 elements considered) is represented in the column “# El (confirmed)”. Only products which contain at least one element are considered for lifetimes. Higher amounts of elements present in a given product gave priority to the lifetime collection efforts.

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HS17	HS17 (4 d	Description	# EI (confirmed)	Stage	Stage (EUC)	LT need (FIN only)	LT need (EUC)	Partner	Completed	Model	UNU key	LT (UNU	LT (HS (	LT (HS -	LT (ma
940510	9405	Chandeliers and other electric ceiling or wall light fittings;	15	SM_FIN	INT	1	0		1		0506	14.2	-	-	
940520	9405	Lamps, electric; floor-standing or for table, desk or bedside	15	SM_FIN	CONS	1	1		1		0506	14.2	-	-	
940530	9405	Lighting sets; of a kind used for Christmas trees	15	SM_FIN	CONS	1	1		1		0506	14.2	-	-	
940540	9405	Lamps and light fittings; electric, n.e.c. in heading no. 9405	15	SM_FIN	INT	1	0		1		0507	10.4	-	-	
940550	9405	Lamps and light fittings; non-electric	2	SM_FIN	INT	1	0		0		-	-	-	-	
940560	9405	Illuminated signs, name plates and the like	2	SM_FIN	INT	1	0		0		-	-	-	-	
940591	9405	Lamps and light fittings; parts thereof, of glass	2	SM_FIN	INT	1	0		0		-	-	-	-	
940592	9405	Lamps and light fittings; parts thereof, of plastics	2	SM_FIN	INT	1	0		0		-	-	-	-	
940599	9405	Lamps and light fittings; parts thereof, of materials other th	3	SM_FIN	INT	1	0		0		-	-	-	-	
940610	9406	Buildings; prefabricated, of wood	2	SM_FIN	INT	1	0		0		-	-	-	-	
940690	9406	Buildings; prefabricated, not of wood	2	SM_FIN	INT	1	0		0		-	-	-	-	
950300	9503	Tricycles, scooters, pedal cars and similar wheeled toys; do	15	SM_FIN	CONS	1	1		1		0701	3.5	5	-	
950420	9504	Billiard articles and accessories of all kinds	2	SM_FIN	CONS	1	1		0		-	-	-	-	
950430	9504	Games; operated by coins, banknotes, bank cards, tokens c	2	SM_FIN	CAP	1	1		0		-	-	-	-	
950440	9504	Games; playing cardsGames; playing cards	2	SM_FIN	CONS	1	1		0		-	-	-	-	
950450	9504	Games; video game consoles and machines, other than tho	15	SM_FIN	CONS	1	1		1		0702	3.5	5	-	
950490	9504	Games; articles for funfair, table or parlour games, includir	15	SM_FIN	CAP	1	1		1		0701	3.5	-	-	
950510	9505	Christmas festivity articlesChristmas festivity articles	2	SM_FIN	CONS	1	1		0		-	-	-	-	
950590	9505	Festive, carnival or other entertainment articles including r	2	SM_FIN	CONS	1	1		0		-	-	-	-	
		Completed: Completed: Completed: Completed:							31%						

Figure 7. **Screenshot of lifetime coverage sheet**

An additional condition for the requirement to collect lifetime data was the commodities' respective stage in the value chain. For this, the commodities were classified as one of the following end-use categories according to the OECD's Bilateral Trade in Goods by Industry and End-use Category (BTDIxE) system:[5]

- INT: Intermediate goods
- CONS: Household consumption
- CAP: Capital goods
- XMEDIC: Packed medicines
- XPC: Personal computers
- XCARS: Passenger cars
- XPHONE: Personal phones (fixed and mobile)
- XPRCS: Precious goods
- XMISC: Miscellaneous

In principle, intermediate goods (INT) are not relevant regarding lifetimes, only the finished goods in which they ultimately get integrated, since their lifetimes generally determine the fixation of the elements in anthropogenic stocks (see above). The same is true for packed medicines (XMEDIC), as they do not constitute durable goods. Therefore, the intermediate goods and packed medicines categories were conceptually excluded from the research of lifetime data. This yielded a list of 951 final products for which lifetimes were to be collected. In order to provide an initial focus for the data collection, capital goods (CAP), which mainly comprise industrial durable goods, were at first also left out. The remaining categories thus include household durables totalling 286

[5] https://www.oecd.org/sti/ind/bilateraltradeingoodsbyindustryandend-usecategory.htm

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individual commodities. Additional columns in the coverage sheet indicate the degree of completion and methodology of data generation.

Lifetime data is reported in a variety of formats ranging from single data points indicating average lifetimes, to more detailed descriptions of lifetime distributions. While for some product groups, the parameters of such lifetime distributions have been defined based on surveys or samples of discarded products (see section on Global E-waste Monitor below), the majority of lifetime data in the literature is reported as simple averages and lifetime distributions have to be defined based on assumptions or similar product groups. However, as Glöser et al. (2013) have shown, the average lifetimes have a much larger influence on stock dynamics than the shape of the lifetime distributions. The lifetime research in PANORAMA thus prioritized complete coverage of average lifetimes and collected additional information where available.

Product lifetimes information system

An overview of the existing product lifetime data revealed that it is quite limited. Hence, the product lifetimes reporting, and information system was developed.[6] This online platform, which is currently in its test phase, collects and stores consumers' reports on use and disposal patterns for various products they have owned. This allows for the analysis of the harvested data using Markov chains to estimate the durability (time until the first failure) and the total lifetimes (from cradle-to-grave) of the different consumer products. The results are updated live after every new contribution to the platform and are presented in a user-friendly visual format ranking various products' manufactures and models according to the estimated lifetimes (see Figure 8). The product classification presented on the online platform is not finalised yet, so the results of the data harvesting are not finalised.

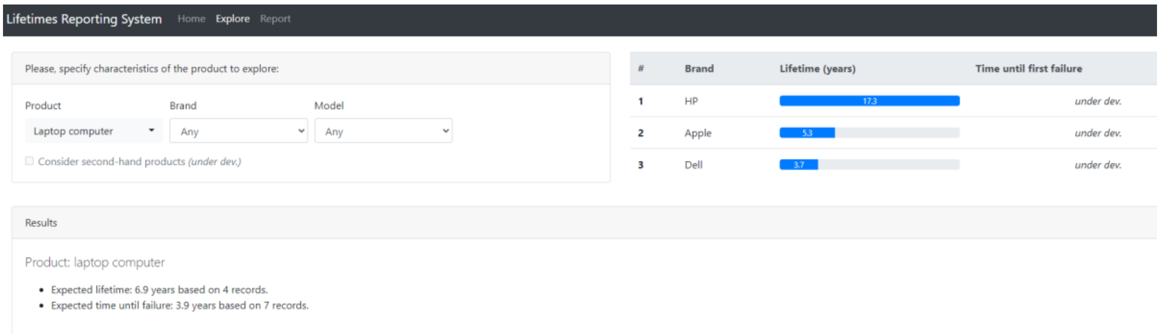

Figure 8. Screenshot of Lifetimes Reporting System

[6] https://lt-platform.web.app/

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Product lifetimes – Global E-waste Monitor

For specific product groups, targeted approaches were used. One example is Electric and Electronic Equipment (EEE), which after disposal, is commonly referred to as Waste of Electric and Electronic Equipment (WEEE). For the portrayal of (W)EEE, the above definition of lifetimes is used. The lifetime, $L^{(p)}$ (t, n), is the lifetime profile of an EEE sold in historical year *t,* which reflects its probable obsolescence rate in evaluation year *n*. The lifetime profile for a product based on discarding can be modelled using several probability functions. The Weibull distribution function is considered to be the most suitable to describe discard behaviour for EEE and has been applied in the scientific literature (Wang et al. 2014; Xianlai et al., 2016). Due to social and technical developments, the lifetime of a product can be time-dependent. For instance, the cathode ray tube monitor rapidly became outdated, due to the technological developments of flat-screen monitors. In that case, lifetime distributions should ideally be modelled for each historical sales year. The Weibull function is defined by a time-varying shape parameter α(t) and a scale parameter β(t) as described in Eq. [1]:

[1] $$L^{(p)}(t,n) = \frac{\alpha(t)}{\beta(t)^{\alpha(t)}}(n-t)^{\alpha(t)-1} e^{-[(n-t)/\beta(t)]^{\alpha(t)}}$$

For other, more stable products, time-independent lifetimes sufficiently describe actual behaviour. In those cases, the variations of the shape and scale parameter over time are minor and can be neglected. In that case, the distribution of product lifetime can be simplified as follows in Eq. [2]:

[2] $$L^{(p)}(t,n) = \frac{\alpha}{\beta^{\alpha}}(n-t)^{\alpha-1} e^{-[(n-t)/\beta]^{\alpha}}$$

Figure 9 shows an example of different lifetime profiles expressed as Weibull functions per type of product in the European Union.

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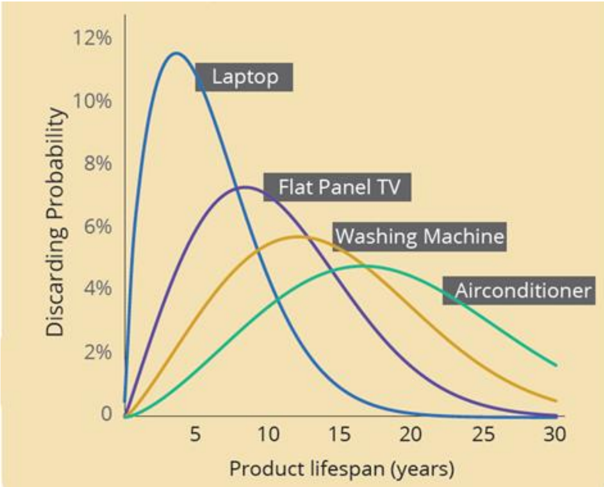

Figure 9. Exemplary lifetimes of typical EEE products

Lifetime data for WEEE was thus obtained for the EU member states using the Weibull distribution. The distributions have been calculated for three economy groups based on the Purchasing Power Parity of each country. Due to the absence of data outside the EU, it was assumed that the higher residence times per product in the EU were approximately applicable for non-EU countries as well.

2.3 End-of-life characteristics

To be able to track substance flows beyond the lifetimes of the products in which they are contained, it is important to know what happens to these products after they have reached the ends of their lifetimes. Within the PANORAMA project, so called End-of-Life (EoL) characteristics are therefore also researched for the product group of electrical and electronic equipment. This narrow focus is necessary because EoL characteristics involve a number of relevant parameters and cannot be determined for all product groups within the scope of PANORAMA. Within the project, EoL characteristics of WEEE are addressed in two different ways:

- An analysis is done on the e-waste that is formally collected and recycled worldwide
- An analysis is done on the recycling efficiency of different metals found in e-waste

E-waste formally collected and recycled

For the EU, the total amount of e-waste formally collected and recycled was extracted from the Eurostat database for 32 countries. The latest data refer to the year 2017. For other countries in the world, data was collected from questionnaires conducted by SCYCLE, OECD, and UNSD. Questionnaires have been distributed to more than 80 countries in total, but in most cases,

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countries did not have any information, and for those that responded, the datasets were far from complete and harmonised. If data was not available, relevant information was searched in the literature. On average, data on e-waste formally collected and recycled refer to the year 2016.

Recycling efficiency of different metals found in e-waste

Data on the recycling efficiency of Aluminium, Iron, Cobalt, Copper, Palladium and Platinum was collected in various ways: a questionnaire was constructed and shared with recyclers and smelters located in different world regions. More than 20 questionnaires were distributed but only two filled it out, of which only one recycler (from Belarus) provided recycling rates for different elements. Due to the scarcity of data collected via the questionnaires, it was decided to conduct a literature review to collect relevant recycling rates of metals found in e-waste in different countries and regions.

It must be noted that data availability is very scarce since data are not collected in a harmonised way from Governments and the information is usually available only at the private sector level. Thus, private companies might not be willing to disclose the information because it may be sensitive and might affect the competitiveness of the company. Data quality is highly affected by the fact that recycling rates of metals found in E-waste collected from the literature may refer to different stages of the recycling process. For example, it may refer to a pre-processing phase or an advanced phase. In the latter case, the recycling rate may be lower due to losses during the recycling processes. In addition, the recycling rate of different metals very much depends on the component that is recycled. As an example, PCB is usually the component that is likely to be recycled the most. Therefore the recycling rate of metals from PCBs may be considerably higher than in other WEEE components. Finally, recycling rates gathered from reports of specific companies may not be representative for the entire country or region where the company is located because each may use different technologies or different recycling processes.

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3. Data coverage and characterisation

3.1 Compositions

Coverage

Of the 5388 commodities in the six-digit HS 2017 code list, 2210 were labelled as containing at least one of the 16 elements either by the binary TNO dataset or by the other sources cited above. Since many commodities contain multiple of these elements, this led to a total of 10,285 possible data points for elementary contents in commodities. Of these, 7252 data points had been identified by the binary TNO dataset, of which 3824 had already been assigned values by the existing sources listed above. These sources also identified an additional 3033 element contents in commodities, which are not listed in the TNO dataset.

Table 3. Summary of composition data points gathered and additional data points from other sources

	Assumed present	Covered	Within PANORAMA	Content indeter-minate	Presence not confirmed	Existing sources	Additional
Co	307	307	62	161	11	73	333
In	107	107	37	35	5	30	202
C	195	195	35	8	152	0	0
Nb	131	131	83	24	0	24	210
W	247	247	121	23	76	27	205
Cu	1347	1347	637	160	166	384	55
Ge	84	84	43	9	0	32	200
Ta	142	142	0	10	65	67	212
Pd	202	202	69	54	26	53	179
Pt	192	192	102	28	0	62	264
Ce	292	292	50	149	19	74	158
La	306	306	50	120	68	68	164
Nd	279	279	84	81	25	89	244
Dy	194	194	97	35	0	62	172
Al	1384	1384	5	19	56	1304	210
Fe	1843	1843	22	184	162	1475	225

Based on the theoretical presence of elements in commodities as defined by the TNO dataset and the already assigned values, a total of 3428 data points were researched within PANORAMA. Among these 3428 data points, 1497 unique element contents were identified, 1100 contents

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could not be unambiguously identified and in 831 cases, the presence of the respective element in a given commodity was ruled out in the course of the research within PANORAMA. Among the 1497 content values, approximately 30% were reported as ranges. The data points covered within PANORAMA plus those from the additional sources are summarised in Table 3. As a comparison of the first two columns indicates, the coverage of all 16 elements can be considered complete. However, Table 3 also indicates that for some elements, the fraction of indeterminate element contents (fourth column) is relatively high, which may caution further research. The coverage is also summarized in Figure 10.

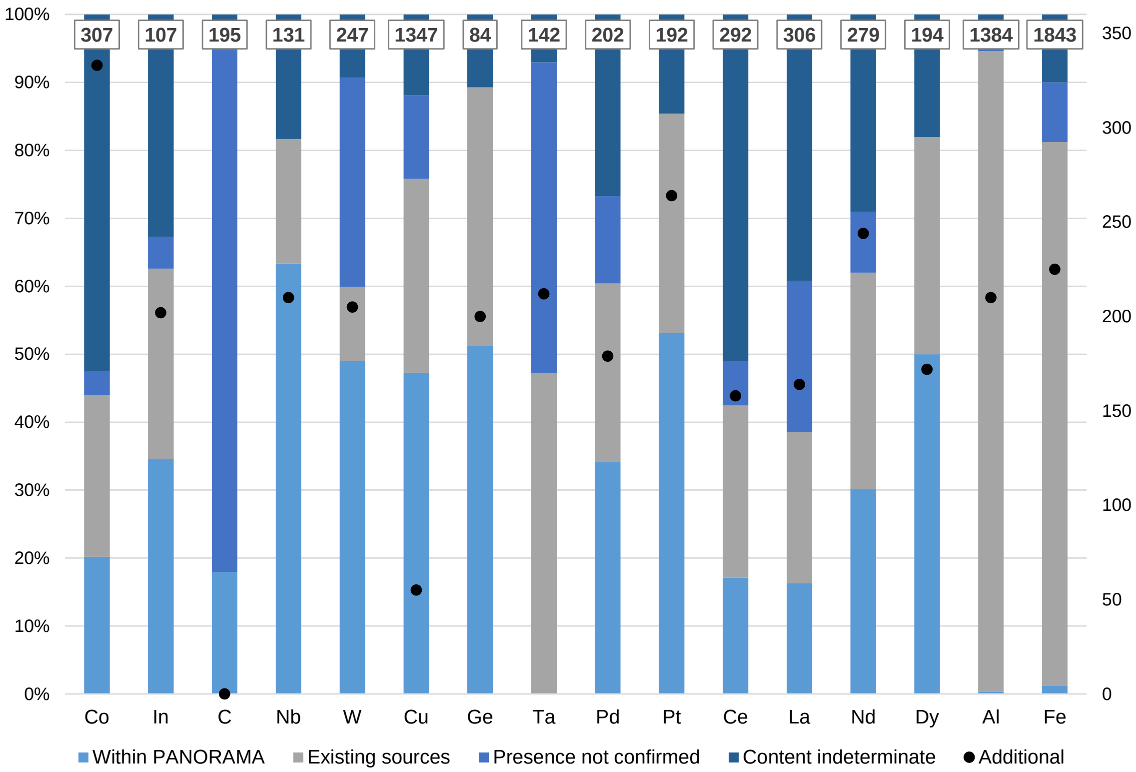

Figure 10. Overview of composition data coverage. Left axis for bars with total coverage in boxes above, right axis for dots.

The coverage of additional information for each composition data point is mixed. Only half of all data points were assigned a value for the year of their generation, while 90% of them contained information on which country they apply to. 93% of data points were specified regarding the type of source they were taken from, while in 81% of the cases the method of the data generated within these sources was reported. All data points were assigned a quality score, while only in

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30% of the cases, the rationale for assigning this score was provided. About one-quarter of all data points contained additional comments on sources, assumptions etc. For a summary, see Table 4.

Table 4. Coverage of additional information next to composition data of all 16 elements

Year	Country	Type of source	Method of data generation	Quality score	Quality score comments	Other comments
50%	90%	93%	81%	100%	30%	26%

Data quality

The quality scores of the composition data are distributed as summarized in Table 5. Only about 1% of the data points were assigned the highest quality (score 1), 28% were assigned the baseline score of 2, while the majority of data points (61%) were assigned the score 3. 11% of the data points received the second-lowest score, while the lowest quality score was only assigned to 0.04% of the data points. Overall, this implies that the majority of the data points is considered relatively robust, while only a small fraction is characterized by high degrees of uncertainty or assumptions that may not hold.

Table 5. Distribution of data quality scores

Score	1	2	3	4	5
Occurrence	1%	28%	61%	11%	0.04%

3.2 Lifetimes

General coverage

From the literature and the Global E-waste Monitor, more than 700 data points have been collected. However, they contain a considerable degree of overlap and mainly correspond to electronic products, buildings and transport. Therefore, approximately 50 additional sources have been consulted, leading to a coverage of nearly 100% for household durables (285 of 286 data points have been assigned lifetime values so far). For industrial capital goods (CAP), 661 of the required 665 data points could be assigned lifetime values, which equals a coverage of 99%. The global coverage of the required 951 lifetimes thus also equals 99% with 946 entries.

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Table 6. **Coverage of lifetime data for different categories**

Caetgory	CAP	CONS	XCARS	XMISC	XPC	XPHONE	XPRCS
Required	665	253	13	6	10	1	3
Covered	661	252	13	6	10	1	3
Coverage	99%	100%	100%	100%	100%	100%	100%

Lifetimes of WEEE

Lifetime data for WEEE was obtained for the EU member states using the Weibull distribution. Ideally, the lifetime of each product is determined empirically per product per type of country. At this stage, only harmonised European residence times of EEE were available from extensive studies performed for the EU and were found to be quite homogeneous across Europe, leading to a 10% deviation in outcomes (Magalini et al. 2014). Since data for non-EU countries were estimated from EU values, in some cases, this would lead to an underestimation, as a product could last longer in developing countries than in developed countries because residents of developing countries are likelier to repair products. However, it can also lead to an overestimation, as the quality of products is often lower in developing countries because reused equipment or more cheaply produced versions that do not last as long might enter the domestic market. However, in general, it is assumed that this process leads to relatively accurate estimates. Table 7 presents the lifetime distributions estimated by UNU in this way for both EU and non-EU countries.

Table 7. Lifetime distributions estimated by UNU for both EU and non-EU countries

UNU_KEYs	**Weibull Lifetime distribution in the Netherlands, France and Belgium**		**Weibull Lifetime distribution in Italy**		**Proxy of Weibull Lifetime distribution used for non-EU countries**	
* Data refers to 2016	*α*	*β*	*α*	*β*	*α*	*β*
0001	2.00	14.21	2.00	14.21	2.00	14.21
0002	3.50	25.00	3.50	25.00	NA	NA
0101	1.95	17.52	1.14	16.07	1.92	16.07
0102	1.64	14.20	1.37	14.28	1.79	17.13
0103	2.47	18.04	1.31	19.35	2.00	19.35
0104	2.20	15.16	2.20	13.65	1.85	13.32
0105	2.58	15.73	2.58	15.73	2.58	18.08
0106	2.00	13.47	1.22	18.80	2.00	13.47

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0108	2.20	16.43	2.36	18.50	2.20	16.71
0109	2.74	24.20	1.28	18.55	1.28	18.55
0111	2.69	14.52	1.05	7.53	2.00	20.60
0112	2.39	13.56	1.29	8.29	2.36	13.36
0113	2.44	20.56	2.50	18.02	1.60	15.36
0114	1.90	14.07	1.33	9.05	2.07	17.99
0201	1.25	8.17	0.83	6.53	1.22	7.97
0202	2.06	11.22	1.15	9.57	2.02	11.02
0203	1.73	7.80	1.18	7.61	1.18	7.61
0204	1.45	10.25	1.22	10.59	1.22	10.59
0205	1.26	10.67	1.20	8.09	1.20	8.09
0301	1.25	5.91	1.30	6.15	1.30	6.15
0302	1.58	8.95	1.57	8.91	1.80	10.33
0303	1.60	6.57	1.66	6.81	1.94	8.76
0304	1.68	9.91	1.53	6.88	1.88	9.31
0305	1.24	7.22	1.32	7.70	1.32	7.70
0306	1.56	6.26	1.52	5.62	1.52	5.62
0307	1.46	7.78	1.46	7.78	1.46	7.78
0308	2.41	12.53	1.40	15.94	1.40	15.94
0309	2.33	7.39	2.33	7.39	2.30	12.18
0401	1.30	9.87	1.30	9.87	1.30	9.87
0402	0.79	7.97	1.11	5.56	1.50	10.01
0403	2.09	15.54	1.25	13.99	2.30	10.00
0404	1.67	10.47	1.14	8.33	1.14	8.33
0405	1.49	10.78	1.13	12.54	1.13	12.54
0406	1.41	8.12	1.19	6.75	1.19	6.75
0407	2.49	12.08	2.49	12.08	2.49	12.08
0408	2.01	11.75	2.01	11.75	1.88	10.95
0501	1.42	8.72	1.42	8.72	1.42	8.72
0502	1.60	8.43	1.60	8.43	NA	NA
0503	1.93	8.43	1.93	8.43	1.75	5.79
0504	1.60	6.90	1.60	6.90	1.60	6.90
0505	1.42	11.00	1.42	11.00	NA	NA
0506	2.34	16.59	2.34	16.59	2.34	16.59
0507	2.00	11.84	2.00	11.84	2.00	12.50
0601	1.82	11.28	1.82	11.28	1.77	14.98
0602	2.50	15.50	2.50	15.50	2.50	15.50

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0701	1.43	4.56	1.43	4.56	1.43	4.56
0702	1.14	4.78	1.14	4.78	1.14	4.78
0703	2.40	11.56	2.40	11.56	2.40	11.56
0801	1.99	13.46	1.99	13.46	1.99	13.46
0802	2.41	13.52	2.41	13.52	2.41	13.52
0901	1.55	5.89	1.55	5.89	1.55	5.89
0902	1.92	11.56	1.92	11.56	1.92	11.56
1001	2.00	10.06	2.00	10.06	2.00	10.06
1002	2.00	10.06	2.00	10.06	2.00	15.00

3.3 End-of-life characteristics

E-waste formally collected and recycled

Table 8 summarises the formal collection and recycling rates for all countries for which it was possible to gather data.

Table 8. Formal collection and recycling rates by country

Country	Year	Source	Coll_rate
ARG	2013	Telecom Argentina	3%
AUS	2018	Australian Ministry of Environment	11%
AUT	2017	Eurostat_2019	69%
BEL	2016	Eurostat_2019	55%
BGR	2017	Eurostat_2019	70%
BLR	2017	UNSD_Questionnaire_2019	8%
BRA	2012	Informe de Sostenibilidad Corporativa 2012	0.01%
CHN	2018	China Ministry of Environment	16%
CMR	2018	Solidarite Technologique	0%
CYP	2016	Eurostat_2019	17%
CZE	2017	Eurostat_2019	57%
DEU	2017	Eurostat_2019	52%
DNK	2017	Eurostat_2019	54%
ECU	2017	UNSD_Questionnaire_2019	0.01%
ESP	2017	Eurostat_2019	33%
EST	2017	Eurostat_2019	76%
FIN	2017	Eurostat_2019	61%
FRA	2017	Eurostat_2019	56%

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GBR	2017	Eurostat_2019	57%
GRC	2017	Eurostat_2019	31%
HKG	2013	Hong Kong EPD	41%
HND	2015	Rush Martinez et. al, 2015	1%
HRV	2017	Eurostat_2019	78%
HUN	2017	Eurostat_2019	51%
IND	2016	Assocham India	1%
IRL	2017	Eurostat_2019	59%
ISL	2017	Eurostat_2019	71%
ITA	2016	Eurostat_2019	34%
JAM	2017	TMG - National Solid Waste Management Authority	0.3%
JOR	2018	Jordan National Statistics Office	2%
KAZ	2017	UNSD_Questionnaire_2019	7%
LCA	2015	Roldan, 2017	2%
LTU	2017	Eurostat_2019	40%
LUX	2017	Eurostat_2019	55%
LVA	2017	Eurostat_2019	46%
MLT	2016	Eurostat_2019	27%
MUS	2011	Africa Institute 2012	22%
NAM	2019	Namigreen	0.2%
NLD	2017	Eurostat_2019	46%
NOR	2017	Eurostat_2019	72%
PER	2017	Peruvian Ministry of Health	1%
POL	2017	Eurostat_2019	60%
PRT	2017	Eurostat_2019	42%
ROU	2016	Eurostat_2019	23%
RUS	2014	Analytical Center for the Governament of Russian Federation	6%
RWA	2018	Ministry of Trade and Industry	11%
SLV	2012	MINED	2%
SRB	2015	IENE	22%
SVK	2017	Eurostat_2019	45%
SVN	2016	Eurostat_2019	41%
SWE	2017	Eurostat_2019	70%
TUR	2015	Exitcom	18%
UGA	2018	Computers for School Uganda	1%
UKR	2017	UNSD_Questionnaire_2019	13%

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USA	2017	US EPA	15%
ZAF	2015	Lydall M. et al., 2017	5%
ZWE	2017	UNSD_Questionnaire_2019	0.2%

Recycling efficiency of different metals found in e-waste

In the context of this study, a desktop research was conducted to collect data regarding the recycling efficiency of specific elements embedded in e-waste. The recycling efficiency is defined as the percentage of material that can be recycled from e-waste by means of any recycling method. In this study, the main goal was to collect data on the recycling efficiency in countries with different income levels to investigate whether countries that are likely to have a better e-waste management system are also showing higher recycling efficiencies. In contrast, countries where the e-waste recycling is done mostly manually, may reach higher levels of recycling efficiency because in some cases the manual dismantling and recycling is more efficient than the mechanical one (this is the case of gold, for example).

The recycling efficiency of Aluminium, Copper, Cobalt, Iron and Palladium found in e-waste was collected for four groups of countries according to their Purchasing Power Parity (PPP). The groups of countries are in line with the categorization developed in the Global E-waste Monitor 2020 (Forti et al, 2020). However, only group 1, 2, 3 and 4 were selected due to the absence of data for the lower income countries in group 5. The groups are defined as follows:

- Group 1: highest PPP (higher than $32,312 USD per capita in 2016)
- Group 2: high PPP ($32,312 USD - $13,560 USD per capita in 2016)
- Group 3: mid PPP ($13,560 - $6,217 USD per capita in 2016)
- Group 4: low PPP ($6,217 - $1,769 USD per capita in 2016)
- Group 5: lowest PPP (lower than $1,769 USD per capita in 2016).

The data collected referred to the following countries (in brackets it is specified the economic group):

Table 9: Country groups according to PPP

EU (1,2,3)	US (1)	Switzerland (1)
China (2)	France	Germany (1)
Japan (1)	Belgium (1)	India (3)

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South-Africa (3)	Australia (1)	Ghana (4)

In total, 93 data points were collected for 12 different countries/regions and for the elements listed above. The data was collected from 19 different sources and ranges from 2007 to 2017. The recycling rates were sometimes referred to specific products (e.g. washing machines, CRT TVs, desktops, mobile phones, laptops etc.) and it was not possible to collect recycling efficiency data for all the selected elements and for all countries. Therefore, a methodology was developed to estimate the missing data points and to validate or discard the ones collected from the literature. The main steps that were undertaken were:

1) Collection of any data related to the recycling efficiency of the selected elements (Al, Co, Cu, Fe, Pd);
2) Data analysis and estimation methods that included:
    a. Priority is given to the recycling efficiency data that refers to a specific country and product;
    b. If data at point a. was not available, a general recycling efficiency by country was selected;
    c. If the data collected was considered outliers, the data points were substituted with an average recycling efficiency per stratum;
    d. Missing data for specific countries and elements were estimated using the average recycling efficiency per stratum.

Recycling rate of specific elements found in e-waste formally collected and recycled

As described above, the first step was to collect data on the e-waste formally collected and recycled and consequently to calculate the recycling rate as:

$$Recycling\ rate\ of\ e-waste\ in\ Country\ A = \frac{total\ e{-}waste\ formally\ collected\ and\ recycled\ in\ Country\ A}{total\ e{-}waste\ generated\ in\ the\ country\ in\ Country\ A}$$

Both indicators needed to calculate the recycling rate of e-waste are sourced from the Global E-waste Monitor 2020 (Forti et al., 2020). The second step was to collect data on the recycling efficiency of specific elements (Aluminium, Copper, Cobalt, Iron and Palladium) for a sample of countries representative of different income levels.

As a third step, the recycling efficiency of the specific elements were linked to the recycling rates of the e-waste to derive the actual recycling rate of specific elements treated in a formal manner. The recycling rate of specific elements found in e-waste formally collected and recycled is calculated as follows:

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$$Recycling\ rate\ of\ element\ 1\ found\ in\ e-waste\ in\ Country\ A$$
$$= Recycling\ rate\ of\ e-waste\ in\ Country\ A$$
$$* Recycling\ efficiency\ \ of\ element\ 1\ in\ Country\ A$$

Figure 11 shows that higher income countries, which normally reach higher formal collection and recycling rates, also show a higher recycling of the elements listed above.

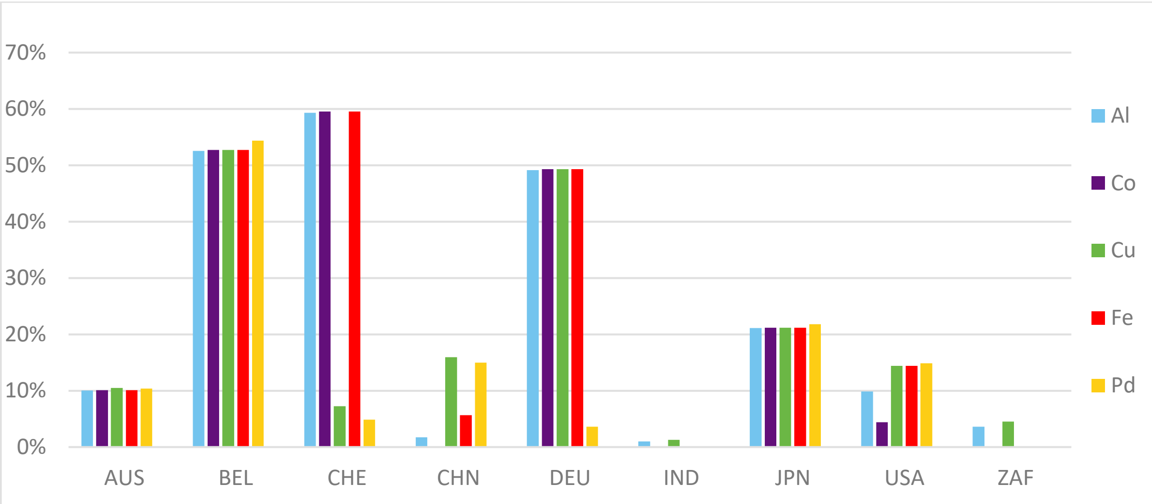

Figure 11: Recycling rate of specific elements found in e-waste formally collected and recycled

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4. Conclusions

The composition and lifetime data collection involved a considerable degree of manual scanning of various types of documents, using different terminologies, definitions as well as product and sector delineations and classifications. While some data points could be determined by researching a single number, others required in-depth research of not just product characteristics but also other parameters, such as market shares. In addition to composition and lifetime data, end-of-life characteristics, such as collection rates and recycling efficiencies, were collected for the product group of electrical and electronic equipment. This narrow focus was necessary because EoL characteristics involve a number of relevant parameters and could not be determined for all product groups within the scope of the PANORAMA project.

In the case of compositions, a total of 3428 data points were researched, of which 1497 were unique element contents assigned to the respective products, while 1100 contents were indeterminate and in 831 cases, the presence of the respective element in a given product was ruled out. Of the determined contents, approximately 30% were reported as ranges, reflecting different variants of the products summarized under individual HS codes that have different contents, as well as uncertainty in the data in some cases. In addition, the contents of the considered elements were often reported in different units, such as in mass per unit of product, in weight fractions or in weight percentages. To have a harmonised unit system, weight percentages and weight fractions were selected as the preferred units for composition data within PANORAMA. This required the conversion of composition data reported in other units, for instance, by using the reported mass of the target product. This conversion might have added more uncertainty to the data points, as the product weight might differ for different sources, specific product technologies or reference year of production.

A certain degree of uncertainty was also reflected in the distribution of the quality scores, which were dominated by medium scores, though with a skew towards higher scores. While the composition data is labelled as complete, additional research could go into the 1100 instances in which element contents could not be unambiguously determined. In addition, data points with low quality scores could be revisited in order to find more robust values. It is also conceivable that the balancing routine in Work Package 5 will reveal discrepancies between aggregate production and trade numbers of raw materials and the results of the calculations utilising the composition data. Such discrepancies may thus indicate the need for further research.

Assigning HS codes to the products for which composition data was collected was a challenging task and required interpretation of the code descriptions. The HS codes consist of a standardised

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classification method based on technical terms to describe a product or commodity. In some cases, the HS description of a product uses terminologies well known within the respective industrial sectors or the trade community, but these terms are less known by the general public. When assigning a specific HS code to a product, which was reported in the literature by its usual or commercial name, a good understanding or interpretation of the HS codes description was required. Often, the link between HS code description and the common product name was not straightforward, but an HS code was assigned based on basic research and interpretation of the technical terms used. In some cases, one HS code description could be related to several categories of the same products, such as one code referring to different chemistries and compositions of lithium-ion batteries. On the other hand, for some products, very specific HS codes were available whereas the product reported in the literature was less specific. An example is a product reported by different sources as “printer” or “printing machine”, without further specification of the product. In the HS code list, a total of 13 codes refer to “printing machinery” and its parts or accessories. In cases like this, the content value reported in the literature was applied to all codes initially assigned as containing the element.

The collection of lifetime data is nearly completed. Of the 951 products for which lifetime data was to be collected, approximately 98% are covered. The dataset will undergo a final quality check before it will be submitted. For the majority of products, average lifetimes were found without further information on lifetime distributions. In such cases, assumptions will have to be made on likely distributions or reported distributions of similar products will have to be used. Additional insights may be gained over time from the lifetimes reporting platform.

Data on the formal recycling of specific elements found in e-waste are scattered and not harmonized worldwide for various reasons: different product scope in the national legislations leads to unreported data, only few countries in the world are collecting statistics on e-waste formally collected and recycled, data in the literature regarding both e-waste formally collected and recycled and the recycling efficiency of different elements are very scarce. In particular, the latter information is highly dependent on the recycling processes, technology used, type of product recycled, geographical location of the recycler etc. Nevertheless, from the analysis conducted in this study, it is possible to conclude that higher income countries such as European countries usually reach higher formal recycling rates and consequently higher efficiency in terms of recycling of the elements embedded in the e-waste. On the other end, lower income countries may have a strong informal sector and therefore the recycling efficiency of certain elements can still be rather high, but since these activities are undertaken by the informal sector, there is hardly any data available on the amount of e-waste that is formally collected and recycled.

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Next steps include (i) additional research on composition data for indeterminate contents ("X -"); (ii) refinement of the existing composition data for which the data quality was judged to be low; and (iii) revising the data points based on results of the balancing routines (WP5). Further research regarding composition and lifetime data could also be outsourced by publishing the datasets on a platform, which allows for the revision of data points based on specific expertise.

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