Supplementary Material for:

Where Do Our Resources Go? Indium, Neodymium, and Gold Flows Connected to the Use of Electronic Equipment in Switzerland

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S1 Content

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S4 Metal content

S4.1 Data quality indicators

The quality of mass and metal content data varies highly, depending on the data source. In order to assess the quality of these input data, we introduced data quality indicators, similar to the pedigree matrix of Weidema and Wesnæs.[1] The indicators include the sample size, the measurement or modelling approach and the analysis method, referring to the "reliability", "completeness" and "further technical correlation" indicators proposed by Weidema and Wesnæs.[1] A "temporal correlation" indicator has not been taken into account since all sources included for mass and metal content data have a maximum difference of 4 years to the year of the study. A "geographical correlation" indicator was also not included since mass and metal content of electronic equipment (EE) does not vary between countries or regions. The scores with its explanation and weighting factors were adopted from Loevik et al.[2] Table S1, S2 and S3 describe in detail the different indicators and the related scores.

For metals contents in EE, various observations are available. In order to provide data with good data quality with more weight in the subsequent conversion to a probabilistic distribution, the sum of the three indicators for each observation are translated to a weighting factor according to Table S4. For example, if the neodymium content in mobile phones is measured by inductively coupled spectroscopy from a sample of 50 devices, the data is given a higher weight compared to data resulting from one device and unspecified chemical analysis. However, despite low data quality, all available data is included to express the wide range of observations and the related uncertainty.

Table S1: Sample size indicators

Sample size	Indicator score
Sample size >1	Log_2(sample size)
Sample size = 1	1
Sample size unknown	1

Table S2: Measurement or modelling approach indicators

Measurement or modelling approach	Indicator score
No modelling. Data is directly from measurement.	5
Hot-spot approach: the composition of an entire product or component is measured based on a subset of components	4
Sum of various sources	3
Average over various device types	2
Other modelling approaches	2
Values derived from other device type	1
Unknown method	1

Table S3: Analysis method indicators

Analysis method	Indicator score
Full materials declarations	5
Inductively coupled spectroscopy	5
Data from producer	5
Weighing, after dismantling components or materials	5
Atomic Absorption Spectrometry	4
X-Ray Fluorescence Analysis	3
Unspecified chemical analysis	3
Data from market analysis	2
Unknown	1

Table S4: Weighting factors based on summed up indicators

Sum indicator	Description	Weighting factor w_i
1-6	dubious	1
7-12	less confident	2
13-18	confident	3
>18	highly confident	4

S4.2 Triangular distribution

According to Gottschalk et al. [3] who proposed probabilistic material flow modelling, triangular distributions are used if the most probable outcome (mode or modal value) is vaguely known. Triangular distributions have finite limits and may be skewed or symmetrical. For metals contents with various observations available a weighted mean $\bar{x}_w$ is calculated according to Equation (S1). The lower and upper limit of the triangular distribution was calculated by Equation (S2) and (S3).

$$\bar{x}_w = \frac{\sum_{i=1}^{n} w_i \cdot x_i}{\sum_{i=1}^{n} w_i} \qquad \text{(S1)}$$

With:

n: Number of observations

w_i: weighting factor [-] (see Table S4)

x_i: observation [kg/product]

$$ll = \bar{x}_w - (\bar{x}_w - o_l) \cdot EF \quad \text{(S2)}$$

$$ul = \bar{x}_w + (o_h - \bar{x}_w) \cdot EF \quad \text{(S3)}$$

With:

ll: lower limit [kg/product]

ul: upper limit [kg/product]

$\bar{x}_w$: weighted mean [kg/product]

o_l: lowest observation [kg/product]

o_h: highest observation [kg/product]

EF: extension factor

The extension factors depend on the sample size and are determined according to information from JCGM.[4] They correspond to twice the standard deviation of the standard deviation, so that the lower and upper limit of the triangular distribution should lie within the 95% confidence interval of the mass or metal content. Figure S1 illustrates an example of a triangular distribution.

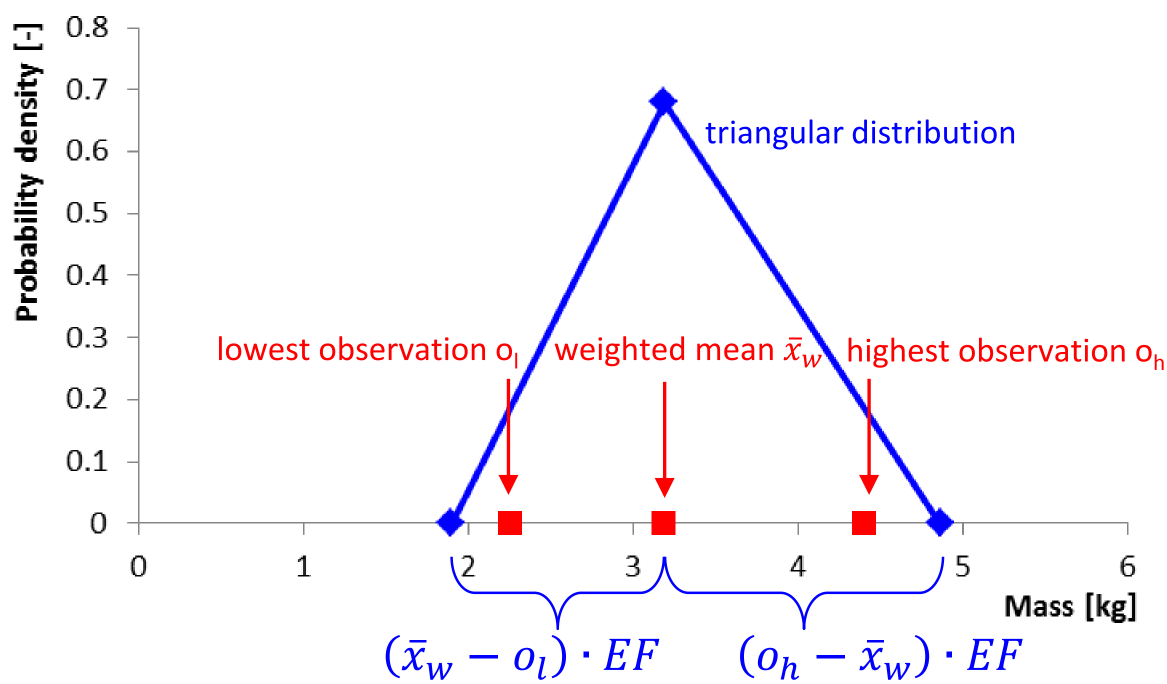

Figure S1: Calculation of upper and lower limit of triangular distribution

For metals contents with only one observation available, the best matching device and the same metal was chosen as a proxy for the uncertainty. Of each proxy, the ratios r_l and r_u of the distance between the weighted mean and the upper and lower limit, over the weighted mean are calculated according to

Equations (S4) and (S5). Based on the available observation combined with r_l and r_u of the proxy, the lower and upper limits of the triangular distribution are calculated.

$$r_l = \frac{(\bar{x}_w - ll)}{\bar{x}_w} \tag{S4}$$

$$r_u = \frac{(ul - \bar{x}_w)}{\bar{x}_w} \tag{S5}$$

With:

$\bar{x}_w$: weighted mean [kg/product]

ll: lower limit [kg/product]

ul: upper limit [kg/product]

The resulting data are presented in Table S5, S6 and S8.

Table S5: Parameters for triangular distribution of indium content in mg/product

Device type	Lower limit	Weighted mean/ observation	Upper limit	Data source
Desktop computer	-	-	-	-
Laptop computer	0.28	48.4	77.0	[5–8]
Monitor	54.5	74.8	101	[5–8]
FPD TV	9.01	227	442	[5–8]
CRT TV	-	-	-	-
Mobile phones	0	2.26	6.31	[8,9]
Smartphones	0	0.825	2.87	[8,10]
Headsets	-	-	-	-
DVD player	-	-	-	-

Table S6: Parameters for triangular distribution of neodymium content in magnets in mg/product

Device type	Lower limit	Weighted mean/ observation	Upper limit	Data source
Desktop computer HDD	4019	5033	5620	[7,11–14]
Desktop computer SSD	0.4518	168.4	252.4	[13,14]
Laptop computer Hard disk drive (HDD)	1240	3137	6346	[5,7,11,13,14]
Laptop computer Solid state disk (SSD)	618.3	1075	1570	[5,7,11,13,14]
Monitor	67.39	75.57	79.67	[14]
FPD TV	313.9	352.0	371.0	[13,14]
CRT TV	0.000	159.1	358.5	[13,14]
Mobile phones	51.41	107.5	163.6	[5,7,11,13,14]
Smartphones	42.37	103.3	185.2	[5,7,10,14]
Headsets	64.37	97.45	119.5	[7,11]
DVD player	58.05	222.1	376.7	[9,13–15]

For the dynamic material flow analysis (MFA), we distinguish between flows of neodymium in magnets and printed wiring boards (PWBs). Table S7 lists the triangular distribution parameter of the share of neodymium in magnets and PWBs. In the simulation process, the random values of these transfer coefficients are adjusted after sampling to avoid combinations violating mass balance constraints. This is done by using a normalization factor over all involved transfer coefficients according to Bornhöft et al.[16]

Table S7: Parameters for triangular distribution of share of neodymium in magnets and printed wiring boards (PWBs)

Device type	Fraction	Lower limit	Weighted mean/ observation	Upper limit	Data source
Desktop computer Hard disk drive (HDD)	Magnet	0.96	0.97	1.00	[7,11–14]
Desktop computer HDD	PWB	0.00	0.03	0.04	[7,11–14]
Laptop computer HDD	Magnet	0.93	0.96	1.00	[5,7,11,13,14]
Laptop computer HDD	PWB	0.00	0.04	0.07	[5,7,11,13,14]
Laptop computer Solid state disk (SSD)	Magnet	0.73	0.87	1.00	[5,7,11,13,14]
Laptop computer SSD	PWB	0.00	0.13	0.27	[5,7,11,13,14]
Mobile phones	Magnet	0.89	0.94	1.00	[5,7,14]
Mobile phones	PWB	0.00	0.06	0.11	[5,7,14]

Device type	Fraction	Lower limit	Weighted mean/ observation	Upper limit	Data source
Smartphones	Magnet	0.90	0.94	1.00	[5,7,10,14]
Smartphones	PWB	0.00	0.06	0.10	[5,7,10,14]
DVD player	Magnet	0.27	0.57	0.66	[9,13–15]
DVD player	PWB	0.34	0.43	0.73	[9,13–15]

Table S8: Parameters for triangular distribution of gold content in mg/product

Device type	Year	Lower limit	Weighted mean/ observation	Upper limit	Data source
Mobile phones	2009	5.58	45.9	81.2	[5,13,17,18]
Smartphones	2009	3.64	30.0	53.0	[5]
Headsets	all years	-	-	-	-
Laptop computer	2006	11.3	165	319	[5,13]
Desktop computer	2006	152	313	364	[13,17,18]
Monitor	all years	13.4	196	379	[5,6]
CRT TV	all years	0.00	11.1	17.1	[13,17]
FPD TV	all years	0.00	284	653	[5,6,13]
DVD player	all years	45.2	71.5	115	[13,17,18]

The temporal change of the gold content in desktop and laptop computers as well as mobile and smart phones was calculated based on data from Bangs et al.[19] They show a declining gold content by 40% in high grade printed wiring boards received for recycling between 2003 and 2015 or an average decline of 3.3% per year

The available gold content data was published between 2010 and 2012 for the four device types. Desktop and laptop computers have a median lifetime of 5 years, mobile and smartphones of 3 years.[20] We assumed that the available data origin from obsolete devices collected on average in 2011 and are most representative for computers sold in 2006 and phones sold in 2009. From here we assumed a linear increase back to the year 2003 and a decrease to the year 2015. Due to the lack of data, we assumed a constant value of gold content before 2003. The lower and upper limits of the triangular distributions for each yearly data input was also assumed to linearly increase back to the year 2003 and decrease to the year 2015.

We further assumed that the neodymium content before 1983 was zero for all devices according to Du and Graedel.[21]

S4.3 SSD technology diffusion model

Desktop and laptop computers arecurrently undergoing a technology change from hard disk drives (HDDs) to solid state drives (SSDs). The resulting decrease in neodymium content was computed by assuming a simple logistic diffusion model for the SSD technology according to equation (S6). The parameters were fitted with the "least square method" to available data on the share of desktop and laptop computers with SSD sold in Switzerland in 2015 and 2016.[22] The resulting diffusion curves are depicted in Figure S2. The fitting to only two data points was backed up with plausibility considerations: the first SSDs were put on the end-user market in 2006[23] and experts from Hitachi Data Systems expect, that between 2020 and 2025, most desktops and laptops sold will only contain SSDs.[24]The uncertainties of desktop and laptop inflow data were modeled as normal distributions, with a standard deviation estimated at 20% of the inflow value.

$$Inflow(t) = \frac{p_1}{1 + \mathrm{e}^{-p_2((t-t_0)-p_3)}} \qquad (S6)$$

Desktop:	Laptop:
$t_0 = 1983$	$t_0 = 1989$
$p_1 = 1$	$p_1 = 1$
$p_2 = 0.76$	$p_2 = 0.41$
$p_3 = 33.99$	$p_3 = 27.29$

With:
p_1: saturation value of devices containing SSDs [-]
p_2: steepness of the sigmoidal curve [-]
p_3: midpoint of the growth trajectory [-]

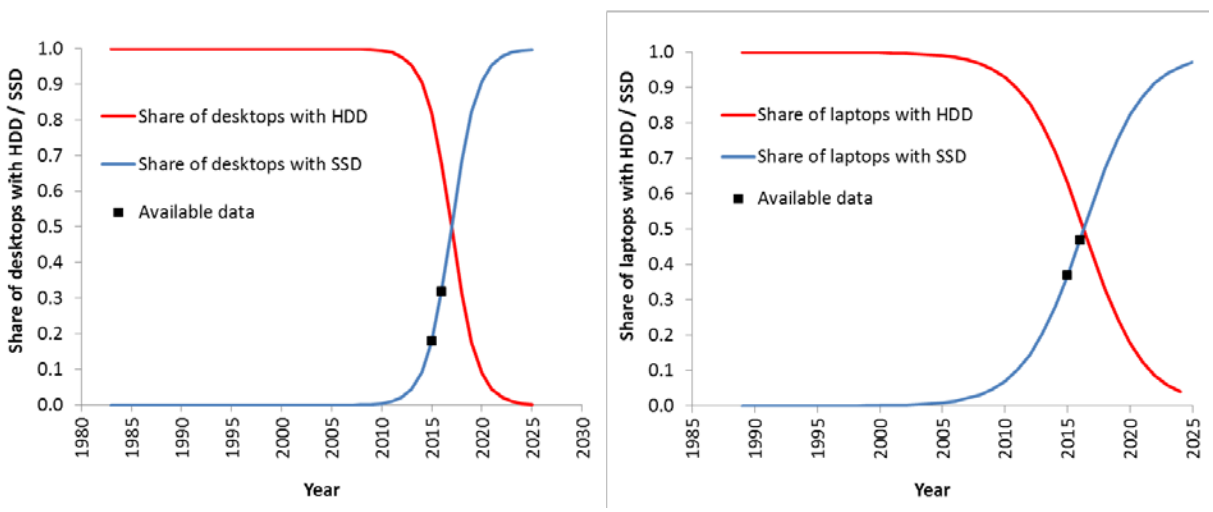

Figure S2: Diffusion model of desktop and laptop computer with SSDs.

S5 Extrapolation of sales data

For the prospective MFA of neodymium in magnets, we extrapolated sales data from 2014/2015, taken from Thiébaud et al.,[25] up to the year 2050. As yearly sales flows are often fluctuating, we assume an increasing uncertainty from 2014/2015 up to 2050, modeled as normal distributions. The uncertainty in the year 2014/2015 are adopted from Thiébaud et al.25 The data sources and all extrapolation parameters are listed in Table S9.

Cumulated sales of conventional mobile phones and smartphones have been stable for the last 5 years. The stock growth of the sum of mobile phones and smartphones has been close to 0 for the last 4 years. Thus the stock is saturated and new phones are only bought to replace obsolete phones.[25,26] The total number of sold mobile phones is assumed to remain in a steady state at the level of 2015. Future smartphone sales are modeled with a logistic function fitted to current sales data. The uncertainty increases from 10% in 2016 to 30% in 2050.Sales of conventional mobile phones are an inverse proportion to sales of smartphones and are again modeled up to the year 2050 with a logistic function fitted to current sales data. It is assumed that conventional mobile phones sales are stabilizing at a 1% rate, as there will remain a small demand for conventional mobile phones (Figure S3).

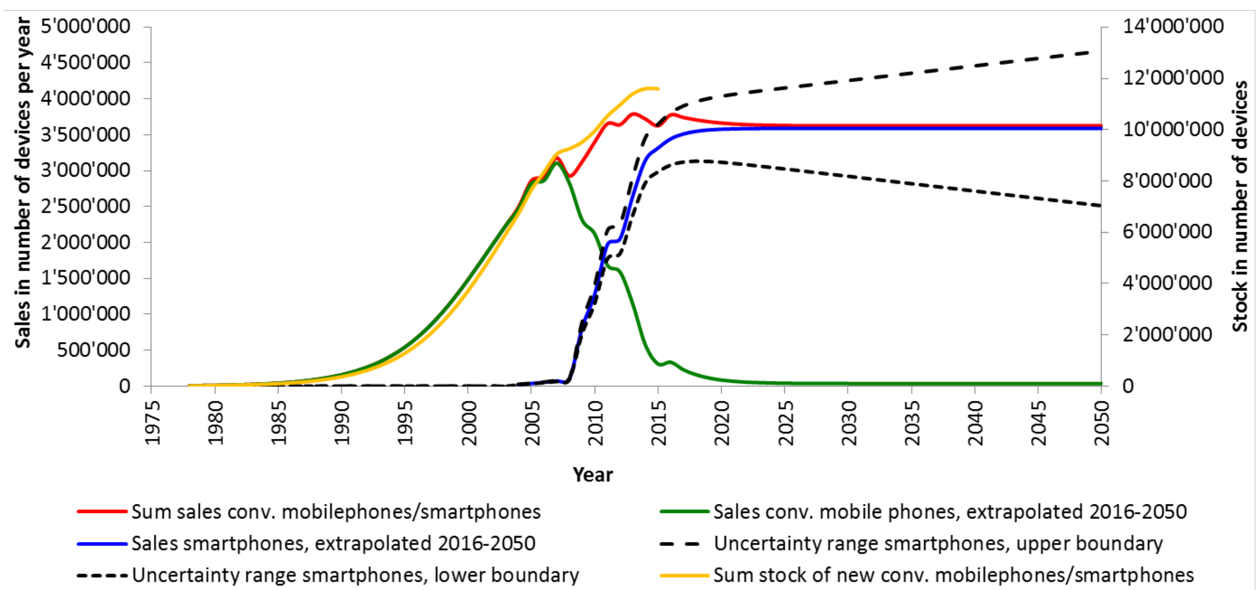

Figure S3: Sales and stock of conventional mobile phones and smartphones, with sales extrapolated to the year 2050. For the sake of simplicity, we refrain from illustrating the uncertainty ranges of mobile phones.

Sales of laptop computers have been fluctuating in the past ten years. The stock of new devices, however, is saturated. [25,26] Sales decreases due to the introduction of tablet computers have ceased in 2014. We therefore modeled laptop sales as a steady state inflow at the level of 2014.[27] The total number of laptop sales is then divided into laptops containing HDDs and SSDs, according to the SSD technology diffusion model. The uncertainty increases from 20% in 2015 to 30% in 2050 (Figure S4).

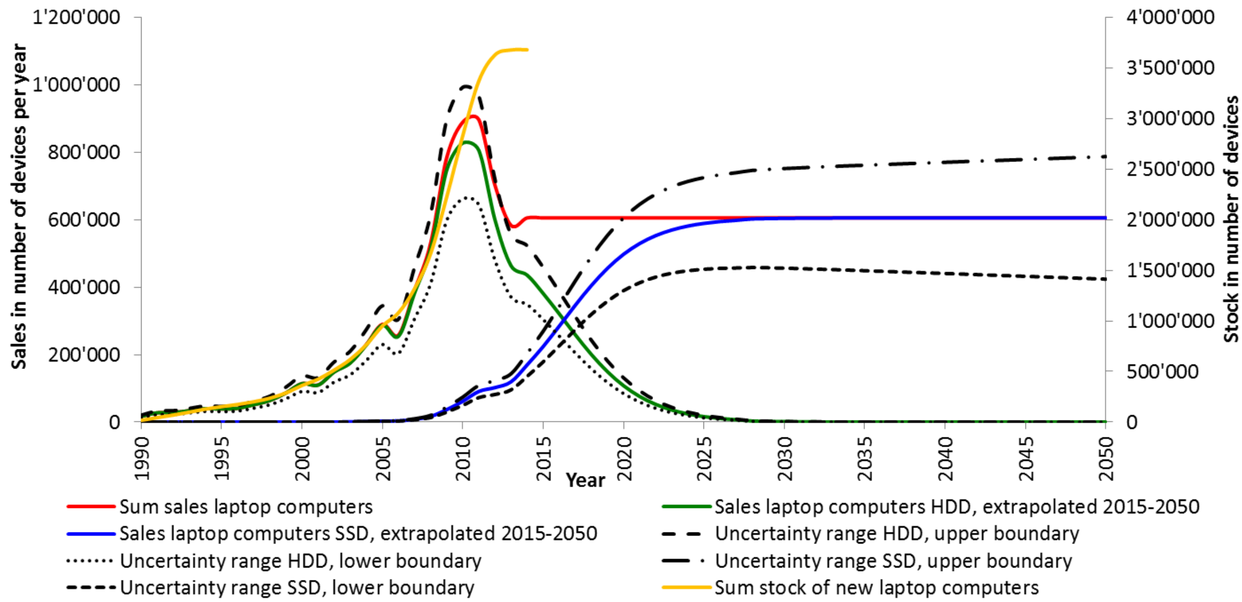

Figure S4: Sales and stock of laptop computers, with sales extrapolated to the year 2050.

Desktop sales have been declining in the past ten years, mostly due to increased sales of laptops. The stock of new devices is declining as well. It is difficult to estimate the future role of desktop computers in our society and all assumptions bear high uncertainties. However, as desktop computers with HDDs are replaced by desktops with SSDs that contain no neodymium magnets, our model of future sales of desktop computers is not very relevant. It is assumed that desktop sales will further decline and stabilize at a 50% level of sales in 2014. The total number of desktop sales is then divided into desktops containing HDDs and SSDs, according to the SSD technology diffusion model. The uncertainty increases from 20% in 2015 to 30% in 2050 (Figure S5).

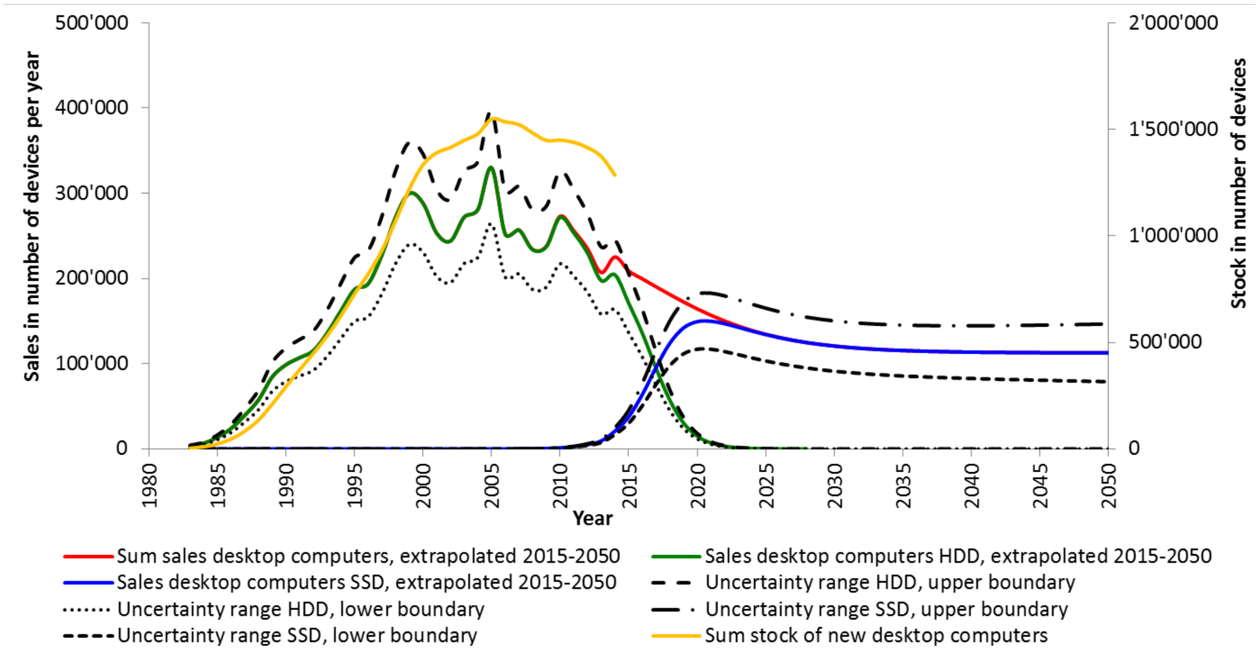

Figure S5: Sales and stock of desktop computers, with sales extrapolated to the year 2050.

Sales of headphones have been declining slightly and the stock of headphones is saturated. [25,26] We assume that the use of headphones will remain constant at the level of sales in 2015, based on a logistic function fitted to current sales data. The uncertainty is set to 30% for all sales years (Figure S6).

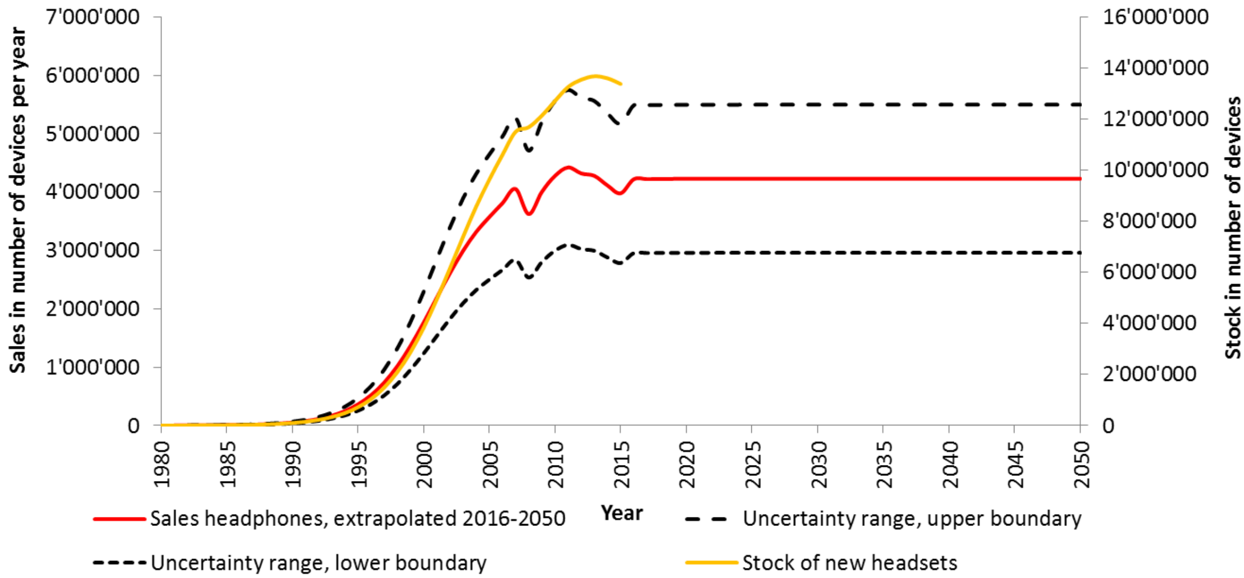

Figure S6: Sales and stock of headphones, with sales extrapolated to the year 2050.

Sales of DVD players have been decreasing due to the introduction of Blu-ray disc players and streaming services. As this decrease is very similar to mobile phones, we fitted a logistic function to current sales data of DVD players, assuming that their sales will eventually decrease to zero. The uncertainty is set to 10% for all sales years (Figure S7).

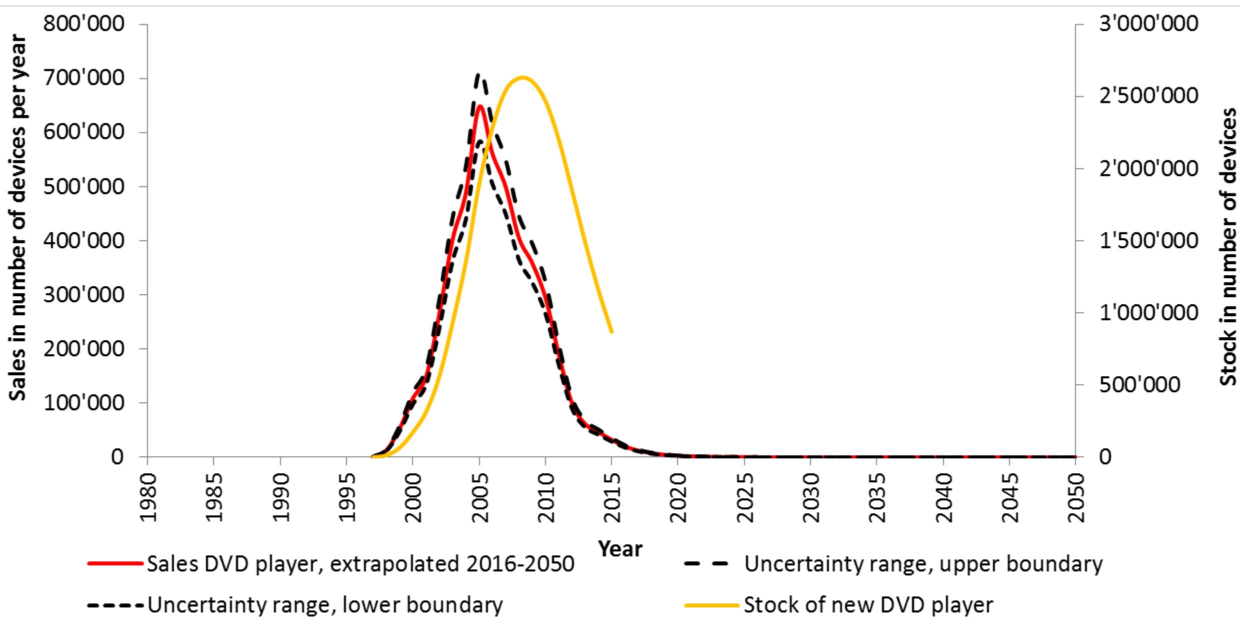

Figure S7: Sales and stock of DVD player, with sales extrapolated to the year 2050.

Table S9: Extrapolation methods and parameter for sales data extrapolation up to the year 2050

Device type	Data Source	Extrapolation method	Parameter
Mobile phones	GfK Switzerland; GfK Retail and Technology; FSO[28–30]	Fitting of logistic function with least square method $Inflow(t) = \frac{p_1}{1 + e^{-p_2((t-t_0)-p_3)}} + p_4$	$t_0 = 2007$ $p_1 = 3{,}452{,}608$ $p_2 = -0.47$ $p_3 = 3.96$ $p_4 = 36{,}250$
Smartphones	GfK Switzerland; GfK Retail and Technology; FSO[28–30]	Fitting of logistic function with least square method $Inflow(t) = \frac{p_1}{1 + e^{-p_2((t-t_0)-p_3)}}$	$t_0 = 2007$ $p_1 = 3{,}588{,}750$ $p_2 = 0.65$ $p_3 = 4.15$
Laptop	Weiss[31,32]	$Inflow(t) = Inflow(t_0)$	$t_0 = 2014$
Desktop	Weiss[31,32]	Fitting of logistic function with least square method $Inflow(t) = \frac{p_1}{1 + e^{-p_2((t-t_0)-p_3)}} + p_4$	$t_0 = 1999$ $p_1 = 171{,}804$ $p_2 = -0.22$ $p_3 = 17.11$ $p_4 = 112'644$
Headsets	GfK Switzerland[28]	Fitting of logistic function with least square method $Inflow(t) = \frac{p_1}{1 + e^{-p_2((t-t_0)-p_3)}}$	$t_0 = 1980$ $p_1 = 4{,}227{,}632$ $p_2 = 0.41$ $p_3 = 20.83$
DVD player	GfK Switzerland[28]	Fitting of logistic function with least square method $Inflow(t) = \frac{p_1}{1 + e^{-p_2((t-t_0)-p_3)}}$	$t_0 = 2005$ $p_1 = 721{,}173$ $p_2 = -0.49$ $p_3 = 3.80$

S6 Electronic equipment in the Swiss collection, recycling and disposal phase

Swico Recycling, the Swiss electronic equipment (EE) recycling system, offers free collection of EE either from collection points or specialist shops. From here, the collected EE is transferred to various Swiss waste electric and electronic equipment (WEEE or e-waste) recyclers. Refurbishment and reuse of EE in general does not take place, once a device has reached the official collection stream.[33] The possibility of refurbishment and reuse, before a device reaches the collection system, is taken into account in the cascade model adopted from Thiébaud et al.[25]

Mobile phones and smartphones are exceptions to this type of colletion of EE. Many telecommunication companies reimburse customers who bring their phone for refurbishment. The refurbished phones are either exported or sold in the Swiss market. The quantities of refurbished phones, however, are still low.[34–37]

For example, Swisscom AG sends all mobile phones collected in their shops for refurbishment. Around 25 – 30% of these phones are refurbished and sold abroad as large batches, around 70 – 75% is recycled. All resulting profits are donated.[34,38]

Preprocessing and downstream processes of indium, neodymium or gold-containing devices and fractions vary highly and are subsequently described for each device type. For reasons of confidentiality, recycler specific data cannot be disclosed.

S6.1 Desktop computer

Around 50% of all desktop computers are manually dismantled.[39–42] Manual dismantling includes the separation of metals, plastics, cables, batteries, printed wiring boards (PWBs), hard disk drives (HDDs) and optical drives.

Gold and neodymium-containing PWBs are directly sent to precious metal smelters, where over 95% of the gold is recovered, while neodymium is lost in the slag.[43,44] 50% of desktop computers are directly sent to mechanical preprocessing. In the mechanical process, most of the gold and neodymium in PWBs end up in PWB or fine fractions and reach precious metal smelters. Gold losses in the preprocessing is estimated to be between 2% and 20%.[14,40–42]

All neodymium-containing HDDs and optical drives are mechanically processed for further separation of different metals and plastics. Some recyclers include them in their mechanical treatment, others export them for further processing. Neodymium magnets are not disassembled prior to mechanical preprocessing and are therefore distributed to various output fractions or stick to the internal walls of the different processing equipment.[45] According to data from measurements and recyclers estimates, most neodymium ends up in the fine fraction sent to precious metal smelters or in the iron fraction sent to iron smelters.[14,40–42] In both cases, neodymium is lost in the slag.[44]

S6.2 Laptop computer

All laptop computers are manually dismantled, in order to remove and dismantle the flat panel display (FPD), which possibly includes mercury containing cold cathode fluorescent lamps (CCFLs). The indium-containing liquid crystal display (LCD) modules are either sent to municipal waste incineration or stored.[39–42]

Around 30% of all laptops are further manually dismantled[39–42] and PWBs are directly sent to precious metal smelters, where over 95% of the gold is recovered, while neodymium is lost in the slag.[43,44] 60% of laptop computers are sent from manual dismantling to mechanical preprocessing. In the mechanical process, most of the gold and neodymium in PWBs end up in PWB or fine fractions and reaches precious metal smelters. Gold losses in the preprocessing is estimated to be between 2 and 20%.[14,40–42]

All neodymium-containing HDDs, optical drives and loudspeakers are mechanically processed for further separation of different metals and plastics.[39–42] Some recyclers include them in their mechanical treatment, others export them for further processing. Neodymium magnets are not disassembled prior to mechanical preprocessing and are therefore distributed to various output fractions or stick to the internal walls of different processing equipment.[45] According to data from measurements and recyclers estimates, most neodymium ends up in the fine fraction sent to precious metal smelters or in the iron fraction sent to iron smelters.[14,40–42] In both cases, neodymium is lost in the slag.[44]

S6.3 FPD monitors, FPD televisions (TVs)

All FPD monitors and FPD TVs are manually dismantled, in order to remove any mercury containing CCFLs. The indium-containing LCD modules are either sent for municipal waste incineration or stored.[39–42] Gold and neodymium-containing PWBs are directly sent to precious metal smelters, where over 95% of the gold is recovered, while neodymium is lost in the slag.[43,44]

S6.4 Cathode ray tube televisions (CRT TVs)

All CRT TVs are manually dismantled in order to remove the CRT glass from the casing. 90% of all PWBs, which contain only a small amount of gold and neodymium, are mechanically treated.[39–42] In the mechanical process, most of the gold and neodymium in PWBs end up in PWB or fine fractions and reaches precious metal smelters. Gold losses in the preprocessing is estimated to be between 2 and 20%.[14,40–42]

S6.5 Mobile phones, smartphones

Mobile phones and smartphones are manually separated from the remaining WEEE. Batteries, that are easily removed, are sent to battery recycling.[39–42] Otherwise, the entire devices are sent to precious metal smelters, where over 95% of the gold is recovered, while neodymium and indium are lost in the slag.[43,44]

S6.6 Digital video disk (DVD) player, Headphones

DVD players and headphones are mechanically treated.[39–42] In the mechanical process, most of the gold and neodymium in PWBs end up in PWB or fine fractions and reaches precious metal smelters. Gold losses in the preprocessing are estimated between 2 and 20%.[14,40–42]

According to data from measurements and recyclers estimates, most of the neodymium ends up in the fine fractions sent to precious metal smelters or in the iron fraction sent to iron smelters.[14,40–42] In both cases, neodymium is lost in the slag.[44]

Data availability on blu-ray and cd-players are very poor. As they only play a minor role regarding their content of neodymium and gold, these device types are not considered in our analysis. However, neodymium and gold stocks and flows are thus probably slightly underestimated.

S7 Statistical entropy analysis

Statistical entropy analysis (SEA), as proposed by Rechberger and Graedel[46] is used to measure the distribution or concentration of indium, neodymium and gold during its route through the current system, including the use, collection, recycling and disposal phase.

The SEA is connected to an MFA based on the system structure. The whole system transfers the input step by step, with each step assigned as a "stage". The MFA system (Figure 1 in the main article) is thus transferred to the system depicted in Figure 4 in the main article, according to the procedure described in Rechberger and Graedel.[46]

For every flow in the system, we need data on the material flows (e.g. flows of devices, metals, plastics or PWBs containing indium, neodymium or gold), the substance (indium, neodymium and gold) content in each of these material flows and the resulting substance flows. The material flow, concentrations and substance flows are related according to equation S7.[46]

$$\dot{X}_i = \dot{M}_i \cdot c_i \qquad \text{(S7)}$$

$\dot{X}_i$ = Substance flow
$\dot{M}_i$ = Material flow,
c_i = metal content
i = specific flow in a stage

First, m_i for each stage is calculated (equation S8) and subsequently, the entropy $H(c_i, m_{i)}$ is calculated for each stage (equation S9).[46]

$$m_i = \frac{\dot{M}_i}{\sum_{i=1}^{k} \dot{X}_i} \qquad \text{(S8)}$$

$$H(c_i, m_{i)} = -\sum_{i=1}^{k} m_i \cdot c_i \cdot ld(c_i) \geq 0 \qquad \text{(S9)}$$

m_i = standardized mass fractions of a material set
k = total number of flows per stage
$H(c_i, m_i)$ = entropy in a specific stage
ld = logarithm to the second base

In each stage, the entropy H is compared to the entropy H_{max}. This results in the relative statistical entropy (RSE, equation S10). In industrial ecology, H_{max} often refers to the average earth crust content (equation S11). Thus, a stage with entropy H = H_{max} defines a point at which enhanced material resources no longer exist.[46]

$$RSE \equiv H/H_{max} \qquad \text{(S10)}$$

$$H_{max} = ld\left(\frac{1}{c_{EC}}\right) \qquad \text{(S11)}$$

RSE = relative statistical entropy
H_{max} = maximum statistical entropy
c_{EC} = average content of the earth crust

In order to calculate the material flows, we extended the model described in Thiébaud et al.[25] with a simple MFA of the collection, recycling and disposal phase for each device type.

The different device types follow the collection and recycling route as described in section S6. In the preprocessing the devices are manually or mechanically dismantled, sorted into various fractions and sent to downstream processes. Examples of fractions resulting from the preprocessing and the considered downstream processes are listed in Table S10.

The transfer coefficients to different downstream processes are modeled with triangular distributions, based on batch tests run by Swico Recycling.[47] . For each device type, various batch tests are available, from which we took the mean, the lowest observation and the highest observation The lower and upper limits of the triangular distributions are then calculated according to equation (S2) and (S3). In the simulation process, the random values of the transfer coefficients are adjusted after sampling to avoid combinations violating mass balance constraints. This is done by using a normalization factor over all involved transfer coefficients according to Bornhöft et al.[16] As the batch tests of recyclers include confidential data, we have only presented the cumulated transfer coefficients of all fractions going to a specific downstream process. For more information on individual fractions, please refer to Reference 40.

Table S11 lists the resulting cumulated transfer coefficients including uncertainty for all device types.

Table S10: Fractions resulting from preprocessing and considered downstream processes.

Fractions (examples)	Downstream process
Printed wiring boards, connectors, precious metal containing fine fractions	Precious metal smelter
Iron, copper, aluminum, other metals	Metal smelter
Plastics	Plastic Recycling
Plastics, liquid crystal display modules, shredder light fraction, packaging waste	Municipal waste incineration
Cable, glass, cathode ray tube glass, batteries, capacitors, lamps, other pollutants	Other processes

Table S11: Cumulated transfer coefficients to different downstream processes. -: no flow.

	Desktop computer			Laptop computer			FPD monitor		
	lower limit	mean	upper limit	lower limit	mean	upper limit	lower limit	mean	upper limit
Precious metal smelter	0.12	0.16	0.24	0.0054	0.12	0.19	0.062	0.067	0.090
Metal smelter	0.67	0.72	0.80	0.25	0.36	0.47	0.23	0.40	0.48
Plastic recycling	0.058	0.093	0.12	0	0.052	0.25	0.064	0.26	0.47
MWI	-	-	-	0.078	0.36	0.55	0.012	0.19	0.43
Other	0.018	0.027	0.035	0	0.11	0.33	0	0.028	0.068
	FPD TV			**CRT TV**			**Mobile phone/ Smartphone**		
	lower limit	mean	upper limit	lower limit	mean	upper limit	lower limit	mean	upper limit
Precious metal smelter	0.058	0.09	0.12	0.056	0.081	0.10	0.17	0.24	0.36
Metal smelter	0.38	0.52	0.81	0.097	0.10	0.10	-	-	-
Plastic recycling	0	0.15	0.36	-	-	-	-	-	-
MWI	0.046	0.18	0.43	0.14	0.17	0.21	-	-	-
Other	0	0.064	0.24	0.63	0.65	0.66	0.64	0.76	0.83
	DVD player			**Headphone**					
	lower limit	mean	upper limit	lower limit	mean	upper limit			
Precious metal smelter	0.00074	0.016	0.076	-	-	-			
Metal smelter	0.41	0.58	0.73	0.13	0.18	0.23			
Plastic recycling	0	0.11	0.44	-	-	-			
MWI	0.014	0.25	0.53	0.045	0.82	1			
Other	0	0.045	0.081	-	-	-			

The metal content of each material flow was calculated by dividing the respective total metal flow (sum over all device types) by the total material flow (sum over all device types).

The exceptions are metal contents in the slag disposal flows. This is due to the downstream processes, where materials from EE are mixed with other material. The metal contents of the resulting slags are therefore not directly related to the metal flows and material flows from EE.

The indium, neodymium and gold contents in the slags from the two processes "municipal waste incineration" and "incineration" are calculated according to information taken from Morf et al.[48]

For the indium, neodymium and gold contents from precious metal smelters and metal smelters, no data has been found. According to information from Umicore[49], the slags of their precious metal smelter result not only from the processing of electronic waste but from all processed materials. The very small input quantities of indium, neodymium and gold in PWB's, mobile phones, smartphones and fine fractions are mixed with large amounts of other materials that do not contain indium, neodymium and gold. PWBs, mobile phones, smartphones and metal containing fine fractions generate relatively little slag compared to, for example, catalysts on ceramic carriers that are predominantly converted into slag. The slag content of indium and neodymium is thus extremely low. The recovery rate of gold in precious metal smelters is well above 95% and the gold content in the slag is well below the content in gold ores. Due to the lack of better data, we assume an indium, neodymium and gold content in the slag similar to the average Earth's crust content[50–52], as it defines a point where enhanced resources no longer exist.[46]

For metal smelters not specialized in processing fractions from EE, such as iron smelters, the input of neodymium and gold is negligible compared to the total amount of metals processed. For example, in Switzerland around 1.5 Million metric tons of iron scrap is produced each year.[53] A neodymium and gold input of 385kg and 2kg per year (2014), respectively, into this flow is thus negligible. We therefore again assume a slag content similar to the average Earth's crust content.[50–52]

In order to test the sensitivity of our assumptions for the precious metal smelter and metal smelter slag content, we calculated the mean between the contents calculated according to Morf et al.[48] and the average Earth's crust content. We then simulated the SEA both with Earth's crust contents and the mean between the incineration slag contents and Earth's crust contents. As the changes in the results of the SEA were insignificant, we decided to run our analysis with precious metal smelter and metal smelter slag contents similar to Earth's crust, as justified above.

All relevant contents are listed in Table S12.

Table S12: Metal content in municipal waste incineration slag and in Earth's crust in kg/kg

Metal	**Content in municipal waste incineration slag [kg/kg]**	**Content in** Earth's crust **[kg/kg]**
Indium	1.26E-06[48]	4.90E-08[50]
		2.50E-07[51]
		1.60E-07[52]
		1.00E-07[54]
Neodymium	3.25E-05[48]	3.80E-05[50]
		4.15E-05[51]
		3.30E-05[52]
Gold	1.67E-06[48]	1.1E-09[50]
		3.10E-09[52]
		4.00E-09[51]

All equations to calculate the statistical entropy H and the relative statistical entropy (RSE) are described in Rechberger and Graedel.[46] As the dynamic MFA results in time series of stocks and flows, we compute the RSE over all stages and years. For the RSE, the statistical entropy H of each stage is therefore divided by the maximum statistical entropy H_{max}. H_{max} is calculated from the average Earth's crust content of each respective metal according to Table S12.

S8 Extended calculation tool

The pymfa tool is an open source tool, written in Python 3 (https://www.python.org), utilizing the numpy, scipy, and matplotlib library. The core of the tool can be used as a Python library and provides the necessary functionality to run analyses through a command line interface and an interactive web application that can also be run locally, as shown in Figure S8. The simulation tool has been made available via https://bitbucket.org/Xeelk/pymfa2/src

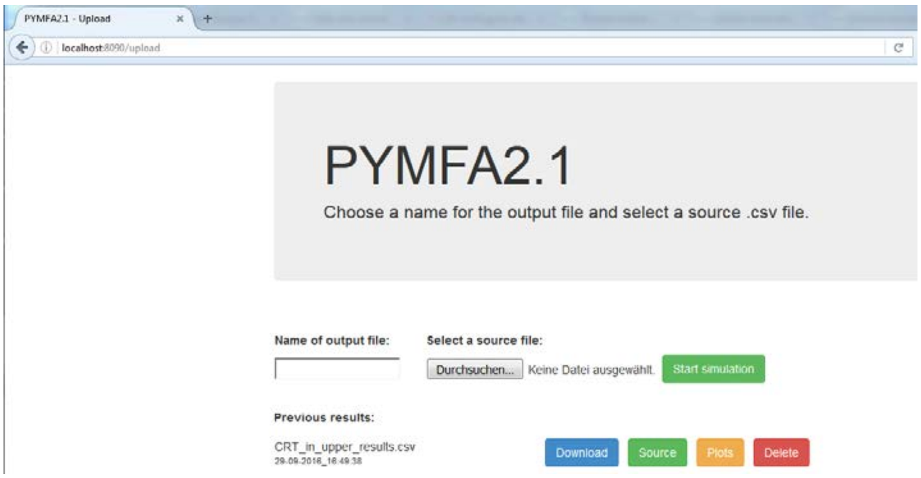

Figure S8: Interactive web application for pymfa2.1, run locally under localhost:8090.

The tool presented in Thiébaud et al.[25] has been extended for SEA, which will allow the calculation of the relative statistical entropy (RSE) over all system stages and years. In the source file, H_{max}, the stages per material or substance flows and the contents for all material flows have to be indicated. An extract from an example of a SEA model description source CSV file is shown in Table S13. The output file, as well as presenting the resulting stocks and flows by means of Monte Carlo simulation also lists the RSE over all stages and years.

Table S13: Extract from an example of statistical entropy analysis model description source CSV file for pymfa2.1.

<table>
<tr><td>Runs:</td><td>10000</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Periods:</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Median:</td><td>yes</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Percentiles:</td><td>10|90</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Plots:</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>entropyHmax:</td><td>28.45</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Transfer Type</td><td>Source Node</td><td>Source Material</td><td>Source Unit</td><td>Target Node</td><td>Target Material</td><td>Target Unit</td><td>Stages</td><td>Description</td><td>1994</td><td>1995</td><td>1996</td></tr>
<tr><td>Inflow</td><td></td><td></td><td></td><td>Metal_all_devices</td><td>Gold</td><td>g</td><td></td><td></td><td>fix|93.409</td><td>fix|108.308</td><td>fix|118.834</td></tr>
<tr><td>Rate</td><td>Metal_all_devices</td><td>Gold</td><td>g</td><td>TotalStock</td><td>Gold</td><td>g</td><td>1|x</td><td></td><td>fix|1|1</td><td>fix|1|1</td><td>fix|1|1</td></tr>
<tr><td>Delay</td><td>TotalStock</td><td>Gold</td><td>g</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>2|3|4|5|6|7|8|9|10|x</td><td></td><td>fix|1|1|weibull|1.9,9.3|0</td><td>fix|1|1|weibull|1</td><td>fix|1|1|weibull|1</td></tr>
<tr><td>Rate</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>Export1</td><td>Gold</td><td>g</td><td>2|x</td><td></td><td>fix|0.087|0</td><td>fix|0.087|0</td><td>fix|0.088|0</td></tr>
<tr><td>Rate</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>Collection</td><td>Gold</td><td>g</td><td>2|x</td><td></td><td>fix|0.778|0</td><td>fix|0.777|0</td><td>fix|0.777|0</td></tr>
<tr><td>Rate</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>MWI</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|x</td><td></td><td>fix|0.04|0</td><td>fix|0.04|0</td><td>fix|0.04|0</td></tr>
<tr><td>Rate</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>Other</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|10|x</td><td></td><td>fix|0.095|0</td><td>fix|0.095|0</td><td>fix|0.095|0</td></tr>
<tr><td>Rate</td><td>Export1</td><td>Gold</td><td>g</td><td>RefurbishmentA</td><td>Gold</td><td>g</td><td>3|x</td><td></td><td>fix|0.113|0</td><td>fix|0.117|0</td><td>fix|0.124|0</td></tr>
<tr><td>Rate</td><td>Export1</td><td>Gold</td><td>g</td><td>Export</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|10|x</td><td></td><td>fix|0.887|0</td><td>fix|0.883|0</td><td>fix|0.876|0</td></tr>
<tr><td>Rate</td><td>Collection</td><td>Gold</td><td>g</td><td>SlagLandfillSwiss</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|10|x</td><td></td><td>fix|0.0|0</td><td>fix|0.0|0</td><td>fix|0.0|0</td></tr>
<tr><td>Rate</td><td>Collection</td><td>Gold</td><td>g</td><td>Recycler</td><td>Gold</td><td>g</td><td>3|4|x</td><td></td><td>fix|0.997|0</td><td>fix|0.997|0</td><td>fix|0.997|0</td></tr>
<tr><td>Rate</td><td>Collection</td><td>Gold</td><td>g</td><td>Export</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|10|x</td><td></td><td>fix|0.001|0</td><td>fix|0.001|0</td><td>fix|0.001|0</td></tr>
<tr><td>Rate</td><td>Collection</td><td>Gold</td><td>g</td><td>RefurbishmentB</td><td>Gold</td><td>g</td><td>3|x</td><td></td><td>fix|0.002|0</td><td>fix|0.002|0</td><td>fix|0.002|0</td></tr>
<tr><td>Rate</td><td>RefurbishmentA</td><td>Gold</td><td>g</td><td>Recycler</td><td>Gold</td><td>g</td><td>4|x</td><td></td><td>fix|0.725|0</td><td>fix|0.725|0</td><td>fix|0.725|0</td></tr>
<tr><td>Rate</td><td>RefurbishmentA</td><td>Gold</td><td>g</td><td>Export</td><td>Gold</td><td>g</td><td>4|5|6|7|8|9|10|x</td><td></td><td>fix|0.275|0</td><td>fix|0.275|0</td><td>fix|0.275|0</td></tr>
<tr><td>Rate</td><td>RefurbishmentB</td><td>Gold</td><td>g</td><td>Recycler</td><td>Gold</td><td>g</td><td>4|x</td><td></td><td>fix|0.028|0</td><td>fix|0.028|0</td><td>fix|0.028|0</td></tr>
<tr><td>Rate</td><td>RefurbishmentB</td><td>Gold</td><td>g</td><td>ReuseCH</td><td>Gold</td><td>g</td><td>4|5|6|7|8|9|10|x</td><td></td><td>fix|0.972|0</td><td>fix|0.972|0</td><td>fix|0.972|0</td></tr>
<tr><td>Rate</td><td>Recycler</td><td>Gold</td><td>g</td><td>Recycler1</td><td>Gold</td><td>g</td><td>5|x</td><td></td><td>fix|0.004|0</td><td>fix|0.004|0</td><td>fix|0.005|0</td></tr>
<tr><td>Rate</td><td>Recycler</td><td>Gold</td><td>g</td><td>Recycler2</td><td>Gold</td><td>g</td><td>5|x</td><td></td><td>fix|0.035|0</td><td>fix|0.044|0</td><td>fix|0.053|0</td></tr>
<tr><td>Rate</td><td>Recycler</td><td>Gold</td><td>g</td><td>Recycler3</td><td>Gold</td><td>g</td><td>5|x</td><td></td><td>fix|0.015|0</td><td>fix|0.019|0</td><td>fix|0.023|0</td></tr>
<tr><td>Rate</td><td>Recycler</td><td>Gold</td><td>g</td><td>Recycler4</td><td>Gold</td><td>g</td><td>5|x</td><td></td><td>fix|0.007|0</td><td>fix|0.009|0</td><td>fix|0.011|0</td></tr>
<tr><td>Rate</td><td>Recycler1</td><td>Gold</td><td>g</td><td>Manual1</td><td>Gold</td><td>g</td><td>6|x</td><td></td><td>fix|0.321|0</td><td>fix|0.341|0</td><td>fix|0.362|0</td></tr>
<tr><td>Rate</td><td>Recycler1</td><td>Gold</td><td>g</td><td>MechanicalPreprocessing</td><td>Gold</td><td>g</td><td>6|7|8|x</td><td></td><td>fix|0.679|0</td><td>fix|0.659|0</td><td>fix|0.638|0</td></tr>
<tr><td>Rate</td><td>Manual1</td><td>Gold</td><td>g</td><td>InStorage</td><td>Gold</td><td>g</td><td>7|8|9|10|x</td><td></td><td>fix|0.0|0</td><td>fix|0.0|0</td><td>fix|0.0|0</td></tr>
<tr><td>Rate</td><td>Manual1</td><td>Gold</td><td>g</td><td>ManualPreprocessing</td><td>Gold</td><td>g</td><td>7|x</td><td></td><td>fix|0.024|0</td><td>fix|0.031|0</td><td>fix|0.039|0</td></tr>
<tr><td>Rate</td><td>Manual1</td><td>Gold</td><td>g</td><td>MechanicalPreprocessing</td><td>Gold</td><td>g</td><td>7|8|x</td><td></td><td>fix|0.002|0</td><td>fix|0.004|0</td><td>fix|0.006|0</td></tr>
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<table>
<tr><td>Concentration</td><td>Metal_all_devices</td><td>Gold</td><td>g</td><td>TotalStock</td><td>Gold</td><td>g</td><td>1|x</td><td></td><td>6.28E-06</td><td>6.97E-06</td><td>7.35E-06</td></tr>
<tr><td>Concentration</td><td>TotalStock</td><td>Gold</td><td>g</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>2|3|4|5|6|7|8|9|10|x</td><td></td><td>3.75E-06</td><td>4.57E-06</td><td>5.37E-06</td></tr>
<tr><td>Concentration</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>Export1</td><td>Gold</td><td>g</td><td>2|x</td><td></td><td>1.10E-05</td><td>1.16E-05</td><td>1.22E-05</td></tr>
<tr><td>Concentration</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>Collection</td><td>Gold</td><td>g</td><td>2|x</td><td></td><td>1.58E-06</td><td>1.93E-06</td><td>2.32E-06</td></tr>
<tr><td>Concentration</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>MWI</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|x</td><td></td><td>1.32E-05</td><td>1.36E-05</td><td>1.40E-05</td></tr>
<tr><td>Concentration</td><td>Stockoutflow</td><td>Gold</td><td>g</td><td>Other</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|10|x</td><td></td><td>6.10E-06</td><td>6.26E-06</td><td>6.61E-06</td></tr>
<tr><td>Concentration</td><td>Export1</td><td>Gold</td><td>g</td><td>RefurbishmentA</td><td>Gold</td><td>g</td><td>3|x</td><td></td><td>2.55E-04</td><td>2.55E-04</td><td>2.56E-04</td></tr>
<tr><td>Concentration</td><td>Export1</td><td>Gold</td><td>g</td><td>Export</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|10|x</td><td></td><td>5.75E-06</td><td>6.74E-06</td><td>7.68E-06</td></tr>
<tr><td>Concentration</td><td>Collection</td><td>Gold</td><td>g</td><td>SlagLandfillSwiss</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|10|x</td><td></td><td>1.67E-06</td><td>1.67E-06</td><td>1.67E-06</td></tr>
<tr><td>Concentration</td><td>Collection</td><td>Gold</td><td>g</td><td>Recycler</td><td>Gold</td><td>g</td><td>3|4|x</td><td></td><td>2.49E-06</td><td>3.00E-06</td><td>3.51E-06</td></tr>
<tr><td>Concentration</td><td>Collection</td><td>Gold</td><td>g</td><td>Export</td><td>Gold</td><td>g</td><td>3|4|5|6|7|8|9|10|x</td><td></td><td>2.55E-04</td><td>2.56E-04</td><td>2.55E-04</td></tr>
<tr><td>Concentration</td><td>Collection</td><td>Gold</td><td>g</td><td>RefurbishmentB</td><td>Gold</td><td>g</td><td>3|x</td><td></td><td>2.55E-04</td><td>2.55E-04</td><td>2.56E-04</td></tr>
<tr><td>Concentration</td><td>RefurbishmentA</td><td>Gold</td><td>g</td><td>Recycler</td><td>Gold</td><td>g</td><td>4|x</td><td></td><td>2.55E-04</td><td>2.55E-04</td><td>2.56E-04</td></tr>
<tr><td>Concentration</td><td>RefurbishmentA</td><td>Gold</td><td>g</td><td>Export</td><td>Gold</td><td>g</td><td>4|5|6|7|8|9|10|x</td><td></td><td>2.55E-04</td><td>2.55E-04</td><td>2.56E-04</td></tr>
<tr><td>Concentration</td><td>RefurbishmentB</td><td>Gold</td><td>g</td><td>Recycler</td><td>Gold</td><td>g</td><td>4|x</td><td></td><td>2.55E-04</td><td>2.56E-04</td><td>2.56E-04</td></tr>
<tr><td>Concentration</td><td>RefurbishmentB</td><td>Gold</td><td>g</td><td>ReuseCH</td><td>Gold</td><td>g</td><td>4|5|6|7|8|9|10|x</td><td></td><td>2.55E-04</td><td>2.55E-04</td><td>2.56E-04</td></tr>
<tr><td>Concentration</td><td>Recycler</td><td>Gold</td><td>g</td><td>Recycler1</td><td>Gold</td><td>g</td><td>5|x</td><td></td><td>2.51E-06</td><td>3.03E-06</td><td>3.54E-06</td></tr>
<tr><td>Concentration</td><td>Recycler</td><td>Gold</td><td>g</td><td>Recycler2</td><td>Gold</td><td>g</td><td>5|x</td><td></td><td>2.52E-06</td><td>3.03E-06</td><td>3.55E-06</td></tr>
<tr><td>Concentration</td><td>Recycler</td><td>Gold</td><td>g</td><td>Recycler3</td><td>Gold</td><td>g</td><td>5|x</td><td></td><td>2.52E-06</td><td>3.03E-06</td><td>3.55E-06</td></tr>
<tr><td>Concentration</td><td>Recycler</td><td>Gold</td><td>g</td><td>Recycler4</td><td>Gold</td><td>g</td><td>5|x</td><td></td><td>2.52E-06</td><td>3.04E-06</td><td>3.55E-06</td></tr>
<tr><td>Concentration</td><td>Recycler1</td><td>Gold</td><td>g</td><td>Manual1</td><td>Gold</td><td>g</td><td>6|x</td><td></td><td>8.52E-07</td><td>1.11E-06</td><td>1.38E-06</td></tr>
<tr><td>Concentration</td><td>Recycler1</td><td>Gold</td><td>g</td><td>MechanicalPreprocessing</td><td>Gold</td><td>g</td><td>6|7|8|x</td><td></td><td>3.14E-05</td><td>3.03E-05</td><td>2.96E-05</td></tr>
<tr><td>Concentration</td><td>Manual1</td><td>Gold</td><td>g</td><td>InStorage</td><td>Gold</td><td>g</td><td>7|8|9|10|x</td><td></td><td>0.00E+00</td><td>0.00E+00</td><td>0.00E+00</td></tr>
<tr><td>Concentration</td><td>Manual1</td><td>Gold</td><td>g</td><td>ManualPreprocessing</td><td>Gold</td><td>g</td><td>7|x</td><td></td><td>1.21E-06</td><td>1.54E-06</td><td>1.90E-06</td></tr>
<tr><td>Concentration</td><td>Manual1</td><td>Gold</td><td>g</td><td>MechanicalPreprocessing</td><td>Gold</td><td>g</td><td>7|8|x</td><td></td><td>2.13E-07</td><td>3.40E-07</td><td>4.80E-07</td></tr>
</table>

S9 Results

Table S14: Share of stocks, losses and sinks out of the total amount of indium, neodymium and gold in the year 2014

Location	Type	Process	Indium	Neodymium	Gold
Switzerland	Stock	In-use stock	0.62	0.38	0.40
Switzerland	Stock	Storage stock	0.12	0.18	0.17
Switzerland	Stock	Storage recycling stock	0.025	-	-
Rest of the World (RoW)	Loss	Export from Switzerland to RoW	0.011	0.021	0.019
Switzerland/RoW	Loss	Unknown	0.058	0.038	0.051
Switzerland	Sink	Landfill disposal Switzerland	0.16	0.030	0.021
RoW	Sink	Landfill disposal RoW	-	0.0022	0.00072
RoW	Sink	Slag used for construction	0.020	0.35	0.019
RoW	Recovered resource	Material recovery	-	-	0.31

-: no stock

Table S15: Relative statistical entropy values for indium for the years 1990, 2000, 2010 and 2014, as illustrated in Figure 5 in the main article.

Stage	Year			
	1990	2000	2010	2014
Stage 1	1.026	0.892	0.746	0.745
Stage 2	1.115	0.961	0.814	0.780
Stage 3	1.043	0.955	0.813	0.780
Stage 4	1.043	0.955	0.813	0.780
Stage 5	1.043	0.955	0.808	0.775
Stage 6	1.043	0.944	0.795	0.759
Stage 7	1.043	0.876	0.732	0.683
Stage 8	1.043	0.876	0.732	0.683
Stage 9	1.044	0.944	0.827	0.824

Table S16: Relative statistical entropy values for neodymium for the years 1990, 2000, 2010 and 2014, as illustrated in Figure 5 in the main article.

Stage	Year			
	1990	2000	2010	2014
Stage 1	0.974	0.889	0.858	0.879
Stage 2	0.992	0.958	0.879	0.883
Stage 3	1.230	0.922	0.874	0.850
Stage 4	1.230	0.922	0.874	0.850
Stage 5	1.230	0.890	0.865	0.841
Stage 6	1.230	0.860	0.845	0.792
Stage 7	1.230	0.841	0.829	0.769
Stage 8	1.230	0.949	0.896	0.882
Stage 9	1.233	0.952	0.921	0.942

Table S17: Relative statistical entropy values for gold for the years 1990, 2000, 2010 and 2014, as illustrated in Figure 5 in the main article.

Stage	Year			
	1990	2000	2010	2014
Stage 1	0.631	0.575	0.551	0.556
Stage 2	0.694	0.609	0.562	0.566
Stage 3	0.647	0.600	0.565	0.553
Stage 4	0.647	0.600	0.565	0.553
Stage 5	0.647	0.592	0.565	0.554
Stage 6	0.647	0.589	0.563	0.553
Stage 7	0.647	0.527	0.512	0.483
Stage 8	0.647	0.525	0.504	0.468
Stage 9	0.649	0.321	0.324	0.204

S10 References

(1) Weidema, B. P.; Wesnæs, M. S. Data Quality Management for Life Cycle Inventories—an Example of Using Data Quality Indicators. *Journal of Cleaner Production* **1996**, *4* (3), 167–174.

(2) Loevik, A. N.; Haarman, A.; Scheepens, A.; Rösslein, M.; Wäger, P. A.; Huisman, J. Prospecting Secondary Raw Materials in the Urban Mine: Data Quality and Uncertainty of Product Compositions; 2016.

(3) Gottschalk, F.; Scholz, R. W.; Nowack, B. Probabilistic Material Flow Modeling for Assessing the Environmental Exposure to Compounds: Methodology and an Application to Engineered Nano-TiO2 Particles. *Environmental Modelling & Software* **2010**, *25* (3), 320–332.

(4) JCGM. *JCGM 100:2008. Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement (GUM)*; Joint Committee for Guides in Metrology, 2008.

(5) Buchert, M.; Manhart, A.; Bleher, D.; Pingel, D. *Recycling Critical Raw Materials from Waste Electronic Equipment*; Oeko-Institut e.V., 2012.

(6) IUTA; fem. *Metallurgische Rückgewinnung von Indium, Gallium Und Germanium Aus Elektronikschrott Und Entwicklung Entsprechender Aufbereitungsmethoden Für Die Verwertungsindustrie*; AiF-FV Nummer: 16040; fem Forschungsinstitut Edelmetalle und Metallchemie, Schwäbisch-Gmünd und Institut für Energie- und Umwelttechnik e.V., Duisburg: Schäbisch Gmünd & Duisburg, 2011.

(7) Böni, H.; Wäger, P.; Thiébaud, E.; Du, X.; Figi, R.; Nagel, O.; Bunge, R.; Stäubli, A.; Spörry, A.; Wolfensberger-Malo, M.; et al. *Projekt E-Recmet - Rückgewinnung von Kritischen Metallen Aus Elektronikschrott Am Beispiel von Indium Und Neodym. Schlussbericht [Project e-Recmet – Recovery of Critical Metals from e-Waste, the Example of Indium and Neodymium. Final Report]*; Empa: St. Gallen, 2015.

(8) Ueberschaar, M.; Schlummer, M.; Jalalpoor, D.; Kaup, N.; Rotter, V. S. Potential and Recycling Strategies for LCD Panels from WEEE. *Recycling* **2017**, *2* (1), 7.

(9) MoE and METI. *Report of the Study Group for Less Common Metal Recovery from Used Small Electric Appliances 2009 (in Japanese).*; Ministry of Environment and Ministry of Economy, Trade and Industry: Tokyo, Japan, 2010.

(10) Sander, K.; Schilling, S.; Marscheider-Weidemann, F.; Wilts, H.; von Gries, N.; Hobohm, J. Abfallwirtschaftliche Produktverantwortung Unter Ressourcenschutzaspekten, Meilensteinbericht August 2012; Ökopol GmbH, Fraunhofer Gesellschaft ISI, TU Darmstadt, TU Hamburg-Harburg: Hamburg, Germany, 2012.

(11) Westphal, L.; Kuchta, K. Permanent Magnets from Small Waste Electrical and Electronic Equipment. In *Proceedings Sardinia 2013*; Sardinia, Italy, 2013.

(12) Ueberschaar, M.; Rotter, V. S. Enabling the Recycling of Rare Earth Elements through Product Design and Trend Analyses of Hard Disk Drives. *J Mater Cycles Waste Manag* **2015**, *17* (2), 266–281.

(13) Blaser, F.; Castelanelli, S.; Wäger, P.; Widmer, R. *Seltene Metalle in Elektro- Und Elektronikaltgeräten - Vorkommen Und Rückgewinnungstechnologien*; Bundesamt für Umwelt: Bern, 2011.

(14) Wäger, P.; Widmer, R.; Restrepo, E.; Fernandes, M. *Seltene Technische Metalle in Fraktionen Aus Der Maschinellen Aufbereitung von WEEE.*; Federal Office for the Environment: Bern, Switzerland, 2014.

(15) Habib, K.; Schibye, P. K.; Vestbø, A. P.; Dall, O.; Wenzel, H. Material Flow Analysis of NdFeB Magnets for Denmark: A Comprehensive Waste Flow Sampling and Analysis Approach. *Environ. Sci. Technol.* **2014**, *48* (20), 12229–12237.

(16) Bornhöft, N. A.; Sun, T. Y.; Hilty, L. M.; Nowack, B. A Dynamic Probabilistic Material Flow Modeling Method. *Environmental Modelling & Software* **2016**, *76*, 69–80.

(17) Oguchi, M.; Murakami, S.; Sakanakura, H.; Kida, A.; Kameya, T. A Preliminary Categorization of End-of-Life Electrical and Electronic Equipment as Secondary Metal Resources. *Waste Management* **2011**, *31* (9–10), 2150–2160.

(18) Chancerel, P. Substance Flow Analysis of the Recycling of Small Waste Electrical and Electronic Equipment; An assessment of the recovery of gold and palladium; Technische Universität Berlin, Institut für Technischen Umweltschutz, ITU-Schriftenreihe: Berlin, Germany, 2010.

(19) Bangs, C.; Meskers, C.; Van Kerckhoven, T. Trends in Electronic Products - the Canary in the Urban Mine. In *Electronic Goes Green 2016+, Sept 7-9, 2016, Berlin, Germany, Proceedings*; Fraunhofer IZM: Berlin, 2016.

(20) Thiébaud (-Müller), E.; Hilty, L. M.; Schluep, M.; Widmer, R.; Faulstich, M. Service Lifetime, Storage Time and Disposal Pathways of Electronic Equipment: A Swiss Case Study. *Journal of Industrial Ecology* **2017**, *22* (1), 196–208.

(21) Du, X.; Graedel, T. E. Global Rare Earth In-Use Stocks in NdFeB Permanent Magnets. *Journal of Industrial Ecology* **2011**, *15* (6), 836–843.

(22) Vogel, M. SSD-Adoption: Schweiz geht voran http://www.itreseller.ch/Artikel/83003/SSD-Adoption_Schweiz_geht_voran.html (accessed Oct 10, 2016).

(23) ssd-ratgeber.de. SSD - Entwicklungsgeschichte von Anfang bis Heute | ssd-ratgeber.de. (accessed Jul 8, 2018).

(24) Bracher, P.; Brügger, A.; Hofmann, M. *Nutzungszeit Und Entsorgungswege von Elektronischen Geräten Im Geschäftsumfeld. Wissenschaftliches Praxisprojekt*; Berner Fachhochschule Wirtschaft: Bern, Schweiz, 2016.

(25) Thiébaud, E.; Hilty, L. M.; Schluep, M.; Faulstich, M. Use, Storage, and Disposal of Electronic Equipment in Switzerland. *Environ. Sci. Technol.* **2017**.

(26) Streicher-Porte, M. SWICO/S.EN.S, the Swiss WEEE Recycling Systems and Best Practices from Other European Systems. In *Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, 2006.*; 2006; pp 281–287.

(27) Müller, E.; Hilty, L. M.; Widmer, R.; Schluep, M.; Faulstich, M. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environ. Sci. Technol.* **2014**, *48* (4), 2102–2113.

(28) GfK Switzerland. *Verkäufe von Informations- Und Kommunikationstechnologien Und Unterhaltungselektronik in Der Schweiz*; GfK Switzerland AG: Hergiswil, Switzerland 2015.

(29) GfK Retail and Technology. Telecom, Total Market Estimations Switzerland: Hergiswil, Switzerland, 2008.

(30) FSO. Federal Statistical Office, Informationsgesellschaft - Gesamtindikatoren, Infrasturkturen - Telefoninfrastruktur http://www.bfs.admin.ch/bfs/portal/de/index/themen/16/04/key/approche_globale.indicator.30101.1.html (accessed Jan 4, 2016).

(31) Weiss, R. *Weissbuch 2015*; Männedorf, Switzerland 2015.

(32) Weiss, R. *Weissbuch 2014*; Männedorf, Switzerland 2014.

(33) Media Markt Management AG. Personal Communication with Head Business Process Management & Masterdata, Media Markt Management AG: Zürich, Switzerland, 2016.

(34) Swisscom AG. Personal Communication with Senior Corporate Responsibility Manager: Zürich, Switzerland, 2016.

(35) Swisscom AG. Mobile Bonus - Mobile phone trade-ins and resale http://mobile-bonus.swisscom.ch/en?lang=eng?ext-campID=SEA_GDE_MBA_LE&gclid=CPrH_LHi8dECFWUz0wodWGsAkg (accessed Feb 2, 2017).

(36) Salt Mobile SA. Personal Communication with Director Logistics and Retail Development: Zürich, Switzerland, 2016.

(37) Salt Mobile SA. Salt Mobile - CashBack - Sell your device https://www.salt.ch/en/cashback/ (accessed Feb 2, 2017).
(38) Swisscom AG. Donate to Swisscom Mobile Aid https://www.swisscom.ch/en/about/company/sustainability/mobile-aid.html (accessed Oct 26, 2016).
(39) Bühlmann Recycling AG. Personal Communication with Head Environmental Officer: Münchenwiler, Switzerland, 2016.
(40) Immark AG. Personal Communication with Head Material Flow Management: Regensdorf, Switzerland 2016.
(41) RUAG Environment AG. Personal Communication with Head Quality Management / Deputy Head of Production: Altdorf, Switzerland 2016.
(42) Solenthaler Recycling AG. Personal Communication with Head Quality Management: Gossau SG, Switzerland, 2016.
(43) Hagelüken, C.; Meskers, C. Complex Life Cycles of Precious and Special Metals. In *Linkages of Sustainability, Edited by Thomas E. Graedel and Ester van der Voet*; Strüngmann Forum Reports.
(44) UNEP. *Metal Recycling: Opportunities, Limits, Infrastructure,*; A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M. A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C., 2013.
(45) Habib, K.; Parajuly, K.; Wenzel, H. Tracking the Flow of Resources in Electronic Waste - The Case of End-of-Life Computer Hard Disk Drives. *Environ. Sci. Technol.* **2015**, *49* (20), 12441–12449.
(46) Rechberger, H., Graedel, T. E. The Contemporary European Copper Cycle: Statistical Entropy Analysis. *Ecological Economics* **2002**, *42* (1–2), 59–72.
(47) SWICO. *Swico Tätigkeitsberichte 2006-2015 (Swico Activity Reports 2006-2015)*; SWICO Recycling: Zürich, Switzerland 2016.
(48) Morf, L. S.; Gloor, R.; Haag, O.; Haupt, M.; Skutan, S.; Lorenzo, F. D.; Böni, D. Precious Metals and Rare Earth Elements in Municipal Solid Waste – Sources and Fate in a Swiss Incineration Plant. *Waste Management* **2013**, *33* (3), 634–644.
(49) Umicore AG & Co. KG. Personal Communication with Director EU Government Affairs, 2017.
(50) Barbalace, K. Periodic Table of Elements. EnvironmentalChemistry.com. 1995 - 2017. https://environmentalchemistry.com/yogi/periodic/ (accessed Apr 4, 2017).
(51) Jefferson Lab. It's Elemental - The Periodic Table of Elements http://education.jlab.org/itselemental/index.html (accessed Apr 4, 2017).
(52) Winter, M. WebElements Periodic Table»Abundance in Earth's crust»periodicity. The University of Sheffield and WebElements Ltd, UK https://www.webelements.com/periodicity/abundance_crust/ (accessed Apr 4, 2017).
(53) Swiss Steel. Umwelt: Swiss Steel https://www.swiss-steel.com/unternehmen/umwelt/ (accessed Jul 8, 2018).
(54) Alfantazi, A. M.; Moskalyk, R. R. Processing of Indium: A Review. *Minerals Engineering* **2003**, *16* (8), 687–694.