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Dynamic material flow analysis of critical metals embodied in thin-film photovoltaic cells

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Summary:

Photovoltaic cells are a contributor to the global energy mix of growing importance. Among the different photovoltaic technologies, thin-film technologies such as copper-indium-gallium-(di)selenide (CIGS) or cadmium-telluride (CdTe) have shown a significant growth in market share caused among other things by their reduced manufacturing costs and increased versatility. These cells require materials like indium, gallium, cadmium and tellurium that have been identified to be critical in terms of their economic importance and supply risks in various studies. Also, significant stocks of these materials will develop in the anthroposphere and secondary flows in a significant scale will arise at some point in the future. In this article material stocks and flows – including secondary flows and material demands- of indium, gallium, cadmium, and tellurium resulting from global deployment of photovoltaic cells up to 2050 have been analyzed considering three different scenarios regarding the future development. Based on this, potential future material shortages are discussed.

Keywords: Industrial Ecology; material flow analysis; thin-film photovoltaic; critical materials; secondary materials.

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Introduction

Photovoltaic cells are a contributor to the global energy mix of constantly growing importance, a trend which is very likely to continue for the coming decades. The installed capacity has increased significantly within the past years. In 2010, approximately 15,000 MW have been installed on a global basis. Further growth is expected for the future, in some scenarios even up to about 4,669 GW in 2050 (EPIA 2011). On the technological side, so far there are basically two types to distinguish: silicon based cells and thin film cells. Other types of PV cells like compound semiconductors and nanotechnology cells are so far not relevant for commercial energy production (El Chaar, lamont, and El Zein 2011).

In thin film photovoltaic cells the active layer has a thickness of between 1 and 10 μm which results in reduced manufacturing and material costs as well as an increased versatility. Efficiencies of thin film cells are still lower than of crystalline cells but costs, temperature robustness and versatility lead to a significant gain in market share over the past years (El Chaar, lamont, and El Zein 2011). A further growth is to be expected (e.g., Moss et al. 2011; U.S. Department of Energy 2011; European Commission 2010) resulting in increases in demand for certain metals such as indium, gallium, cadmium and tellurium. These materials have been identified to be "critical" or "strategic" in various studies (e.g. indium and gallium in European Commission 2010; Buchert, Schüler, and Bleher 2009, tellurium in Moss et al. 2011; Thomason et al. 2010, and cadmium in Achzet et al. 2011). Some studies highlighted particularly their importance for energy technologies and low carbon technologies or – the other way around – identified these materials to be a potential bottle neck for the expansion of renewable energies (e.g., Achzet et al. 2011; APS and MRS 2011; Buchert, Schüler, and Bleher 2009). With the continuous growth of installed photovoltaic capacity and at the same time a growing share of thin film photovoltaic cells within the technology mix, a further increase in demand for these critical metals can be expected. At the same time anthropogenic stocks will develop and secondary material flows in a significant scale will arise at some point in the future. Knowledge about these stocks and flows is required for building up the required recycling infrastructure to avoid the materials' dissipation as well as for urban mining activities.

Against this background, a dynamic material flow analysis (MFA) of selected critical metals with consideration of flows into use as well as secondary materials flows is presented in this article. First, the methodological approach and data for the product-centric analysis of historic and future flows of critical metals embodied in thin-film photovoltaic cells – CIGS, CdTe and a-Si – are described. Then results calculated for different scenarios from the European Photovoltaic Industry Association (EPIA) for future installations which range from rather modest to very optimistic estimations regarding the future deployment of photovoltaic cells are presented. Finally, the results are compared to other studies and possible conclusions especially regarding the materials' availability and criticality are discussed.

Methodology and data

The analysis focuses on material flows connected with the installation, use and (future) disposal of photovoltaic cells. The material production stage which is widely independent from the further use of the refined material is not considered in the analysis. Studies focusing particularly on the metals production for photovoltaic cells have for example been published by Fthenakis, Wang, and Kim (2009).

The input into the use phase depends on the material embodied in the installed photovoltaic cells and is calculated as the product of installations in MW and the amount of critical material per installed MW (i.e. the material intensity). Within the use phase the life span is a crucial parameter and the time the cells spend in the use phase is modeled assuming a Weibull distribution. Based on this, an estimation of the material demand is derived by taking the calculated material flows into use and applying material efficiency rates for the production of the different thin-film technologies, hereby the fabrication and manufacturing stage are include in the analysis. The system boundaries of the analysis are shown in Figure 1.

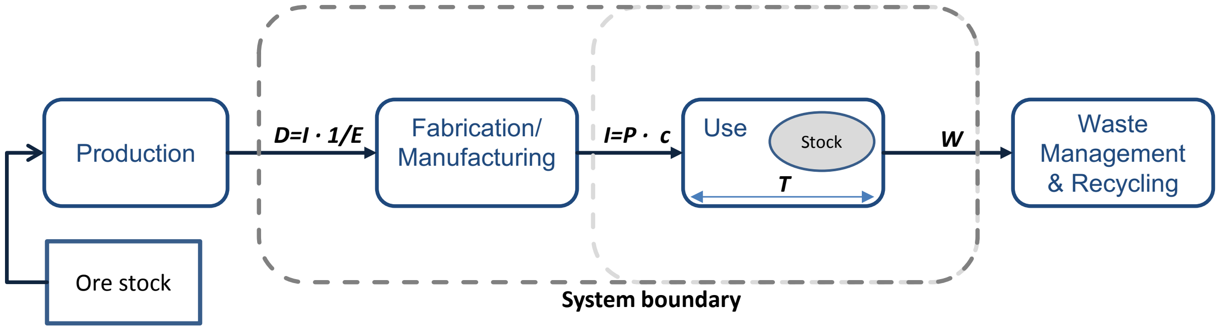

Figure 1: System boundary of the study. I: material flow into use; P: installations in MW; c: Metal concentration per MW; T: lifespan; W: potential waste flow/ secondary material flows; E: material efficiency in fabrication/ manufacturing; D: material demand

As said initially, the study focuses on metals that have been identified to be critical in various studies in terms of their economic importance or the vulnerability of the respective system to a supply restriction, respectively, and the risk of a supply shortage. Additionally but also contributing to this combined importance and risk of supply, very low recycling rates (Graedel et al. 2011) and high dissipative losses along the life cycle (Zimmermann and Gößling-Reisemann 2013) can be observed. Against this background, knowledge about future demand, stocks and secondary flows is of great importance for an efficient and sustainable management of these metals.

Flows into use

The main parameters defining the use phase are the amount of products entering it, the material intensity per MW and the time spent in the use phase. The former parameter – products entering the use phase – is not assessed based on the number of installed modules but on the installed capacity in megawatt. Here, scenarios from a study published by the EPIA (2011) have been used. Three different scenarios are distinguished in this study: a rather moderate scenario (labeled "reference scenario", assuming 388,623 MW in 2050), an accelerated scenario (2,988,095 MW in 2050) and a "paradigm-shift" scenario (4,669,100 MW in 2050). The installations for selected years and additional information are given in the annex.

For the material intensity per MW a broad literature screening has been carried out and additional data from experts and manufacturers have been included. Further details on this are given in a separate section.

The third parameter – the product lifespan - is of great importance within the model (see section "lifespan distributions"). The system under study and the industrial metabolism in general are dynamic and changes to the lifespan result in changes to the system. As highlighted by Murakami et al. (2010), various differing definitions of lifespan are used in science and literature. In this study, lifespan is understood as the time span from entering the use phase to leaving the use phase. This complies with the "domestic service lifespan" described by Murakami et al. (2010). Instead of using average values, life span distributions are used in the model.

Lifespan distributions and Weibull parameters

Lifespan distributions of products are commonly approximated using probability distribution functions. The good suitability of the Weibull distribution for modeling lifespans of various products has been shown and described in multiple studies (e.g., Oguchi et al. 2008; Tasaki et al. 2004; Kagawa, Tasaki, and Moriguchi 2006; Cullen and Frey 1999) and can be considered the most widely applied distribution. Examples for the application of the Weibull distribution to model other products' lifespans can be found, for example, in Zimmermann, Rehberger, Gößling-Reisemann (2013) for wind energy converters or Kagawa, Tasaki and Moriguchi (2006) for automobiles.

Kumar and Sarkan (2013) analyze the reliability of photovoltaic modules using Weibull distributions and highlight that the behavior of PV modules is comparable to other products. Also Kuitche (2010) identifies the Weibull distribution among different statistical failure distribution models (exponential distribution, Weibull distribution, lognormal distribution) to match real-life data gathered for PV modules best. Following this, a Weibull distribution of the product lifespans is assumed in this study, too. The Weibull distribution can be defined as:

$$f(t, \lambda, k) = \lambda k (\lambda t)^{k-1} e^{-(\lambda t)^k}$$

t is the time in years, k and λ are the shape and scale parameters. Further details on the application of the Weibull function and related functions are given elsewhere (e.g. Qiu and Vuorinen 2005; Cullen and Frey 1999; Wilker 2010; Abramowitz and Stegun 1972) and will not be explained here.

The Weibull shape parameter has been analyzed for different products in various publications (e.g., NIES 2010; Oguchi et al. 2008). For most products the shape parameters vary between 1 and 3, some products show higher values of between 3 and 5.6. There are few studies analyzing the respective parameters specifically for photovoltaic cells. Kuitche (2010) analyzes c-Si photovoltaic cells based on accelerated testing and field data from different climates (hot-dry, cold, dry, hot-humid) and states a shape parameter of 5.3759 which lies at the upper end of the range found for other products. The lower and upper bound identified in Kuitche’s analysis are 3.3 and 8.7484, respectively. Significantly higher values are given by Kumar and Sarkan (2013). Here, 9.982 and 14.41 have been calculated for two different sets of photovoltaic cells; a specification of the respective PV technology is not given, here. In their model for PV lifetime prediction, Laronde et al. (2010)

calculate values of 2.6, 5.03 and 7.56 for different sets of c-Si photovoltaic modules using a petri network and literature data but no first-hand field data.

A relatively large spread for shape parameters for photovoltaic cells can thus be observed. For the further analysis, a shape parameter of k=5.3759 is assumed based on Kuitche (2010). This data is assumed to be the most reliable since it is based on field data as well as on accelerated testing. Given the range of values found in literature, however, the changes resulting from a value of k=2.6 and k=14.41 will be assessed additionally in a sensitivity analysis that can be found in the annex.

Technologies under assessment and material intensity

Contrary to crystalline cells, thin film cells are produced by depositing thin layers of materials on glass or stainless steel substrates (El Chaar, lamont, and El Zein 2011). The thickness of this layer is in the range of few microns compared to hundreds of microns for silicon cells. CIGS, CdTe and a-Si cells are analyzed in this study. For each of the considered technologies the material intensity (material required per kilowatt or megawatt peak) is identified. The material demand per MWp is depending on several factors:

- the thickness of the active layer,
- the share of the different materials in the layer,
- the efficiency of the module.

The data for the material intensity has been taken from literature but also includes primary data from manufacturers and expert judgments. Literature data is partly referring to different reference units (e.g. g/m^2) and needs to be normalized to g/kW_p (or MW_p, respectively). This calculation has been performed based on the efficiency of the cells.

CIGS is a mixture of CIS (copper-indium-di-selenide) and CGS (copper-gallium-di-selenide). Its chemical formula is $CuIn_xGa_{(1-x)}Se_2$. The x value can be between 0 and 1 reflecting different rations of CIS to CGS (Speirs et al. 2011). The thickness of the active layer of CIGS cells ranges from 1 to 3 μm. Most modules show a thickness of around 2 μm. The efficiency of commercial modules lies between 10 and 12 per cent (e.g., El Chaar, lamont, and El Zein 2011; Fthenakis 2009). Although CIGS cells differ in their gallium content, it can be said that modules without gallium do not have a significant role while cells with gallium can be considered as common (Sander et al. 2007). Additional differences in the material intensity result from different thicknesses of the active layer and differences in the module’s efficiency. These variations in the material intensity are reflected in the literature and primary data.

The structure of a CIGS PV cell consists of several layers between layers of glass. Molybdenum is deposited on glass as back contact followed by the active layer and a transparent conductive layer (see Figure 2 a).

ZnO transparent oxide	Glass Substrate
CdS buffer layer (or InS)	Front contact (ITO/ZnO)
CIGS (absorber)	CdS n-type layer
Mo contact layer	CdTe p-type layer
Glass	Back contact

Figure 2: (a) Sections of a CIGS cell (b) Sections of a CdTe cell (according to El Chaar, lamont, and El Zein 2011)

In **CdTe** cells a layer of CdTe is combined with a layer of CdS. In addition indium-tin-oxide is used as transparent conductive oxide (TCO). The basic structure – as shown in Figure 2 (b) – is similar to CIGS. The thickness of the active layer varies between 2 and 3.3 μm (Fthenakis 2009; El Chaar, lamont, and El Zein 2011; Moss et al. 2011).

Amorphous silicon (**a-Si**) is one of the oldest thin-film photovoltaic technologies (El Chaar, lamont, and El Zein 2011). The first publications on a-Si appeared already in the late 1960s and the first products were available in the early 1980s (Goetzberger, Hebling, and Schock 2003). Amorphous silicon is an alloy of silicon with hydrogen (Goetzberger, Hebling, and Schock 2003).

The a-Si:H is deposited on glass coated with a TCO (Shah et al. 1999). As for CdTe cells, indium tin oxide is commonly used as TCO with SnO_2 being an alternative option (Shah et al. 1999; Goetzberger, Hebling, and Schock 2003; Moss et al. 2011; Chopra, Paulson, and Dutta 2004).

For these three technologies a data collection has been carried out. Besides literature data, primary data from two manufacturers (a German and a Japanese manufacturer) could be obtained for CIGS and CdTe cells and expert judgments (from "Helmholtz-Zentrum Berlin für Materialien und Energie GmbH" and "German Solar Industry Association – BSW Solar") for complementing and validating the collected data have been included. Especially for gallium used in CIGS cells the data collection showed a relatively large spread. This difference could not be explained by the age of the consulted data, technological development or else, but is supposed to be caused by differences in the design between different producers such as a variation in the gallium-indium ratio (see description above). Also for the other metals embodied in CIGS and CdTe cells ranges have been identified that are supposedly caused by differences in cell design and production processes. Since information about the shares of different cell design representing different material intensities has not been available, the calculations have been carried out for the lower and upper bound of the data range as well as for a mean value (as the arithmetic mean of lower and upper bound). Hereby, the range of the actual material flows that are subject to the share of different cell designs is made transparent despite this lack of more accurate data. This approach is considered favorable to choosing one data set for the material intensity for all calculations as it has been done in similar studies (e.g. Reiser, Rodrigues, and Rosa 2009; Moss et al. 2011, among others).

An overview of the material intensity data for the different thin-film technologies is given in Table 1. As it can be seen, the values for CIGS cells differ most but also for CdTe cells the collected data differs, especially for tellurium. For a-Si cells only one reference stating values for the indium content could be found.

Table 1: Material intensity of different thin-film technologies. Data from experts, manufacturers and literature (U.S. Department of Energy 2011; Moss et al. 2011; Andersson 2000)

		Material intensity [kg/MW]		
		Lower bound	Mean value	Upper bound
CIGS	Indium	9.8	16.5	23.1
	Gallium	2.3	11.0	19.7
CdTe	Indium	15.4	16.9	18.3
	Cadmium	140.1	153.4	166.6
	Tellurium	93.3	137.7	182.0
a-Si	Indium	5.3	5.3	5.3

Lifespan

Since thin-film photovoltaic cells are a relatively young technology (at least regarding large scale deployment) empiric data on the modules' lifespan is quite rare. In most LCA and other studies a lifespan of between 20 and 30 years is stated (e.g., Sherwani, Usmani, and Varun 2010; García-Valverde et al. 2009; Stoppato 2008; Berger et al. 2010; Briem et al. 2004; Azzopardi and Mutale 2010; Held and Ilg 2011; Raugei and Fthenakis 2010). Considering only studies dealing explicitly and exclusively with the technologies analyzed here, generally the same picture can be observed. However, it is indicated in some studies that the lifespan of thin film modules is more than 25 years (Berger et al. 2010; EPIA 2011). In one of the few studies dealing with life span observations of PV-modules a lifespan of 29.6 years is reported (Kuitche 2010). A characteristic lifespan of between 27.7 and 28 years is reported by Kumar and Sarkan (2013). Against this background, an average lifespan of 28 years is assumed in this study, differing lifespans are assessed in a sensitivity analysis (see annex).

Material efficiency in production

CIGS cells are manufactured by vacuum methods (co-evaporation, selenization) as well as non-vacuum methods (electrodeposition, spray pyrolysis, paste coating). The highest efficiencies have been achieved by co-evaporation processes (Kaelin, Rudmann, and Tiwari 2004). Vacuum processes are currently mostly used in thin film PV manufacturing (Speirs et al. 2011). In CdTe electrochemical deposition is very common, too (Cunningham, Rubcich, and Skinner 2002). a-Si cells are mostly manufactured by plasma-enhanced chemical vapor deposition, hot-wire chemical vapor deposition being an alternative (Wolden et al. 2011).

Data regarding the material efficiency within the manufacturing process varies quite a bit. For CIGS cells data ranging from 30 to 50% for current processes can be found while in experimental processes 75% are already achievable. These numbers mostly refer to indium, identical values are assumed for gallium. For CdTe cells data vary even more with efficiencies between 40 and 95%. However, most studies indicate efficiencies between 75% and 100% (see Speirs et al. 2011). These numbers mostly refer to tellurium, identical values are assumed for cadmium. Material efficiency data for a-Si cells could not be found. Due to lack of data, the same values as found for indium in CIGS cells are used.

Up to 2050 an increase of the material efficiency to the current maximum laboratory efficiency of 95% is assumed for all materials, following a linear development from 2012 on.

Efficiency development

Since the study has a prospective character and looks into the future until 2050, probable increases in the cell efficiency need to be considered. Since the material demand is analyzed based on the installations in MW an increase in cell efficiency is reflected in an according reduction of the material requirement per MW.

By Fthenakis (2009) a forecast is made regarding the development of cell efficiency up to 2020 as well as the future development of layer thickness. In EPIA (2011) a continuous growth of cell efficiency is foreseen, too, but at a declining growth rate. In 2030 efficiencies of thin-film technologies between 12 and about 16 percent are predicted (EPIA 2011), still lying below current record lab efficiencies. Goetzberger, Luther and Willeke (2002) also highlight that the development of cell efficiency significantly slows down when the technology gets older and gives an estimation of the development of maximum laboratory efficiencies up to 2060. Against this background, it is assumed that the development of the cell efficiency will follow the "most likely" scenario up to 2020, then – with a reduced growth rate – will increase further up to 2050 to a level around the current record lab efficiency (see Table 2). In terms of material intensity this means that the material intensity per MW decreases up to 2050 by a factor of 1.8 for CIGS, 1.5 for CdTe and 1.9 for a-Si cells.

Table 2: (a) Material efficiency in thin-film PV production and (b) Future development of cell efficiency (efficiency in 2020 based on Fthenakis 2009, record lab efficiency from EPIA 2011, 2050 efficiency from Goetzberger, Luther, and Willeke 2002); values used in the model are grey-shaded.

(a) Material efficiency in production [%]							
	(Green 2009)	(Chopra, Paulson, and Dutta 2004) commercial processes (experimental processes)	(Zweibel 1999)	(Behrendt et al. 2010)	(Speirs et al. 2011)	Assumption 2012	Assumption 2050
CIGS	40	- / 50 / 75 (In)	50% (In)	50	30 – 50	40	95
CdTe	40	75 / 95 (Te)	75/ 95 (Te)	50	40	50	95
a-Si	-	-	-	-	-	40	95

(b) Cell efficiency [%]							
	2008	2011	2020			2050	
PV type	Commercial efficiency	Max. lab efficiency	Conservative	Most likely	Optimistic	Max. lab efficiency	Assumed commercial efficiency
CIGS	11.2	20.3	14	15.9	16.3	26	20
CdTe	10.8	16.5	13	13.2	14		16
a-Si	6.7	13.2	9	9.7	10	17	13

Technology mix

Regarding the share of the different technologies statistics are available in PHOTON (2012) for the years 1999 to 2011. For the following years up to 2050 a JRC scenario assuming a "thin-film uptake" is used (Moss et al. 2011). These data are completed with EPIA (2011) data for the years before 1999 from. In addition, a linear development between the years for which data have been available has been assumed. For the years before 1998 the installations of CdTe and CIGS can be considered as negligible. From 2020 on, it is predicted that the shares of CIGS, CdTe and a-Si remain constant with shares of 8% for CdTe, 18% for CIGS and 15% for a-Si. The shares of each thin film type up to 2050 are given in the annex.

Results

Based on the approach and parameters described above, the material flows of indium, gallium, cadmium and tellurium connected with the deployment of CIGS, CdTe, and a-Si cells have been calculated. The calculation comprises the material flows embodied in the installed photovoltaic cells, the secondary material flows occurring at the cells end-of-life as well as the material required as input for cell production for the different scenarios. The parameter settings are as follows (for parameter variation see sensitivity analysis in the annex):

- Shape parameter: k=5.3759 in all scenarios
- Ø Life span: 28 years in all scenarios
- PV installations: according to the scenarios (reference, accelerated and paradigm-shift)

The results are set into relation to the current world production to provide a clearer picture of the magnitude of the material flows. According to data from the U.S. Geological Survey (USGS) indium production was 670 tonnes in 2012, gallium production was 273 tonnes and cadmium production was 23,000 tonnes in 2012. Data regarding tellurium production was not available from the USGS; therefore other sources had to be used. Green (2006) estimated the amount of Te available from Cu refineries in 2005 to 430 tonnes based on a recovery rate of 33 percent. Varying estimations and projections are discussed by Fthenakis (2009). Based on studies on copper production, a tellurium availability (metallurgical-grade) of 1,450 tonnes in 2020 is predicted (Fthenakis 2009). Based on this, a conservative estimation for Te production in 2012 assuming an annual growth rate of 3.1 percent per year but neglecting increases in recovery efficiency can be made. Te production would then amount to about 532 tonnes.

Reference scenario

Flows into use and material demand

The reference scenario – assuming a moderate growth of up to 377 GW in 2050 – shows maximum flows of materials into use (material embodied in installed cells) per year of 61 tonnes for indium (±15 tonnes), 23 tonnes for gallium (±18 tonnes), 151 tonnes for tellurium (±49 tonnes), and 168 tonnes for cadmium (±15 tonnes). The resulting material demands amount to 73 tonnes of indium (± 19 tonnes), 28 tonnes of gallium (± 16 tonnes), 187 tonnes of tellurium (± 71 tonnes), and 208 tonnes of cadmium (± 18 tonnes). The material flows over time (flows into use and material demand) are shown in Figure 3. Although the material flows expectably lie within a certain range resulting from the material intensity data, the order of magnitude can be clearly identified for each metal – with some limitations regarding gallium where the range is comparably large. The peaks occurring in ten year intervals at 2020, 2030, and 2040 result from the underlying expansion scenarios which assume significant changes in the annual installations every ten years that are reflected in the graphs.

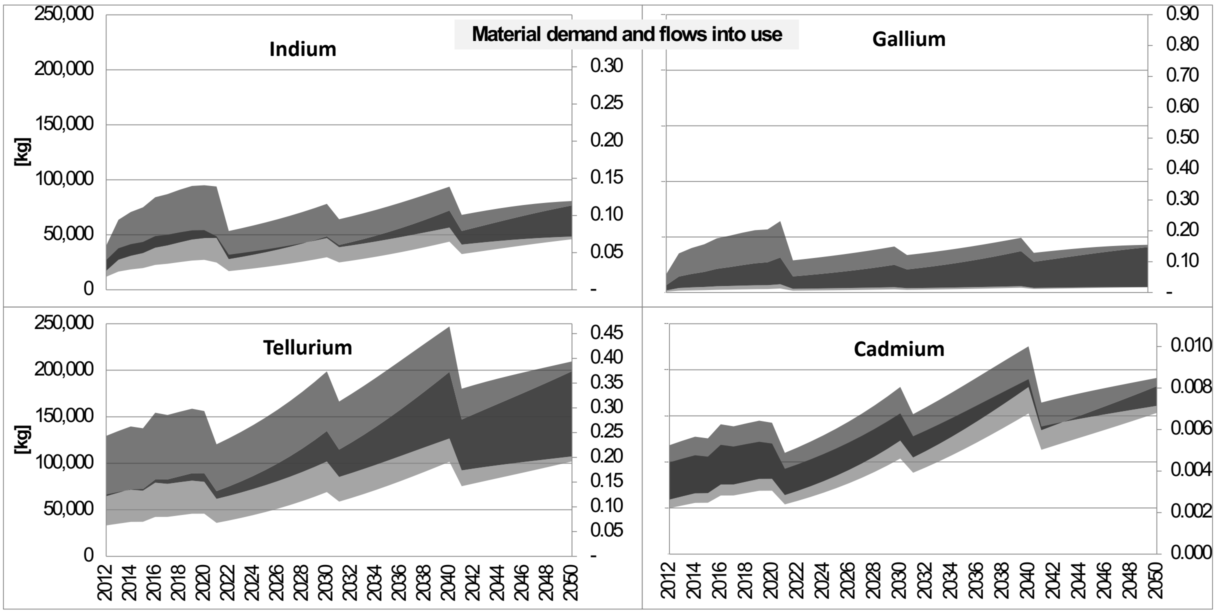

Figure 3: Flows of critical materials into use and material demand in the reference scenario. The secondary x-axis shows the ratio to the 2012 world production of the respective metal. Material flows into use are shaded in lighter-grey, material demand in darker grey.

Put into relation to the 2012 world production, it can be seen that the demand for critical metals resulting from a PV deployment according to the reference scenario will amount to between 4 to 14 percent of the current world production of indium, 1.5 to 24 percent of the gallium production and up to about 1 percent of the cadmium production. The tellurium demand will amount to between 12 and 48 percent of 2012's Te production.

Secondary material flows and metal stocks

The secondary material flows at the PV modules end-of-life show a steady growth until 2050. Here again, tellurium and cadmium show the biggest flows in terms of mass, followed by indium and gallium. In the reference scenario, in 2050, about 30 tonnes of indium (±8 tons) arise from modules reaching their end-of-life; for gallium there arise about 11.5 tonnes (±9 tonnes), for tellurium about 67.4 tonnes (±22 tonnes) and cadmium about 75 tonnes (±7 tonnes). Given a PV deployment according to the reference scenario, for the decade 2021-2030 between 9.6 and 13.5 tonnes of indium, 0.5 to 4.1 tonnes of gallium, 34.1 to 66.4 tonnes of tellurium and 51.1 to 60.8 tonnes of cadmium are to be expected as secondary materials from end-of-life thin film modules. For the following decade these numbers increase significantly, e.g. to about 182 to 304 tonnes of indium and 19 to 163 tons of gallium for the years 2041 to 2050. As the flows into and out of use increase so do the critical metal stocks as shown in Figure 4.

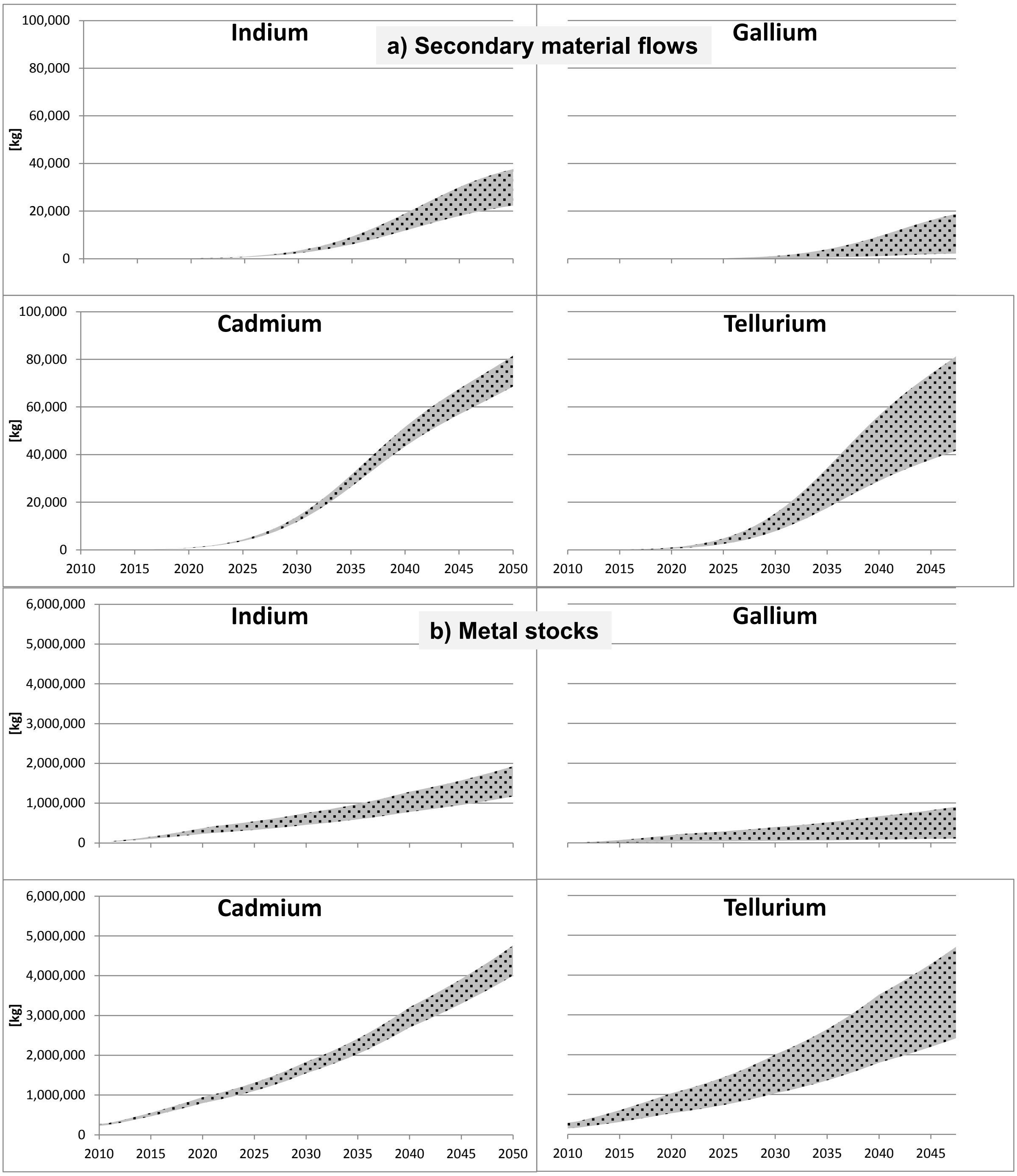

Figure 4: (a) Secondary material flows and (b) Critical metal stocks

Alternative scenarios

While the reference scenario discussed in the previous section assumes a rather moderate growth of installed PV capacity, the alternative scenarios – accelerated and paradigm shift scenario – assume a significantly enhanced deployment. This results in considerably increased material flows. Again the results are subject to the underlying material intensity data and therefore show ranges for the flows of each material. Focusing on the differences between the scenarios, only the results for the mean values will be considered in the following. This still provides a clear picture of the order of magnitude in which the material flows in the different scenarios differ. The entire ranges of results are shown in the figures given in the annex.

Evidently, the alternative scenarios results show significantly increased material flows. The demand for indium, for example, amounts to about 589 (accelerated scenario) and 1,549 tonnes (paradigm shift scenario) in 2020, 658 and 914 tonnes in 2030, and 516 and 839 tonnes in 2050. This means, the indium demand increases to about between 98 percent of current annual world production in the accelerated scenario and to about 231 percent of the current world production in the paradigm shift scenario. A similar statement can be made regarding gallium where the demand increases to about 90 percent of the 2012 world production in the accelerated scenario and 126 percent in the paradigm shift scenario. The maximum tellurium demand per year is even higher with between 257 and 595 percent of the 2012 production. In Table 3 the accumulated material demand and secondary material flows of the different scenarios are shown for each decade from 2020 to 2050 illustrating the material flows connected with a more ambitious deployment of photovoltaic cells over a longer timeframe. The average annual material demands and secondary material flows of each decade are then put into relation to the 2012 world production of each metal.

Table 3: Material demand and secondary flows of critical metals in different EPIA scenarios

Metal	Decade	Reference scenario		Accelerated scenario				Paradigm shift scenario			
		Material demand	Secondary flows	Material demand		Flows out of use		Material demand		Flows out of use	
		[t]	[t]	[t]	Ø rel. to 2012 [%]	[t]	Ø rel. to 2012 [%]	[t]	Ø rel. to 2012 [%]	[t]	Ø rel. to 2012 [%]
In	'21-30	539	12	4,720	172.9	22	0.8	7,229	264.8	34	1.2
	'31-40	628	89	4,733	173.4	308	11.3	7,293	267.1	567	20.8
	'41-50	606	243	4,887	179.0	1,419	52.0	7,459	273.2	2,622	96.0
Ga	'21-30	211	2	1,825	66.8	6	0.2	2,820	103.3	10	0.4
	'31-40	229	27	1,755	64.3	103	3.8	2,705	99.1	193	7.1
	'41-50	224	91	1,759	64.4	518	19.0	2,733	100.1	955	35.0
Te	'21-30	1,180	50	10,416	195.8	83	1.6	15,740	295.9	119	2.2
	'31-40	1,559	279	11,347	213.3	863	16.2	17,472	328.4	1,550	29.1
	'41-50	1,479	568	11,877	223.3	3,494	65.7	18,537	348.4	6,487	121.9
Cd	'21-30	1,314	56	11,604	5.0	92	0.0	17,535	7.6	133	0.1
	'31-40	1,736	311	12,640	5.5	961	0.4	19,464	8.5	1,727	0.8
	'41-50	1,648	633	13,232	5.8	3,892	1.7	20,651	9.0	7,227	3.1

Comparison to other studies

Different studies have been published in the past years analyzing material flows or material demand, respectively, too. Most of them do not assume lifespan distributions (or assume a simultaneous exit function) and do not look at secondary material flows. They differ partly in their considered time spans and some focus on a particular geographic area like the EU. A comparison of the material demands from the different studies including this one is shown in Table 4. To increase the comparability with the results from this study, the average material demand of ten-year intervals has been calculated.

Table 4: Forecasts of demand for thin-film materials in different studies

			Material demand per year [t]			
Reference	Year/ Period	Geographic scope	Indium	Gallium	Tellurium	Cadmium
This study, reference scenario	'21-30	global	53.9	21.1	118	131
	'31-40		62.8	22.9	156	174
	'41-50		60.6	22.4	148	165
This study, accelerated scenario	'21-30		472	182	1,042	1,160
	'31-40		473	176	1,135	1,264
	'41-50		479	176	1,188	1,323
This study, paradigm-shift scenario	'21-30		723	282	1,574	1,753
	'31-40		729	270	1,747	1,946
	'41-50		746	273	1,853	2,065
Reiser, Rodrigues, and Rosa 2009	'08-10	global	13	2.0	57	-
	'10-15		49	7.2	56	-
	'15-20		161	23.8	174	-
	'20-30		688	102	745	-
U.S. Department of Energy 2011	'25	global	250 to 300	10 to 300	1,000 to 2,200	-
Moss et al. 2011	'20	EU	40	1	40	50
	'30		240	6	250	330
Zuser and Rechberger 2011	'10-40	global	870 to 4,333	373 to 1,855	2,843 to 15,690	3,806 to 16,536

Some further constraints regarding comparability have to be mentioned. By Reiser, Rodrigues, and Rosa (2009), for example, indium required for TCO in CdTe and a-Si cells has not been accounted for. Also, in most studies it is not clear in how far replacements of installed modules have been taken into account as it has been done in this study. A major difference is that most studies do not assess secondary flows but focus exclusively on the input side. Marwede and Reller (2012) published one of few studies focusing on the secondary waste streams of photovoltaic cells. Using the Weibull distribution, three scenarios for different technological developments are compared. Tellurium demand, stock and recycled tellurium from end-of-life modules are quantified. The amount of tellurium in end-of-life modules in 2040 varies between 60 and 160 tonnes (Marwede and Reller 2012). These numbers are in the range of the accelerated and paradigm-shift scenario analyzed in this study.

Discussion and conclusions

In this study, demand for critical metals, flows of critical metals into the use phase, and secondary (end-of-life) flows of critical metals resulting from deployment of photovoltaic cells have been analyzed. The results show that a significant increase in demand for critical metals – namely indium, gallium, tellurium and cadmium – is to be expected resulting from future installations of photovoltaic cells. Contrary to other studies, ranges for the material intensity have been used in the calculations representing actual differences found in modules from different manufacturers and different scenarios regarding the future development have been considered. Even though this leads to significant differences in the results, it has been shown that even in the most conservative scenario (i.e. the EPIA 'reference scenario') the additional demand for indium, gallium and tellurium is in a scale that can be considered problematic. Assuming a development closer to the EPIA scenarios "accelerated" and "paradigm-shift", material availability is very likely to become a serious stumbling block. So far, photovoltaic cells account for only 1 to 2 percent of the global gallium and less than 5 percent of the global indium consumption. Against this background, the probable implications of the calculated future demand in the reference scenario of 4 to 14 percent of the current world production for indium, between 1.5 and 24 percent for gallium and between 12 and 48 percent for tellurium become more evident. Shortages of supply and increasing prices are to be expected.

If the development turns out to be closer to the analyzed alternative scenarios, tellurium demand will even amount to 257 to 595 percent of the current world production posing a serious problem. A similar situation has been shown for indium where the maximum annual demand increases to – depending on the underlying scenario – between 98 and 231 percent of the global production of 2012. Regarding the comparison to the 2012 production of the respective materials, it has to be noted that a future decrease of production might be considered a reasonable scenario. The "peak minerals" problematic - the eventually unavoidable decline of production - is discussed in detail for example by Mudd, Prior, Giurco and colleagues (Mudd and Ward 2008; Giurco et al. 2010; Prior et al. 2011). Even if production of the analyzed metals continues to grow for the coming decades a thin-film photovoltaic deployment as assumed in the two alternative scenarios seems rather unlikely due to expectable material shortages.

This underlines the importance of improvements in the material intensity (kg/MW ⇩) – which have already been considered in the study. Hereby, the absolute demand for critical materials can be reduced. However, it has to be noted that a significantly increased material intensity will potentially decrease the technological or economic feasibility of recycling activities. As the efficient recovery of secondary material will have a crucial importance in the future supply of resources, this aspect has to be paid attention to, too. In addition to this, the importance of developing new materials and technologies has to be pointed out. This may provide additional options for substitutions on a material as well as on technological level and will enable possible reactions to future supply shortages.

Besides the growing demand for critical metals the study showed that secondary flow in a significantly growing scale will arise at the photovoltaic cells' end-of-life. Average secondary flows of tellurium between 2041 and 2050 amount to between 29 and 122 percent of the global production in 2012. In the same decade, indium secondary flows amount to between 29 and 122 percent of 2012's production. Gallium shows a similar situation. Especially given the scarcity and criticality of the assessed metals the benefit of an efficient recovery of these flows becomes evident. Given today's situation there are barely any activities recovering critical metals from EOL modules. However, there are processes already applied to production waste and various recycling processes are currently being developed (examples for recycling of CdTe modules can be found in Marwede and Reller 2012; recycling processes for CIGS cells are for example being developed by the Germany companies Loser Chemie, Solarcycle and Lobbe). By an efficient recovery of secondary critical materials a reduction of the gross demand by up to one third appears to be possible.

While currently almost no end-of-life recycling activities can be observed for indium, gallium and tellurium (e.g., Graedel et al. 2011) accompanied by an almost complete dissipation of these metals along their life cycle (e.g., Zimmermann and Gößling-Reisemann 2013) a future metals management has to aim at eliminating these defects. Especially given the metals' criticality and their importance for low carbon technologies the need for a sustainable metals management as for example described by Gleich (2006) appears urgently required.

Annex

Background data

Energy scenarios

As described in the main article, the future installations of photovoltaic cells are modeled based on scenarios developed by the European Photovoltaic Industry Association (EPIA) in cooperation with Greenpeace (EPIA 2011).

The EPIA reference scenario is based on the International Energy Agency`s 2009 World Energy Outlook (IEA 2009). This scenario is based on an annual growth rate of the world gross domestic product (GDP) of 3.1% over the period 2007 to 2030. It could also be named “business-as-usual” scenario as it assumes that no fundamental changes to existing policies are made.

The accelerated scenario assumes a faster PV deployment than it has been seen in recent years. It is described as a possible result of a continuation of current support policies and easily achievable in 20 years without major technology changes (EPIA 2011).

The paradigm shift scenario is supposed to “estimate the full potential of PV in the next 40 years” (EPIA 2011). In the paradigm shift scenario it is assumed that by 2030 12% of the electricity consumption in Europe and in many countries from the Sunbelt including China and India comes from PV.

The assumed PV installations in the different scenarios as well as the assumed energy production are shown in Table 5.

Table 5: Historic and future photovoltaic installations. Historic numbers based on (Maycock 2005; Maycock 2007; EPIA 2012), scenarios from (EPIA 2011)

Year	Reference scenario [MW]	Accelerated scenario [MW]	Paradigm-shift scenario [MW]
1990	490		
2000	1,425		
2010	40,019		
2020	76,852	345,232	737,173
2030	155,849	1,081,147	1,844,937
2040	268,893	2,013,424	3,255,905
2050	377,263	2,988,095	4,669,100

Technology mix

To get from the total PV installations to the installations of the different types of PV cells a certain technology mix had to be assumed. Table 6 shows the share of each thin film type up to 2050. The numbers are based on statistics from PHOTON (2012) for the years 1999 to 2011 and from a JRC scenario assuming a "thin-film uptake" for the following years up to 2050 (Moss et al. 2011). This data is completed with numbers for the years before 1999 from (EPIA 2011), since the Photon data only reached back to 1999. A linear development has been assumed for the years missing in the underlying data.

Table 6: Development of technology shares (based on PHOTON 2012; Moss et al. 2011; EPIA 2011)

Year	CIGS [%]	CdTe [%]	a-Si [%]	Year	CIGS [%]	CdTe [%]	a-Si [%]
1987			24.60%	**2005**	0.20%	1.40%	4.70%
1988			25.40%	**2006**	0.20%	2.70%	4.70%
1989			26.20%	**2007**	0.50%	4.70%	5.20%
1990			27.00%	**2008**	1.00%	6.40%	5.10%
1991			24.00%	**2009**	1.70%	9.00%	6.10%
1992			21.00%	**2010**	1.60%	5.30%	5.00%
1993			18.00%	**2011**	2.40%	5.50%	3.40%
1994			15.00%	**2012**	4.13%	5.78%	4.69%
1995			12.00%	**2013**	5.87%	6.06%	5.98%
1996			12.08%	**2014**	7.60%	6.33%	7.27%
1997			12.15%	**2015**	9.33%	6.61%	8.56%
1998	0.05%	0.13%	12.23%	**2016**	11.07%	6.89%	9.84%
1999	0.10%	0.25%	12.30%	**2017**	12.80%	7.17%	11.13%
2000	0.15%	0.38%	9.60%	**2018**	14.53%	7.44%	12.42%
2001	0.20%	0.50%	8.90%	**2019**	16.27%	7.72%	13.71%
2002	0.20%	0.70%	6.40%	**2020**	18%	8%	15%
2003	0.60%	1.10%	4.50%	**2030**	18%	8%	15%
2004	0.40%	1.10%	4.40%	**2050**	18%	8%	15%

Results

In addition to the numbers given in the main article additional figures concerning the alternative scenarios – accelerated and paradigm-shift - are shown in the following. While the main article focused on the differences between the scenarios, the following figures show the entire ranges of results calculated for both alternative scenarios.

Accelerated scenario

Figure 5 and Figure 6 show the flows into and out use for the accelerated scenario.

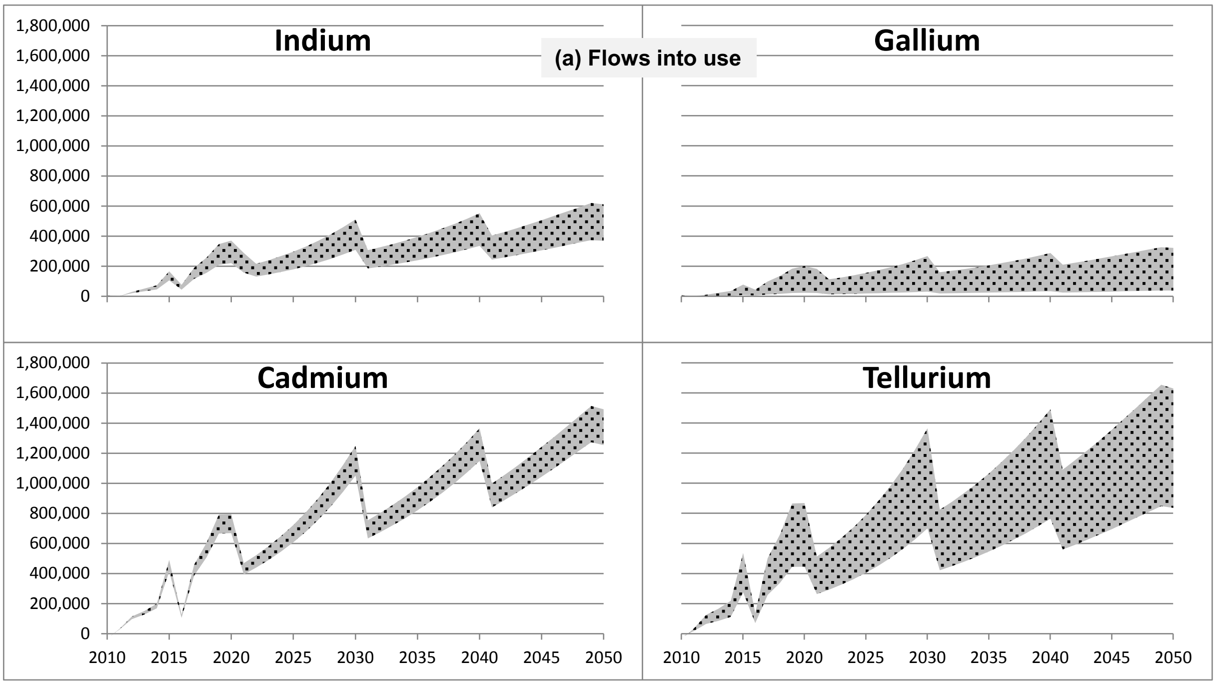

Figure 5: Flows into use - accelerated scenario

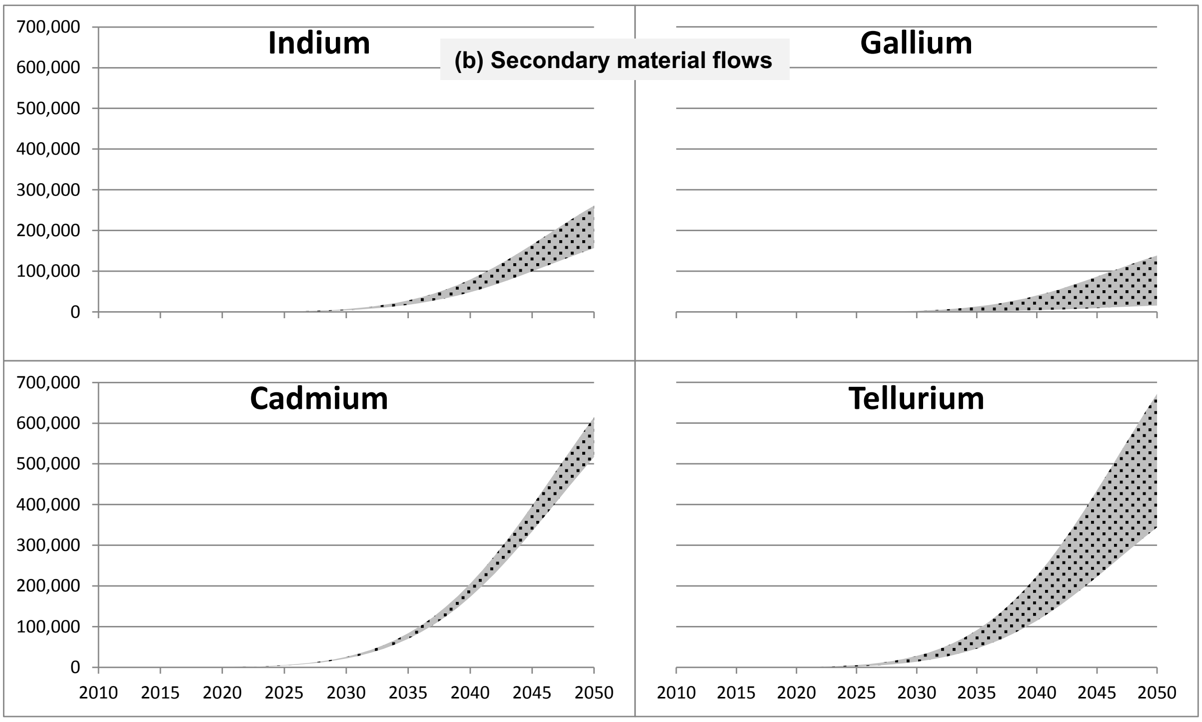

Figure 6: Flows out of use - accelerated scenario

Paradigm-shift scenario

Figure 7 and Figure 8 show the flows into and out of use for the paradigm shift scenario.

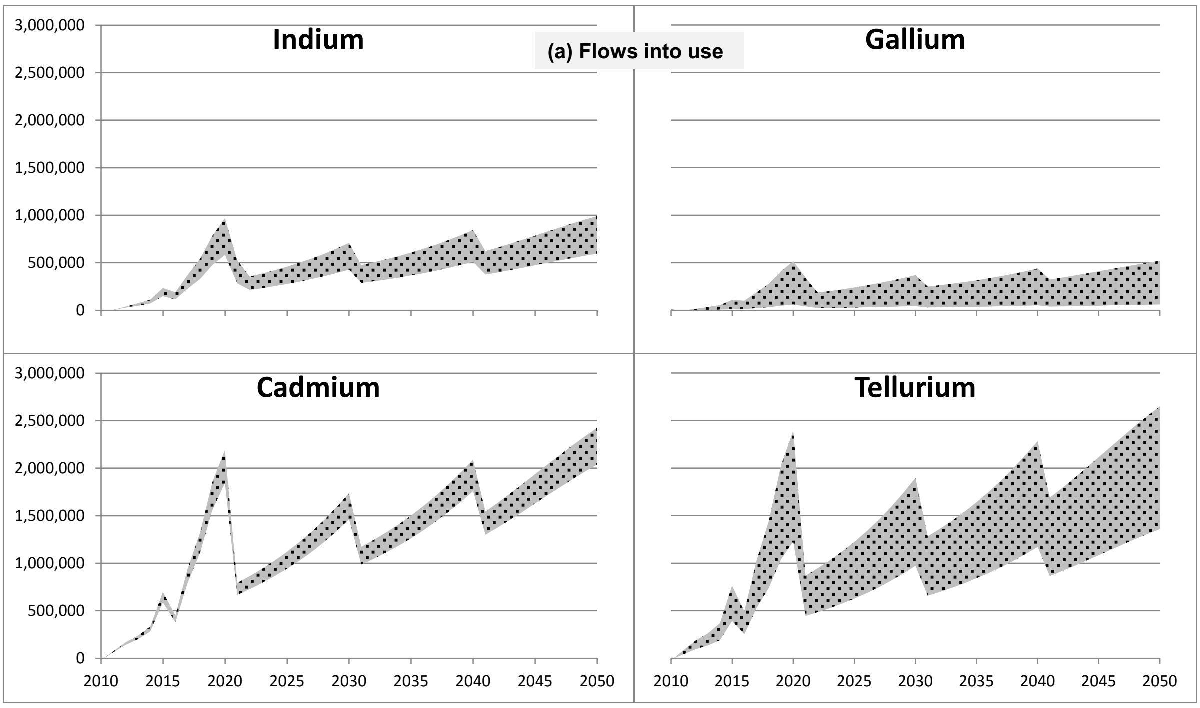

Figure 7: Flows into use - paradigm shift scenario

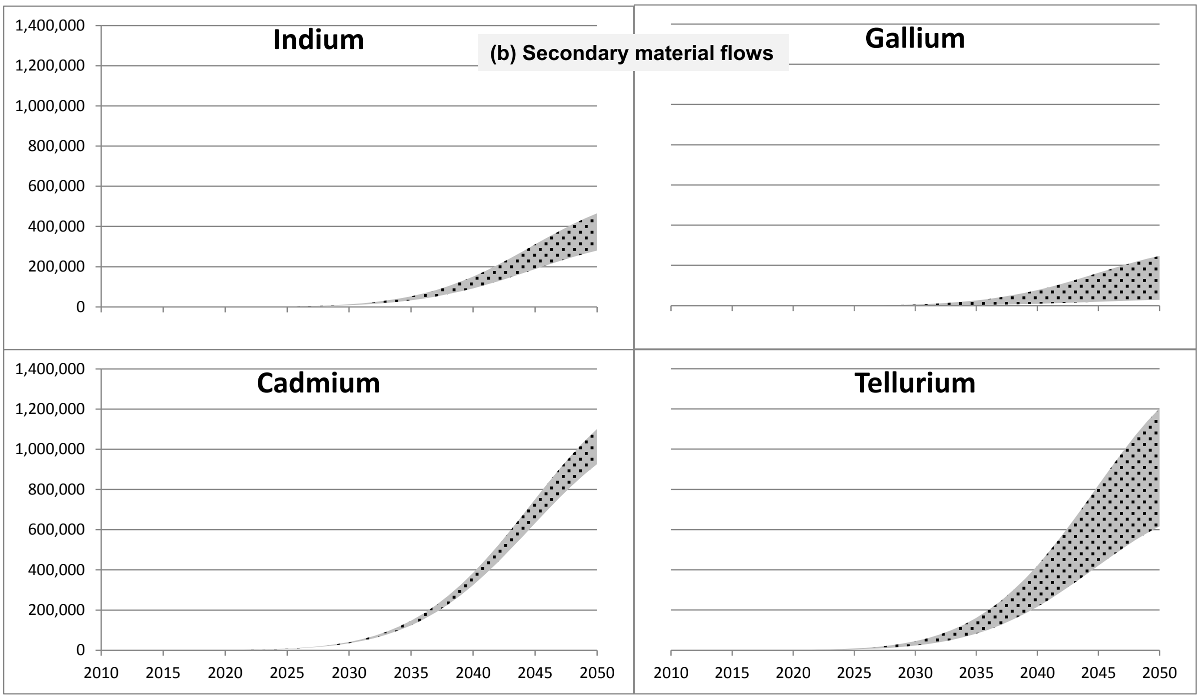

Figure 8: Flows out of use - paradigm shift

Sensitivity analysis

As described in the main article, differing shape parameters than the one used in this study can be found in literature. The effect of differing shape parameters that determine the shape of the life span distribution is analyzed in the following. Further explanations on the Weibull function and its parameters are for example given in (Wilker 2010; Weibull.com 2002; Lehman 1963).

With regard to the range found in literature, values of k=2.6 and k=14.41 are analyzed for the reference scenario. Additionally, the results of a variation of the life span can be found below. Only the mean values for the metal intensity have been considered in the sensitivity analysis.

The analysis of different shape parameter shows differences in the material flows that are increasing over time. Up to around 2020-2025 the differences appear insignificant but get more significant in the following decades. Figure 9 shows the indium flows into use and out of use for the different shape parameter values. While in 2020 the difference between the flows into use is around 3 percent, it increases to about 16 percent in 2030. Overall however, the differences concerning the flows into use are not that significant compared to the variations resulting from the different deployment scenarios and uncertainties in the material intensity data.

Concerning the flows out of use, the situation is somewhat different. In 2035 for example, the flows calculated for k=2.6 amount to the twofold flows calculated for k=14.41. Ten years later, the situation changes and the flows for k=14.41 are 20 percent higher than the flows calculated for k=2.6.

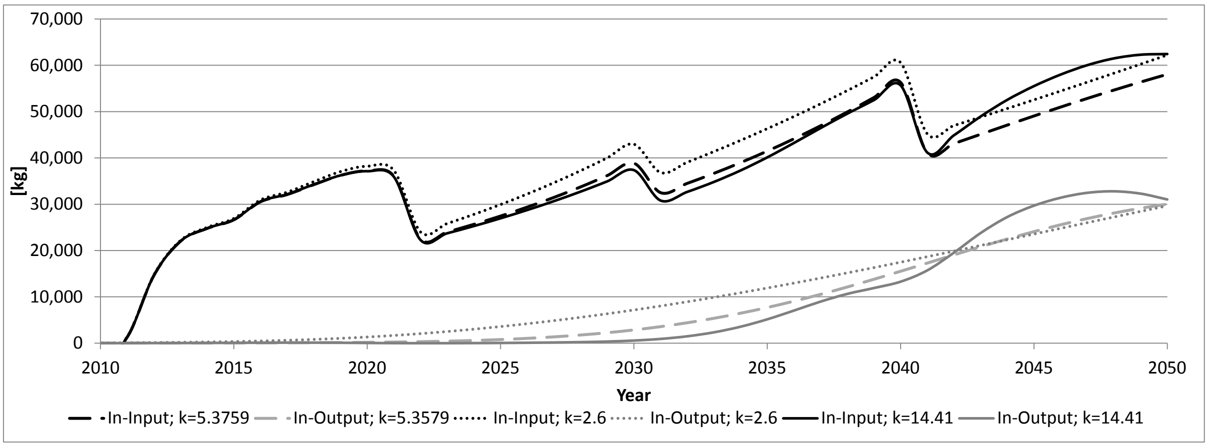

Figure 9: Flows into and out of use, given different shape parameters

Regarding a variation of the converter lifespan, a significant impact on the material flows can be identified. Evidently, a shortened lifespan of 20 years results in higher material flows than a longer lifespan due to an earlier replacement of installed PV modules. The graph shows the indium flows into use calculated for the different scenarios. Up to 2020/2022 the differences between the assessed scenarios remain relatively small, but afterwards grow steadily. In 2030, a lifespan of 20 years results in about 46 t while a lifespan of 35 years results in 38 t. In 2040, the indium flows amount to about 73 t for a lifespan of 20 years and 51 t for a lifespan of 35 years and in 2050 to about 75 tons and 53 t, respectively.

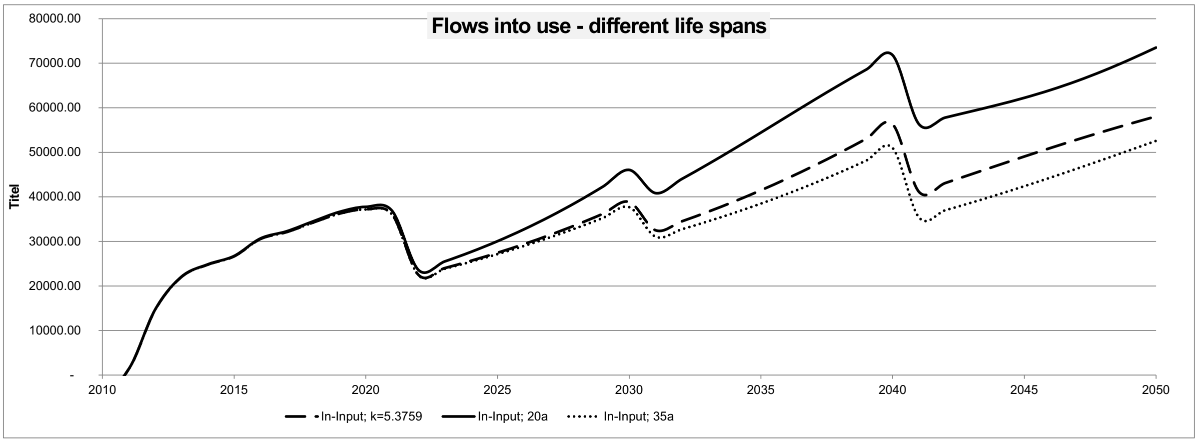

Figure 10: Flows into use for different life spans - reference scenario

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