

Shedding Light on the Anthropogenic Europium Cycle in the EU–28. Marking Product Turnover and Energy Progress in the Lighting Sector

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Supplementary Material

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Table S1. List of Prodcom commodities, end–use segment correspondence, associated market penetration rates of europium in each product, and europium contents with references applied in the model.

Prodcom code	Description	End-use segment	Market penetration rate	Unit	Average	Lower	Upper	Source
26201100	Laptop PCs and palm-top organisers	Small IT	100% (assuming 100% fluorescent lamps backlighting until 2004. From 2005, prorated on LED backlighting penetration: from 1% in 2005 to 99% in 2016)	% Eu (w/w)	From 0.0000041% in 1998 to 0.0000010% in 2016 (weighted averagely on fluorescent lamps and LED contents and penetration rates)	From 0.0000034% in 1998 to 0.0000008% in 2016	From 0.0000047% in 1998 to 0.0000011% in 2016	[1,2]
26302100	Line telephone sets with cordless handsets	Small IT	100%	% Eu (w/w)	0.0000049%	0.0000008%	0.0000090%	[1,2]
26302200	Telephones for cellular networks or for other wireless networks	Small IT	100%	% Eu (w/w)	0.0000049%	0.0000008%	0.0000090%	[1,2]
26302340	Portable receivers for calling or paging	Small IT	100%	% Eu (w/w)	0.0000025% (set at 50% of europium content in telephones)	0.0000004% (set at 50% of europium content in telephones)	0.0000045% (set at 50% of europium content in telephones)	[1,2]
26302370	Other apparatus for the transmission or reception of voice, images or other data, including apparatus for communication in a wired or wireless network (such as a local or wide area network), other than transmission or reception apparatus of code 8443, 8525, 8527 or 8528	Small IT	100%	% Eu (w/w)	0.0000049%	0.0000008%	0.0000090%	[1,2]
26403300	Video camera recorders	Small IT	100%	% Eu (w/w)	0.0000025% (set at 50% of europium content in telephones)	0.0000004% (set at 50% of europium content in telephones)	0.0000045% (set at 50% of europium content in telephones)	[1,2]

26701300	Digital cameras	Small IT	100%	% Eu (w/w)	0.0000025% (set at 50% of europium content in telephones)	0.0000004% (set at 50% of europium content in telephones)	0.0000045% (set at 50% of europium content in telephones)	[1,2]
27402400	Illuminated signs, illuminated name-plates and the like (including road signs)	Luminaires	30% (10-50%)	% Eu (w/w)	0.057% (set as europium content in fluorescent lamps)	0.022% (set as europium content in fluorescent lamps)	0.082% (set as europium content in fluorescent lamps)	[1-3]
27402100	Portable electric lamps worked by dry batteries, accumulators or magnetos (excluding those for cycles or motor vehicles)	Luminaires	From 33% in 2009 to 40% in 2016	% Eu (w/w)	From 0.0080% in 2003 to 0.0054% in 2016	From 0.0016% in 2003 to 0.0010% in 2016	From 0.0023% in 2003 to 0.015% in 2016	[1-3]
27402200	Electric table, desk, bedside or floor-standing lamps	Luminaires	From 33% in 2009 to 40% in 2016	% Eu (w/w)	From 0.0080% in 2003 to 0.0054% in 2016	From 0.0016% in 2003 to 0.0010% in 2016	From 0.0023% in 2003 to 0.015% in 2016	[1-3]
27403930	Electric lamps and lighting fittings, of plastic and other materials, of a kind used for filament lamps and tubular fluorescent lamps	Luminaires	From 33% in 2009 to 40% in 2016	% Eu (w/w)	From 0.0080% in 2003 to 0.0054% in 2016	From 0.0016% in 2003 to 0.0010% in 2016	From 0.0023% in 2003 to 0.015% in 2016	[1-3]
27907030	Electrical signalling, safety or traffic control equipment for roads, inland waterways, parking facilities, port installations or airfields (in tons)	Luminaires	10% (5-15%)	% Eu (w/w)	0.057% (set as europium content in fluorescent lamps)	0.022% (set as europium content in fluorescent lamps)	0.082% (set as europium content in fluorescent lamps)	[1-3]
26201300	Desktop PCs (CRT monitors)	CRTs	From 100% until 1997 to 0% in 2016 (complementary to fluorescent lamps and LED backlighting in desktop PCs)	% Eu (w/w)	0.0010% Until 2007; 0.0023% From 2008 onwards	0.00071% Until 2007; 0.0017% From 2008 onwards	0.0012% Until 2007; 0.0028% From 2008 onwards	[1,2,4,5]
26111100	Cathode-ray television picture tubes; television camera tubes; other cathode-ray tubes	CRTs	100%	% Eu (w/w)	0.0018%	0.0015%	0.0021%	[1,2,4,5]
26403440	Colour video monitors with cathode-ray tube	CRTs	100%	% Eu (w/w)	0.0018%	0.0015%	0.0021%	[1,2,4,5]

27401510	Fluorescent hot cathode discharge lamps (excluding ultraviolet lamps, with double ended cap)	Fluorescent lamps	100%	% Eu (w/w)	0.057%	0.022%	0.082%	[4,6,7]
27401530	Fluorescent hot cathode discharge lamps, with double ended cap (excluding ultraviolet lamps)	Fluorescent lamps	100%	% Eu (w/w)	0.057%	0.022%	0.082%	[4,6,7]
26112220	Semiconductor light emitting diodes (LEDs)	LED lamps	100%	µg Eu/unit	0.032	0.027	0.037	[3,8]
29102400	Other motor vehicles for the transport of persons (excluding vehicles for transporting ≥ 10 persons, snowmobiles, golf carts and similar vehicles)	Automotive	From 0% in 1995 to 21% in 2016	g Eu/unit	0.0050	0.0010	0.0090	[8–10]
29101300	Vehicle compression–ignition internal combustion piston engines (diesel or semi-diesel) (excluding for railway or tramway rolling stock)	Automotive	From 0% in 1995 to 21% in 2016	g Eu/unit	0.0050	0.0010	0.0090	[8–10]
29102100	Vehicles with spark-ignition engine of a cylinder capacity ≤ 1500 cm ³ , new	Automotive	From 0% in 1995 to 21% in 2016	g Eu/unit	0.0050	0.0010	0.0090	[8–10]
29102230	Motor vehicles with a petrol engine > 1500 cm ³ (including motor caravans of a capacity > 3000 cm ³) (excluding vehicles for transporting ≥ 10 persons, snowmobiles, golf carts and similar vehicles)	Automotive	From 0% in 1995 to 21% in 2016	g Eu/unit	0.0050	0.0010	0.0090	[8–10]
29102310	Motor vehicles with a diesel or semi-diesel engine ≤ 1500 cm ³ (excluding vehicles for transporting ≥ 10 persons, snowmobiles, golf carts and similar vehicles)	Automotive	From 0% in 1995 to 21% in 2016	g Eu/unit	0.0050	0.0010	0.0090	[8–10]
29102330	Motor vehicles with a diesel or semi-diesel engine > 1500 cm ³ but ≤ 2500 cm ³ (excluding vehicles for transporting ≥ 10 persons, motor caravans, snowmobiles, golf carts and similar vehicles)	Automotive	From 0% in 1995 to 21% in 2016	g Eu/unit	0.0050	0.0010	0.0090	[8–10]
29102340	Motor vehicles with a diesel or semi-diesel engine > 2500 cm ³	Automotive	From 0% in 1995 to 21% in 2016	g Eu/unit	0.0050	0.0010	0.0090	[8–10]

	(excluding vehicles for transporting ≥ 10 persons, motor caravans, snowmobiles, golf carts and similar vehicles)							
26201300	Desktop PCs (fluorescent lamp backlighting)	Flat panel displays	Increased from 10% in 1998 to 60% in 2008. From 2008, decreased to 25% in 2016	% Eu (w/w)	0.0000036% (until 2007) 0.0000086% (from 2008 onwards)	0.0000031% (until 2007) 0.0000073% (from 2008)	0.0000042% (until 2007) 0.0000099% (from 2008)	[1,2]
26201300	Desktop PCs (LED backlighting)	Flat panel displays	From 5% in 2005 to 75% in 2016	% Eu (w/w)	0.00000018% until 2008) 0.00000043% (from 2008 onwards)	0.00000015% until 2008) 0.00000036% (from 2008 onwards)	0.00000021% until 2008) 0.00000049% (from 2008 onwards)	[1,2]
27902020	Indicator panels incorporating liquid crystal display (LCD)	Flat panel displays	100%	% Eu (w/w)	0.0000222% (until 2007); 0.0000064% (from 2008 onwards)	0.0000218% (until 2007); 0.0000063% (from 2008 onwards)	0.0000226% (until 2007); 0.0000065% (from 2008 onwards)	[1,2]
27902050	Indicator panels incorporating LEDs	Flat panel displays	100%	% Eu (w/w)	0.00000111%	0.00000109%	0.00000113%	[1,2]
26201700	Monitors and projectors principally used in an automatic data processing system	Flat panel displays	100%	% Eu (w/w)	0.0000222% (until 2007); 0.0000064% (from 2008 onwards)	0.0000218% (until 2007); 0.0000063% (from 2008 onwards)	0.0000226% (until 2007); 0.0000065% (from 2008 onwards)	[1,2]
26403460	Flat panel video monitor, LCD or plasma, etc., without tuner (colour video monitors) (excluding those with cathode-ray tubes)	Flat panel displays	100%	% Eu (w/w)	0.0000222% (until 2007); 0.0000064% (from 2008 onwards)	0.0000218% (until 2007); 0.0000063% (from 2008 onwards)	0.0000226% (until 2007); 0.0000065% (from 2008 onwards)	[1,2]

P.C. = personal computers. IT = information technology. CRT = cathode ray tube. LED = light emitting diode. LCD = liquid crystal display.

Table S2. Parameters used in the dynamic material flow analysis (MFA) model.

End-use	Distribution	Scale parameter	Shape parameter	UNU Keys	Source
CRT TVs and monitors	Weibull	10.6	2.1	302, 308, 407	Computed as arithmetical mean based on lifetime expectancy reported in [2]
Flat panel displays	Weibull	9.8	2.3	302, 309, 408	Computed as arithmetical mean based on lifetime expectancy reported in [2]
Small IT	Weibull	7.0	1.2	303, 306, 406	Computed as arithmetical mean based on lifetime expectancy reported in [2]
Luminaires	Weibull	14.2	2.2	506, 507	Computed as arithmetical mean based on lifetime expectancy reported in [2]
Automotive	Weibull	13.2	3.6	-	LED lamps set to last as long as a vehicle lifetime expectancy, (based on [11–14])
Fluorescent lamps	Weibull	8.4	1.8	502, 503	Computed as arithmetical mean based on lifetime expectancy reported in [2]
LED lamps	Weibull	4.6	1.2	505	Computed as arithmetical mean based on lifetime expectancy reported in [2]

Table S3. Collection rates of end-of-life products containing europium.

End-use	End-of-life collection rate
CRT TVs and monitors	84%
Flat panel displays	84%
Small IT	47%
Luminaires	38%
Automotive	95%
Fluorescent lamps	49%
LED lamps	49%

Note: own estimate based on [15].

Table S4. Life cycle assessment factors employed in the calculation of potentials energy savings and greenhouse gas emissions reduction associated with europium recycling in the EU–28.

Process	CED (MJ/kg Eu)			GWP (kgCO ₂ eq/kg Eu)		
	Min	Mean	Max	Min	Mean	Max
Primary (virgin) Eu	6020	7750	10100	314	395	505
Secondary (recycled) Eu	597	882	1167	39	53	66

See the “Eu LCA Supplementary Material” spreadsheet for more details. CED = Cumulative Energy Demand. GWP = Global Warming Potential.

Figure S1. Market shares of europium demand for semi-finished products fabrication.

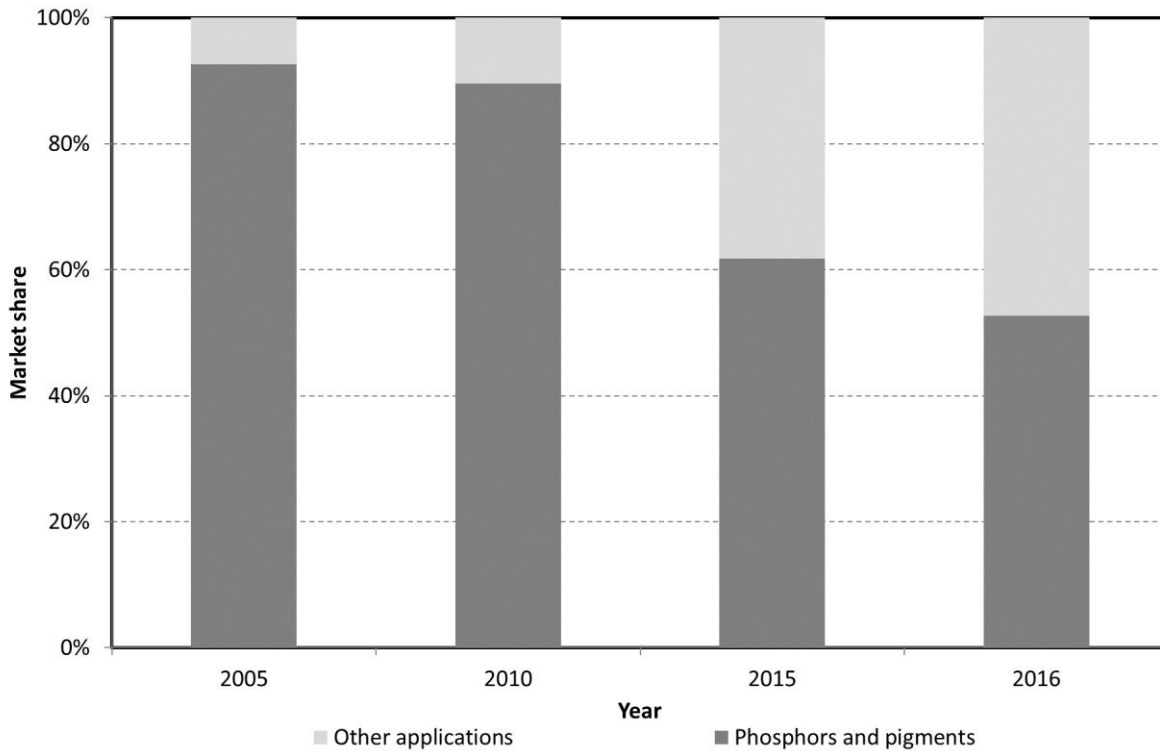


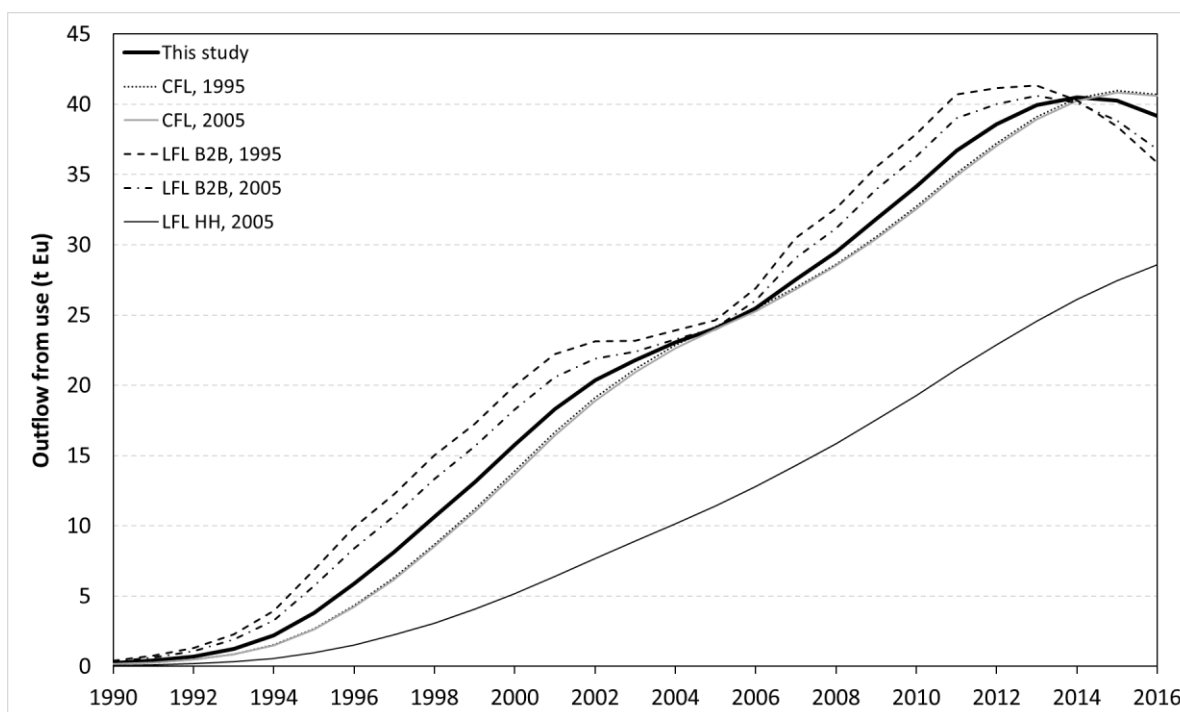
Table S5. Europium flow into use, net-addition to stock, and outflow from use by end-use segment for selected years. Values in tons of europium.

End-use	Flow into use			Net-addition to stock			Outflow from use		
	2005	2010	2015	2005	2010	2015	2005	2010	2015
CRT TVs and monitors	8.6	0.4	0.2	-5.3	-12.7	-7.3	14.3	12.2	6.4
Flat panel displays	0.02	0.03	0.01	0.02	0.03	-0.007	0.001	0.01	0.02
Small IT	0.01	0.01	0.007	0.004	<0.001	<0.001	0.003	0.01	0.01
Luminaires	3.8	3.34	4.1	3.4	2.2	1.9	0.4	1.4	2.4
Automotive	0.04	0.03	0.04	0.04	0.03	0.02	<0.001	0.005	0.02
Fluorescent lamps	27.8	49.9	24.5	4.6	18.1	-16.1	24.2	34.1	40.5
LED lamps	<0.001	0.001	0.02	<0.001	<0.001	0.02	<0.001	<0.001	0.008

Table S6. Alternative lifespan distribution for fluorescent lamps (used for sensitivity analysis). Reproduced from Wang and colleagues [16]

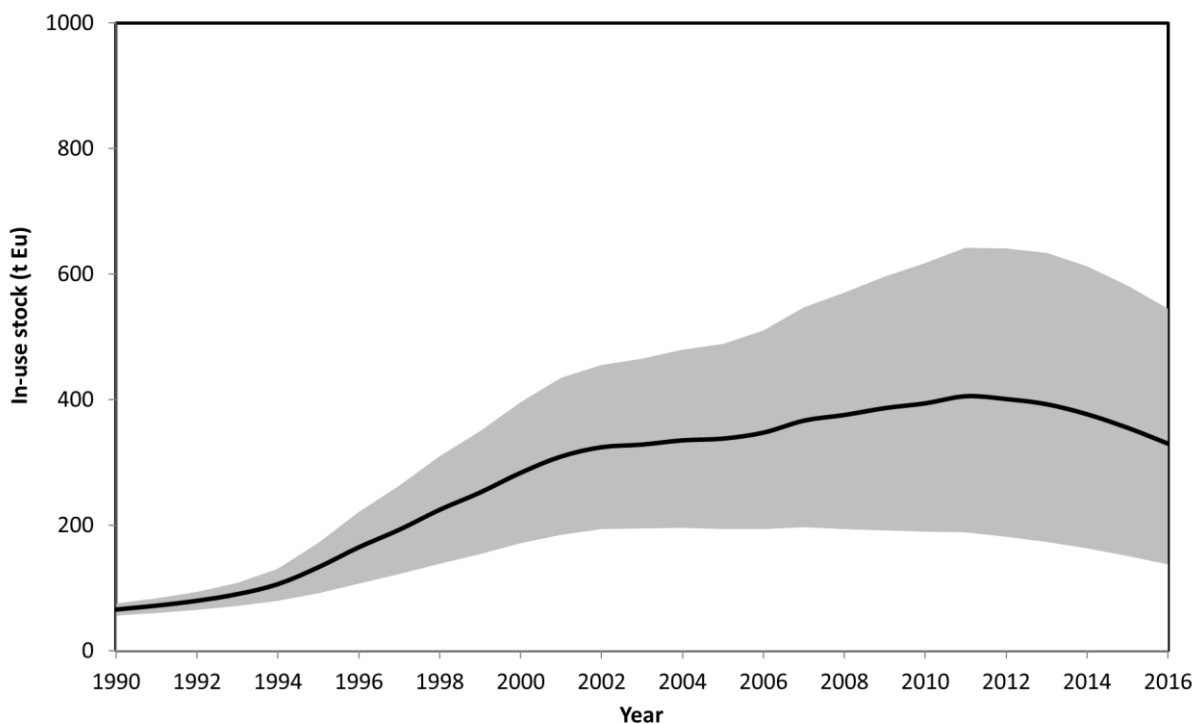
End-use	Distribution	1995		2005	
		Scale parameter	Shape parameter	Scale parameter	Shape parameter
Compact fluorescent lamps	Weibull	2.1	9	2.1	9.1
Straight fluorescent lamps (business to business)	Weibull	1.3	6.6	1.4	7.4
Straight fluorescent lamps (household)	Weibull	1.9	17.8	1.9	17.8

Figure S2. Sensitivity analysis results for europium outflow from use in fluorescent lamps in the EU-28.



Based on values in Table S6. CFL = compact fluorescent lamps. LFL = linear fluorescent lamps. B2B = business to business; HH = household.

Figure S3. Uncertainty analysis results for the in-use stock of europium in the EU-28.



References

1. Buchert, M.; Manhart, A.; Bleher, D.; Pingel, D. Recycling critical raw materials from waste electronic equipment. Commissioned by the North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection. Oeko-Institut e.V., Darmstadt: 2012.
2. Baldè, C.P.; Kuehr, R.; Blumenthal, K.; Fondeur Gill, S.; Kern, M.; Micheli, P.; Magpantay, E.; Huisman, J. E-waste statistics: Guidelines on classifications, reporting and indicators. United nations university, ias-scycle, bonn, germany. United Nations University, Vice Rectorate in Europe – Sustainable Cycles Programme (SCYCLE), Bonn, Germany: 2015.
3. Deubzer, O.; Jordan, R. Cycled - cycling resources embedded in systems containing light emitting diodes. Deliverable 2.1: Categorization of led products. 2012.
4. U.S. Department of the Energy (DOE). Critical materials strategy. DOE: Washington, DC, USA: 2010.
5. Méar, F.; Yot, P.; Cambon, M.; Ribes, M. The characterization of waste cathode-ray tube glass. *Waste Management* **2006**, *26*, 1468-1476.
6. Punkkinen, H.; Mroueh, U.M.; Wahlström, M.; Youhanan, L.; Stenmarck, A. *Critical metals in end-of-life products. Recovery potential and opportunities for removal of bottle-necks of recycling*. Nordic Council of Ministers: 2017.
7. Belardi, G.; Ippolito, N.; Piga, L.; Serracino, M. Investigation on the status of rare earth elements contained in the powder of spent fluorescent lamps. *Thermochimica Acta* **2014**, *591*, 22-30.
8. Wilburn, D.R. Byproduct metals and rare-earth elements used in the production of light-emitting diodes - overview of principal sources of supply and material requirements for selected markets. Scientific investigation report 2012-5215. U. S. Geological survey, reston, virginia. 2012.
9. Cullbrand, K.; Magnusson, O. The use of potentially critical materials in passenger cars. Chalmers University of Technology, Gothenburg, Sweden: 2011.
10. International Organization of Motor Vehicle Manufacturers. Production statistics. Available at <http://www.Oica.Net/production-statistics/>. Accessed on May 2018

11. Du, X.; Graedel, T.E. Global in-use stocks of the rare earth elements: A first estimate. *Environmental Science & Technology* **2011**, *45*, 4096-4101.
12. Adachi, K.; Tainosho, Y. Characterization of heavy metal particles embedded in tire dust. *Environment International* **2004**, *30*, 1009-1017.
13. OSRAM. <https://http://www.Osram.Com/am/light-for/index.Jsp> (accessed on August 2018).
14. Philips. <https://http://www.Philips.Com.Au/> (accessed on August 2018).
15. European Union. Eurostat. In <http://ec.Europa.Eu/eurostat> (accessed on August 2018).
16. Wang, F.; Huisman, J.; Stevels, A.; Baldé, C.P. Enhancing e-waste estimates: Improving data quality by multivariate input–output analysis. *Waste Management* **2013**, *33*, 2397-2407.