Supplementary Materials: Urban Mines of Copper: Size and Potential for Recycling in the EU

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1. Accounting Material Flows and Stock in MFA

This Supplementary Material is intended to provide a detailed description of the material flow analysis (MFA) model and to report the main data sources utilized to characterize the lifecycle of Cu in the EU-28. More details on accounting equations can be found in [1,2].

As shown in Figure S1, lifecycle processes of a substance are linked by materials flows that describe the transformation from primary forms to finished goods and recycling: the rigorous definition distinguishes between imports and exports for flows crossing the system boundaries (i.e., the EU-28 in this study), and inputs and outputs for those entering or leaving a process. Quantifying flows and stocks is carried out in accordance with the law of the conservation of matter by a material balance of flows for every single process [3].

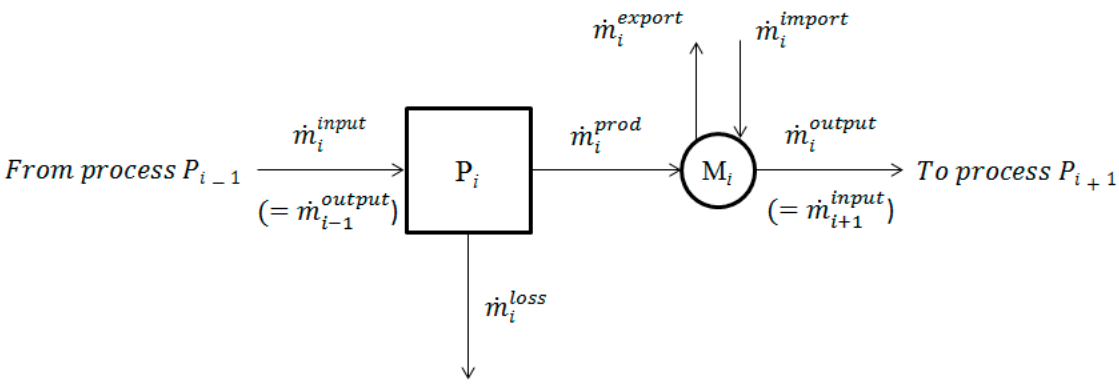

Figure S1. Mass balance for a generic process in the model created. Note: $\dot{m}$—generic mass flow of a substance in kg/year; P_i—generic process of Cu lifecycle; M_i—Cu market.

For a generic process, with the exception of the use phase, total inflow of a lifecycle process should be equal to total outflow from the same process as explained by Equation (S1):

$$\dot{m}_{i,j}^{input} + \dot{m}_{i,j}^{import} = \dot{m}_{i,j}^{output} + \dot{m}_{i,j}^{export} + \dot{m}_{i,j}^{loss} \quad \text{(S1)}$$

where i is the index for a generic lifecycle process, and j is the index for the year of reference. Specifically, in the case of Cu, i refers to ore mining, smelting, refining, fabrication, manufacturing, and waste management, while j covered the years from 1960 to 2014. Mass flow parameter ($\dot{m}$) indicates Cu inflows (and outflows) to (from) a given process; $\dot{m}_{i,j}^{input}$ quantifies the amount of Cu contained in the material demanded by the i-th lifecycle process to produce Cu-containing products in the j-the year and entering domestic market of the region (i.e., $\dot{m}_{i,j}^{output}$); $\dot{m}_{i,j}^{import}$ and $\dot{m}_{i,j}^{export}$ account respectively for the import and export of Cu embodied in Cu-containing products from the i-th lifecycle process in the j-the year; $\dot{m}_{i,j}^{loss}$ is the amount of Cu loss from the i-th lifecycle process in the j-the year.

The mass balance Equation (S1) assumes, in first approximation, that temporary stocks of Cu are negligible in the long term; an example of temporary Cu stock concerns the accumulation of unwrought Cu forms in industrial and commercial warehouses. Based on reported stock of unwrought Cu forms (see Table S1), an accounting term for Cu accumulation in (or depletion from) temporary stocks was added to the right member of Equation (S1):

$$\Delta S_{i,j} = S_{i,j} - S_{i,j-1}$$

where $\Delta S_{i,j}$ measures the temporary stock change generated from *i*-th lifecycle process by the end of the year *j* as difference between the temporary stock of Cu generated by the end of the same year and that of the year before (i.e., *j* − 1).

Two further indices, production ($\dot{m}_{i,j}^{prod}$) and apparent consumption ($\dot{m}_{i,j}^{cons}$), are important for calculation purposes and fundamental to express the results of Cu MFA. The amount of Cu produced from the *i*-th process in the *j*-th year ($\dot{m}_{i,j}^{prod}$) can be calculated as:

$$\dot{m}_{i,j}^{prod} = \dot{m}_{i,j}^{input} - \dot{m}_{i,j}^{loss}$$

The amount of Cu apparently consumed by the *i*-th process in the *j*-th year ($\dot{m}_{i,j}^{cons}$) is calculated as:

$$\dot{m}_{i,j}^{cons} = \dot{m}_{i,j}^{prod} + \dot{m}_{i,j}^{import} - \dot{m}_{i,j}^{export}$$

And equals the amount of Cu demanded from the process *i*+1 (see Figure S1), i.e.,

$$\dot{m}_{i,j}^{cons} = \dot{m}_{i+1,j}^{input}$$

Historic information on domestic production of Cu commodities was found for several lifecycle processes in metal statistics yearbooks (see Table S1). For lifecycle processes (except the use phase) for which historic records were not available, $\dot{m}_{i,j}^{input}$ was deduced according to mass balance equations.

1.1. Quantifying Trade Flows

European trade statistics were considered to characterize imports and exports of commodities containing Cu; historic records were derived from metal statistics yearbooks and the United Nations Commodity Trade Statistics (UN COMTRADE) database (see Tables S2 and S3). Because in the UN COMTRADE database trade flows are expressed in terms of product weight, mass conversion factors were required to transform that information into Cu weight according to Equation (S2). To this aim, average Cu contents for ores and concentrates, Cu matte, semifinished, and finished goods were applied [4–7]. The term "good" is intended as "any economic entity of matter with a positive or negative economic value" [3].

$$\dot{m}_{i,j} = \dot{g}_{i,j} \times C_{i,j} \tag{S2}$$

where $\dot{g}_{i,j}$ is a generic good containing the substance of interest, and $C_{i,j}$ is the concentration of such substance in the good itself, at process and time defined. Equation (S2) was applied to imports and exports of Cu-containing products. The difference between imports and exports of Cu in the *j*-th year results in the net-import quantification (S3).

$$\dot{m}_{i,j}^{net-import} = \dot{m}_{i,j}^{import} - \dot{m}_{i,j}^{export} \tag{S3}$$

1.2. Quantifying Process Losses

Process losses of Cu were calculated according to Equation (S4):

$$\dot{m}_{i,j}^{loss} = \dot{m}_{i,j}^{input} \times r_{i,j}^{loss} \tag{S4}$$

where, $r_{i,j}^{loss}$ is the loss rate of Cu for the *i*-th process in the *j*-th year. Loss rates are reported in Table S4.

1.3. Secondary Cu Sources

According to common definitions, secondary Cu sources include residues from fabrication and manufacturing phases (known as new scrap) and Cu waste and scrap generated at end-of-life from discarded goods and collected for recycling (i.e., old scrap). Depending on the scrap quality, secondary Cu flows can follow two main routes: direct melting, in which high quality scrap are melted by fabricators, and secondary smelting, in which the Cu scrap of lower quality need further refining before its utilization in new materials and goods. The modeling of these two types of flows is described in the following sections.

1.4. Quantification of Cu New Scrap

Cu new scrap sources are fabrication and manufacturing. In the model, for each major end-use application sector, fabrication and manufacturing recovery efficiency rates (see Table S5) were multiplied by Cu manufacturing input to estimate the amount of new scrap generated in a given year.

1.5. Quantification of Cu Old Scrap

A top-down approach (Figure S2) was applied to estimate the amount of Cu generated at end-of-life. Such an approach required firstly to identify major end-use applications of Cu; secondly, the amount of Cu utilized in each end-use was quantified; thirdly, lifetime distribution models were applied to simulate the generation of obsolete Cu-containing products at end-of-life. To this aim, end-use market shares were employed to disaggregate the utilization of Cu into its major applications: building and construction, electrical and electronic products, industrial machinery and equipment, transportation equipment, consumer and general products (see Table S6). In the model, the Weibull distribution was chosen to represent the probability density function of the lifetime distribution for each end-use application sector (see Table S7).

Annual Cu flows out of use generated from each application sector were then aggregated into five waste type categories (see Table S8) to enable a representative modeling of the regional waste management. Collection and preprocessing rates for construction and demolition waste, electrical and nonelectrical industrial waste, end-of-life vehicles, waste of electrical and electronic equipment, and municipal solid waste were applied to compute the amount of old Cu scrap domestically recovered for recycling in a given year (see Table S9).

1.6. The Recycling of Secondary Cu Flows

Annual amount of secondary Cu collected domestically for recycling is given by the sum of new scrap and old scrap generated in the same year. This flow increases in years in which imports of Cu waste and scrap are greater than exports, or decreases when the EU-28 net-exported secondary Cu flows. Depending on the quality of secondary Cu flows, the resulting amount of Cu waste and scrap domestically processed can be directly melted by fabricators or can enter secondary smelting for cathodes production. Because of its quality, the largest fraction (~90%) of new scrap generally enters the fabrication of semifinished goods [8]. Annual amounts of Cu new scrap utilized by fabricators were subtracted to historic statistics of total Cu directly melted in the EU-28 to enable an estimate of the amount of Cu deriving from old scrap sources.

The remaining amount of secondary Cu not processed directly by fabricators was modeled to enter secondary smelting plants. Annual inputs of secondary Cu estimated were cross checked and balanced with historic records of secondary Cu cathodes production reported in metal statistics yearbooks [9].

1.7. Quantification of Cu Stocks

Geological surveys provide estimates of reserve and reserve base for many minerals [10,11]. The in-use stock constitutes an anthropogenic reservoir of a substance embedded within the use phase to which is associated with a potential for supporting secondary material production. Annual net-additions to the in-use stock are computed as difference between annual flows into use and the amount of scrap generated within the same year and estimated by means of the top-down approach. The sum of annual net-addition to the in-use stock gives the contemporary in-use stock of Cu. Equations (S5) and (S6) summarize the mass balance equations for the use phase.

$$\dot{m}_{u,j}^{IUS} = \dot{m}_{u,j}^{input} - \dot{m}_{u,j}^{output} - \dot{m}_{u,j}^{loss} \tag{S5}$$

$$m^{IUS} = \sum_{j=1}^{k} \dot{m}_{u,j}^{IUS} \tag{S6}$$

where $\dot{m}_{u,j}^{IUS}$ is the annual mass flow accumulated in the cumulative in-use stock m^{IUS}, over the k years considered (i.e., 1960–2014).

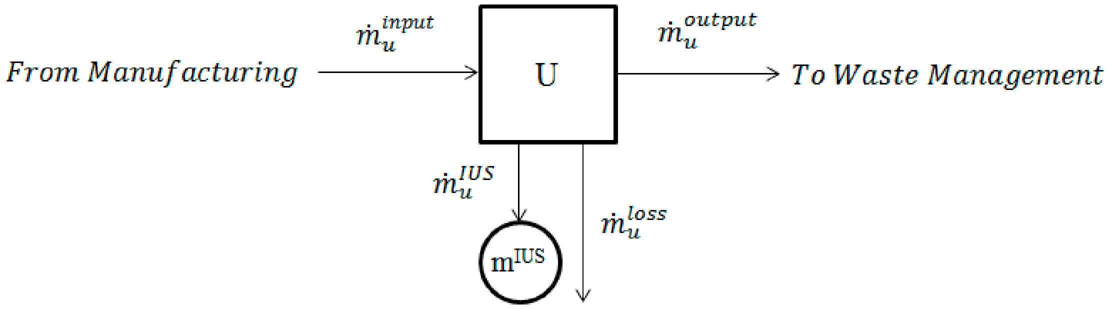

Figure S2. Mass balance for the use phase in the model created.

Table S1. Historic statistics of Cu production in the EU-28 for selected years; from [9,12]. Values are in Gg Cu.

Year	Mining	Total Refining	Direct Melting	Fabrication
1960	170	1010	582	2419
1970	299	1395	727	3155
1980	596	1870	844	3907
1990	664	1922	873	4553
2000	758	2379	1050	5981
2010	754	2623	1042	

Table S2. Historic statistics of import and export of unrefined, refined, waste and scrap of Cu in the EU-28 for selected years; from [9]. Values are in Gg Cu.

	Unrefined		Refined		Waste and Scrap	
Year	**Import**	**Export**	**Import**	**Export**	**Import**	**Export**
1960	243	10	1255	313	126	39
1970	395	13	1335	443	343	130
1980	406	43	2038	560	511	360
1990	334	34	2099	679	873	641
2000	269	252	2719	797	1315	1186
2010	445	210	2139	1172	1950	2404

Table S3. Commodity codes of Cu-containing goods considered in the analysis as recorded by the United Nations Commodity Trade Statistics database [13]. Average Cu contents of finished goods are from [4].

Life Process	Code	Classification	Description	Average Cu Contents
Production	28311	SITC 1	Ores and concentrates of copper	28%
	28312	SITC 1	Copper matte	98%
Fabrication	68221	SITC 1	Bars, rods, angles, shapes, wire of copper	75%
	68222	SITC 1	Plates, sheets, and strip of copper	79%
	68223	SITC 1	Copper foil	98%
	68224	SITC 1	Copper powders and flakes	99.9%
	68225	SITC 1	Tubes, pipes, and blanks, hollow bars of copper	98%
	68226	SITC 1	Tubes and pipe fittings of copper	98%
	69312	SITC 1	Wire, cables, ropes etc., not insulated of copper	99.9%

			Manufacturing	
Building and construction	69312	SITC 3	Stranded wire, ropes, cables, plaited bands, slings and the like, of copper	100.0%
	69352	SITC 3	Cloth (including endless bands), grill, netting and fencing, of copper wire	100.0%
	6943	SITC 3	Nails, tacks, etc., made of copper	100.0%
	69734	SITC 3	Cooking or heating apparatus of a kind used for domestic purposes, non-electric	100.0%
	69742	SITC 3	Household articles and parts thereof, n.e.s., of copper	100.0%
	69752	SITC 3	Sanitary ware and parts thereof, n.e.s., of copper	100.0%
	69942	SITC 3	Copper springs	100.0%
	69971	SITC 3	Chain of copper and parts thereof	100.0%
	69973	SITC 3	Articles of copper, n.e.s.	100.0%
	7414	SITC 3	Commercial refrigeration equipment, parts	3.6%
	7415	SITC 3	Air conditioning machines, parts	18.0%
	7752	SITC 3	Domestic refrigerators, freezers	4.0%
Electrical and electronic products	764	SITC 3	Telecommunication equipment parts, n.e.s	10%
	7731	SITC 3	Insulated wire, etc., conductors	40%
	77317	SITC 3	Other electric conductors, for a voltage exceeding 1000 V (to be deducted from S3-773) (assumed to be mainly aluminium cable)	−40%
	77318	SITC 3	Optical fibre cables (to be deducted from S3-773)	−40%
Industrial machinery and equipment	716	SITC 3	Rotating electric plant (motors)	13.0%
	771	SITC 3	Electric power machinery	13.5%
	772	SITC 3	Electric switches, relays, circuits	7.0%
	7758	SITC 3	Electro-thermic appliances, n.e.s	6.0%
	774	SITC 3	Electro-medical and X-ray equipment	10.0%
	776	SITC 3	Transistors, valves, etc.	7.0%
	778	SITC 3	Electric machinery apparatus, n.e.s	10.0%
Transportation equipment	781	SITC 3	Passenger motor vehicles excluding buses	1.5%
	782	SITC 3	Goods and special transport vehicles	1.0%
	783	SITC 3	Road motor vehicles, n.e.s	1.0%
	791	SITC 3	Railway vehicles and equipment	3.0%
	792	SITC 3	Aircraft and equipment	2.4%
	793	SITC 3	Ship, boat, float structures	1.0%
Consumer and general goods	751	SITC 3	Office machines	2.5%
	752	SITC 3	Automatic data processing equipment	8.0%
	759	SITC 3	Parts for office machines	10.0%
	761	SITC 3	Television receivers, etc.	2.8%
	762	SITC 3	Radio-broadcast receivers	10.0%
	763	SITC 3	Sound recorder, phonograph	5.0%
	774	SITC 3	Electro-medical and X-ray equipment	10.0%
	7751	SITC 3	Household laundry equipment	3.0%
	7753	SITC 3	Dishwashing machines of the household type	1.5%
	7754	SITC 3	Electric shavers, clippers, parts	10.0%
	7757	SITC 3	Domestic electro-mechanical appliances	3.0%

Table S4. Loss rates for selected processes of the anthropogenic lifecycle of Cu.

End-Use Application	Recovery Rate	Loss Rate	Source
Ore mining	90.0%	10.0%	[14]
Primary smelting	95.0%	5.0%	[14]
Secondary smelting	95.0%	5.0%	[14]
Primary refining	99.0%	1.0%	Own estimate based on [14]
Secondary refining	97.0%	3.0%	Own estimate based on [14]

Table S5. New scrap generation rates based on [8].

End-Use Application	Process Efficiency Rate	New Scrap Generation Rate
Building and construction	90.0%	10.0%
Electrical and electronic products	87.5%	12.5%
Industrial machinery and equipment	85.0%	15.0%
Transportation equipment	82.0%	18.0%
Consumer and general products	76.3%	23.7%

Table S6. Major end-use application sectors of Cu and related market shares.

Year	Building and Construction	Electrical and Electronic Goods	Industrial Machinery and Equipment	Transportation Equipment	Consumer and General Products	Note/Source
1960	32%	24%	17%	13%	14%	Values set as the US [15]
1961	32%	24%	17%	13%	14%	Values set as the US [15]
1962	32%	24%	17%	13%	14%	Values set as the US [15]
1963	32%	24%	17%	13%	14%	Values set as the US [15]
1964	32%	24%	17%	13%	14%	Values set as the US [15]
1965	32%	24%	17%	13%	14%	Values set as the US [15]
1966	32%	24%	17%	13%	14%	Values set as the US [15]
1967	32%	24%	17%	13%	14%	Values set as the US [15]
1968	32%	24%	17%	13%	14%	Values set as the US [15]
1969	32%	24%	17%	13%	14%	Values set as the US [15]
1970	32%	24%	17%	13%	14%	Values set as the US [15]
1971	32%	24%	17%	13%	14%	Values set as the US [15]
1972	32%	24%	17%	13%	14%	Values set as the US [15]
1973	32%	24%	17%	13%	14%	Values set as the US [15]
1974	32%	24%	17%	13%	14%	Values set as the US [15]
1975	32%	24%	17%	13%	14%	Linearly interpolated
1976	32%	25%	16%	15%	12%	Linearly interpolated
1977	33%	26%	16%	14%	11%	Linearly interpolated
1978	33%	26%	16%	13%	12%	Linearly interpolated
1979	32%	27%	16%	13%	12%	Linearly interpolated
1980	32%	28%	17%	11%	12%	Linearly interpolated
1981	32%	28%	17%	11%	12%	Linearly interpolated
1982	34%	28%	16%	11%	12%	Linearly interpolated
1983	37%	25%	15%	12%	11%	Linearly interpolated
1984	37%	25%	14%	13%	11%	Linearly interpolated
1985	40%	23%	14%	13%	10%	Linearly interpolated
1986	41%	23%	15%	12%	9%	Linearly interpolated
1987	43%	23%	13%	11%	9%	IWCC; [16]
1988	41%	23%	14%	12%	10%	Linearly interpolated
1989	41%	23%	14%	12%	10%	IWCC; [16]
1990	40%	24%	14%	12%	10%	Linearly interpolated
1991	42%	24%	13%	11%	10%	IWCC; [16]
1992	41%	24%	13%	12%	10%	Linearly interpolated
1993	41%	25%	13%	11%	10%	IWCC; [16]
1994	41%	25%	14%	11%	9%	Linearly interpolated
1995	40%	25%	15%	10%	10%	IWCC; [16]
1996	41%	25%	15%	10%	9%	Linearly interpolated
1997	40%	26%	16%	9%	9%	Linearly interpolated
1998	40%	26%	16%	9%	9%	Linearly interpolated
1999	40%	26%	17%	8%	9%	Linearly interpolated
2000	40%	25%	17%	8%	9%	Linearly interpolated
2001	41%	25%	17%	9%	8%	Linearly interpolated
2002	41%	25%	17%	9%	8%	Linearly interpolated
2003	41%	24%	17%	10%	8%	Linearly interpolated
2004	41%	24%	18%	10%	7%	Linearly interpolated
2005	41%	23%	18%	11%	7%	Linearly interpolated
2006	42%	23%	18%	11%	7%	Linearly interpolated
2007	42%	22%	18%	12%	6%	Linearly interpolated
2008	42%	22%	18%	12%	6%	[17]
2009	42%	23%	17%	12%	6%	[17]

2010	41%	23%	18%	12%	6%	[17]
2011	40%	24%	18%	12%	6%	[17]
2012	39%	24%	19%	12%	6%	[17]
2013	38%	24%	19%	13%	6%	[17]
2014	36%	25%	19%	14%	6%	[17]

Table S7. Lifetime distribution models and related parameters applied to the major end-use application sectors of Cu; values based on [4,8,18].

End-Use Application	Average Lifetime	Shape Parameter	Distribution
Building and construction	40	4	Weibull
Electrical and electronic products	25	4	Weibull
Industrial machinery and equipment	18	4	Weibull
Transportation equipment	16	4	Weibull
Consumer and general products	8	4	Weibull

Table S8. Transfer coefficients for Cu end-use applications to major waste categories (based on [8]).

End-Use Application	C&D	IW	ELV	MSW	WEEE
Building and construction	0.91	-	-	0.09 (from 1960 to 2002) 0.0 (from 2003 to 2014)	0.0 (from 1960 to 2002) 0.09 (from 2003 to 2014)
Electrical and electronic products	0.6	0.2	-	0.2 (from 1960 to 2002) 0.0 (from 2003 to 2014)	0.0 (from 1960 to 2002) 0.2 (from 2003 to 2014)
Industrial machinery and equipment	-	0.9	-	0.1 (from 1960 to 2002) 0.0 (from 2003 to 2014)	0.0 (from 1960 to 2002) 0.1 (from 2003 to 2014)
Transportation equipment	-	-	1.0	-	-
Consumer and general products	-	-	-	1.0 (from 1960 to 2002) 0.25 (from 2003 to 2014)	0.0 (from 1960 to 2002) 0.75 (from 2003 to 2014)

Note: C&D—Construction and demolition waste; IW—industrial waste; ELV—end-of-life vehicles; MSW—municipal solid waste; WEEE—waste electrical and electronic equipment.

Table S9. End-of-life collection (for recovery) rates and pre-processing efficiency of the main Cu waste category. Based on [4].

End-Use Application	Collection Rate	Pre-processing Rate
Construction and demolition waste	78%	91%
Industrial waste	81%	87%
End-of-life vehicles	67%	61%
Municipal SolidWaste	52%	62%
Waste electrical and electronic equipment	50%	85%

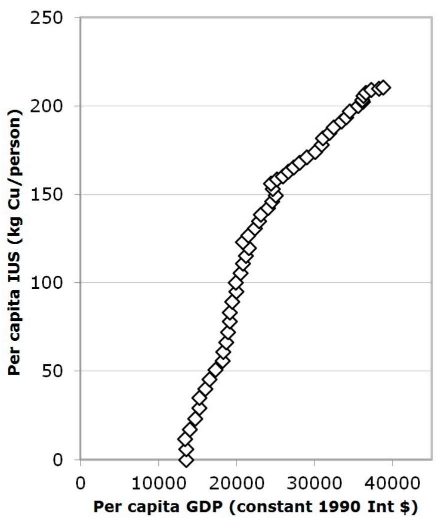

Figure S3. Intensity of Cu in-use stock per economic activity: per capita in-use stock of Cu versus per capita gross domestic product (at constant 1990 international $).

Table S10. Uncertainty ranges applied to Cu flows in this study.

Flow	Uncertainty
Domestic Cu production	Negligible
Trade of Cu ores and concentrates	±10%
Trade of unrefined and refined Cu forms	±10%
Trade of semifinished goods	±10%
Trade of finished goods	±20%
Trade of Cu waste and scrap	±20%

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