Supplementary Material
for
Classification of anthropogenic mineral for sustainable resource governance

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- Supplementary Dataset

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Abbreviations and Acronyms

Material-related

AM	Anthropogenic mineral
AMB	Anthropogenic mineral reserve base
AME	Anthropogenic mineral resource
AMR	Anthropogenic mineral reserve
AMSE	Anthropogenic mineral subeconomic resource
AMTB	Anthropogenic mineral technique-limited reserve base
GM	Geological mineral
PAMR	Potential anthropogenic mineral reserve (by current economic and technical conditions of urban mining)
PGM	Platinum group metal
DGMR	Discovered geological mineral reserve
REE	Rare earth element

Product-related

AC	Air conditioner
BEV	Battery electric vehicle
CRT	Cathode-ray tube
EEE	Electrical and electronic equipment
ELV	End-of-life vehicle
EoL	End-of-life (product)
EWH	Electric water heater
EV	Electric vehicle
FM	Fax machine
GWH	Gas water heater
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
LCD	Liquid-crystal display
MP	Mobile phone
RH	Range hood
VP	Video player
WEEE	Waste electrical and electronic equipment
WM	Washing machine

Method-related

CRIRSCO	Committee for Mineral Reserves International Reporting Standards
HS	High scenario (for urban mining)
LS	Low scenario (for urban mining)
UNFC	United Nations Framework Classification for Resources

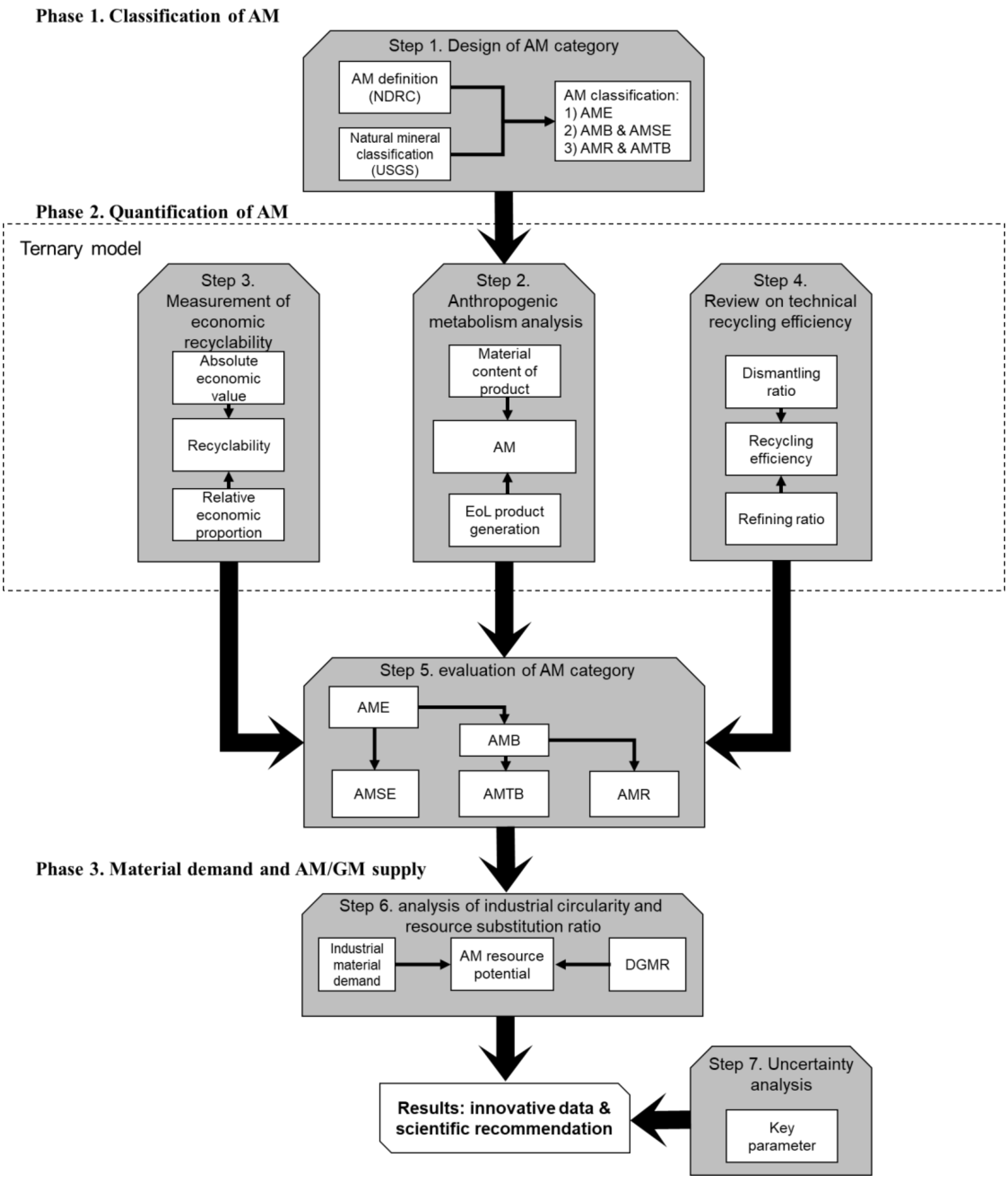
Name-related

NDRC	National Development and Reform Commission of China
SDGs	Sustainable Development Goals
USGS	United States Geological Survey

Supplementary Methods

Text 1. Technology roadmap

This study mainly consists of three phases: classification of AM, quantification of AM, and analysis of AM loss and resupply; seven steps: design of AM categories, dynamic anthropogenic metabolism modeling, measurement of economic recyclability, review of technical recycling efficiencies, evaluation of AM categories, analysis of industrial circularity and resource substitution ratios, and uncertainty analysis, as shown in the below **flow chart**.



Flow chart. Visualization of technology roadmap

During **phase 1**, based on information (definition of AM and GM classification code) from the National Development and Reform Commission of China and USGS[1, 2], five AM categories were designed. Their inclusion relation can be found in Supplementary Fig. 2. So, an AM classification framework was built (**step 1**).

During **phase 2**, the ternary model consisting of a dynamical anthropogenic metabolism analysis, a measurement of product economic recyclability, and a review of material recycling efficiency was developed to convert AM from AME into AMB, then to AMR. We chose China as the study case and considered 42 target metals in 21 modern products[3]. In the beginning, the quantities of AME were estimated by combining material contents of products and amounts of EoL products (**step 2**). Secondly, the economic recyclability of products was measured using AMB threshold of absolute economic value and threshold of relative economic proportion (**step 3**). Thirdly, the technical recycling efficiencies of metals were identified by a review (the overall recycling efficiencies sometimes were found directly, sometimes were calculated by combining dismantling ratios and refining ratios) (**step 4**). Afterward, by integrating all these intermediate results, quantities of AM categories were clarified (**step 5**).

During **phase 3**, We depleted and redelivered AM in WEEE and ELV in China in 2021, considering the five stages of the material life cycle: extraction, production, use, recycling, and disposal[4]. We have analyzed the industrial circularity of EEE and automobiles, assuming that their internal material cycles are established. We analyzed the resource substitution rate of PAMR versus DGMR in complementary AM-GM supply systems (**step 6**).

Finally, an uncertainty analysis was conducted to help to improve the implementation of innovative data and scientific recommendations found by this study (**step 7**).

Text 2. Necessity of an AM assessment methodology

In recent years, researchers, engineers, and policymakers in the field of resources and the environment have used various terms (e.g., recovery potential, recycling potential, or recycling capacity) to describe the availability (theoretical maximum amount) of secondary resources[5, 6]. Sometimes their meanings have overlapped or been inconsistently used, causing nonuniformity and confusion. To mine AMs efficiently, a systematic assessment on their quantities and distributions in the anthroposphere is essential to increase confidence levels on the accessibility (practical retrievable amount) of AM from preliminary exploration to subsequent extraction.

Although AMs are derived from GMs, there are distinct differences between them. First, GMs are formed by geological processes underground, and their discovery can be unpredictable; whereas AMs are derived from human-made activities, and their formation is predictable. Second, AMs generally have higher grades than GMs, but their impurity compositions are more complex, which confers an advantage in refining but a disadvantage in dismantling compared with GMs. Third, GM mining is not time-bound and can be exploited whenever needed, whereas AM mining is basically time-bound because of stockpiling costs and potential environmental impacts. In practice this means it is better to extract them sooner than later, or they will be lost to the environment. These differences mean that the division of AMs cannot directly duplicate that of GMs. An exclusively designed AM assessment methodology, based on existing GM classification and quantification principles, with consideration of the characteristics of anthropogenic metabolism, is needed to guide and foster urban mining practices.

Table 1. Comparison between GM and AM classification codes

Term (source)	Definition
GM resource (USGS[2])	"A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible."
GM reserve base (USGS[2])	"The encompassed part of the resource that has a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technologies and current economics."
GM reserve (USGS[2])	"The part of the reserve base which can be economically extracted or produced at the time of determination."
GM subeconomic resource (USGS[2])	"The part of the identified resource that does not meet the economic criteria of reserves and marginal reserves. The term 'economic' implies that profitable extraction or production under defined investment assumptions has been established, analytically demonstrated, or assumed with reasonable certainty."
DGMR (USGS[2])	"The reserve for which location, grade, quality, and quantity are known or estimated from specific geologic, technical, and economic evidence."
AM (NDRC[1])	"Recyclable materials such as metals, plastics, and rubbers in EoL products such as obsolete industrial machinery, electric cables, communication equipment, automobiles, and EEE generate in processes of anthropogenic metabolism."
AME (this study)	An embedded material (pure substance or compound) in related EoL products generated by anthropogenic metabolism, in forms and amounts that urban mining of it is possible now or in the future.
AMB and AMSE (this study)	The encompassed part of AME that has reasonable potential for being economically extracted at present, whereas the economically unextractable part is regarded as AMSE.
AMR and AMTB (this study)	The encompassed part of AMB that can be functionally extracted by proven techniques currently, whereas the unfunctional extractable part and final residue are regarded as AMTB.
PAMR (this study)	The inferred functionally extracted part of a material's all anthropogenic stocks based on current available economic and technical conditions of urban mining. It approximately reflects the accessibility of the material in its in-use products, whose theoretical basis is that anthropogenic stocks are yet not AM but will eventually become AM when reaching their service lifespans.

Note, the AME consists of the AMB and AMSE; the AMB consists of the AMR and AMTB; the PAMR is inferred from its all anthropogenic material stocks (cumulative in-use products).

Table 2. Target metals and products

Considered element[3]

H				Base metal	Specialty metal	REE	PGM										He
3 Li	4 Be											B	C	N	O	F	Ne
Na	12 Mg											13 Al	Si	P	S	Cl	Ar
K	Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	As	Se	Br	Kr
Rb	Sr	39 Y	Zr	41 Nb	42 Mo	Tc	Ru	45 Rh	46 Pd	47 Ag	Cd	49 In	50 Sn	51 Sb	Te	I	Xe
Cs	Ba		Hf	73 Ta	74 W	Re	Os	Ir	78 Pt	79 Au	Hg	81 Tl	82 Pb	83 Bi	Po	At	Rn
	Lanthanide		57 La	58 Ce	59 Pr	60 Nd	Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	Ho	68 Er	Tm	Yb	Lu

Considered Product[7]	Identified element in product[8-10]
ICEV HEV BEV	**41 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ga, Ge, Ta, Ti, Be, In, Ni, Li, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Er, Sc, Y
CRT TV	**36 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ti, Be, Tl, Ni, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Sc, Y
LCD TV	**36 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ti, Be, Tl, In, Ni, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Pr, Nd, Sm, Eu, Gd, Dy, Er, Sc, Y
Printer	**25 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ti, Be, Pb, Ni, Ag, Au, Pd, Pt, Rh, Sc, Y
Copier	**25 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ti, Be, Pb, Ni, Ag, Au, Pd, Pt, Rh, Sc, Y
Laptop	**42 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ga, Ge, Ta, Ti, Be, Tl, In, Ni, Li, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Er, Sc, Y
CRT desktop	**40 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ga, Ge, Ta, Ti, Be, Tl, Ni, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Er, Sc, Y
LCD desktop	**42 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ga, Ge, Ta, Ti, Be, Tl, In, Ni, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Er, Sc, Y
VP	**36 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ti, Be, Tl, Ni, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Sc, Y
FM	**36 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ti, Be, Tl, Ni, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Sc, Y
MP	**42 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ga, Ge, Ta, Ti, Be, Tl, In, Ni, Li, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Er, Sc, Y
AC WM	**35 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ti, Be, Tl, Ni, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Pr, Nd, Sm, Eu, Gd, Dy, Er, Sc, Y
Refrigerator Dishwasher EWH GWH RH Microwave	**36 metals**: Fe, Al, Cu, Cr, Zn, Sn, Mn, Mg, Sb, Bi, W, Nb, V, Mo, Ti, Be, Tl, Ni, Co, Pb, Ag, Au, Pd, Pt, Rh, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Sc, Y

Table 3. Typical weights of products

Product	Sample 1	Sample 2	Sample 3	Average
	Unit: kg			
ICEV	1088	1240	972	1100
HEV	1410	1377	933	1240
BEV	1285	1438	1359	1361
CRT TV	9.2	10	5.7	8.3
LCD TV	20	13	14	16
Printer	6.0	22	9.5	12
Copier	72	89	73	78
Laptop	2.2	2.8	1.7	2.2
CRT desktop	17	15	8.3	13
LCD desktop	6.0	8.0	8.1	7.4
VP	0.89	1.0	0.87	0.92
FM	2.2	9.0	4.0	5.1
MP	0.07	0.10	0.06	0.08
AC	76	87	67	77
Refrigerator	20	135	48	68
WM	26	80	28	45
DW	40	44	38	41
EWH	19	20	32	24
GWH	12	14	11	12
RH	24	39	28	30
Microwave	9.9	15	6.9	11

Note, data sources are mainly online databases and academic articles[11, 12]. AC has two separated indoor and outdoor parts, here the shown weight is the total weight.

Table 4. Typical concentrations of metals in products

Material	Total	Automobile part				
	ICEV	Engine, frame, rest	Catalytic converter	Electronic controller	Pb-acid battery	Motor
	Unit: ppm					
Fe	5.67E+05	5.77E+05	3.49E+03	1.72E+04	1.04E+05	6.57E+05
Al	1.30E+05	1.32E+05	9.19E+05	4.98E+04	5.22E+04	1.43E+02
Cu	3.46E+04	3.29E+04	2.54E+01	5.41E+04	1.39E+04	3.29E+05
Cr	7.52E+03	7.72E+03	2.26E+02	1.36E+03	-	2.90E+01
Zn	1.82E+04	1.86E+04	8.48E+02	3.69E+03	-	-
Sn	5.02E+02	3.31E+02	4.24E+00	2.56E+04	-	-
Mn	6.67E+03	6.85E+03	1.91E+01	2.06E+02	-	3.08E+02
Mg	4.59E+03	4.54E+03	3.67E+04	1.89E+04	-	-
Sb	7.48E+01	7.35E+01	2.83E+00	4.63E+02	-	-
Bi	3.12E+01	3.09E+01	-	1.59E+02	-	-
W	1.20E+01	4.43E+00	7.77E+00	7.43E+02	-	4.05E+02
Nb	9.78E+01	1.00E+02	2.33E+01	4.97E+01	-	-
V	5.15E+01	5.27E+01	2.83E+00	2.72E+01	-	-
Mo	2.79E+02	2.85E+02	1.20E+02	2.66E+02	-	-
Ga	3.18E-01	1.07E-01	3.74E+01	2.53E+01	-	-
Ge	1.82E+00	2.59E-02	-	2.56E+02	-	-
Ta	7.10E+00	6.20E+00	-	1.52E+02	-	-
Ti	7.08E+02	6.98E+02	2.90E+02	3.94E+03	-	1.75E+02
Be	1.23E-01	1.26E-01	-	4.26E-02	-	-
Tl	-	-	-	-	-	-
In	9.09E-01	3.36E-01	-	8.30E+01	-	-
Ni	2.69E+03	2.75E+03	1.20E+02	2.99E+03	-	1.81E+00
Li	1.06E+01	1.07E+01	2.26E+01	1.71E+01	-	-
Co	6.16E+01	5.75E+01	1.41E+00	3.00E+01	-	9.07E+02
Pb	1.20E+04	4.16E+03	4.24E+00	5.62E+03	6.00E+05	-
Ag	2.58E+01	2.46E+01	1.41E+00	2.68E+02	-	-
Au	2.35E+00	2.03E+00	-	5.32E+01	-	-
Pd	3.76E+00	2.48E+00	9.19E+02	6.23E+01	-	-
Pt	6.82E-01	3.19E-02	6.32E+02	3.89E+00	-	-
Rh	3.64E-01	2.03E-02	3.46E+02	3.52E-01	-	-
La	1.82E+01	8.65E+00	3.96E+03	1.54E+02	-	7.94E+02
Ce	5.01E+01	4.42E+00	3.32E+04	1.86E+03	-	-
Pr	5.75E+00	5.49E+00	2.12E+00	5.77E+01	-	-
Nd	3.49E+00	2.36E+00	9.89E+00	3.49E+01	-	1.57E+02
Sm	5.09E+00	5.07E+00	1.41E+00	2.14E+01	-	-
Eu	9.09E-02	8.61E-02	-	1.02E+00	-	-
Gd	2.73E-01	7.66E-02	1.41E+00	2.80E+01	-	-
Tb	9.09E-02	8.53E-02	2.12E+00	8.37E-01	-	-
Dy	3.15E+00	2.98E+00	2.83E+00	4.91E+00	-	3.50E+01
Er	5.45E-01	8.33E-02	2.12E+00	1.02E+00	-	7.56E+01
Sc	1.82E-01	4.73E-02	-	1.94E+01	-	-
Y	1.89E+00	1.62E+00	1.34E+01	4.27E+01	-	-
Non-metal	2.15E+05	2.12E+05	3.99E+02	8.12E+05	2.29E+05	1.10E+04

Note, -: none or no data. Data were mainly collected or estimated from academic literatures[6, 8-10, 13-19]. ppm: one part per million denotes one part per 1,000,000 parts, and a value of 10^{-6}.

Continue to previous table

Material	Total	Automobile part				
	ICEV	**Engine, frame, rest**	**Catalytic converter**	**Electronic controller**	**NiMH battery**	**Motor**
	Unit: ppm					
Fe	5.59E+05	5.69E+05	3.36E+03	1.32E+04	2.82E+05	6.44E+05
Al	1.50E+05	1.54E+05	9.38E+05	5.63E+04	1.01E+04	3.21E+02
Cu	4.94E+04	4.72E+04	6.33E+01	5.69E+04	5.37E+01	3.22E+05
Cr	5.78E+03	6.00E+03	4.77E+02	9.27E+02	9.26E+01	-
Zn	1.96E+04	2.03E+04	1.09E+02	2.98E+03	2.15E+03	-
Sn	4.74E+02	2.59E+02	1.88E+01	2.41E+04	1.21E+01	-
Mn	6.28E+03	6.21E+03	2.27E+01	1.59E+02	1.74E+04	1.49E+02
Mg	3.49E+03	3.43E+03	3.75E+04	1.28E+04	2.15E+03	-
Sb	1.23E+02	1.25E+02	7.82E-01	3.95E+02	2.68E+00	-
Bi	3.85E+01	3.89E+01	3.75E+01	1.10E+02	-	-
W	5.77E+00	-	1.33E+02	4.93E+02	6.71E+00	8.24E+01
Nb	7.36E+01	7.63E+01	2.35E+00	3.59E+01	-	-
V	5.07E+01	5.25E+01	4.93E+01	2.02E+01	2.68E+00	-
Mo	2.63E+02	2.72E+02	7.35E+01	1.77E+02	1.07E+01	-
Ga	7.98E+00	-	4.69E+01	1.79E+01	4.43E+02	-
Ge	1.83E+00	1.36E-16	1.56E+00	1.71E+02	1.34E+01	-
Ta	6.81E+00	6.09E+00	-	1.01E+02	-	-
Ti	5.19E+02	5.01E+02	3.21E+03	3.31E+03	2.42E+02	-
Be	3.25E+01	3.38E+01	-	2.83E-02	-	-
Tl	-	-	-	-	-	-
In	8.88E-01	3.64E-16	-	9.48E+01	-	-
Ni	8.97E+03	9.23E-13	1.64E+02	2.50E+03	5.10E+05	6.32E+00
Li	2.03E+02	2.01E+02	7.82E+00	1.53E+01	5.90E+02	-
Co	6.06E+02	1.14E-03	2.35E+01	2.26E+01	3.35E+04	1.52E+03
Pb	7.17E+03	7.42E+03	-	4.61E+03	2.68E+00	-
Ag	2.45E+01	2.31E+01	2.35E+01	2.47E+02	-	-
Au	4.23E+00	4.02E+00	-	3.97E+01	-	-
Pd	3.37E+00	-	3.05E+03	6.44E+01	-	-
Pt	1.53E+00	5.07E-02	1.61E+03	2.31E+00	-	-
Rh	1.77E-01	1.76E-02	1.72E+02	4.72E-01	-	-
La	1.47E+03	4.29E-01	1.33E+03	1.04E+02	8.32E+04	3.80E+02
Ce	6.32E+02	6.32E-01	8.60E+03	1.24E+03	3.49E+04	-
Pr	6.24E+01	1.22E-14	2.35E+00	3.87E+01	3.49E+03	7.31E+01
Nd	4.18E+02	8.39E-02	3.05E+01	2.39E+02	1.09E+04	2.01E+04
Sm	3.94E+00	3.96E+00	7.82E-01	1.49E+01	-	-
Eu	8.72E-03	1.42E-18	-	9.31E-01	-	-
Gd	1.70E+00	-	6.96E+01	1.88E+01	8.32E+01	-
Tb	6.94E-01	6.41E-01	2.35E+00	5.57E-01	4.03E+00	-
Dy	5.70E+01	-	-	1.21E+01	2.68E+00	5.08E+03
Er	7.70E-02	-	-	6.79E-01	4.03E+00	-
Sc	1.35E-01	2.27E-17	1.09E+01	1.34E+01	-	-
Y	1.51E+02	-	7.82E-01	1.12E+01	8.59E+03	-
Non-metal	1.85E+05	1.84E+05	1.66E+03	8.18E+05	2.63E+02	6.84E+03

Continue to previous table

Material	Total	Automobile part			
	BEV	Engine, frame, rest	Electronic controller	Li-ion battery	Motor
	Unit: ppm				
Fe	5.30E+05	8.15E+05	1.28E+04	1.90E+02	6.31E+05
Al	4.85E+04	3.49E+04	5.49E+04	7.60E+04	3.57E+02
Cu	6.59E+04	4.67E+04	5.96E+04	9.30E+04	3.16E+05
Cr	4.92E+03	7.67E+03	8.92E+02	9.00E+00	-
Zn	1.78E+04	2.77E+04	3.07E+03	1.50E+01	-
Sn	4.27E+02	2.97E+02	2.37E+04	7.40E+01	-
Mn	5.75E+04	1.06E+00	1.54E+02	1.70E+05	4.62E+01
Mg	3.84E+03	5.74E+03	1.23E+04	1.70E+02	-
Sb	2.06E+02	3.17E+02	3.79E+02	-	-
Bi	2.01E+01	3.00E+01	1.06E+02	-	-
W	7.41E+00	-	4.71E+02	7.00E+00	6.53E+01
Nb	1.46E+02	2.27E+02	3.44E+01	-	-
V	1.27E+02	1.94E+02	1.97E+01	8.00E+00	-
Mo	3.03E+02	4.70E+02	1.70E+02	1.00E+00	-
Ga	3.91E+00	9.96E-16	1.74E+01	1.00E+01	2.91E+01
Ge	1.47E+00	2.18E-02	1.63E+02	-	-
Ta	1.15E+01	1.65E+01	1.02E+02	-	-
Ti	6.02E+02	8.78E+02	3.33E+03	3.20E+01	-
Be	2.94E+01	4.59E+01	2.71E-02	-	-
Tl	-	-	-	-	-
In	8.09E-01	2.49E-16	9.07E+01	-	-
Ni	1.76E+04	5.66E-13	2.57E+03	5.20E+04	2.92E+00
Li	7.10E+03	-	1.51E+01	2.10E+04	-
Co	4.43E+03	1.99E-13	2.18E+01	1.30E+04	2.87E+03
Pb	6.56E+03	1.02E+04	4.42E+03	-	-
Ag	2.63E+01	3.71E+01	2.88E+02	-	-
Au	3.42E+00	4.80E+00	3.90E+01	-	-
Pd	1.62E+00	1.65E+00	6.27E+01	-	-
Pt	1.62E-01	2.22E-01	2.21E+00	-	-
Rh	1.62E-01	2.46E-01	4.51E-01	-	-
La	4.76E+00	-	9.97E+01	-	3.01E+02
Ce	1.06E+01	-	1.19E+03	-	-
Pr	2.05E+01	-	3.71E+01	9.00E+00	1.33E+03
Nd	4.47E+02	1.15E-01	2.29E+02	-	3.46E+04
Sm	3.28E+00	4.92E+00	1.43E+01	-	-
Eu	7.95E-03	1.95E-18	8.91E-01	-	-
Gd	1.61E-01	-	1.80E+01	-	-
Tb	6.39E-01	9.90E-01	6.23E-01	-	-
Dy	1.37E+02	-	1.31E+01	-	1.07E+04
Er	5.88E-03	1.38E-04	6.49E-01	-	-
Sc	3.85E-01	1.01E-01	1.28E+01	6.10E-01	-
Y	1.38E-01	-	1.55E+01	-	-
Non-metal	2.34E+05	5.00E+04	8.19E+05	5.74E+05	2.55E+03

Continue to previous table

Material	CRT TV	LCD TV	Printer	Copier	Laptop	CRT desktop
	Unit: ppm					
Fe	1.23E+05	3.00E+05	3.20E+05	1.60E+05	2.00E+05	4.50E+05
Al	2.00E+04	4.00E+04	1.80E+05	2.00E+05	1.50E+04	3.50E+04
Cu	3.67E+04	1.00E+04	5.00E+03	3.50E+04	5.70E+04	5.65E+04
Cr	1.66E+00	3.11E+00	1.94E+01	6.56E+00	1.47E+01	2.80E+00
Zn	4.72E-02	8.86E-02	3.56E+02	1.20E+02	2.57E-01	7.24E-02
Sn	1.44E+03	2.71E+03	1.44E+03	4.88E+02	2.74E+03	6.37E+02
Mn	6.18E-01	1.16E+00	2.33E+00	7.87E-01	3.84E+00	2.72E+00
Mg	2.18E+01	4.10E+01	2.18E+01	7.37E+00	8.56E+01	1.99E+01
Sb	7.44E-01	1.40E+00	8.66E+01	2.93E+01	8.35E-01	8.92E-02
Bi	4.03E+00	7.57E+00	4.03E+00	1.36E+00	5.63E+00	1.31E+00
W	6.89E-01	1.29E+00	6.89E-01	2.33E-01	1.58E+01	3.67E+00
Nb	2.38E-01	4.47E-01	2.38E-01	8.03E-02	1.38E+00	3.20E-01
V	3.57E-02	6.70E-02	1.11E-01	3.74E-02	1.39E+00	4.17E-01
Mo	8.75E-01	1.64E+00	8.61E-02	2.91E-02	3.50E+00	3.44E-01
Ga	-	-	-	-	3.42E+00	7.95E-01
Ge	-	-	-	-	1.22E+01	2.83E+00
Ta	-	-	-	-	8.00E+00	1.86E+00
Ti	3.54E+01	6.65E+01	3.54E+01	1.20E+01	2.33E+02	5.42E+01
Be	8.20E-04	1.54E-03	1.23E-02	4.16E-03	8.53E-03	3.30E-03
Tl	3.69E-03	6.93E-03	-	-	1.28E-02	6.61E-04
In	-	1.02E+02	-	-	3.61E+02	-
Ni	2.05E-03	3.85E-03	1.90E+02	6.42E+01	1.56E-02	9.25E-04
Li	-	-	-	-	9.24E+03	0.00E+00
Co	1.05E-01	1.96E-01	-	-	3.38E+00	1.72E-01
Pb	1.43E-01	2.68E-01	1.40E+02	4.73E+01	1.15E+00	1.53E-01
Ag	1.21E+01	2.27E+01	4.97E+01	1.68E+01	9.04E+01	2.08E+01
Au	1.35E+00	2.53E+00	8.16E+00	2.76E+00	3.17E+01	7.42E+00
Pd	8.00E-01	1.50E+00	8.00E-01	2.70E-01	1.69E+01	3.93E+00
Pt	2.05E-02	3.85E-02	2.05E-02	6.93E-03	6.11E-01	1.42E-01
Rh	6.15E-02	1.16E-01	6.15E-02	2.08E-02	8.10E-01	1.88E-01
La	2.81E+02	4.00E-03	-	-	3.73E-01	2.27E+02
Ce	2.34E+00	-	-	-	6.84E-01	2.18E+00
Pr	1.76E+01	1.39E-02	-	-	5.55E-02	1.42E+01
Nd	1.39E-02	2.61E-02	-	-	1.73E-01	6.94E-02
Sm	2.62E-03	4.93E-03	-	-	3.70E-02	1.39E-02
Eu	5.74E-03	1.08E-02	-	-	3.06E-01	3.44E-02
Gd	2.50E-03	4.70E-03	-	-	1.92E-01	5.48E-02
Tb	-	-	-	-	1.98E-01	4.60E-02
Dy	1.17E+01	3.31E-03	-	-	4.41E-02	9.53E+00
Er	1.72E-03	3.23E-03	-	-	1.28E-02	4.63E-03
Sc	1.07E+00	2.00E+00	1.64E-02	5.54E-03	2.08E+00	8.34E-01
Y	3.30E-02	6.21E-02	1.31E-01	4.43E-02	1.42E-02	7.10E-02
Non-metal	8.18E+05	6.47E+05	4.93E+05	6.04E+05	7.15E+05	4.58E+05

Continue to previous table

Material	LCD desktop	VP	FM	MP	AC	Refrigerator
	Unit: ppm					
Fe	1.80E+05	5.00E+05	3.00E+05	1.93E+05	5.02E+05	4.90E+05
Al	3.60E+04	6.60E+04	1.50E+05	2.81E+04	7.90E+04	1.80E+04
Cu	7.20E+04	6.00E+04	4.00E+04	4.13E+04	1.80E+05	3.70E+04
Cr	2.40E+00	5.83E-01	5.16E-01	2.67E-01	1.06E-01	6.30E-02
Zn	6.19E-02	6.62E-04	6.12E-04	1.32E+00	4.92E-04	1.10E-03
Sn	5.45E+02	2.59E+02	5.39E+02	4.05E+03	3.77E+01	1.90E+01
Mn	2.33E+00	2.16E-01	5.32E-01	7.05E+00	1.60E-02	1.64E-02
Mg	1.70E+01	3.91E+00	8.14E+00	1.26E+02	5.69E-01	2.87E-01
Sb	7.63E-02	1.93E+00	5.06E-01	4.13E+00	3.77E-02	9.86E-03
Bi	1.12E+00	7.23E-01	1.50E+00	8.32E+00	1.05E-01	5.31E-02
W	3.14E+00	1.23E-01	2.57E-01	2.33E+01	1.80E-02	9.07E-03
Nb	2.74E-01	4.26E-02	8.87E-02	2.04E+00	6.21E-03	3.13E-03
V	3.56E-01	6.10E-03	3.32E-02	2.01E+00	1.95E-03	4.34E-03
Mo	2.94E-01	1.19E-01	3.45E-01	2.88E+00	2.48E-02	1.95E-02
Ga	6.80E-01	-	-	5.05E+00	-	-
Ge	2.42E+00	-	-	1.80E+01	-	-
Ta	1.59E+00	-	-	1.18E+01	-	-
Ti	4.64E+01	6.35E+00	1.32E+01	3.44E+02	9.24E-01	4.67E-01
Be	2.83E-03	1.47E-04	2.45E-04	1.89E-02	4.28E-05	2.92E-05
Tl	5.65E-04	8.75E-04	3.01E-02	4.83E-03	5.99E-05	1.30E-04
In	1.08E+02	-	-	3.97E+02	-	-
Ni	7.92E-04	9.56E-05	4.74E-04	6.72E-02	3.42E-05	1.24E-05
Li	-	-	-	1.85E+04	-	-
Co	1.48E-01	5.49E-02	6.17E-02	4.06E+00	1.07E-02	4.28E-03
Pb	1.31E-01	1.09E-01	7.77E-02	1.32E+00	4.22E-03	1.04E-03
Ag	1.78E+01	1.00E+00	4.08E-01	1.10E+02	2.01E-02	1.93E-01
Au	6.35E+00	1.39E-01	3.64E-02	6.63E+01	2.17E-03	4.92E-03
Pd	3.36E+00	1.43E-01	2.98E-01	2.50E+01	2.09E-02	1.05E-02
Pt	1.22E-01	3.68E-03	7.65E-03	9.03E-01	5.35E-04	2.70E-04
Rh	1.61E-01	1.10E-02	2.30E-02	1.20E+00	1.61E-03	8.10E-04
La	1.39E-01	4.48E-03	9.49E-03	1.44E+03	1.28E-03	1.50E-03
Ce	2.49E-01	2.33E-02	-	1.28E+01	-	1.67E-03
Pr	2.35E-02	7.35E-04	3.21E-03	9.01E+01	1.82E-01	3.08E-04
Nd	5.94E-02	2.28E-03	8.11E-03	5.19E-01	4.60E-01	8.26E-04
Sm	1.19E-02	4.78E-04	1.53E-03	4.41E-02	8.10E-02	1.67E-04
Eu	2.94E-02	4.19E-03	5.81E-04	4.85E-01	8.56E-05	4.70E-05
Gd	4.69E-02	8.09E-04	1.07E-03	2.69E-01	1.07E-04	4.16E-04
Tb	3.93E-02	-	-	2.92E-01	-	-
Dy	7.35E-02	4.19E-04	1.53E-03	6.00E+01	7.10E-02	1.35E-04
Er	3.96E-03	3.01E-04	9.18E-04	1.76E-02	4.92E-05	6.48E-05
Sc	7.13E-01	1.51E-01	1.23E-01	6.90E+00	2.97E-02	1.12E-02
Y	6.08E-02	1.81E-02	7.50E-03	3.59E-01	9.42E-04	1.66E-03
Non-metal	7.11E+05	3.74E+05	5.09E+05	7.12E+05	2.39E+05	4.55E+05

Continue to previous table, in total six sub-tables

Material	WM	Dishwasher	EWH	GWH	RH	Microwave
	Unit: ppm					
Fe	4.96E+05	5.00E+05	3.50E+05	3.00E+05	3.00E+05	7.13E+05
Al	3.87E+04	2.50E+04	1.00E+05	1.00E+05	8.00E+04	3.90E+04
Cu	3.13E+04	2.50E+04	5.00E+04	8.00E+04	1.00E+05	3.90E+04
Cr	7.06E-04	6.30E-02	6.30E-02	6.30E-02	6.30E-02	6.30E-02
Zn	7.48E-03	1.10E-03	1.10E-03	1.10E-03	1.10E-03	1.10E-03
Sn	4.88E+02	1.90E+01	1.90E+01	1.90E+01	1.90E+01	1.90E+01
Mn	8.60E-01	1.64E-02	1.64E-02	1.64E-02	1.64E-02	1.64E-02
Mg	7.37E+00	2.87E-01	2.87E-01	2.87E-01	2.87E-01	2.87E-01
Sb	2.76E-01	9.86E-03	9.86E-03	9.86E-03	9.86E-03	9.86E-03
Bi	1.36E+00	5.31E-02	5.31E-02	5.31E-02	5.31E-02	5.31E-02
W	2.33E-01	9.07E-03	9.07E-03	9.07E-03	9.07E-03	9.07E-03
Nb	8.03E-02	3.13E-03	3.13E-03	3.13E-03	3.13E-03	3.13E-03
V	2.05E-02	4.34E-03	4.34E-03	4.34E-03	4.34E-03	4.34E-03
Mo	1.06E+00	1.95E-02	1.95E-02	1.95E-02	1.95E-02	1.95E-02
Ga	-	-	-	-	-	-
Ge	-	-	-	-	-	-
Ta	-	-	-	-	-	-
Ti	1.20E+01	4.67E-01	4.67E-01	4.67E-01	4.67E-01	4.67E-01
Be	4.16E-04	2.92E-05	2.92E-05	2.92E-05	2.92E-05	2.92E-05
Tl	2.35E-03	1.30E-04	1.30E-04	1.30E-04	1.30E-04	1.30E-04
In	-	-	-	-	-	-
Ni	5.12E-04	1.24E-05	1.24E-05	1.24E-05	1.24E-05	1.24E-05
Li	-	-	-	-	-	-
Co	1.21E-01	4.28E-03	4.28E-03	4.28E-03	4.28E-03	4.28E-03
Pb	5.35E-02	1.04E-03	1.04E-03	1.04E-03	1.04E-03	1.04E-03
Ag	2.15E-01	1.93E-01	1.93E-01	1.93E-01	1.93E-01	1.93E-01
Au	1.25E-01	4.92E-03	4.92E-03	4.92E-03	4.92E-03	4.92E-03
Pd	2.70E-01	1.05E-02	1.05E-02	1.05E-02	1.05E-02	1.05E-02
Pt	6.93E-03	2.70E-04	2.70E-04	2.70E-04	2.70E-04	2.70E-04
Rh	2.08E-02	8.10E-04	8.10E-04	8.10E-04	8.10E-04	8.10E-04
La	2.01E-02	1.50E-03	1.50E-03	1.50E-03	1.50E-03	1.50E-03
Ce	-	1.67E-03	1.67E-03	1.67E-03	1.67E-03	1.67E-03
Pr	2.60E-01	3.08E-04	3.08E-04	3.08E-04	3.08E-04	3.08E-04
Nd	6.40E-01	8.26E-04	8.26E-04	8.26E-04	8.26E-04	8.26E-04
Sm	1.20E-01	1.67E-04	1.67E-04	1.67E-04	1.67E-04	1.67E-04
Eu	1.39E-03	4.70E-05	4.70E-05	4.70E-05	4.70E-05	4.70E-05
Gd	2.08E-03	4.16E-04	4.16E-04	4.16E-04	4.16E-04	4.16E-04
Tb	-	-	-	-	-	-
Dy	4.30E-01	1.35E-04	1.35E-04	1.35E-04	1.35E-04	1.35E-04
Er	1.66E-03	6.48E-05	6.48E-05	6.48E-05	6.48E-05	6.48E-05
Sc	4.23E-01	1.12E-02	1.12E-02	1.12E-02	1.12E-02	1.12E-02
Y	2.77E-02	1.66E-03	1.66E-03	1.66E-03	1.66E-03	1.66E-03
Non-metal	4.34E+05	4.50E+05	5.00E+05	5.20E+05	5.20E+05	2.09E+05

Table 5. Historical new-sale numbers of products in China in 2000−2021

Year	ICEV	HEV	BEV	CRT TV	LCD TV	Printer	Copier
1990	1.57E+05	-	-	2.75E+06	3.44E+05	-	1.00E+04
1991	1.58E+05	-	-	3.21E+06	4.02E+05	-	2.61E+04
1992	1.54E+05	-	-	3.55E+06	4.44E+05	-	4.23E+04
1993	1.45E+05	-	-	3.83E+06	4.79E+05	-	5.84E+04
1994	1.40E+05	-	-	4.50E+06	5.63E+05	1.00E+04	7.45E+04
1995	1.37E+05	-	-	5.49E+06	6.86E+05	1.32E+05	9.06E+04
1996	1.44E+05	-	-	6.77E+06	8.46E+05	2.53E+05	1.07E+05
1997	1.49E+05	-	-	7.23E+06	9.04E+05	2.44E+06	1.23E+05
1998	1.59E+05	-	-	9.33E+06	1.17E+06	4.62E+06	1.39E+05
1999	2.51E+06	-	-	1.14E+07	1.42E+06	6.81E+06	8.55E+05
2000	3.51E+06	-	-	1.05E+07	1.31E+06	9.00E+06	1.57E+06
2001	3.82E+06	-	-	1.09E+07	1.36E+06	1.02E+07	1.44E+06
2002	3.37E+06	-	-	1.37E+07	1.72E+06	1.15E+07	2.07E+06
2003	4.34E+06	-	-	1.74E+07	2.18E+06	1.27E+07	2.64E+06
2004	4.51E+06	-	-	1.98E+07	2.48E+06	1.40E+07	3.25E+06
2005	5.29E+06	-	-	2.21E+07	2.76E+06	1.52E+07	4.04E+06
2006	6.73E+06	-	-	2.23E+07	2.79E+06	1.64E+07	4.68E+06
2007	6.08E+06	-	-	2.15E+07	3.39E+06	1.77E+07	4.52E+06
2008	7.63E+06	1.67E+02	-	2.20E+07	4.29E+06	1.89E+07	5.84E+06
2009	1.25E+07	3.33E+02	-	2.24E+07	5.28E+06	2.02E+07	4.21E+06
2010	1.53E+07	6.66E+02	3.29E+03	2.52E+07	7.10E+06	2.14E+07	5.35E+06
2011	1.62E+07	1.12E+03	5.54E+03	2.45E+07	8.15E+06	2.26E+07	6.55E+06
2012	1.77E+07	1.68E+03	8.30E+03	2.39E+07	9.40E+06	2.39E+07	6.10E+06
2013	2.03E+07	2.33E+03	1.15E+04	2.21E+07	1.02E+07	2.51E+07	6.35E+06
2014	2.21E+07	1.05E+04	5.17E+04	2.14E+07	1.16E+07	2.64E+07	7.13E+06
2015	2.33E+07	4.41E+04	2.18E+05	2.08E+07	1.32E+07	2.49E+07	7.34E+06
2016	2.72E+07	6.79E+04	3.36E+05	2.04E+07	1.53E+07	2.65E+07	7.40E+06
2017	2.75E+07	1.04E+05	6.50E+05	1.71E+07	1.52E+07	2.91E+07	7.46E+06
2018	2.57E+07	1.69E+05	1.17E+06	1.56E+07	1.66E+07	3.08E+07	7.52E+06
2019	2.47E+07	1.60E+05	1.10E+06	1.37E+07	1.86E+07	3.10E+07	7.58E+06
2020	2.33E+07	1.45E+05	1.37E+06	1.07E+07	1.78E+07	3.12E+07	7.64E+06
2021	2.25E+07	2.92E+05	3.52E+06	9.20E+06	2.02E+07	3.14E+07	7.70E+06

Note, -: none or no data. Data were mainly collected or estimated from government statistics and online database[20, 21].

Continue to previous table

Year	Laptop	CRT desktop	LCD desktop	VP	FM	MP	AC
1990	1.57E+05	-	-	2.75E+06	3.44E+05	-	1.00E+04
1991	1.58E+05	-	-	3.21E+06	4.02E+05	-	2.61E+04
1992	1.54E+05	-	-	3.55E+06	4.44E+05	-	4.23E+04
1993	1.45E+05	-	-	3.83E+06	4.79E+05	-	5.84E+04
1994	1.40E+05	-	-	4.50E+06	5.63E+05	1.00E+04	7.45E+04
1995	1.37E+05	-	-	5.49E+06	6.86E+05	1.32E+05	9.06E+04
1996	1.44E+05	-	-	6.77E+06	8.46E+05	2.53E+05	1.07E+05
1997	1.49E+05	-	-	7.23E+06	9.04E+05	2.44E+06	1.23E+05
1998	1.59E+05	-	-	9.33E+06	1.17E+06	4.62E+06	1.39E+05
1999	2.51E+06	-	-	1.14E+07	1.42E+06	6.81E+06	8.55E+05
2000	3.51E+06	-	-	1.05E+07	1.31E+06	9.00E+06	1.57E+06
2001	3.82E+06	-	-	1.09E+07	1.36E+06	1.02E+07	1.44E+06
2002	3.37E+06	-	-	1.37E+07	1.72E+06	1.15E+07	2.07E+06
2003	4.34E+06	-	-	1.74E+07	2.18E+06	1.27E+07	2.64E+06
2004	4.51E+06	-	-	1.98E+07	2.48E+06	1.40E+07	3.25E+06
2005	5.29E+06	-	-	2.21E+07	2.76E+06	1.52E+07	4.04E+06
2006	6.73E+06	-	-	2.23E+07	2.79E+06	1.64E+07	4.68E+06
2007	6.08E+06	-	-	2.15E+07	3.39E+06	1.77E+07	4.52E+06
2008	7.63E+06	1.67E+02	-	2.20E+07	4.29E+06	1.89E+07	5.84E+06
2009	1.25E+07	3.33E+02	-	2.24E+07	5.28E+06	2.02E+07	4.21E+06
2010	1.53E+07	6.66E+02	3.29E+03	2.52E+07	7.10E+06	2.14E+07	5.35E+06
2011	1.62E+07	1.12E+03	5.54E+03	2.45E+07	8.15E+06	2.26E+07	6.55E+06
2012	1.77E+07	1.68E+03	8.30E+03	2.39E+07	9.40E+06	2.39E+07	6.10E+06
2013	2.03E+07	2.33E+03	1.15E+04	2.21E+07	1.02E+07	2.51E+07	6.35E+06
2014	2.21E+07	1.05E+04	5.17E+04	2.14E+07	1.16E+07	2.64E+07	7.13E+06
2015	2.33E+07	4.41E+04	2.18E+05	2.08E+07	1.32E+07	2.49E+07	7.34E+06
2016	2.72E+07	6.79E+04	3.36E+05	2.04E+07	1.53E+07	2.65E+07	7.40E+06
2017	2.75E+07	1.04E+05	6.50E+05	1.71E+07	1.52E+07	2.91E+07	7.46E+06
2018	2.57E+07	1.69E+05	1.17E+06	1.56E+07	1.66E+07	3.08E+07	7.52E+06
2019	2.47E+07	1.60E+05	1.10E+06	1.37E+07	1.86E+07	3.10E+07	7.58E+06
2020	2.33E+07	1.45E+05	1.37E+06	1.07E+07	1.78E+07	3.12E+07	7.64E+06
2021	2.25E+07	2.92E+05	3.52E+06	9.20E+06	2.02E+07	3.14E+07	7.70E+06

Continue to previous table, in total three sub-tables

Year	Refrigerator	WM	Dishwasher	EWH	GWH	RH	Microwave
1990	1.57E+05	0.00E+00	0.00E+00	2.75E+06	3.44E+05	-	1.00E+04
1991	1.58E+05	0.00E+00	0.00E+00	3.21E+06	4.02E+05	-	2.61E+04
1992	1.54E+05	0.00E+00	0.00E+00	3.55E+06	4.44E+05	-	4.23E+04
1993	1.45E+05	0.00E+00	0.00E+00	3.83E+06	4.79E+05	-	5.84E+04
1994	1.40E+05	0.00E+00	0.00E+00	4.50E+06	5.63E+05	1.00E+04	7.45E+04
1995	1.37E+05	0.00E+00	0.00E+00	5.49E+06	6.86E+05	1.32E+05	9.06E+04
1996	1.44E+05	0.00E+00	0.00E+00	6.77E+06	8.46E+05	2.53E+05	1.07E+05
1997	1.49E+05	0.00E+00	0.00E+00	7.23E+06	9.04E+05	2.44E+06	1.23E+05
1998	1.59E+05	0.00E+00	0.00E+00	9.33E+06	1.17E+06	4.62E+06	1.39E+05
1999	2.51E+06	0.00E+00	0.00E+00	1.14E+07	1.42E+06	6.81E+06	8.55E+05
2000	3.51E+06	0.00E+00	0.00E+00	1.05E+07	1.31E+06	9.00E+06	1.57E+06
2001	3.82E+06	0.00E+00	0.00E+00	1.09E+07	1.36E+06	1.02E+07	1.44E+06
2002	3.37E+06	0.00E+00	0.00E+00	1.37E+07	1.72E+06	1.15E+07	2.07E+06
2003	4.34E+06	0.00E+00	0.00E+00	1.74E+07	2.18E+06	1.27E+07	2.64E+06
2004	4.51E+06	0.00E+00	0.00E+00	1.98E+07	2.48E+06	1.40E+07	3.25E+06
2005	5.29E+06	0.00E+00	0.00E+00	2.21E+07	2.76E+06	1.52E+07	4.04E+06
2006	6.73E+06	0.00E+00	0.00E+00	2.23E+07	2.79E+06	1.64E+07	4.68E+06
2007	6.08E+06	0.00E+00	0.00E+00	2.15E+07	3.39E+06	1.77E+07	4.52E+06
2008	7.63E+06	1.67E+02	0.00E+00	2.20E+07	4.29E+06	1.89E+07	5.84E+06
2009	1.25E+07	3.33E+02	0.00E+00	2.24E+07	5.28E+06	2.02E+07	4.21E+06
2010	1.53E+07	6.66E+02	3.29E+03	2.52E+07	7.10E+06	2.14E+07	5.35E+06
2011	1.62E+07	1.12E+03	5.54E+03	2.45E+07	8.15E+06	2.26E+07	6.55E+06
2012	1.77E+07	1.68E+03	8.30E+03	2.39E+07	9.40E+06	2.39E+07	6.10E+06
2013	2.03E+07	2.33E+03	1.15E+04	2.21E+07	1.02E+07	2.51E+07	6.35E+06
2014	2.21E+07	1.05E+04	5.17E+04	2.14E+07	1.16E+07	2.64E+07	7.13E+06
2015	2.33E+07	4.41E+04	2.18E+05	2.08E+07	1.32E+07	2.49E+07	7.34E+06
2016	2.72E+07	6.79E+04	3.36E+05	2.04E+07	1.53E+07	2.65E+07	7.40E+06
2017	2.75E+07	1.04E+05	6.50E+05	1.71E+07	1.52E+07	2.91E+07	7.46E+06
2018	2.57E+07	1.69E+05	1.17E+06	1.56E+07	1.66E+07	3.08E+07	7.52E+06
2019	2.47E+07	1.60E+05	1.10E+06	1.37E+07	1.86E+07	3.10E+07	7.58E+06
2020	2.33E+07	1.45E+05	1.37E+06	1.07E+07	1.78E+07	3.12E+07	7.64E+06
2021	2.25E+07	2.92E+05	3.52E+06	9.20E+06	2.02E+07	3.14E+07	7.70E+06

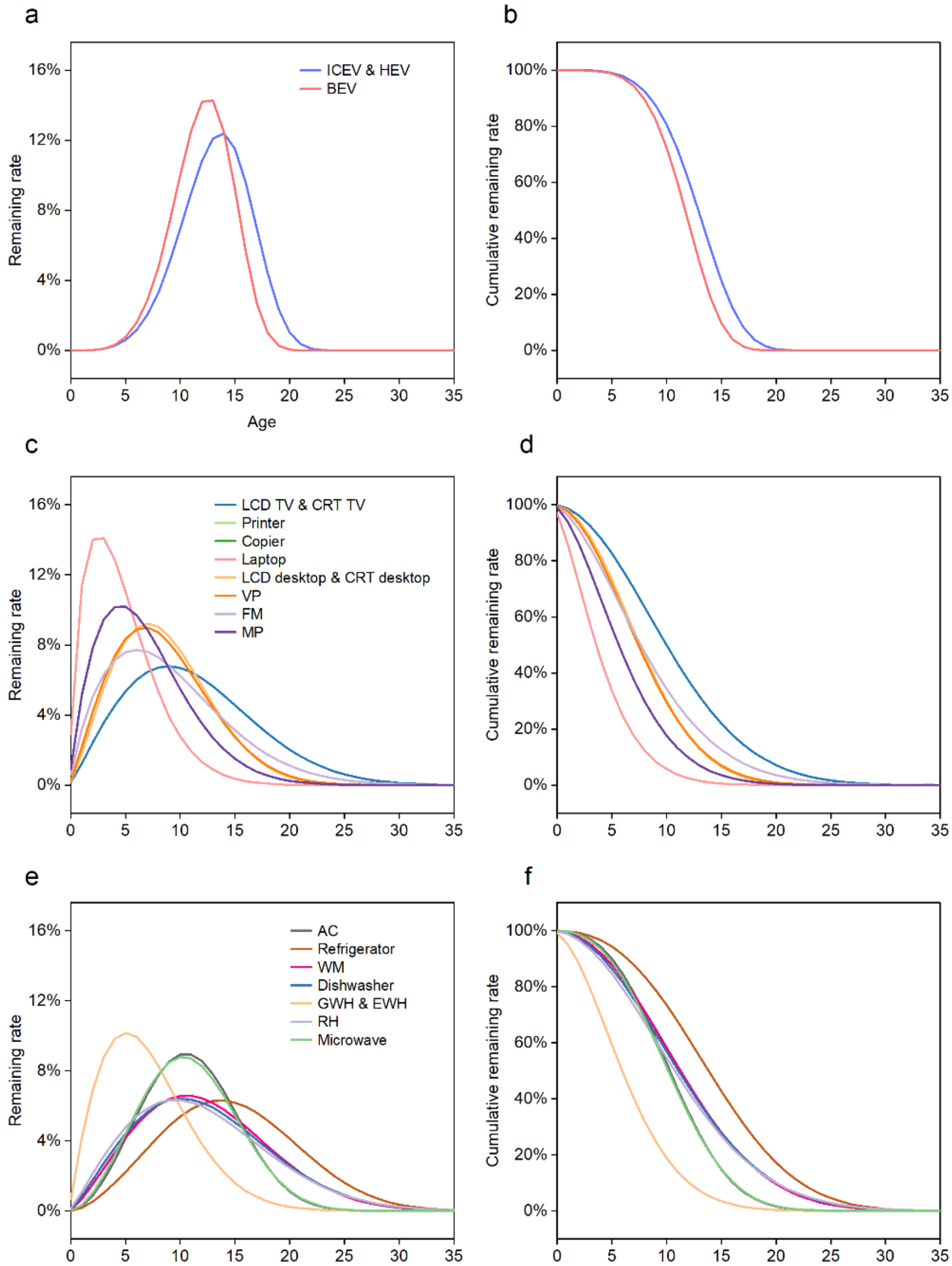


Fig. 1. Lifespan distributions of products in China

Note, **a** and **b** refer to remaining rate and cumulative remaining rate of automobiles; **c** and **d** refer to remaining rate and cumulative remaining rate of electronic devices; **e** and **f** refer to remaining rate and cumulative remaining rate of electric home appliances. In the Weibull distribution, the estimated shape parameter (μ) and scale parameter (η) are 4.79 and 14.46 for ICEV and BEV, 5.08 and 13.11 for BEV, 2.00 and 12.60 for TV, 1.70 and 10.10 for printer, copier and FM, 1.50 and 5.20 for laptop, 2.10 and 9.60 for desktop, 2.00 and 9.50 for VP, 1.70 and 7.60 for MP, 2.80 and 12.30 for AC, 2.60 and 16.50 for refrigerator, 2.20 and 13.90 for WM, 2.10 and 13.80 for dishwasher, 1.80 and 7.90 for water heater, 2.00 and 13.50 for RH, 2.70 and 12.20 for microwave, respectively[7, 22].

Table 6. Estimated in-use numbers of products in China in 2000−2021

Year	ICEV	HEV	BEV	CRT TV	LCD TV	Printer	Copier
2000	7.29E+06	0.00E+00	0.00E+00	5.94E+07	7.43E+06	2.21E+07	2.87E+06
2001	1.11E+07	0.00E+00	0.00E+00	6.74E+07	8.42E+06	3.11E+07	4.16E+06
2002	1.44E+07	0.00E+00	0.00E+00	7.75E+07	9.69E+06	4.08E+07	5.99E+06
2003	1.86E+07	0.00E+00	0.00E+00	9.07E+07	1.13E+07	5.09E+07	8.27E+06
2004	2.30E+07	0.00E+00	0.00E+00	1.06E+08	1.32E+07	6.14E+07	1.10E+07
2005	2.81E+07	0.00E+00	0.00E+00	1.22E+08	1.52E+07	7.22E+07	1.43E+07
2006	3.46E+07	0.00E+00	0.00E+00	1.37E+08	1.72E+07	8.32E+07	1.80E+07
2007	4.03E+07	0.00E+00	0.00E+00	1.51E+08	1.96E+07	9.43E+07	2.13E+07
2008	4.74E+07	1.67E+02	0.00E+00	1.64E+08	2.27E+07	1.06E+08	2.55E+07
2009	5.91E+07	5.00E+02	0.00E+00	1.76E+08	2.67E+07	1.17E+08	2.78E+07
2010	7.33E+07	1.17E+03	3.29E+03	1.90E+08	3.22E+07	1.28E+08	3.09E+07
2011	8.81E+07	2.28E+03	8.83E+03	2.02E+08	3.86E+07	1.40E+08	3.49E+07
2012	1.04E+08	3.96E+03	1.71E+04	2.12E+08	4.59E+07	1.51E+08	3.80E+07
2013	1.22E+08	6.29E+03	2.87E+04	2.19E+08	5.37E+07	1.62E+08	4.10E+07
2014	1.41E+08	1.67E+04	8.04E+04	2.25E+08	6.24E+07	1.74E+08	4.44E+07
2015	1.60E+08	6.08E+04	2.98E+05	2.28E+08	7.22E+07	1.82E+08	4.77E+07
2016	1.83E+08	1.29E+05	6.34E+05	2.31E+08	8.35E+07	1.91E+08	5.07E+07
2017	2.05E+08	2.33E+05	1.28E+06	2.29E+08	9.40E+07	2.02E+08	5.34E+07
2018	2.25E+08	4.02E+05	2.45E+06	2.25E+08	1.05E+08	2.13E+08	5.58E+07
2019	2.42E+08	5.61E+05	3.55E+06	2.20E+08	1.18E+08	2.23E+08	5.79E+07
2020	2.57E+08	7.05E+05	4.91E+06	2.10E+08	1.28E+08	2.32E+08	5.98E+07
2021	2.69E+08	9.95E+05	8.42E+06	2.00E+08	1.41E+08	2.40E+08	6.15E+07

Note, data in this table was estimated from **Supplementary Table 5** and **Supplementary Fig. 1**, detailed methods are provided in the Anthropogenic Metabolism Analysis section.

Continue to previous table

Year	Laptop	CRT desktop	LCD desktop	VP	FM	MP	AC
2000	0.00E+00	1.43E+07	6.15E+05	1.13E+08	8.89E+06	1.91E+08	4.42E+07
2001	0.00E+00	1.68E+07	1.17E+06	1.42E+08	1.14E+07	2.49E+08	5.69E+07
2002	0.00E+00	1.95E+07	1.99E+06	1.68E+08	1.35E+07	3.09E+08	7.40E+07
2003	7.57E+06	2.23E+07	3.13E+06	1.91E+08	1.99E+07	3.70E+08	1.01E+08
2004	1.62E+07	2.51E+07	4.62E+06	2.12E+08	2.70E+07	4.33E+08	1.36E+08
2005	2.66E+07	2.79E+07	6.50E+06	2.29E+08	3.58E+07	4.99E+08	1.72E+08
2006	3.86E+07	3.06E+07	8.78E+06	2.43E+08	4.53E+07	5.68E+08	2.08E+08
2007	5.35E+07	3.31E+07	1.15E+07	2.55E+08	5.10E+07	6.43E+08	2.49E+08
2008	7.25E+07	3.54E+07	1.47E+07	2.65E+08	5.48E+07	7.22E+08	2.88E+08
2009	9.33E+07	3.74E+07	1.83E+07	2.73E+08	5.72E+07	8.09E+08	3.25E+08
2010	1.16E+08	3.91E+07	2.24E+07	2.78E+08	5.40E+07	9.04E+08	3.76E+08
2011	1.36E+08	4.04E+07	2.70E+07	2.83E+08	5.14E+07	1.01E+09	4.42E+08
2012	1.49E+08	4.10E+07	3.17E+07	2.86E+08	4.86E+07	1.12E+09	5.00E+08
2013	1.54E+08	4.08E+07	3.62E+07	2.83E+08	4.49E+07	1.25E+09	5.53E+08
2014	1.59E+08	4.01E+07	4.07E+07	2.78E+08	4.10E+07	1.39E+09	6.11E+08
2015	1.59E+08	3.86E+07	4.48E+07	2.67E+08	3.75E+07	1.54E+09	6.69E+08
2016	1.59E+08	3.67E+07	4.89E+07	2.52E+08	3.39E+07	1.82E+09	7.23E+08
2017	1.59E+08	3.44E+07	5.30E+07	2.34E+08	3.05E+07	2.04E+09	7.72E+08
2018	1.59E+08	3.18E+07	5.70E+07	2.14E+08	2.72E+07	2.19E+09	8.18E+08
2019	1.59E+08	2.89E+07	6.11E+07	1.95E+08	2.41E+07	2.30E+09	8.58E+08
2020	1.59E+08	2.56E+07	6.54E+07	1.75E+08	2.13E+07	2.31E+09	8.95E+08
2021	1.60E+08	2.26E+07	6.93E+07	1.56E+08	1.87E+07	2.34E+09	9.27E+08

Continue to previous table, in total three sub-tables

Year	Refrigerator	WM	Dishwasher	EWH	GWH	RH	Microwave
2000	5.23E+07	5.94E+07	0.00E+00	9.72E+06	6.76E+06	1.83E+07	1.04E+07
2001	5.92E+07	6.48E+07	0.00E+00	1.11E+07	7.11E+06	2.03E+07	1.36E+07
2002	6.72E+07	7.13E+07	0.00E+00	1.29E+07	7.74E+06	2.21E+07	1.64E+07
2003	7.87E+07	7.95E+07	0.00E+00	1.62E+07	9.15E+06	2.27E+07	1.76E+07
2004	9.43E+07	9.06E+07	0.00E+00	2.16E+07	1.16E+07	2.58E+07	2.25E+07
2005	1.09E+08	1.04E+08	0.00E+00	2.86E+07	1.49E+07	2.91E+07	2.78E+07
2006	1.27E+08	1.20E+08	0.00E+00	3.85E+07	1.97E+07	3.48E+07	3.68E+07
2007	1.50E+08	1.38E+08	0.00E+00	5.14E+07	2.60E+07	4.10E+07	4.64E+07
2008	1.74E+08	1.58E+08	0.00E+00	6.52E+07	3.29E+07	4.97E+07	5.98E+07
2009	2.04E+08	1.80E+08	0.00E+00	7.82E+07	3.93E+07	5.86E+07	7.35E+07
2010	2.42E+08	2.09E+08	5.93E+03	9.17E+07	4.60E+07	6.92E+07	8.99E+07
2011	2.86E+08	2.39E+08	1.77E+04	1.09E+08	5.44E+07	7.93E+07	1.06E+08
2012	3.29E+08	2.68E+08	4.13E+04	1.21E+08	6.07E+07	9.02E+07	1.22E+08
2013	3.74E+08	2.98E+08	8.81E+04	1.39E+08	6.96E+07	1.03E+08	1.41E+08
2014	4.15E+08	3.27E+08	1.82E+05	1.56E+08	7.81E+07	1.18E+08	1.65E+08
2015	4.50E+08	3.54E+08	3.69E+05	1.66E+08	8.29E+07	1.32E+08	1.86E+08
2016	4.81E+08	3.79E+08	8.94E+05	1.74E+08	8.70E+07	1.45E+08	2.07E+08
2017	5.11E+08	4.02E+08	1.75E+06	1.80E+08	9.01E+07	1.57E+08	2.25E+08
2018	5.38E+08	4.23E+08	2.94E+06	1.85E+08	9.26E+07	1.68E+08	2.43E+08
2019	5.62E+08	4.41E+08	4.44E+06	1.89E+08	9.44E+07	1.78E+08	2.58E+08
2020	5.84E+08	4.58E+08	6.24E+06	1.91E+08	9.57E+07	1.87E+08	2.71E+08
2021	6.03E+08	4.72E+08	9.40E+06	1.93E+08	9.66E+07	1.95E+08	2.83E+08

Table 7. Estimated EoL numbers of products in China in 2000−2021

Year	ICEV	HEV	BEV	CRT TV	LCD TV	Printer	Copier
2000	2.99E+04	0.00E+00	0.00E+00	2.41E+06	3.01E+05	6.91E+05	8.20E+04
2001	4.39E+04	0.00E+00	0.00E+00	2.97E+06	3.71E+05	1.19E+06	1.50E+05
2002	6.25E+04	0.00E+00	0.00E+00	3.57E+06	4.47E+05	1.83E+06	2.41E+05
2003	8.76E+04	0.00E+00	0.00E+00	4.25E+06	5.31E+05	2.59E+06	3.63E+05
2004	1.23E+05	0.00E+00	0.00E+00	5.01E+06	6.26E+05	3.45E+06	5.23E+05
2005	1.74E+05	0.00E+00	0.00E+00	5.88E+06	7.35E+05	4.41E+06	7.24E+05
2006	2.50E+05	0.00E+00	0.00E+00	6.86E+06	8.57E+05	5.44E+06	9.73E+05
2007	3.63E+05	0.00E+00	0.00E+00	7.92E+06	9.91E+05	6.53E+06	1.26E+06
2008	5.28E+05	1.67E-05	0.00E+00	9.05E+06	1.14E+06	7.67E+06	1.58E+06
2009	7.60E+05	3.24E-03	0.00E+00	1.02E+07	1.32E+06	8.85E+06	1.93E+06
2010	1.07E+06	4.04E-02	2.05E-04	1.14E+07	1.52E+06	1.01E+07	2.26E+06
2011	1.47E+06	2.30E-01	5.45E-02	1.26E+07	1.78E+06	1.13E+07	2.61E+06
2012	1.96E+06	8.89E-01	7.65E-01	1.38E+07	2.09E+06	1.25E+07	2.97E+06
2013	2.51E+06	2.72E+00	4.56E+00	1.49E+07	2.46E+06	1.38E+07	3.34E+06
2014	3.12E+06	7.08E+00	1.78E+01	1.60E+07	2.90E+06	1.50E+07	3.70E+06
2015	3.78E+06	1.65E+01	5.42E+01	1.70E+07	3.41E+06	1.63E+07	4.06E+06
2016	4.49E+06	3.64E+01	1.47E+02	1.79E+07	3.99E+06	1.75E+07	4.43E+06
2017	5.28E+06	8.21E+01	3.85E+02	1.87E+07	4.65E+06	1.86E+07	4.78E+06
2018	6.18E+06	1.90E+02	9.99E+02	1.92E+07	5.39E+06	1.97E+07	5.12E+06
2019	7.25E+06	4.33E+02	2.50E+03	1.97E+07	6.19E+06	2.09E+07	5.44E+06
2020	8.51E+06	9.48E+02	5.92E+03	1.99E+07	7.05E+06	2.20E+07	5.74E+06
2021	9.99E+06	1.95E+03	1.31E+04	1.99E+07	7.96E+06	2.31E+07	6.01E+06

Note, data in this table was estimated from **Supplementary Table 5**, **Supplementary Fig. 1**, and **Supplementary Table 6**, detailed methods are provided in the Anthropogenic Metabolism Analysis section.

Continue to previous table

Year	Laptop	CRT desktop	LCD desktop	VP	FM	MP	AC
2000	0.00E+00	8.21E+05	7.43E+03	4.11E+06	5.40E+05	1.18E+07	8.76E+05
2001	0.00E+00	1.03E+06	1.95E+04	6.27E+06	6.75E+05	1.77E+07	1.25E+06
2002	0.00E+00	1.27E+06	4.19E+04	8.82E+06	8.45E+05	2.46E+07	1.74E+06
2003	2.29E+05	1.52E+06	7.96E+04	1.16E+07	1.06E+06	3.22E+07	2.35E+06
2004	1.18E+06	1.80E+06	1.38E+05	1.46E+07	1.41E+06	4.04E+07	3.14E+06
2005	2.59E+06	2.10E+06	2.22E+05	1.75E+07	1.87E+06	4.91E+07	4.17E+06
2006	4.44E+06	2.40E+06	3.37E+05	2.03E+07	2.48E+06	5.82E+07	5.50E+06
2007	6.71E+06	2.72E+06	4.89E+05	2.29E+07	3.18E+06	6.78E+07	7.18E+06
2008	9.55E+06	3.04E+06	6.82E+05	2.53E+07	3.86E+06	7.80E+07	9.23E+06
2009	1.30E+07	3.35E+06	9.19E+05	2.73E+07	4.47E+06	8.87E+07	1.17E+07
2010	1.71E+07	3.65E+06	1.21E+06	2.90E+07	4.98E+06	1.00E+08	1.45E+07
2011	2.14E+07	3.92E+06	1.54E+06	3.05E+07	5.28E+06	1.13E+08	1.77E+07
2012	2.55E+07	4.17E+06	1.93E+06	3.16E+07	5.43E+06	1.26E+08	2.13E+07
2013	2.87E+07	4.39E+06	2.37E+06	3.25E+07	5.46E+06	1.41E+08	2.52E+07
2014	3.09E+07	4.55E+06	2.84E+06	3.31E+07	5.37E+06	1.57E+08	2.95E+07
2015	3.23E+07	4.65E+06	3.34E+06	3.33E+07	5.18E+06	1.75E+08	3.41E+07
2016	3.31E+07	4.69E+06	3.85E+06	3.31E+07	4.93E+06	1.96E+08	3.90E+07
2017	3.35E+07	4.66E+06	4.37E+06	3.26E+07	4.63E+06	2.22E+08	4.40E+07
2018	3.37E+07	4.57E+06	4.88E+06	3.16E+07	4.30E+06	2.50E+08	4.91E+07
2019	3.38E+07	4.41E+06	5.39E+06	3.02E+07	3.95E+06	2.76E+08	5.43E+07
2020	3.38E+07	4.19E+06	5.89E+06	2.85E+07	3.59E+06	2.98E+08	5.95E+07
2021	3.39E+07	3.93E+06	6.39E+06	2.66E+07	3.24E+06	3.15E+08	6.45E+07

Continue to previous table, in total three sub-tables

Year	Refrigerator	WM	Dishwasher	EWH	GWH	RH	Microwave
2000	1.00E+06	2.21E+06	0.00E+00	8.83E+05	7.79E+05	8.34E+05	1.46E+05
2001	1.28E+06	2.66E+06	0.00E+00	1.05E+06	8.47E+05	9.71E+05	2.37E+05
2002	1.60E+06	3.12E+06	0.00E+00	1.24E+06	9.10E+05	1.11E+06	3.60E+05
2003	1.96E+06	3.61E+06	0.00E+00	1.45E+06	9.84E+05	1.26E+06	5.16E+05
2004	2.36E+06	4.13E+06	0.00E+00	1.75E+06	1.10E+06	1.40E+06	6.99E+05
2005	2.81E+06	4.69E+06	0.00E+00	2.19E+06	1.28E+06	1.55E+06	9.11E+05
2006	3.33E+06	5.31E+06	0.00E+00	2.82E+06	1.56E+06	1.72E+06	1.16E+06
2007	3.92E+06	6.02E+06	0.00E+00	3.70E+06	1.97E+06	1.94E+06	1.46E+06
2008	4.59E+06	6.83E+06	0.00E+00	4.87E+06	2.53E+06	2.20E+06	1.83E+06
2009	5.35E+06	7.76E+06	0.00E+00	6.29E+06	3.22E+06	2.53E+06	2.28E+06
2010	6.24E+06	8.82E+06	5.59E+00	7.88E+06	4.00E+06	2.93E+06	2.85E+06
2011	7.28E+06	1.01E+07	6.15E+01	9.63E+06	4.86E+06	3.42E+06	3.56E+06
2012	8.50E+06	1.15E+07	2.29E+02	1.16E+07	5.81E+06	3.97E+06	4.41E+06
2013	9.92E+06	1.31E+07	6.20E+02	1.35E+07	6.79E+06	4.60E+06	5.43E+06
2014	1.16E+07	1.49E+07	1.45E+03	1.57E+07	7.86E+06	5.32E+06	6.60E+06
2015	1.34E+07	1.68E+07	3.17E+03	1.79E+07	8.95E+06	6.13E+06	7.95E+06
2016	1.55E+07	1.89E+07	6.79E+03	1.99E+07	9.94E+06	7.02E+06	9.46E+06
2017	1.77E+07	2.10E+07	1.50E+04	2.16E+07	1.08E+07	7.97E+06	1.11E+07
2018	2.01E+07	2.32E+07	3.10E+04	2.31E+07	1.16E+07	8.96E+06	1.29E+07
2019	2.26E+07	2.53E+07	5.78E+04	2.44E+07	1.22E+07	9.96E+06	1.47E+07
2020	2.51E+07	2.74E+07	9.83E+04	2.54E+07	1.27E+07	1.10E+07	1.66E+07
2021	2.76E+07	2.95E+07	1.56E+05	2.61E+07	1.31E+07	1.19E+07	1.85E+07

Text 3. Survey of ELV and WEEE recyclers in China

To understand the actual situation of ELV and WEEE recycling in China, we conducted two on-site surveys, investigating an ELV recycling enterprise in Sichuan, China and a WEEE recycling enterprise in Guangdong, China (anonymous), as shown in the below **table**.

Table On-site recycling enterprise survey

<table>
<tr><th colspan="3">ELV recycling enterprise</th></tr>
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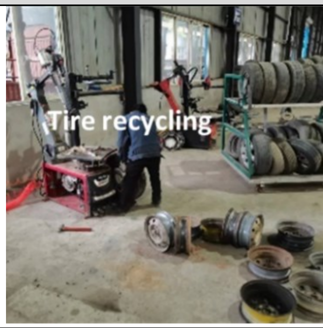
<td>
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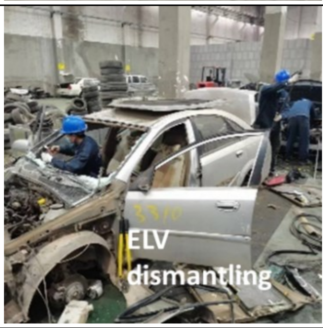
</tr>
<tr>
<td>
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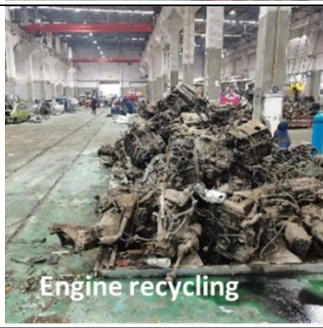
<td>
</td>
<td>
</td>
</tr>
<tr><th colspan="3">WEEE recycling enterprise</th></tr>
<tr>
<td>
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<td>
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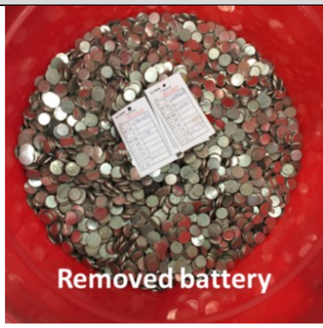
<td>
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Note, PCB: printed circuit board.

The ELV recycling enterprise covers an area of 27,171 m^2 (about 18,000 m^2 workshop area), with an ICEV dismantling line and an EV dismantling line, two sets of waste oil and liquid extraction machines, two sets of refrigerant recovery machines, a set of airbag detonator, a set of general dismantling equipment, a set of power battery dismantling equipment, a set of power battery disconnection equipment, and other recycling supporting facilities. Its annual recycling capacity is about 40,000 ELVs.

The WEEE recycling enterprise mainly engages in pro-processing treatment, dismantling, smelting of rare and precious metals, scrap and other industrial solid waste utilization, and industrialization application research. It is designed to process 20,000 t of waste Printed circuit boards annually, with an annual output of about 4,000 t of anode copper and 700 t of sodium bromide. The plant covers an area of 21,700 m^2, with a total construction area of 8,200 m^2, including four workshops and a comprehensive office building.

Through these surveys, we collected first-hand information and data on recycling objects, technical, and economic situations of Chinese ELV and WEEE recyclers, which is used to analyze the economic recyclability (**Supplementary Tables 9 and 10**) and technical recovery efficiency, especially for the dismantling ratio (**Supplementary Table 11**). In addition, managers of the two recyclers also provided consulting assistance to setting urban mining scenarios (i.e., LS and HS), details can be found in **Supplementary Text 4**.

Text 4. Scenario setting for urban mining

Recycling is a chain of activities. The volume, quality, and value of the metals produced by recycling are determined by the combined stages in that chain. With each stage dependent on its success on the preceding ones, the final result is profoundly affected by the weakest link in the chain[23].

In practice, a major limitation of metal recycling lies in the need for metal production to pay for itself. For many rare and valuable metals, the demand and supply volume of various minor elements generally is too small to justify a dedicated recycling plant for such metals in EoL products. So far, for example, iron, aluminum, copper, tin, titanium, and chromium still represent the largest volumes for metal recycling. The organization of the industry tends to create inertia due to high capital investment, long plant life, etc., encouraging the continuation of single-carrier metal operations. Without enough incentives or new economic patterns, this situation is unlikely to change by itself.

In this study, we set two urban mining scenarios, i.e., LS and HS, to cover the ranges of results caused by different economic and technical recycling intensities, as shown in the below **chart**.

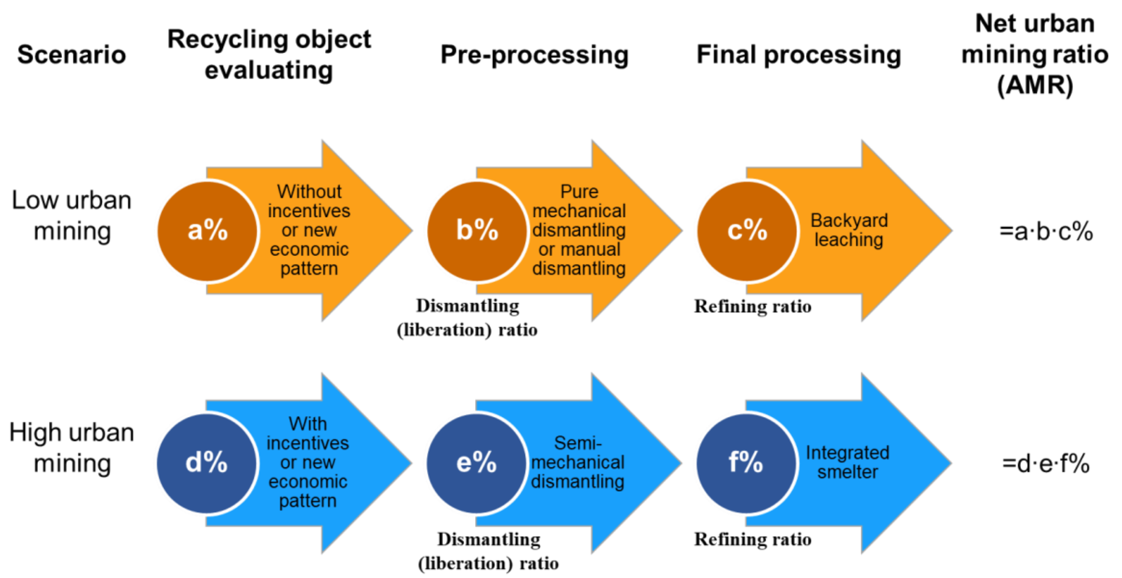

Chart. Scenario setting for LS and HS

The economic viability of recycling is a critical factor in the amount of recycling taking place. Its success is mainly determined by: 1) the supply and demand of metals and their resulting monetary value, including the metal scrap price; 2) the technologies and processes used, including economies of scale; 3) the political support on the economy, affecting designing and operating a metal recycling chain[23].

Pre-processing methods affect the outcome. Purely mechanical dismantling is appropriate for recycling base metals shared main proportions by weight, but it leads to some major losses of precious metals and so on in dust and ferrous fractions. For rare and precious metals, recycling efficiency improves with detailed manual dismantling, but it is limited by efficiency, which is challenging to be used in a large-scale practice. Therefore, a semi-mechanical and multiple-metals treatment becomes the desired option from an economical and eco-efficiency perspective. The refining ratio of metals from recycled sources can vary hugely with the sophistication of the metallurgical processes applied but becomes optimal when using integrated best-available-technique systems.

Table 8. Unit prices of metals

Metal	Note	Average (original unit)	Average (USD/t)
Fe	Iron and steel, producer price index for steel mill products	1.90E+02	1.90E+02
Al	Ingot, average U.S. market (spot), cents per pound	9.64E+01	2.12E+03
Cu	Grade A, annual average, cents per pound	2.68E+02	5.90E+03
Cr	Chromium metal (gross weight), average annual value of imports	9.85E+03	9.85E+03
Zn	Average, cents per pound	1.15E+02	2.54E+03
Sn	Average, cents per pound	8.51E+02	1.88E+04
Mn	Metallurgical-grade ore containing 44% manganese	5.56E+00	5.56E+00
Mg	Annual average	2.31E+03	2.31E+03
Sb	Metal, average, dollars per pound	3.82E+00	8.42E+03
Bi	Average, dollars per pound	4.00E+00	8.81E+03
W	Tungsten trioxide, concentrate, average U.S. spot market	2.52E+02	2.52E+02
Nb	Ferroniobium, unit value, dollars per kilogram	2.18E+01	2.18E+04
V	Vanadium pentoxide, average, dollars per pound	9.26E+00	2.04E+04
Mo	Average value, dollars per kilogram	2.12E+01	2.12E+04
Ga	High-purity, refined, dollars per kilogram	5.63E+02	5.63E+05
Ge	Germanium metal, annual average, dollars per kilogram	1.19E+03	1.19E+06
Ta	Tantalite, Ta2O5 content, dollars per kilogram	1.84E+02	1.84E+05
Ti	Rutile, bulk, minimum 95% TiO2	9.66E+02	9.66E+02
Be	Annual average unit value, beryllium-copper master alloy	5.96E+02	5.96E+05
Tl	Metal, dollars per kilogram	7.73E+03	7.73E+06
In	Annual average, dollars per kilogram	2.18E+02	2.18E+05
Ni	Annual average	1.22E+04	1.22E+04
Li	Annual average, battery-grade lithium carbonate	1.23E+04	2.63E+04
Co	Average, dollars per pound	1.97E+01	4.35E+04
Pb	Average, cents per pound	9.28E+01	2.05E+03
Ag	Bullion, average, dollars per troy ounce	1.74E+01	6.15E+05
Au	Dollars per troy ounce	1.39E+03	4.90E+07
Pd	Dollars per troy ounce	1.23E+03	4.35E+07
Pt	Dollars per troy ounce	9.08E+02	3.20E+07
Rh	Dollars per troy ounce	3.43E+03	1.21E+08
La	99.9% min, free on board (FOB) China	5.40E+03	5.40E+03
Ce	99% min, FOB China	5.50E+03	5.50E+03
Pr	99.5% min, FOB China	1.06E+05	1.06E+05
Nd	99% min, FOB China	6.50E+04	6.50E+04
Sm	99.5% min, FOB China	1.40E+04	1.40E+04
Eu	99.5% min, FOB China	2.95E+05	2.95E+05
Gd	-	-	-
Tb	99.9% min, FOB China	7.80E+05	7.80E+05
Dy	99.5% min, FOB China	3.85E+05	3.85E+05
Er	-	-	-
Sc	99.99% min, ex-works China	3.34E+06	3.34E+06
Y	99.9% min, ex-works China	3.34E+04	3.34E+04

Note, -: none or no data. Sources include the Shanghai Metals Market, London Metal Exchange, European free market, and reports of USGS[2, 24].

Table 9. Estimated current absolute economic value (price) of target metals in products

Metal	ICEV					HEV					BEV				Electronic device										Electric home applicant							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
	Unit: US$/kg																															
Fe	0.11	7E-04	0.003	0.02	0.125	0.108	6E-04	0.003	0.054	0.122	0.155	0.002	4E-05	0.12	0.023	0.057	0.061	0.03	0.038	0.085	0.034	0.095	0.057	0.037	0.095	0.093	0.094	0.095	0.067	0.057	0.057	0.136
Al	0.28	1.952	0.106	0.111	3E-04	0.328	1.993	0.12	0.021	7E-04	0.074	0.117	0.161	8E-04	0.042	0.085	0.382	0.425	0.032	0.074	0.076	0.14	0.319	0.06	0.168	0.038	0.082	0.053	0.212	0.212	0.17	0.083
Cu	0.194	2E-04	0.319	0.082	1.94	0.278	4E-04	0.336	3E-04	1.899	0.275	0.351	0.549	1.863	0.216	0.059	0.03	0.207	0.336	0.333	0.425	0.354	0.236	0.244	1.062	0.218	0.185	0.148	0.295	0.472	0.59	0.23
Cr	0.076	0.002	0.013	-	3E-04	0.059	0.005	0.009	9E-04	-	0.076	0.009	9E-05	-	2E-05	3E-05	2E-04	6E-05	1E-04	3E-05	2E-05	6E-06	5E-06	3E-06	1E-06	6E-07	7E-09	6E-07	6E-07	6E-07	6E-07	6E-07
Zn	0.047	0.002	0.009	-	-	0.052	3E-04	0.008	0.005	-	0.07	0.008	4E-05	-	1E-07	2E-07	9E-04	3E-04	7E-07	2E-07	2E-07	2E-09	2E-09	3E-06	1E-09	3E-09	2E-08	3E-09	3E-09	3E-09	3E-09	3E-09
Sn	0.006	8E-05	0.48	-	-	0.005	4E-04	0.452	2E-04	-	0.006	0.445	0.001	-	0.027	0.051	0.027	0.009	0.051	0.012	0.01	0.005	0.01	0.076	7E-04	4E-04	0.009	4E-04	4E-04	4E-04	4E-04	4E-04
Mn	4E-05	1E-07	1E-06	-	2E-06	3E-05	1E-07	9E-07	1E-04	8E-07	6E-09	9E-07	9E-04	3E-07	3E-09	6E-09	1E-08	4E-09	2E-08	2E-08	1E-08	1E-09	3E-09	4E-08	9E-11	9E-11	5E-09	9E-11	9E-11	9E-11	9E-11	9E-11
Mg	0.01	0.085	0.044	-	-	0.008	0.087	0.03	0.005	-	0.013	0.028	4E-04	-	5E-05	9E-05	5E-05	2E-05	2E-04	5E-05	4E-05	9E-06	2E-05	3E-04	1E-06	7E-07	2E-05	7E-07	7E-07	7E-07	7E-07	7E-07
Sb	6E-04	2E-05	0.004	-	-	0.001	7E-06	0.003	2E-05	-	0.003	0.003	-	-	6E-06	1E-05	7E-04	2E-04	7E-06	8E-07	6E-07	2E-05	4E-06	3E-05	3E-07	8E-08	2E-06	8E-08	8E-08	8E-08	8E-08	8E-08
Bi	3E-04	-	0.001	-	-	3E-04	3E-04	1E-03	-	-	3E-04	9E-04	-	-	4E-05	7E-05	4E-05	1E-05	5E-05	1E-05	1E-05	6E-06	1E-05	7E-05	9E-07	5E-07	1E-05	5E-07	5E-07	5E-07	5E-07	5E-07
W	1E-06	2E-06	2E-04	-	1E-04	-	3E-05	1E-04	2E-06	2E-05	0	1E-04	2E-06	2E-05	2E-07	3E-07	2E-07	6E-08	4E-06	9E-07	8E-07	3E-08	6E-08	6E-06	5E-09	2E-09	6E-08	2E-09	2E-09	2E-09	2E-09	2E-09
Nb	0.002	5E-04	0.001	-	-	0.002	5E-05	8E-04	-	-	0.005	7E-04	-	-	5E-06	1E-05	5E-06	2E-06	3E-05	7E-06	6E-06	9E-07	2E-06	4E-05	1E-07	7E-08	2E-06	7E-08	7E-08	7E-08	7E-08	7E-08
V	0.001	6E-05	6E-04	-	-	0.001	0.001	4E-04	5E-05	-	0.004	4E-04	2E-04	-	7E-07	1E-06	2E-06	8E-07	3E-05	9E-06	7E-06	1E-07	7E-07	4E-05	4E-08	9E-08	4E-07	9E-08	9E-08	9E-08	9E-08	9E-08
Mo	0.006	0.003	0.006	-	-	0.006	0.002	0.004	2E-04	-	0.01	0.004	2E-05	-	2E-05	3E-05	2E-06	6E-07	7E-05	7E-06	6E-06	3E-06	7E-06	6E-05	5E-07	4E-07	2E-05	4E-07	4E-07	4E-07	4E-07	4E-07
Ga	6E-05	0.021	0.014	-	-	-	0.026	0.01	0.249	-	6E-19	0.01	0.006	0.016	-	-	-	-	0.002	4E-04	4E-04	-	-	0.003	-	-	-	-	-	-	-	-
Ge	3E-05	-	0.304	-	-	2E-19	0.002	0.203	0.016	-	3E-05	0.194	-	-	-	-	-	-	0.014	0.003	0.003	-	-	0.021	-	-	-	-	-	-	-	-
Ta	0.001	-	0.028	-	-	0.001	-	0.019	-	-	0.003	0.019	-	-	-	-	-	-	0.001	3E-04	3E-04	-	-	0.002	-	-	-	-	-	-	-	-
Ti	7E-04	3E-04	0.004	-	2E-04	5E-04	0.003	0.003	2E-04	-	8E-04	0.003	3E-05	-	3E-05	6E-05	3E-05	1E-05	2E-04	5E-05	4E-05	6E-06	1E-05	3E-04	9E-07	5E-07	1E-05	5E-07	5E-07	5E-07	5E-07	5E-07
Be	8E-05	-	3E-05	-	-	0.02	-	2E-05	-	-	0.027	2E-05	-	-	5E-07	9E-07	7E-06	2E-06	5E-06	2E-06	2E-06	9E-08	1E-07	1E-05	3E-08	2E-08	2E-07	2E-08	2E-08	2E-08	2E-08	2E-08
Tl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3E-05	5E-05	-	-	1E-04	5E-06	4E-06	7E-06	2E-04	4E-05	5E-07	1E-06	2E-05	1E-06	1E-06	1E-06	1E-06	1E-06
In	7E-05	-	0.018	-	-	8E-20	-	0.021	-	-	5E-20	0.02	-	-	-	0.022	-	-	0.079	-	0.024	-	-	0.087	-	-	-	-	-	-	-	-
Ni	0.034	0.001	0.036	-	2E-05	1E-17	0.002	0.031	6.223	8E-05	7E-18	0.031	0.635	4E-05	3E-08	5E-08	0.002	8E-04	2E-07	1E-08	1E-08	1E-09	6E-09	8E-07	4E-10	2E-10	6E-09	2E-10	2E-10	2E-10	2E-10	2E-10
Li	3E-04	6E-04	4E-04	-	-	0.005	2E-04	4E-04	0.016	-	-	4E-04	0.552	-	-	-	-	-	0.243	-	-	-	-	0.486	-	-	-	-	-	-	-	-
Co	0.003	6E-05	0.001	-	0.039	5E-08	0.001	1E-03	1.46	0.066	9E-18	1E-03	0.566	0.125	5E-06	9E-06	-	-	1E-04	8E-06	6E-06	2E-06	3E-06	2E-04	5E-07	2E-07	5E-06	2E-07	2E-07	2E-07	2E-07	2E-07
Pb	0.009	9E-06	0.011	1.228	-	0.015	-	0.009	5E-06	-	0.021	0.009	-	-	3E-07	5E-07	-	-	2E-06	3E-07	3E-07	2E-07	2E-07	3E-06	9E-09	2E-09	1E-07	2E-09	2E-09	2E-09	2E-09	2E-09
Ag	0.015	9E-04	0.165	-	-	0.014	0.014	0.152	-	-	0.023	0.177	-	-	0.007	0.014	0.031	0.01	0.056	0.013	0.011	6E-04	3E-04	0.068	1E-05	1E-04	1E-04	1E-04	1E-04	1E-04	1E-04	1E-04
Au	0.099	-	2.609	-	-	0.197	-	1.949	-	-	0.235	1.91	-	-	0.066	0.124	0.4	0.135	1.553	0.364	0.311	0.007	0.002	3.253	1E-04	2E-04	0.006	2E-04	2E-04	2E-04	2E-04	2E-04
Pd	0.108	40	2.711	-	-	-	132.8	2.805	-	-	0.072	2.729	-	-	0.035	0.065	0.035	0.012	0.737	0.171	0.146	0.006	0.013	1.088	9E-04	5E-04	0.012	5E-04	5E-04	5E-04	5E-04	5E-04
Pt	0.001	20.26	0.125	-	-	0.002	51.58	0.074	-	-	0.007	0.071	-	-	7E-04	0.001	7E-04	2E-04	0.02	0.005	0.004	1E-04	2E-04	0.029	2E-05	9E-06	2E-04	9E-06	9E-06	9E-06	9E-06	9E-06
Rh	0.002	41.9	0.043	-	-	0.002	20.81	0.057	-	-	0.03	0.055	-	-	0.007	0.014	0.007	0.003	0.098	0.023	0.02	0.001	0.003	0.145	2E-04	1E-04	0.003	1E-04	1E-04	1E-04	1E-04	1E-04
La	2E-05	0.009	3E-04	-	0.002	1E-06	0.003	2E-04	0.186	9E-04	-	2E-04	-	7E-04	6E-04	9E-09	-	-	8E-07	5E-04	3E-07	1E-08	2E-08	0.003	3E-09	3E-09	4E-08	3E-09	3E-09	3E-09	3E-09	3E-09
Ce	1E-05	0.106	0.006	-	-	2E-06	0.027	0.004	0.111	-	-	0.004	-	-	7E-06	-	-	-	2E-06	7E-06	8E-07	7E-08	-	4E-05	-	5E-09	-	5E-09	5E-09	5E-09	5E-09	5E-09
Pr	4E-04	1E-04	0.004	-	-	8E-19	2E-04	0.003	0.231	0.005	-	0.002	6E-04	0.088	0.001	9E-07	-	-	4E-06	9E-04	2E-06	5E-08	2E-07	0.006	1E-05	2E-08	2E-05	2E-08	2E-08	2E-08	2E-08	2E-08
Nd	1E-04	6E-04	0.002	-	0.009	5E-06	0.002	0.014	0.628	1.16	7E-06	0.013	-	1.998	8E-07	2E-06	-	-	1E-05	4E-06	3E-06	1E-07	5E-07	3E-05	3E-05	5E-08	4E-05	5E-08	5E-08	5E-08	5E-08	5E-08
Sm	1E-05	3E-06	5E-05	-	-	9E-06	2E-06	3E-05	-	-	1E-05	3E-05	-	-	6E-09	1E-08	-	-	8E-08	3E-08	3E-08	1E-09	3E-09	1E-07	2E-07	4E-10	3E-07	4E-10	4E-10	4E-10	4E-10	4E-10
Eu	3E-06	-	4E-05	-	-	6E-23	-	4E-05	-	-	8E-23	4E-05	-	-	2E-07	4E-07	-	-	1E-05	1E-06	1E-06	2E-07	2E-08	2E-05	3E-09	2E-09	6E-08	2E-09	2E-09	2E-09	2E-09	2E-09
Gd	2E-06	4E-05	8E-04	-	-	-	0.002	6E-04	0.002	-	-	5E-04	-	-	7E-08	1E-07	-	-	6E-06	2E-06	1E-06	2E-08	3E-08	8E-06	3E-09	1E-08	6E-08	1E-08	1E-08	1E-08	1E-08	1E-08
Tb	6E-05	0.001	6E-04	-	-	4E-04	0.002	4E-04	0.003	-	7E-04	4E-04	-	-	-	-	-	-	1E-04	3E-05	3E-05	-	-	2E-04	-	-	-	-	-	-	-	-
Dy	1E-03	9E-04	0.002	-	0.012	-	-	0.004	9E-04	1.674	-	0.004	-	3.513	0.004	1E-06	-	-	1E-05	0.003	2E-05	1E-07	5E-07	0.02	2E-05	4E-08	1E-04	4E-08	4E-08	4E-08	4E-08	4E-08
Er	3E-06	7E-05	4E-05	-	0.003	-	-	2E-05	1E-04	-	5E-09	2E-05	-	-	6E-08	1E-07	-	-	4E-07	2E-07	1E-07	1E-08	3E-08	6E-07	2E-09	2E-09	6E-08	2E-09	2E-09	2E-09	2E-09	2E-09
Sc	8E-05	-	0.032	-	-	4E-20	0.018	0.022	-	-	2E-04	0.021	0.001	-	0.002	0.003	3E-05	9E-06	0.003	0.001	0.001	3E-04	2E-04	0.012	5E-05	2E-05	7E-04	2E-05	2E-05	2E-05	2E-05	2E-05
Y	8E-06	7E-05	2E-04	-	-	-	4E-06	5E-05	0.042	-	-	8E-05	-	-	2E-07	3E-07	6E-07	2E-07	7E-08	3E-07	3E-07	9E-08	4E-08	2E-06	5E-09	8E-09	1E-07	8E-09	8E-09	8E-09	8E-09	8E-09

Note, -: none or no data. 1−5 are engine/frame/rest, catalytic converter, electronic controller, Pb-acid battery, motor of ICEV; 6−10 are engine/frame/rest, catalytic converter, electronic controller, NiMH battery, motor of HEV; 11−14 are engine/frame/rest, catalytic converter, electronic controller, Li-ion battery, motor of HEV; 15−24 are CRT TV, LCD TV, printer, copier, laptop, CRT desktop, LCD desktop, VP, FM, MP; 25−32 are AC refrigerator, WM, DW, EWH, GWH, RH, microwave, respectively.

Table 10. Estimated current relative economic proportion (a metal/all materials) of target metals in products

Metal	ICEV					HEV					BEV				Electronic device										Electric home applicant							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
	%																															
Fe 铁	10.54	6E-04	0.045	1.346	5.862	9.553	3E-04	0.039	0.579	2.483	13.85	0.038	0.001	1.554	2.405	6.168	4.666	3.297	1.017	6.131	2.226	11.09	5.835	0.6	7	22.24	20.63	26.11	10.24	6.952	6.366	28.18
Al 铝	26.9	1.871	1.464	7.524	0.014	28.94	0.961	1.85	0.231	0.014	6.634	1.832	6.312	0.01	4.36	9.192	29.33	46.07	0.853	5.336	4.976	16.37	32.61	0.978	12.31	9.133	17.99	14.59	32.7	25.9	18.97	17.23
Cu 铜	18.68	1E-04	4.42	5.573	91	24.57	2E-04	5.192	0.003	38.54	24.63	5.52	21.45	24.12	22.2	6.383	2.263	22.39	9	23.92	27.64	41.33	24.15	3.991	77.93	52.14	40.48	40.54	45.41	57.56	65.88	47.85
Cr 铬	7.311	0.002	0.186	-	0.013	5.218	0.002	0.141	0.01	-	6.756	0.138	0.003	-	0.002	0.003	0.015	0.007	0.004	0.002	0.002	7E-04	5E-04	4E-05	8E-05	1E-04	2E-06	2E-04	1E-04	8E-05	7E-05	1E-04
Zn 锌	4.546	0.002	0.129	-	-	4.551	1E-04	0.117	0.059	-	6.292	0.122	0.001	-	1E-05	2E-05	0.069	0.033	2E-05	1E-05	1E-05	2E-07	2E-07	5E-05	9E-08	7E-07	4E-06	8E-07	4E-07	3E-07	3E-07	6E-07
Sn 锡	0.598	8E-05	6.641	-	-	0.429	2E-04	6.987	0.002	-	0.499	6.994	0.054	-	2.779	5.501	2.077	0.992	1.375	0.857	0.665	0.567	1.034	1.242	0.052	0.085	2.003	0.098	0.055	0.043	0.04	0.074
Mn 锰	0.004	1E-07	2E-05	-	8E-05	0.003	6E-08	1E-05	0.001	2E-05	5E-07	1E-05	0.037	3E-06	4E-07	7E-07	1E-06	5E-07	6E-07	1E-06	8E-07	1E-07	3E-07	6E-07	7E-09	2E-08	1E-06	3E-08	1E-08	1E-08	1E-08	2E-08
Mg 镁	1.007	0.081	0.602	-	-	0.699	0.042	0.456	0.053	-	1.184	0.445	0.015	-	0.005	0.01	0.004	0.002	0.005	0.003	0.003	0.001	0.002	0.005	1E-04	2E-04	0.004	2E-04	1E-04	8E-05	7E-05	1E-04
Sb 锑	0.059	2E-05	0.054	-	-	0.093	3E-06	0.051	2E-04	-	0.239	0.05	-	-	6E-04	0.001	0.056	0.027	2E-04	5E-05	4E-05	0.002	4E-04	6E-04	2E-05	2E-05	5E-04	2E-05	1E-05	1E-05	9E-06	2E-05
Bi 铋	0.026	-	0.019	-	-	0.03	2E-04	0.015	-	-	0.024	0.015	-	-	0.004	0.007	0.003	0.001	0.001	8E-04	6E-04	7E-04	0.001	0.001	7E-05	1E-04	0.003	1E-04	7E-05	6E-05	5E-05	1E-04
W 钨	1E-04	2E-06	0.003	-	0.005	-	2E-05	0.002	2E-05	4E-04	-	0.002	7E-05	2E-04	2E-05	4E-05	1E-05	6E-06	1E-04	7E-05	5E-05	4E-06	7E-06	1E-04	3E-07	5E-07	1E-05	6E-07	4E-07	3E-07	3E-07	5E-07
Nb 铌	0.21	5E-04	0.015	-	-	0.147	2E-05	0.012	-	-	0.443	0.012	-	-	5E-04	0.001	4E-04	2E-04	8E-04	5E-04	4E-04	1E-04	2E-04	7E-04	1E-05	2E-05	4E-04	2E-05	1E-05	8E-06	8E-06	1E-05
V 钒	0.103	6E-05	0.008	-	-	0.095	5E-04	0.006	6E-04	-	0.354	0.006	0.006	-	7E-05	1E-04	2E-04	8E-05	8E-04	6E-04	5E-04	1E-05	7E-05	7E-04	3E-06	2E-05	9E-05	2E-05	1E-05	1E-05	1E-05	2E-05
Mo 钼	0.581	0.002	0.078	-	-	0.509	8E-04	0.058	0.002	-	0.891	0.056	8E-04	-	0.002	0.004	1E-04	7E-05	0.002	5E-04	4E-04	3E-04	7E-04	1E-03	4E-05	1E-04	0.005	1E-04	6E-05	5E-05	5E-05	9E-05
Ga 镓	0.006	0.02	0.197	-	-	-	0.013	0.156	2.694	-	5E-17	0.154	0.22	0.212	-	-	-	-	0.052	0.032	0.025	-	-	0.047	-	-	-	-	-	-	-	-
Ge 锗	0.003	-	4.207	-	-	1E-17	9E-04	3.138	0.172	-	0.002	3.05	-	-	-	-	-	-	0.388	0.242	0.188	-	-	0.35	-	-	-	-	-	-	-	-
Ta 钽	0.11	-	0.388	-	-	0.099	-	0.289	-	-	0.271	0.295	-	-	-	-	-	-	0.039	0.025	0.019	-	-	0.036	-	-	-	-	-	-	-	-
Ti 钛	0.065	3E-04	0.053	-	0.008	0.043	0.001	0.049	0.003	-	0.076	0.051	0.001	-	0.004	0.007	0.003	0.001	0.006	0.004	0.003	7E-04	0.001	0.005	7E-05	1E-04	0.003	1E-04	7E-05	5E-05	5E-05	9E-05
Be 铍	0.007	-	4E-04	-	-	1.78	-	3E-04	-	-	2.445	3E-04	-	-	5E-05	1E-04	6E-04	3E-04	1E-04	1E-04	1E-04	1E-05	1E-05	2E-04	2E-06	4E-06	5E-05	5E-06	3E-06	2E-06	2E-06	4E-06
Tl 铊	-	-	0	-	-	-	-	-	-	-	0	0	-	-	0.003	0.006	-	-	0.003	4E-04	3E-04	8E-04	0.024	6E-04	3E-05	2E-04	0.004	3E-04	2E-04	1E-04	1E-04	2E-04
In 铟	0.007	-	0.251	-	-	7E-18	-	0.32	-	-	5E-18	0.311	-	-	0	2.413	-	-	2.108	-	1.538	-	-	1.419	-	-	-	-	-	-	-	-
Ni 镍	3.221	0.001	0.505	-	0.001	1E-15	1E-03	0.472	67.24	0.002	6E-16	0.493	24.8	5E-04	3E-06	5E-06	0.178	0.085	5E-06	8E-07	6E-07	1E-07	6E-07	1E-05	3E-08	4E-08	1E-06	4E-08	2E-08	2E-08	2E-08	3E-08
Li 锂	0.027	6E-04	0.006	-	-	0.466	1E-04	0.006	0.168	-	-	0.006	21.58	-	-	-	-	-	6.499	-	-	-	-	7.95	-	-	-	-	-	-	-	-
Co 钴	0.241	6E-05	0.018	-	1.851	4E-06	5E-04	0.015	15.77	1.338	8E-16	0.015	22.11	1.619	5E-04	9E-04	-	-	0.004	5E-04	4E-04	3E-04	3E-04	0.003	3E-05	4E-05	0.001	5E-05	3E-05	2E-05	2E-05	4E-05
Pb 铅	0.818	8E-06	0.159	83.24	-	1.34	-	0.146	6E-05	-	1.864	0.142	-	-	3E-05	6E-05	0.022	0.01	6E-05	2E-05	2E-05	3E-05	2E-05	4E-05	6E-07	5E-07	2E-05	6E-07	3E-07	3E-07	2E-07	4E-07
Ag 银	1.453	8E-04	2.285	-	-	1.255	0.007	2.35	-	-	2.042	2.786	-	-	0.762	1.509	2.346	1.12	1.488	0.92	0.714	0.072	0.026	1.109	9E-04	0.028	0.029	0.033	0.018	0.014	0.013	0.025
Au 金	9.553	-	36.11	-	-	17.39	-	30.12	-	-	21.03	29.99	-	-	6.788	13.44	30.68	14.65	41.54	26.11	20.26	0.793	0.183	53.23	0.008	0.058	1.344	0.066	0.037	0.029	0.027	0.05
Pd 钯	10.4	38.33	37.52	-	-	-	64.03	43.36	-	-	6.435	42.86	-	-	3.572	7.071	2.67	1.275	19.71	12.28	9.53	0.728	1.329	17.81	0.067	0.109	2.575	0.126	0.071	0.056	0.051	0.095
Pt 铂	0.098	19.41	1.723	-	-	0.143	24.88	1.143	-	-	0.635	1.111	-	-	0.067	0.133	0.05	0.024	0.524	0.326	0.253	0.014	0.025	0.473	0.001	0.002	0.049	0.002	0.001	0.001	1E-03	0.002
Rh 铑	0.237	40.16	0.589	-	-	0.188	10.04	0.883	-	-	2.665	0.858	-	-	0.764	1.512	0.571	0.273	2.624	1.635	1.269	0.156	0.284	2.37	0.014	0.023	0.55	0.027	0.015	0.012	0.011	0.02
La 镧	0.002	0.008	0.005	-	0.083	8E-05	0.001	0.004	2.014	0.017	0	0.004	-	-	0.065	1E-06	-	-	2E-05	0.036	2E-05	1E-06	2E-06	0.053	2E-07	8E-07	1E-05	9E-07	5E-07	4E-07	4E-07	7E-07
Ce 铈	0.001	0.102	0.082	-	-	2E-04	0.013	0.061	1.204	-	0	0.06	-	-	8E-04	-	-	-	6E-05	5E-04	5E-05	9E-06	-	7E-04	-	1E-06	-	1E-06	8E-07	7E-07	6E-07	1E-06
Pr 镨	0.035	1E-04	0.053	-	-	7E-17	7E-05	0.04	2.493	0.098	0	0.038	0.023	1.141	0.119	1E-04	-	-	1E-04	0.067	1E-04	6E-06	2E-05	0.097	9E-04	5E-06	0.004	6E-06	3E-06	2E-06	2E-06	4E-06
Nd 钕	0.013	5E-04	0.028	-	0.425	4E-04	8E-04	0.214	6.783	23.53	6E-04	0.208	-	25.86	8E-05	2E-04	-	-	3E-04	3E-04	2E-04	2E-05	5E-05	5E-04	0.002	1E-05	0.008	1E-05	7E-06	6E-06	5E-06	1E-05
Sm 钐	0.001	3E-06	7E-04	-	-	8E-04	8E-07	5E-04	-	-	1E-03	5E-04	-	-	6E-07	1E-06	-	-	2E-06	2E-06	2E-06	1E-07	3E-07	2E-06	1E-05	9E-08	6E-05	1E-07	6E-08	5E-08	4E-08	8E-08
Eu 铕	3E-04	-	6E-04	-	-	5E-21	-	6E-04	-	-	7E-21	6E-04	-	-	2E-05	5E-05	-	-	3E-04	1E-04	8E-05	2E-05	2E-06	3E-04	3E-07	5E-07	1E-05	5E-07	3E-07	2E-07	2E-07	4E-07
Gd 钆	2E-04	4E-05	0.012	-	-	-	1E-03	0.009	0.027	-	0	0.008	-	-	8E-06	2E-05	-	-	2E-04	1E-04	9E-05	3E-06	3E-06	1E-04	2E-07	3E-06	1E-05	3E-06	2E-06	2E-06	1E-06	3E-06
Tb 铽	0.006	0.001	0.008	-	-	0.04	8E-04	0.006	0.03	-	0.062	0.007	-	-	-	-	-	-	0.004	0.002	0.002	-	-	0.003	-	-	-	-	-	-	-	-
Dy 镝	0.094	9E-04	0.022	-	0.541	-	-	0.062	0.01	33.96	0	0.068	-	45.47	0.396	1E-04	-	-	4E-04	0.225	0.002	2E-05	5E-05	0.324	0.002	1E-05	0.031	1E-05	7E-06	5E-06	5E-06	9E-06
Er 铒	3E-04	7E-05	5E-04	-	0.124	-	-	4E-04	0.002	-	4E-07	4E-04	-	-	6E-06	1E-05	-	-	1E-05	1E-05	9E-06	1E-06	3E-06	1E-05	1E-07	5E-07	1E-05	6E-07	3E-07	3E-07	3E-07	5E-07
Sc 钪	0.008	-	0.447	-	-	3E-18	0.009	0.345	-	-	0.015	0.336	0.04	-	0.183	0.361	0.002	0.001	0.093	0.1	0.077	0.029	0.021	0.188	0.004	0.004	0.154	0.005	0.003	0.002	0.002	0.004
Y 钇	8E-04	6E-05	0.003	-	-	-	2E-06	8E-04	0.454	-	0	0.001	-	-	2E-05	3E-05	5E-05	2E-05	2E-06	2E-05	2E-05	1E-05	4E-06	3E-05	3E-07	2E-06	3E-05	2E-06	1E-06	1E-06	9E-07	2E-06
Non-metal	3.032	6E-05	1.671	2.313	0.077	2.42	1E-04	1.883	4E-04	0.021	0.665	1.913	3.341	0.014	55.51	46.28	24.99	9.746	12.65	21.73	30.6	28.85	34.47	7.71	2.608	16.17	14.13	18.4	11.45	9.432	8.637	6.465

Note, -: none or no data. 1−5 are engine/frame/rest, catalytic converter, electronic controller, Pb-acid battery, motor of ICEV; 6−10 are engine/frame/rest, catalytic converter, electronic controller, NiMH battery, motor of HEV; 11−14 are engine/frame/rest, catalytic converter, electronic controller, Li-ion battery, motor of HEV; 15−24 are CRT TV, LCD TV, printer, copier, laptop, CRT desktop, LCD desktop, VP, FM, MP; 25−32 are AC refrigerator, WM, DW, EWH, GWH, RH, microwave, respectively

Table 11. Estimated current economic recyclability of target metals in products in China under LS

Metal	ICEV					HEV					BEV				Electronic device										Electric home applicant							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Fe	√				√	√					√					√				√		√	√		√	√	√	√	√	√	√	√
Al	√			√		√					√		√			√	√	√		√		√	√		√		√	√	√	√	√	√
Cu	√			√	√	√		√		√	√	√	√	√	√	√		√	√	√	√	√	√		√	√	√	√	√	√	√	√
Cr	√					√					√																					
Zn											√																					
Sn			√					√				√				√																
Mn																																
Mg																																
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Ni									√				√																			
Li													√						√					√								
Co									√				√																			
Pb				√																												
Ag																																
Au	√		√			√		√			√	√			√	√	√	√	√	√	√			√								
Pd	√	√	√				√	√			√	√				√			√	√	√			√								
Pt		√					√																									
Rh		√					√																									
La																																
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Threshold of absolute economic value, 0.05 US$, and relative economic proportion, 5% of the total value; detailed value of each value can be found in **Supplementary Tables 9 and 10**. Note, √: economic recyclable; green: value higher than both absolute economic threshold and relative economic threshold; purple: value only higher than absolute economic threshold; orange: only higher than relative economic threshold. 1−5 are engine/frame/rest, catalytic converter, electronic controller, Pb-acid battery, motor of ICEV; 6−10 are engine/frame/rest, catalytic converter, electronic controller, NiMH battery, motor of HEV; 11−14 are engine/frame/rest, catalytic converter, electronic controller, Li-ion battery, motor of HEV; 15−24 are CRT TV, LCD TV, printer, copier, laptop, CRT desktop, LCD desktop, VP, FM, MP; 25−32 are AC refrigerator, WM, DW, EWH, GWH, RH, microwave, respectively.

Table 12. Estimated current economic recyclability of target metals in products in China under HS

Metal	ICEV					HEV					BEV				Electronic device										Electric home applicant							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Fe	√			√	√	√				√	√			√	√	√	√	√	√	√	√	√	√		√	√	√	√	√	√	√	√
Al	√	√	√	√		√		√			√	√	√		√	√	√	√		√	√	√	√		√	√	√	√	√	√	√	√
Cu	√		√	√	√	√		√		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Cr	√					√					√																					
Zn	√					√					√																					
Sn								√				√			√	√	√		√				√	√								
Mn																																
Mg	√										√																					
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In																√			√		√			√								
Ni	√								√				√																			
Li													√						√					√								
Co					√				√	√			√	√																		
Pb				√		√					√																					
Ag	√		√			√		√			√	√				√	√	√	√					√								
Au	√		√			√		√			√	√			√	√	√	√	√	√	√			√								
Pd	√	√	√				√	√			√	√			√	√	√	√	√	√	√		√	√			√					
Pt		√	√				√	√				√																				
Rh		√					√				√					√			√	√	√			√								
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Threshold of absolute economic value, 0.01 US$, and relative economic proportion, 1% of the total value; detailed value of each value can be found in **Supplementary Tables 9 and 10**. Note, √: economic recyclable; green: value higher than both absolute economic threshold and relative economic threshold; purple: value only higher than absolute economic threshold; orange: only higher than relative economic threshold. 1−5 are engine/frame/rest, catalytic converter, electronic controller, Pb-acid battery, motor of ICEV; 6−10 are engine/frame/rest, catalytic converter, electronic controller, NiMH battery, motor of HEV; 11−14 are engine/frame/rest, catalytic converter, electronic controller, Li-ion battery, motor of HEV; 15−24 are CRT TV, LCD TV, printer, copier, laptop, CRT desktop, LCD desktop, VP, FM, MP; 25−32 are AC refrigerator, WM, DW, EWH, GWH, RH, microwave, respectively.

Table 13. Review on metal dismantling (liberation) and refining ratios

Metal	Main carrier	Separation ratio (LS−HS)	Typical technology	Recovery ratio (LS−HS)[25]	Overall recycling efficiency (LS−HS)	Recycled product
Fe	Iron, steel, magnet	80−100%	BOF, EAF	80−82%[26]	64−82%	Metal
Al	aluminum, alloy	80−100%	Remelt, refine	82−90%	66−90%	Metal
Cu	Wire, printed circuit board	50−90%	Smelt, refine	80−95%[27]	40−86%	Metal
Cr	Steel	80−100%	Refine	30−70%	24−70%	Metal
Zn	Alloy	80−100%	ISP	85−90%[28]	68−90%	Metal
Sn	Steel, solder	50−90%	Smelt, refine	85%[10]	43−77%	Metal
Mn	Steel, battery	80−100%	Refine	80−90%[29]	64−90%	Metal
Mg	Alloy	80−100%	Hydro-metallurgy	80%	64−80%	Metal
Sb	Alloy, battery, solder	80−100%	-	92−95%	74−95%	Metal
Bi	Alloy, magnet, solder	40−60%	-	-	-	-
W	Steel, alloy	50−90%	-	-	-	-
Nb	Steel	80−100%	-	-	-	-
V	Alloy, stainless steel	80−100%	-	-	-	-
Mo	Alloy	80−100%	-	-	-	-
Ga	Semiconductor	40−60%	-	-	-	-
Ge	Semiconductor	40−60%	-	-	-	-
Ta	Alloy, printed circuit board	25−50%	-	-	-	-
Ti	Alloy	80−100%	Pyro-metallurgy	-	-	-
Be	Semiconductor	60−80%	-	-	-	-
Tl	Photoresistor	60−80%	-	-	-	-
In	Displayer	60−80%	-	82−94%	49−75%	Metal, oxide
Ni	Stainless steel, alloy, battery	80−100%	Smelt, refine, acid leaching (Brunp, GEM)	30−85%[30]	24−85%	Metal
Li	Battery	80−100%	Hydro & pyro-metallurgy	0−97%[30]	0−97%	Oxide
Co	Alloy, battery	80−100%	Special battery recycling	90−96%[30]	72−96%	Metal
Pb	Alloy, battery	80−100%	Smelt, refine	95−98%[31]	76−98%	Metal
Ag	Wire, printed circuit board	30−50%	Smelting and electrorefining (Umicore), leaching	89−99%[32, 33]	27−50%	Metal
Au	printed circuit board	40−60%		99−100%[32, 33]	39−60%	Metal
Pd	Catalyst, capacitor	50−90%	Closed electric furnace (Tanaka), leaching	98−99%[32, 33]	49−89%	Metal
Pt	Catalyst, hard disk drives	50−90%		95−96%[32, 33]	48−85%	Metal
Rh	Catalyst, headlight	80−100%		86−92%[32, 33]	69−92%	Metal
La	printed circuit board, battery	50−90%	Hydro-metallurgy, special battery recycling, special magnet recycling	29−50%	14−45%	Oxide
Ce	printed circuit board, catalyst	50−90%		29−50%	14−45%	Oxide
Pr	Magnet	20−40%		31−55%	6−22%	Oxide
Nd	Magnet	20−40%		31−55%	6−22%	Oxide
Sm	Magnet	20−40%		31−55%	6−22%	Oxide
Eu	CRT	40−60%		40−80%	16−48%	Oxide
Gd	Magnet	20−40%		31−55%	6−22%	Oxide
Tb	Kinescope	40−60%		40−80%	16−48%	Oxide
Dy	Magnet	20−40%		31−55%	6−22%	Oxide
Er	Fiber optic	40−60%		40−80%	16−48%	Oxide
Sc	Alloy, lamp	80−100%		-	-	-
Y	Alloy	80−100%		-	-	-

Note, -: none or no data. Separation ratios were presumed based on the on-site survey (**Supplementary Text 3**). Overall recycling efficiencies of Pd, Ni, Co, Li, Ag, Au, Pd, Pt, Rh were calculated from collection and recovery ratios. Brunp and GEM are Chinese recyclers, Umicore and Tanaka are based in Belgium and Japan. Metal phase includes solid and liquid metals. In the table, BOF, EAF, and ISP signify electric arc furnace, basic oxygen furnace, and imperial smelting process, respectively.

Table 14. Review of DGMR (amount and distribution) in China in 2021

Metal	Amount[34] Unit: t (in metal content)
PGM	4.00E+02
Ni	4.00E+06
Cu	2.70E+07
Li	1.50E+06
In	1.30E+04
Co	1.37E+05
Au	1.93E+03
Al	2.50E+08
Ag	5.06E+04
Pb	1.23E+07
Mg	*
Zn	3.09E+07
Sn	7.23E+05
Fe	6.90E+09
Cr	2.86 E+08
REE	2.31E+07
Distribution[35]	

Note, *: Mg metal can be derived from seawater, natural brines, dolomite, serpentine, and other minerals. The reserves for this metal are sufficient to supply current and future requirements[2]. Ni, Cu, Li, Co, Au, Al, Sn, Fe, Cr, and REE are listed as strategic metals in the China (2016) National Mineral Resources Planning (2016-2020).

Additional information for mineral distribution in China

So far, 59 types of metal mineral resources have been discovered in China[36]. The basic characteristics of China's metal mineral resources are: 1) The total amount of resources is relatively large, and the minerals are relatively complete. China has a relatively wide variety of proven mineral resources, and the total amount of resources are relatively abundant. Pillar minerals such as iron, copper, aluminum, lead, and zinc have more proven resource reserves. Mineral resources such as rare earth, tungsten, tin, molybdenum, antimony, titanium, and magnesite have apparent advantages in the world; 2) The per capita resources are small, and the supply and demand of some resources are out of balance. There is a big gap between the supply and demand of mineral resources such as PGM and chromite; 3) Good and bad minerals coexist. There are both high-quality ores and low-grade ores with complex components. Mineral resources such as tungsten, tin, rare earth, molybdenum, antimony, and magnesite are relatively high quality, while iron, manganese, aluminum, copper, and other mineral resources have many poor ores, many symbiotic and associated ores, and many refractory ores.

Supplementary Results

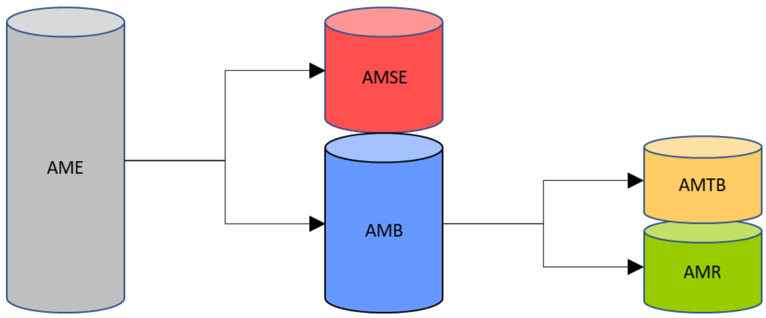


Fig. 2. Inclusion relation between AM categories

Their inclusion relation (three layers) was set as that AME includes AMSE and AMB, and AMB includes AMTB and AMR.

Table 15. Iron characteristics, applications, and recycling

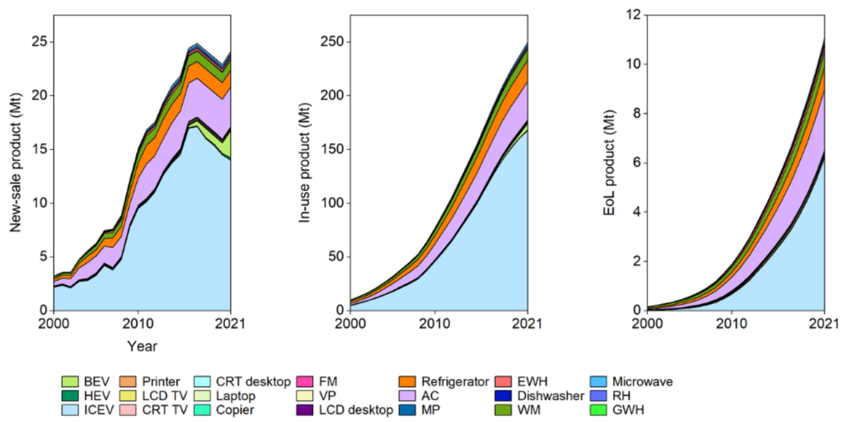
Characteristic	Iron (Fe) is a lustrous, ductile, malleable, and silver-gray metal. It rusts in damp air but not in dry air. Iron dissolves readily in dilute acids. It is chemically active and forms two major chemical compounds: ferrous and ferric compounds[37]. Atomic number: 26; relative atomic mass: 55.845; density: 7.874 g/cm^3; melting point: 1,538 °C (1,811 K)[38]
General application[39]	Most iron is used to manufacture carbon steel in civil engineering (e.g., reinforced concrete, girders) and manufacturing. Alloy steels are carbon steel with other additives such as nickel, chromium, vanadium, tungsten, and manganese. They are stronger and tougher than carbon steel and have various applications, including bridges, electricity pylons, bicycle chains, and automobile engines[40]. Stainless steel is very resistant to corrosion. It is used in architecture, bearings, cutlery, surgical instruments, and jewelry. Iron and its alloys and compounds can make magnets[41].
Use in automobiles and EEE	 Iron in the new-sale products increased from 3.2 Mt to 24 Mt in 2000−2021 (with a pick, 2.5 Mt, in 2017). In this period, iron in in-use products increased 25 times to 250 Mt in 2021, and it in EoL products increased 66 times to 11 Mt. The most essential carriers include ICEV, AC, refrigerator, WM, and recent BEV.
Recycling[42]	Metal cuttings or imperfect products (“new scrap”) are recycled by remelting, recasting, and redrawing entirely within the steel mill. On the other hand, “old scrap” steel makes up a significant percentage of the feed to electric arc and basic oxygen furnaces. The scrap comes from various manufacturing operations using steel as a basic material and discarded or obsolete goods made from iron and steel. One of the largest sources of scrap steel is the reprocessing of old automobile bodies. Overall EoL recycling ratio (from all applications): 52%, 67%, 78%, 90%[25]
Occurrence in nature	Iron is the cheapest and one of the most abundant metals, comprising nearly 5.6% of the earth's crust and almost all of the earth's core. Iron is primarily obtained from the minerals: hematite and magnetite. The minerals: taconite, limonite, and siderite are other important sources[38]. The global largest reserves holders are Australia, Brazil, and Russia[43]; the global top pig iron producer in 2020 was China (70% of the world)[2].

Table 16. Aluminum characteristics, applications, and recycling

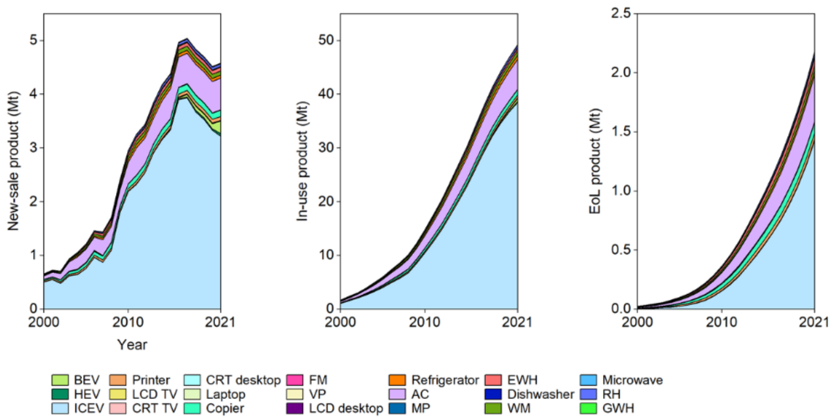
Characteristic	Aluminum (Al) is a soft and lightweight metal. It has a dull silvery appearance because of a thin layer of oxidation that forms quickly when exposed to air. Aluminum is nontoxic, nonmagnetic, and non-sparking[37]. Atomic number: 13; relative atomic mass: 26.982; density: 2.70 g/cm^3 (considered as a light material as about one-third of iron); melting point: 660 °C (933 K)[38]
General application[39]	Aluminum is used in various products, including cans, foils, kitchen utensils, window frames, and beer kegs. Aluminum is often used as an alloy, and its alloys with copper, manganese, magnesium, and silicon are lightweight but strong. They are essential in the construction of airplanes and other forms of transport[44]. Aluminum is a good electrical conductor and is often used in electrical transmission lines[45]. Aluminum coatings have many uses, including telescope mirrors, decorative paper, and toys.
Use in automobiles and EEE	 Aluminum in the new-sale products increased from 0.7 Mt to 4.6 Mt in 2000−2021 (with a pick, 5.0 Mt, in 2017). In this period, aluminum in in-use products increased 29 times to 49 Mt in 2021, and it in EoL products increased 90 times to 2.2 Mt. The most essential carriers include ICEV, AC, copier, and recent BEV.
Recycling[42]	Secondary aluminum reprocessing is a large industry involving recycling machine turnings, rejected castings, siding, and even aluminum covered with decorative plastic. The items are thrown into a reverberatory furnace (in which heat is radiated from the roof into the material treated) and melted while the impurities are burned off. The resulting material is cast into ingots and resold for drawing or forming operations. Aluminum recycling is far less costly and energy-intensive (as many as 95% reduction[46]) than producing new aluminum by electrolysis of alumina[47]. Overall EoL recycling ratio (from all applications): 42%, 60%, 70%[25]
Occurrence in nature	Although aluminum is the most abundant metal in the earth's crust (8.2%), all of the earth's aluminum has combined with other elements to form compounds. Two of the most common compounds are alum, such as potassium aluminum sulfate and aluminum oxide[38]. The global largest reserves holders are Guinea and Australia[43]; the global largest producers in 2020 were China (37 Mt), Russia (3.6 Mt), and India (3.6 Mt)[2].

Table 17. Copper characteristics, applications, and recycling

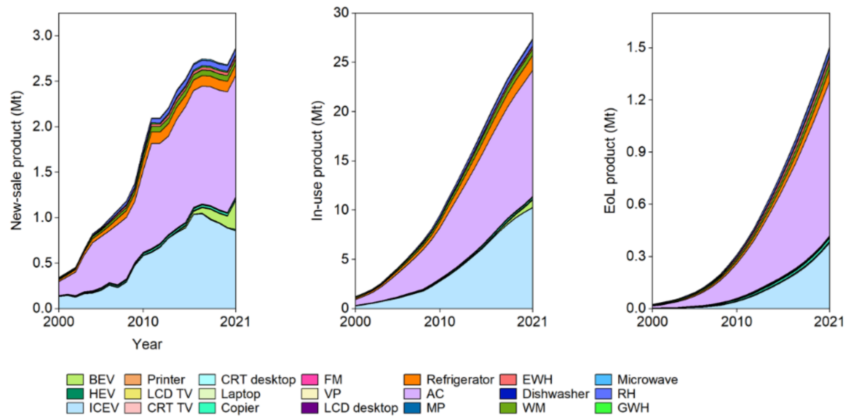
Characteristic	Copper (Cu) is a reddish metal with a face-centered cubic crystalline structure. It is malleable, ductile, and an excellent conductor of heat and electricity[37]. Copper has low chemical reactivity. In moist air, it slowly forms a greenish surface film called patina; this coating protects the metal from further attack[48]. Atomic number: 29; relative atomic mass: 63.546; density: 8.933 g/cm^3; melting point: 1,085 °C (1,358 K)[38]
General application[39]	Traditionally it has been one of the metals used to make coins, along with silver and gold. Nowadays, most copper is used in EEE such as wiring and motors[49]. This is because it conducts heat and electricity very well and can be drawn into wires[50]. It also has uses in construction (e.g., roofing and plumbing) and industrial machinery (e.g., heat exchangers).
Use in automobiles and EEE	 Copper in the new-sale products increased from 342 kt to 2.9 Mt in 2000−2021. In this period, copper in in-use products increased 22 times to 27 Mt in 2021, and it in EoL products increased 60 times to 1.5 Mt. The most essential carriers include ICEV, AC, refrigerator, and recent BEV.
Recycling	Copper is one of the few materials that can be recycled repeatedly without any performance loss. There is also no difference in the quality of recycled copper (secondary production) and mined copper (primary production)[51]. Scrap from the forming or shaping of copper and its alloys is generally reprocessed on the spot, either by remelting and adjusting to grade or by using it as a starting material for less demanding applications. Scrap is also recovered from many obsolete appliances: wire, cables, WEEE, fractions from shredding ELVs and household appliances, etc[52]. Overall EoL recycling ratio (from all applications): 43%, 53%[25]
Occurrence in nature	Copper is primarily obtained from the ores: cuprite, tenorite, malachite, chalcocite, covellite, and bornite[38]. Copper is obtained from these ores and minerals by smelting, leaching, and electrolysis[53]. The largest reserve holders are Chile (200 Mt), Peru (92 Mt), and Australia (88 Mt); the leading refinery producers in 2020 were China (9.8 Mt), Chile (2.4 Mt), and Japan (1.6 Mt)[2].

Table 18. Chromium characteristics, applications, and recycling

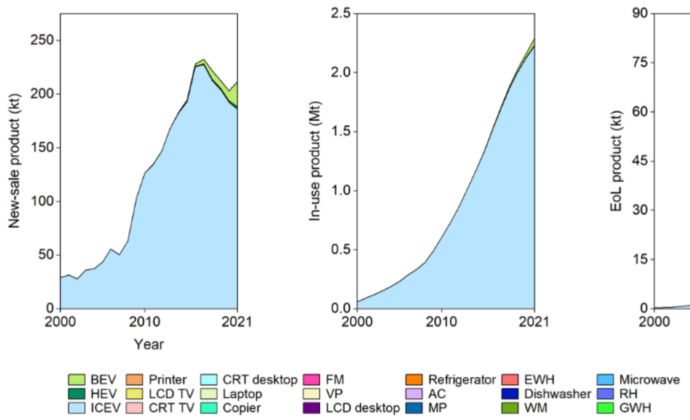
Characteristic	Chromium (Cr) is a lustrous, brittle, hard metal. Its color is silver-gray, and it can be highly polished. It does not tarnish in the air, and when heated, it forms green chromic oxide[37]. Hexavalent chromium, Cr(VI), is toxic and carcinogenic, and chromium trioxide used in industrial electroplating processes is a substance of very serious concern[54]. Atomic number: 24; relative atomic mass: 51.996; density: 7.15 g/cm^3; melting point: 1,907 °C (2,180 K)[38]
General application[39]	Chromium is used to harden steel, manufacture stainless steel, and produce several alloys. Chromium plating can be used to give a polished mirror finish to steel. Chromium-plated automobile parts, such as bumpers. It is also possible to use chromium plate plastics, often used in bathroom fittings[55]. About 90% of all leather is tanned using chrome. However, the waste effluent is toxic[56].
Use in automobiles and EEE	 Chromium in the new-sale products increased from 29 kt to 212 Mt in 2000−2021 (with a pick, 233 kt, in 2017). In this period, chromium in in-use products increased 38 times to 2.3 Mt in 2021, and it in EoL products soared to 83 kt. The most essential carriers are ICEV and BEV.
Recycling	Stainless and heat-resistant steel are recycled with their nickel and chromium contents. Most other chromium-containing steels and alloys can be recycled, but not specifically for their chromium content[57]. Chromium chemicals are typically used for dissipative end uses and are, therefore, not recycled[58]. Overall EoL recycling ratio (from all applications): 87%, 93%[25]
Occurrence in nature	Chromium is primarily obtained by heating the mineral chromite in the presence of aluminum or silicon[38]. Its metal is usually produced by reducing chromite with carbon in an electric-arc furnace or reducing chromium(III) oxide with aluminum or silicon[59]. In 2020, the largest reserve holders are Kazakhstan (230 Mt), South Africa (200 Mt), and India (100 Mt); the leading mine producers in 2020 were South Africa (16 Mt), Kazakhstan (6.7 Mt), and Turkey (6.3 Mt)[2]. In comparison, China lacks chromium ore resources.

Table 19. Zinc characteristics, applications, and recycling

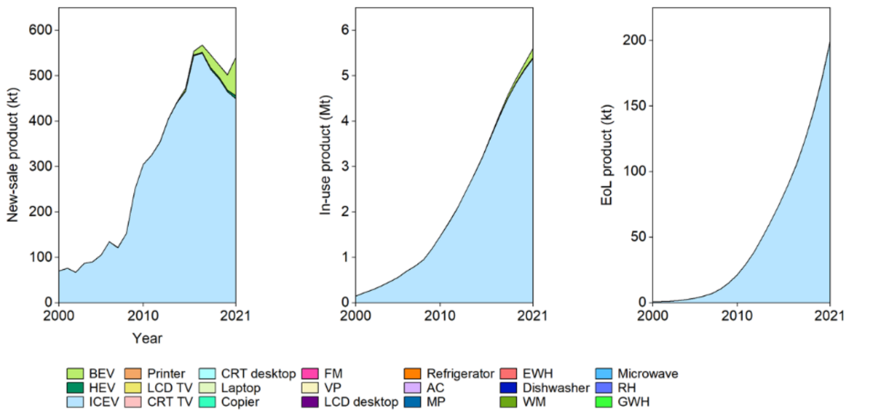
Characteristic	Zinc (Zn) is a lustrous bluish-white metal. It is brittle and crystalline at ordinary temperatures but becomes ductile and malleable when heated between 110°C and 150°C. It is a fairly reactive metal that will combine with oxygen and other non-metals and will react with dilute acids to release hydrogen[37]. Atomic number: 30; relative atomic mass: 65.38; density: 7.134 g/cm^3; melting point: 420 °C (693 K)[38]
General application[39]	Most zinc is used to galvanize other metals, such as iron, to prevent rusting. Galvanized steel is used for car bodies, street lamp posts, safety barriers, and suspension bridges. Large quantities of zinc are used to produce die-castings, which are important in the automobile, electrical, and hardware industries[60]. Zinc is also used in alloys and as solder. Zinc oxide is widely used in the manufacture of very many products such as paints, rubber, plastics, inks, batteries, textiles, and EEE[61].
Use in automobiles and EEE	 Zinc in the new-sale products increased from 70 kt to 542 kt in 2000−2021 (with a pick, 568 kt, in 2017). In this period, zinc in in-use products increased 38 times to 5.6 Mt in 2021, and it in EoL products soared to 200 kt. The most essential carriers are ICEV and BEV.
Recycling	Nowadays, about 34% comes directly from recovered zinc, and the secondary materials included galvanizing residues and crude zinc oxide recovered from electric arc furnace dust[62]. Overall EoL recycling ratio (from all applications): 19%, 34%, 35−60%, 52%[25]
Occurrence in nature	Most zinc is produced through the electrolysis of aqueous zinc sulfate. Commercially, zinc is obtained from its ores by concentrating and roasting the ore, then reducing it to zinc by heating it with carbon or electrolysis[38]. The top three reserve holders are Australia (68 Mt), China (44 Mt), and Mexico and Russia (both have 22 Mt); the leading mine producers in 2020 were China (4.2 Mt), Australia (1.4 Mt), and Peru (1.2 Mt)[2].

Table 20. Tin characteristics, applications, and recycling

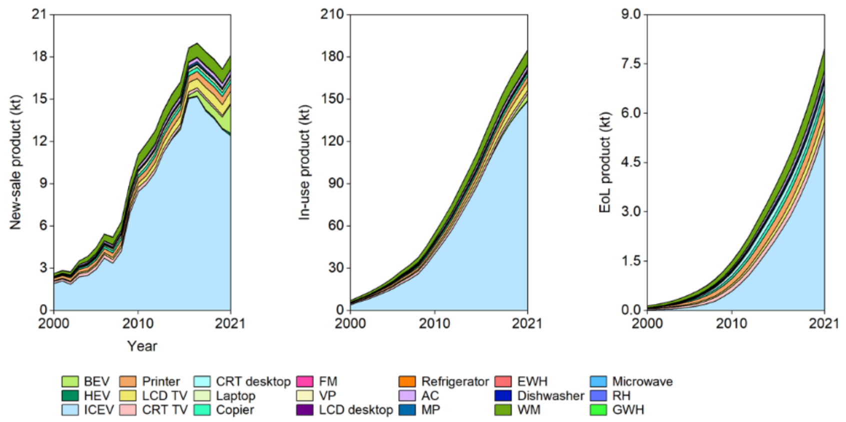
Characteristic	Tin (Sn) is a soft, pliable, silvery-white metal. Tin is not easily oxidized and resists corrosion because an oxide film protects it. Tin resists corrosion from distilled sea and soft tap water[37]. Atomic number: 50; relative atomic mass: 118.710; density: 7.287 g/cm^3; melting point: 232 °C (505 K)[38]
General application[63]	Tin takes a high polish and coats other metals to prevent corrosion, such as in tin cans, which are made of tin-coated steel. Alloys of tin are important for soft solder[64]. A niobium-tin alloy is used for superconducting magnets[65]. Tin(IV) oxide is used for ceramics and gas sensors. Zinc stannate is a fire-retardant used in plastics. Some tin compounds have been used as anti-fouling paint for ships and boats to prevent barnacles.
Use in automobiles and EEE	 Tin in the new-sale products increased from 2.6 kt to 18 kt in 2000−2021 (with a pick, 19 kt, in 2017). In this period, tin in in-use products increased 25 times to 185 kt in 2021, and it in EoL products increased 57 times to 8.0 kt. The most essential carriers include ICEV, HEV, TV, refrigerator, and recent BEV.
Recycling[66]	In 2020 the recycling input rate of tin was 33%. Recycled tin contributed 17% of total tin use, while reused or reformulated alloys made up the remaining portion. The recycling input rate has varied between 30−35% over the last decade, with dips generally corresponding to periods of low tin prices. Overall EoL recycling ratio (from all applications): 30−35%, 75%[25]
Occurrence in nature	Tin is primarily obtained from the mineral cassiterite and is extracted by roasting cassiterite in a furnace with carbon. It makes up only about 0.001% of the earth's crust[38]. However, tin concentrations are low even in the most tin-rich mining areas, which means that to mine 1 kg of cassiterite, as many as 7−8 t of ore must be mined[67]. The largest reserve holders are China (1.1 Mt), Indonesia (0.8 Mt), and the USA (0.4 Mt); the top three mine producers in 2020 were China (81 kt), Indonesia (66 kt), and Myanmar (33 kt)[2].

Table 21. Manganese characteristics, applications, and recycling

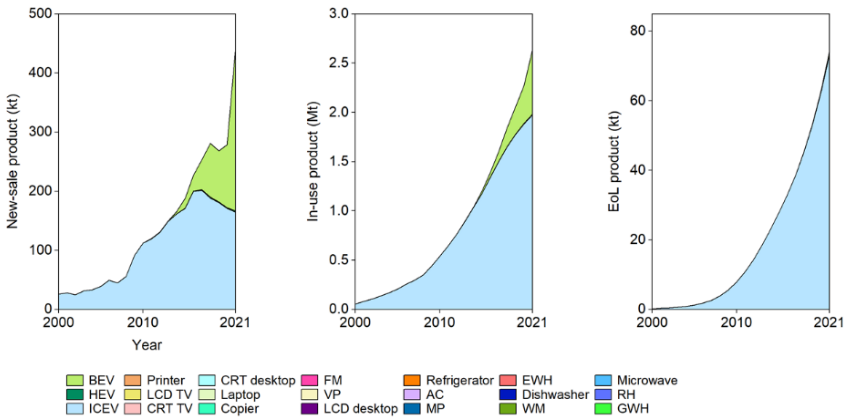
Characteristic	Manganese (Mn) is a pinkish-gray, chemically active element. It is a hard metal and is very brittle. Manganese is hard to melt, but easily oxidized[37]. Atomic number: 25; relative atomic mass: 54.938; density: 7.3 g/cm^3; melting point: 1,246 °C (1,519 K)[38]
General application[39]	Manganese is too brittle to be of much use as a pure metal. It is mainly used in alloys, such as steel. Steel contains about 1.2% manganese, to increase the strength and also improve workability and resistance to wear[68]. Manganese steel contains about 10−14% manganese. This is extremely strong and is used for railway tracks, safes, and rifle barrels[69].
Use in automobiles and EEE	 Manganese in the new-sale products increased from 26 kt to 442 kt in 2000−2021 (with a sharp increase from 2020). In this period, manganese in in-use products increased 49 times to 2.6 Mt in 2021, and it in EoL products soared to 74 kt. The most essential carriers include ICEV and recent BEV.
Recycling	Manganese is recycled into steel scrap and, to a lesser extent, into used aluminum beverage cans. The recycling rate is 37%, and efficiency is estimated at 53%[70]. Overall EoL recycling ratio (from all applications): 53%
Occurrence in nature	Most manganese is obtained from pyrolusite, although it is usually burned in a furnace with powdered aluminum or is treated with sulfuric acid to form manganese sulfate, which is then electrolyzed[38]. The top three reserve holders are South Africa (520 Mt), Brazil (270 Mt), and Australia (230 Mt); the top three mine producers in 2020 were South Africa (5.2 Mt), Australia (3.3 Mt), and Gabon (2.8 Mt). China's reserve is 54 Mt and mine production in 2020 was 1.3 Mt[2].

Table 22. Magnesium characteristics, applications, and recycling

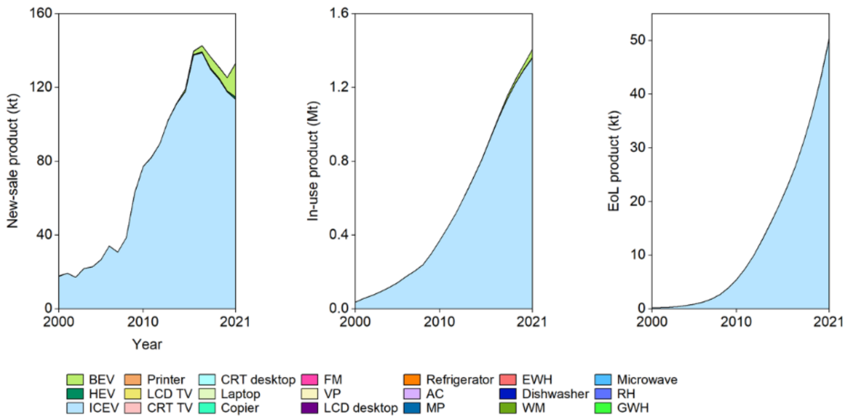
Characteristic	Magnesium (Mg) is silvery white and very light. Magnesium is very chemically active, it takes the place of hydrogen in boiling water, and many metals can be produced by the thermic reduction of its salts and oxidized forms with magnesium[37]. Atomic number: 12; relative atomic mass: 24.305; density: 1.74 g/cm^3 (known as a very lighter structural metal as about one-third of aluminum); melting point: 650 °C (923 K)[38]
General application[39]	Magnesium improves aluminum's mechanical, fabrication, and welding characteristics when used as an alloying agent. These alloys are helpful in airplane and automobile construction[71]. Magnesium is used in products that benefit from being lightweight, such as luggage, laptops, cameras, and power tools. Magnesium hydroxide is added to plastics to make them fire retardant[72].
Use in automobiles and EEE	 Magnesium in the new-sale products increased from 18 kt to 133 kt in 2000−2021 (with a pick, 143 kt, in 2017). In this period, magnesium in in-use products increased 38 times to 1.4 Mt in 2021, and it in EoL products soared to 51 kt. The most essential carriers are ICEV and BEV.
Recycling[29]	Recycling magnesium turnings and chips from machining of die castings is a common recycling process. Most recycling processes involve aqueous washing treatment combined with centrifugal force to remove machining lubricants and oils. The clean material is then pressed into briquettes which allow them to be used as a direct alloying material. "New scrap" recycling reduces the demand for primary material by up to 50%. Overall EoL recycling ratio (from all applications): 39%[25]
Occurrence in nature	Magnesium can be extracted from the minerals dolomite and carnallite, but is most often obtained from seawater[38]. Seawater contains about 0.13% magnesium, mainly in the form of dissolved chloride[73]. The largest reserve holders are Russia, China, and North Korea[43]; the leading smelter producers in 2020 were China (900 kt), Russia (60 kt), and Brazil and Israel (both have 20 kt)[2].

Table 23. Antimony characteristics, applications, and recycling

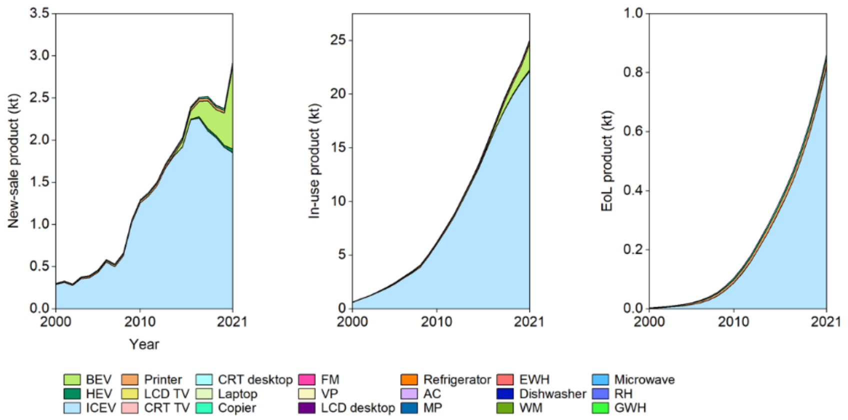
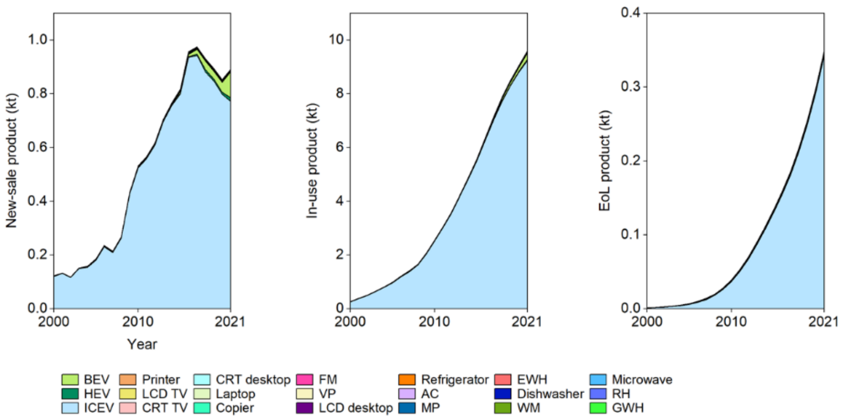
Characteristic	Antimony is a semimetallic chemical element that can exist in two forms: 1) the metallic form is bright, silvery, hard, and brittle; 2) the nonmetallic form is a grey powder. Antimony is a poor conductor of heat and electricity, stable in dry air, and unaffected by diluted acids and bases. Antimony and some of its alloys expand when cooled[37]. Atomic number: 51; relative atomic mass: 121.760; density: 6.685 g/cm^3; melting point: 631 °C (904 K)[38]
General application[39]	Antimony is used in the electronics industry to make semiconductors, such as infrared detectors and diodes. Antimony is alloyed with lead or other metals to improve their hardness and strength. A lead-antimony alloy is used in batteries. Other uses of antimony alloys include type metal (in printing presses) and cable sheathing[74]. Antimony compounds make flame-retardant materials, paints, enamels, glass, and pottery[75].
Use in automobiles and EEE	 Antimony in the new-sale products increased from 0.3 kt to 2.9 kt in 2000−2021. In this period, antimony in in-use products increased 40 times to 25 kt in 2021, and it in EoL products soared to 0.9 kt. The most essential carriers include ICEV and recent BEV.
Recycling[52]	Generally, the main EoL recycling option is from spent lead-acid batteries, where antimony is directly recovered as a lead-antimony alloy. Sufficient technologies are available to make antimony recycling a success, and current recycling rates of approximately 20%[76]. In addition, Umicore developed a process in which antimony is recovered from complex lead-bearing concentrates and various complex residues from the lead/copper/zinc industry. The antimony is extracted during the lead refining process in sodium antimonate. Overall EoL recycling ratio (from all applications): <5%, 20%, 89%[25]
Occurrence in nature	Antimony makes up about 0.00002% of the Earth's crust. It is most often found as antimony sulfide. Antimony is extracted by roasting the antimony sulfide to the oxide and then reducing it with carbon. Antimony can also be found as a native metal[38]. The largest reserve holders are China (480 kt), Russia (350 kt), and Bolivia (310 kt); the top three mine producers in 2020 were China (80 kt), Russia (30 kt), and Tajikistan (28 kt)[2].

Table 24. Bismuth characteristics, applications, and recycling

<table>
<tr><td>Characteristic</td><td>Bismuth is a white, crystalline, brittle metal with a pinkish tinge. It is the most diamagnetic of all metals, and its thermal conductivity is lower than any metal except mercury. Bismuth has a high electrical resistance. It is stable to oxygen and water[37].
Atomic number: 83; relative atomic mass: 208.980; density: 9.807 g/cm^3; melting point: 271 °C (545 K)[38]</td></tr>
<tr><td>General application[39]</td><td>Bismuth alloys with tin or cadmium have low melting points and are used in fire detectors and extinguishers, electric fuses, and solders[77]. Some bismuth compounds are also manufactured and used as pharmaceuticals, starting materials for synthetic fibers and rubbers, and yellow pigments for cosmetics and paints. Chemical manufacturing accounts for about half of bismuth consumption, and metallurgical additives are about 30%[78].</td></tr>
<tr><td>Use in automobiles and EEE</td><td>

Bismuth in the new-sale products increased from 122 t to 891 t in 2000−2021 (with a pick, 975 kt, in 2017). In this period, bismuth in in-use products increased 37 times to 9.6 Mt in 2021, and it in EoL products soared to 350 t. The most essential carriers are ICEV and BEV.</td></tr>
<tr><td>Recycling[52]</td><td>Bismuth is challenging to recycle because it is used in many dissipative applications. It is obtained from the lead, copper, tin, silver, and gold refining process. For example, at Umicore's integrated smelter, bismuth is recovered from lead ingots from the lead blast furnace. Hydrometallurgical recovery of bismuth from copper smelter converter dust has been trialed as a potential secondary source of bismuth recently (up to 92% recovery efficacy)[79].
Overall EoL recycling ratio (from all applications): <1%[25], 92%</td></tr>
<tr><td>Occurrence in nature</td><td>Bismuth does occur freely in nature, such as bismuthinite and bismite. The major commercial bismuth source is a by-product of refining lead, copper, tin, silver, and gold ores[38]. The largest reserve holders are China, Peru, and Mexico[43]; the top three refinery producers in 2020 were China (14 kt), Laos (1,000 t), and South Korea (830 t)[2].</td></tr>
</table>

Table 25. Tungsten characteristics, applications, and recycling

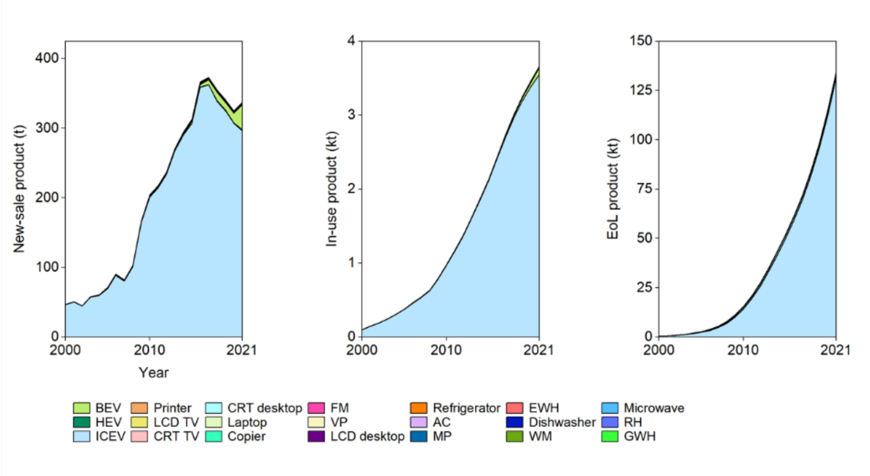
Characteristic	Tungsten (W), also called wolfram, is a lustrous and silvery white metal. The bulk metal resists attack by oxygen, acids and alkalis. Tungsten has the highest melting point of any metal[37]. Atomic number: 74; relative atomic mass: 183.84; density: 19.3 g/cm^3; melting point: 3,422 °C (3,695 K, highest melting point in metals)[38]
General application[39]	Tungsten was used extensively for the filaments of old-style incandescent light bulbs, but these have been phased out in many countries. This is because they are not very energy efficient. Tungsten carbide is tough and is very important to the metal-working, mining, and petroleum industries. Calcium and magnesium tungstate are widely used in fluorescent lighting[80].
Use in automobiles and EEE	 Tungsten in the new-sale products increased from 47 t to 337 t in 2000−2021 (with a pick, 373 kt, in 2017). In this period, tungsten in in-use products increased 37 times to 3.7 kt in 2021, and it in EoL products soared to 135 t. The most essential carriers are ICEV and BEV.
Recycling[52]	The tungsten processing industry can treat almost every kind of tungsten-containing scrap and waste to recover tungsten. Cemented carbide scrap, turnings, grinding, and powder scrap from the tooling industry are oxidized and chemically processed[81]. Overall EoL recycling ratio (from all applications): 10−25%, 66%[25]
Occurrence in nature	Tungsten is primarily obtained from wolframite and scheelite. The Earth's crust, by far the most significant source of tungsten in the ecosphere, is estimated to contain 0.00013% tungsten on a mass basis[82]. The metal is obtained commercially by reducing tungsten oxide with hydrogen or carbon[38]. The largest reserve holders are China (1.9 Mt), Russia (400 kt), and Vietnam (95 kt); the leading mine producers in 2020 were China (69 kt), Vietnam (43 kt), and Russia (22 kt)[2].

Table 26. Niobium characteristics, applications, and recycling

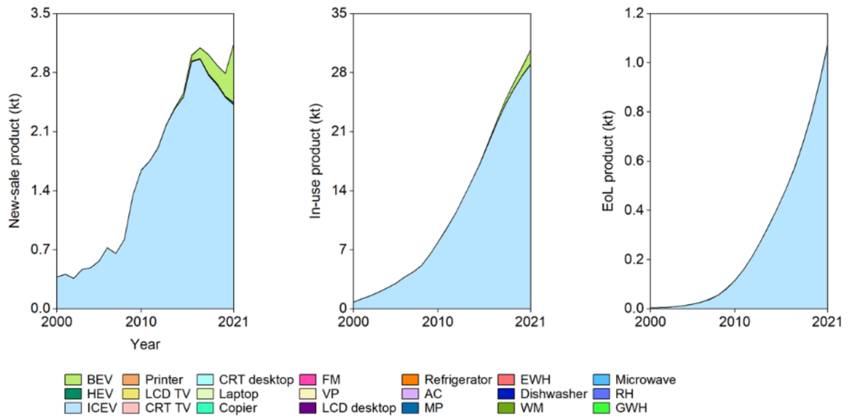
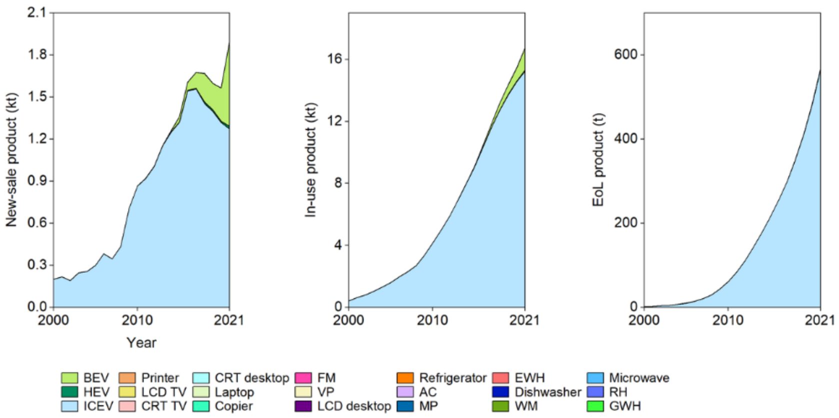
Characteristic	Niobium (Nb) is a rare, soft, malleable, ductile, gray-white metal. Its physical and chemical properties resemble tantalum. Niobium metal is inert to acids, even to aqua regia at room temperatures, but is attacked by hot, concentrated acids, especially by alkalis and oxidizing agents[37]. Niobium becomes a superconductor at low temperatures[83]. Atomic number: 41; relative atomic mass: 92.906; density: 8.57 g/cm^3; melting point: 2,477 °C (2,750 K)[38]
General application[39]	Alloys containing niobium are used in jet engines and rockets, beams and girders for buildings and oil rigs, and oil and gas pipelines. Niobium is used in superconducting magnets for particle accelerators, magnetic resonance imaging scanners, and nuclear magnetic resonance equipment. Niobium can be used to make electron tubes and other electronic vacuum devices[84].
Use in automobiles and EEE	 Niobium in the new-sale products increased from 378 t to 3.1 kt in 2000−2021. In this period, tungsten in in-use products increased 39 times to 31 kt in 2021, and it in EoL products soared to 1.1 kt. The most essential carriers are ICEV and BEV.
Recycling	Niobium scrap from aerospace, manufacturing, and electronics can be recycled. Such waste includes alloy waste, solids, turnings, powders, regrind, tailings, and sludge[85]. Overall EoL recycling ratio (from all applications): 50%, 56%[25]
Occurrence in nature	Niobium is primarily obtained from the minerals columbite and pyrochlore. It is a rare element containing 0.0008% in the earth's crust[86]. These minerals also contain tantalum, and the two elements are mined together. Some niobium is also produced as a by-product of tin extraction.[38] The top two reserve holders are Brazil (16 Mt) and Canada (1.6 Mt); the top two mine producers in 2020 were Brazil (71 kt) and Canada (6.2 kt)[2]. China lacks niobium ore resources.

Table 27. Vanadium characteristics, applications, and recycling

<table>
<tr><td>Characteristic</td><td>Vanadium (V) is a rare, hard, ductile gray-white element found combined in certain minerals and used mainly to produce certain alloys. Vanadium resists corrosion due to a protective film of oxide on the surface[37]. The metal oxidizes in air at around 660 °C to the pentoxide[87].
Atomic number: 23; relative atomic mass: 50.942; density: 6.0 g/cm^3; melting point: 1,910 °C (2,183 K)[38]</td></tr>
<tr><td>General application[39]</td><td>About 80−85% of the vanadium produced is used as a steel additive. Vanadium-steel alloys are very tough and are used for armor plates, axles, tools, piston rods, and crankshafts. Less than 1% of vanadium makes steel shock-resistant and vibration-resistant[88]. Vanadium(V) oxide is used as a pigment for ceramics and glass, as a catalyst, and in producing superconducting magnets[89].</td></tr>
<tr><td>Use in automobiles and EEE</td><td>

Vanadium in the new-sale products increased from 199 t to 1.9 kt in 2000−2021. In this period, vanadium in in-use products increased 41 times to 17 kt in 2021, and it in EoL products soared to 568 t. The most essential carriers are ICEV and BEV.</td></tr>
<tr><td>Recycling[90]</td><td>The use of vanadium in steel is almost completely dissipated because vanadium recovery from scrap steel is chemically hindered under the oxidizing conditions of steelmaking furnaces. The most significant recoveries of vanadium are in the vanadium market's superalloys, other alloys, and catalyst segments.
Overall EoL recycling ratio (from all applications): <1%[25]</td></tr>
<tr><td>Occurrence in nature</td><td>Vanadium is found in about 65 different minerals including vanadinite, carnotite, and patronite. It is also found in phosphate rock, certain iron ores, and some crude oils in the form of organic complexes. Vanadium metal is obtained by reducing vanadium(V) oxide with calcium in a pressure vessel. Vanadium of high purity can be obtained by reducing vanadium(III) chloride with magnesium[39]. The largest reserve holders are China (9.6 Mt), Russia (5.0 Mt), and Australia (4.0 Mt); the leading mine producers in 2020 were China (53 kt), Russia (18 kt), and South Africa (8.2 kt)[2].</td></tr>
</table>

Table 28. Molybdenum characteristics, applications, and recycling

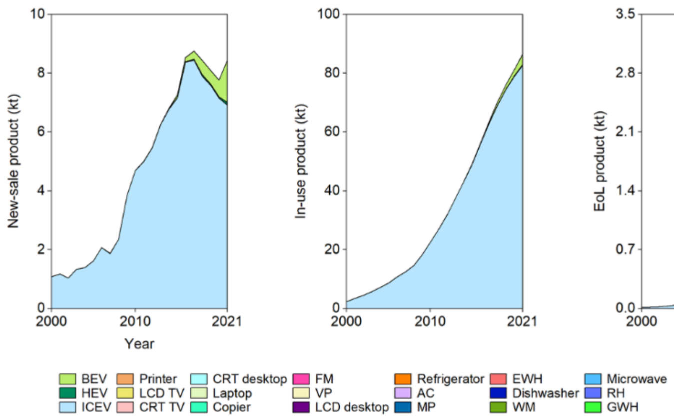
Characteristic	Molybdenum (Mo) metal is silvery white, very hard transition metal. It has a high elastic modulus. Molybdenum has one of the highest melting points of all pure elements[91]. It is attacked slowly by acids[37]. Atomic number: 42; relative atomic mass: 55.95; density: 10.2 g/cm^3; melting point: 2,623 °C (2,896 K)[38]
General application[39]	Most molybdenum is used to make alloys. It is used in steel alloys to increase strength, hardness, electrical conductivity and resistance to corrosion and wear. These moly steel alloys are used in parts of automobile engines[92]. Other alloys are used in heating elements, drills and saw blades. Other uses for molybdenum include catalysts for the petroleum industry, inks for circuit boards, pigments and electrodes[93].
Use in automobiles and EEE	 Molybdenum in the new-sale products increased from 1.1 kt to 8.5 kt in 2000−2021. In this period, molybdenum in in-use products increased 39 times to 87 kt in 2021, and it in EoL products soared to 3.1 kt. The most essential carriers are ICEV and BEV.
Recycling[94]	Molybdenum comes from two sources: 1) mining and 2) recycling. The molybdenum unit returns to the furnace, where it is smelted into steel along with the raw molybdenum and other raw materials. Overall EoL recycling ratio (from all applications): 30%[25]
Occurrence in nature	Most molybdenum is obtained from molybdenite, wulfenite and powellite. These ores typically occur in conjunction with ores of tin and tungsten. Molybdenum is also obtained as a by-product of mining and processing tungsten and copper[38]. The largest reserve holders are China (8.3 Mt), Peru (2.8 Mt), and the USA (2.7 Mt); the top three mine producers in 2020 were China (120 kt), Chile (58 kt), and the USA (49 kt)[2].

Table 29. Gallium characteristics, applications, and recycling

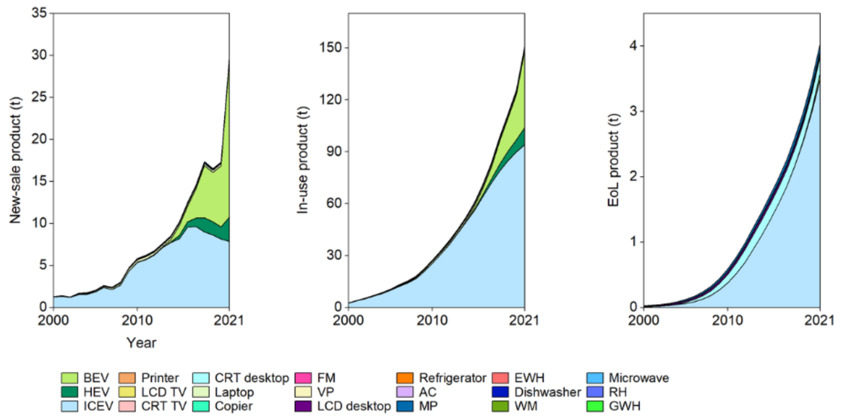
Characteristic	Solid gallium (Ga) is a blue-gray metal, and very pure gallium has a stunning silvery color. Gallium is solid at normal room temperatures, but it becomes liquid when heated slightly. Liquid gallium expands by 3.1% when frozen[95]. Solid gallium is soft enough to be cut with a knife. It is stable in air and water[37]. Atomic number: 31; relative atomic mass: 69.723; density: 5.91 g/cm^3; melting point: 29.76 °C (302,91 K)[38]
General application[39]	Gallium arsenide is an essential component of many semiconductors. It is also used in red light-emitting diodes because it converts electricity to light. Gallium nitride is also a semiconductor. It has important uses in Blu-ray technology, mobile phones, blue and green light-emitting diodes, and pressure sensors for touch switches[96]. Gallium readily alloys with most metals.
Use in automobiles and EEE	 Gallium in the new-sale products increased from 1.3 t to 30 t in 2000−2021 (with a sharp increase from 2020). In this period, gallium in in-use products increased 54 times to 152 t in 2021, and it in EoL products soared to 4.0 t. The most essential carriers include ICEV, HEV, and recent BEV.
Recycling[52]	EoL recycling is challenging due to the dissipative use of gallium. Much of the recovered gallium comes from gallium production residues from epitaxial processes used to make semiconductors. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature	Trace amounts of gallium are found in diaspore, sphalerite, germanite, and bauxite, as well as in the by-products of burning coal. It is mainly produced as a by-product of zinc refining. The metal can be obtained by electrolysis of a gallium(III) hydroxide solution in potassium hydroxide[38]. The largest reserve holders are China, Germany, and Kazakhstan[43]; the leading primary producers in 2020 were China (290 t), Russia (4.0 t), and Japan and South Korea (both have 3.0 t)[2].

Table 30. Germanium characteristics, applications, and recycling

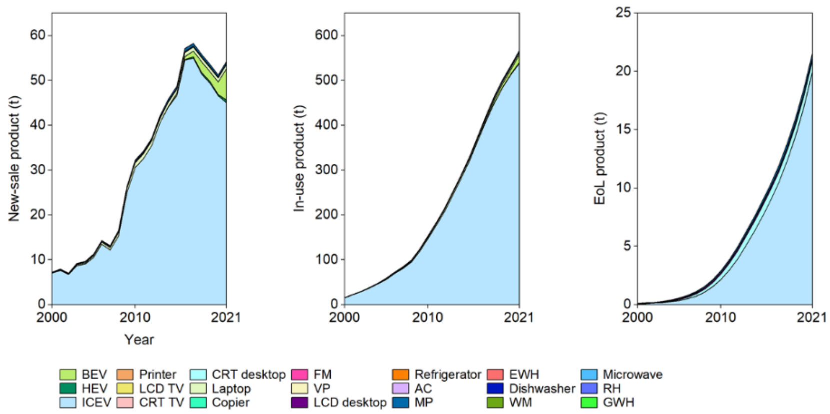
Characteristic	Pure germanium (Ge) is a hard, lustrous, gray-white, brittle metalloid. Germanium is stable in air and water and is unaffected by alkalis and acids, except nitric acid[97]. Atomic number: 32; relative atomic mass: 72.630; density: 5.323 g/cm^3; melting point: 938 °C (1,211 K)[38]
General application[39]	Germanium is a semiconductor. The pure element was commonly doped with arsenic, gallium, or other elements and used as a transistor in thousands of electronic applications. However, other semiconductors have replaced it today[98]. Germanium oxide has a high index of refraction and dispersion. This makes it suitable for wide-angle camera lenses and objective lenses for microscopes. This is now the major use for this element. Germanium is also used as an alloying agent, in fluorescent lamps, and as a catalyst[52].
Use in automobiles and EEE	 Germanium in the new-sale products increased from 7.2 t to 54 t in 2000−2021 (with a pick, 58 t, in 2017). In this period, germanium in in-use products increased 37 times to 567 t in 2021, and it in EoL products soared to 22 t. The most essential carriers are ICEV and BEV.
Recycling[99]	Globally, about 30% of the total germanium consumed is produced from recycled materials. During the manufacture of most optical devices, more than 60% of the germanium metal used is routinely recycled as new scrap. Overall EoL recycling ratio (from all applications): <1%, 76%[25]
Occurrence in nature	Germanium ores are very rare and are found in small quantities as the minerals germanite and argyrodite. Commercial production of germanium is carried out by processing zinc smelter flue dust. It can also be recovered from the by-products of the combustion of coals[38]. The largest reserve holders are China, Russia, and Germany (likely)[43]; the top two primary producers in 2020 were China (86 t) and Russia (5.0 t)[2].

Table 31. Tantalum characteristics, applications, and recycling

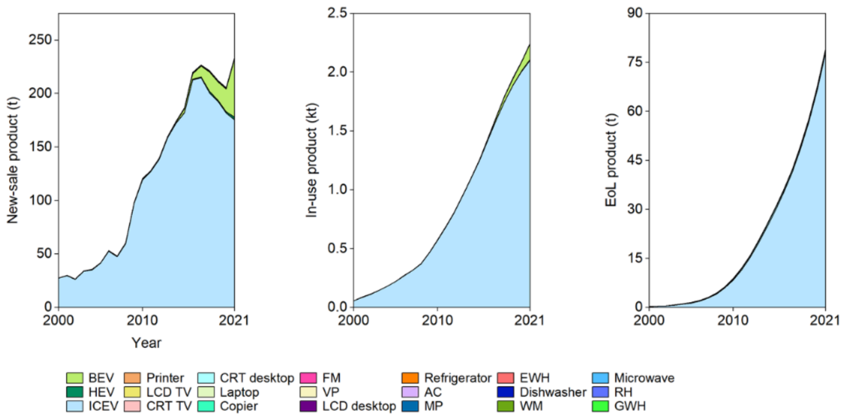
Characteristic	Tantalum (Ta) is a shiny, silvery metal that is soft. When pure, it is almost immune to chemical attack at temperatures below 150 C. Tantalum is virtually resistant to corrosion due to an oxide film on its surface[37]. Atomic number: 73; relative atomic mass: 180.948; density: 16.4 g/cm^3; melting point: 3,017 °C (3,290 K) [38]
General application[39]	Tantalum can be used to coat other metals with a very thin layer, and a high capacitance can be achieved in a small volume. This makes tantalum capacitors attractive for portable electronics such as mobile phones[100]. It is very resistant to corrosion and is used in equipment for handling corrosive materials. It has also found uses as electrodes for neon lights, rectifiers, and in glass for special lenses. Tantalum alloys can be extremely strong and have been used for turbine blades, rocket nozzles, and nose caps for supersonic aircraft[101].
Use in automobiles and EEE	 Tantalum in the new-sale products increased from 28 t to 234 t in 2000−2021. In this period, tantalum in in-use products increased 39 times to 2.3 kt in 2021, and it in EoL products soared to 79 t. The most essential carriers are ICEV and BEV.
Recycling[52]	Tantalum is recovered from slags resulting from the smelting of tin. It is also recovered from powder sweepings, wire scrap of capacitor manufacturing, and EoL capacitors. Overall EoL recycling ratio (from all applications): <1%, 35%[25]
Occurrence in nature	Tantalum is primarily obtained from the minerals columbite, tantalite, and euxenite. There are several complicated steps involved in separating the tantalum from the niobium. A lot of tantalum is obtained commercially as a by-product of tin extraction[39]. The top two reserve holders are Australia (99 kt) and Brazil (40 kt); the leading mine producers in 2020 were Congo (670 t), Brazil (370 t), and Rwanda (270t). China produced 70 t mine in 2020[2].

Table 32. Titanium characteristics, applications, and recycling

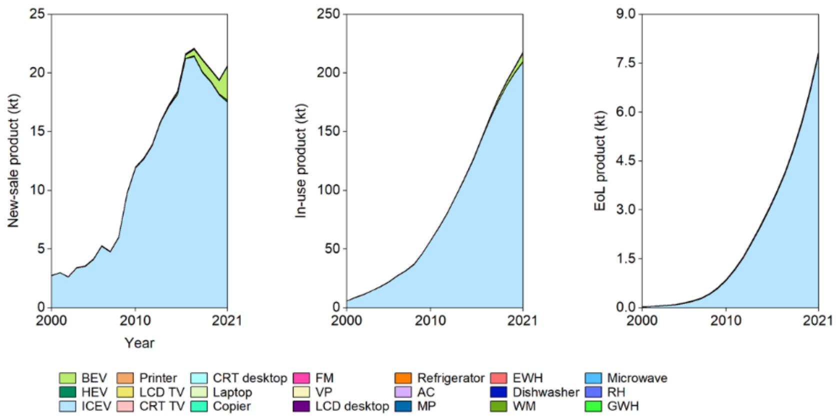
Characteristic	Titanium (Ti) is a transition metal light with a white-silvery-metallic colour. It is strong, lustrous, corrosion-resistant. Pure titanium is not soluble in water but is soluble in concentrated acids. This metal forms a passive but protective oxide coating when exposed to elevated temperatures in air. Titanium is not easily attacked by seawater[37]. Atomic number: 22; relative atomic mass: 47.867; density: 4.5 g/cm^3; melting point: 1,668 °C (1,941 K)[38]
General application[39]	Titanium alloys are mainly used in aircraft, spacecraft, and missiles because of their low density and ability to withstand extremes of temperature. They are also used in golf clubs, laptops, bicycles, and crutches. Power plant condensers use titanium pipes because of their resistance to corrosion[102]. It is used in desalination plants and to protect the hulls of ships, submarines, and other structures exposed to seawater. The largest use of titanium is in the form of titanium(IV) oxide. It is extensively used as a pigment in house paint, artists' paint, plastics, enamels, and paper[103].
Use in automobiles and EEE	 Titanium in the new-sale products increased from 2.8 kt to 21 kt in 2000−2021 (with a pick, 22 kt, in 2017). In this period, titanium in in-use products increased 38 times to 218 kt in 2021, and it in EoL products soared to 7.9 kt. The most essential carriers are ICEV.
Recycling[104]	Titanium is primarily recovered using a process called vacuum arc remelting. Since metals cannot be smelted in open-air furnaces, this method is used instead. Another emerging process, known as cold furnace smelting, is considered more economical, reducing titanium recovery costs. Overall EoL recycling ratio (from all applications): 91%[25]
Occurrence in nature	Titanium is the ninth most abundant element in the Earth's crust (0.57%). It occurs in the minerals: ilmenite, rutile, and sphene and is present in titanates and many iron ores. Titanium is produced commercially by reducing titanium(IV) chloride with magnesium[38]. The largest reserve holders (ilmenite) are China (230 kt), Australia (150 kt), and India (85 kt); the leading ilmenite mine producers in 2020 were China (2.3 kt), South Africa (1000 t), and Australia (800 t)[2].

Table 33. Beryllium characteristics, applications, and recycling

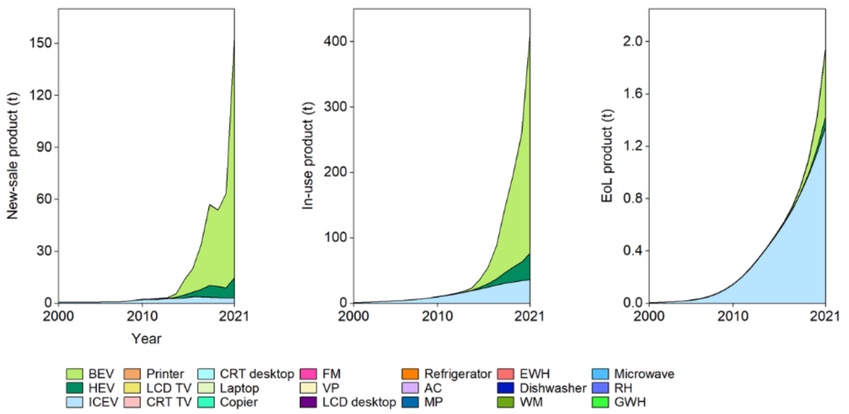
Characteristic	Beryllium (Be) is a toxic bivalent element, steel gray, strong, light-weight, primarily used as a hardening agent in alloys. Beryllium has one of the highest melting points of light metals. It has excellent thermal conductivity, is nonmagnetic, it resists attack by concentrated nitric acid[37]. The elastic modulus of beryllium is about 50% larger than that of steel[105]. Atomic number: 4; relative atomic mass: 9.012; density: 1.85 g/cm^3; melting point: 1,287 °C (1,560 K)[38]
General application[39]	Beryllium is used in alloys with copper or nickel to make gyroscopes, springs, electrical contacts, spot-welding electrodes, and non-sparking tools. Mixing beryllium with these metals increases their electrical and thermal conductivity[106]. Other beryllium alloys are used as structural materials for high-speed aircraft, missiles, spacecraft, and communication satellites[107].
Use in automobiles and EEE	 Beryllium in the new-sale products increased from 477 kg to 155 t in 2000−2021 (with a sharp increase from 2020). In this period, beryllium in in-use products soared to 413 t in 2021, and it in EoL products soared to 2.0 t. The most essential carriers include BEV and HEV.
Recycling[108]	Recycling, mainly from waste generated during the manufacture of beryllium products, can account for up to 10% of apparent consumption. However, due to small component size, separation difficulties, low overall beryllium content per device, and low beryllium content in copper beryllium alloys, recycling EoL products is difficult. Overall EoL recycling ratio (from all applications): <1%, 7%[25]
Occurrence in nature	Beryllium is found in about 30 different mineral species. The most important are beryl and bertrandite. The metal is usually prepared by reducing beryllium fluoride with magnesium metal[39]. The top reserve holder is likely to be the USA[43]; the leading mine producers in 2020 were the USA (150 t), China (70 t), and Mozambique (15 t)[2].

Table 34. Thallium characteristics, applications, and recycling

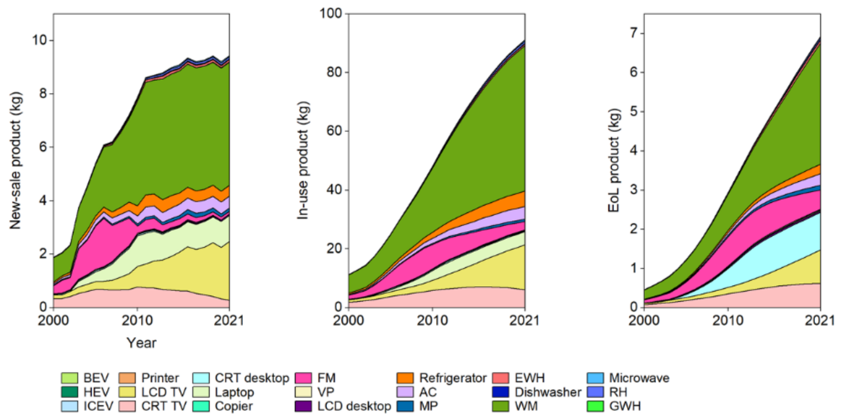
Characteristic	Thallium (Tl) exhibits a metallic luster when freshly exposed to air, but soon develops a blueish-grey tinge. A heavy oxide builds up on thallium if left in the air, and the hydroxide is formed in the presence of water. The metal is very soft and malleable. It can be cut with a knife[109]. Atomic number: 81; relative atomic mass: 204.383; density: 11.8 g/cm^3; melting point: 304 °C (577 K)[38]
General application[39]	The use of thallium is limited as it is a toxic element. Most thallium is used by the electronics industry in photoelectric cells[110]. Thallium oxide is used to produce special glass with a high index of refraction[111].
Use in automobiles and EEE	 Thallium in the new-sale products increased from 1.9 kg to 9.4 kg in 2000−2021. In this period, thallium in in-use products increased 8 times to 91 kg in 2021, and it in EoL products increased 15 times to 6.9 kg. Essential carriers are HEV, LCD TV, laptop, etc.
Recycling	Thallium recycling is currently difficult and challenging[112]. Overall EoL recycling ratio (from all applications): 0%[25]
Occurrence in nature	Thallium is found in the minerals crooksite, lorandite, and hutchinsonite, but is usually obtained as a byproduct of the production of sulfuric acid or as a byproduct of refining zinc or lead. Thallium is also present in manganese nodules found on the ocean floor[113]. Quantitative estimates of thallium reserves are not available[2].

Table 35. Indium characteristics, applications, and recycling

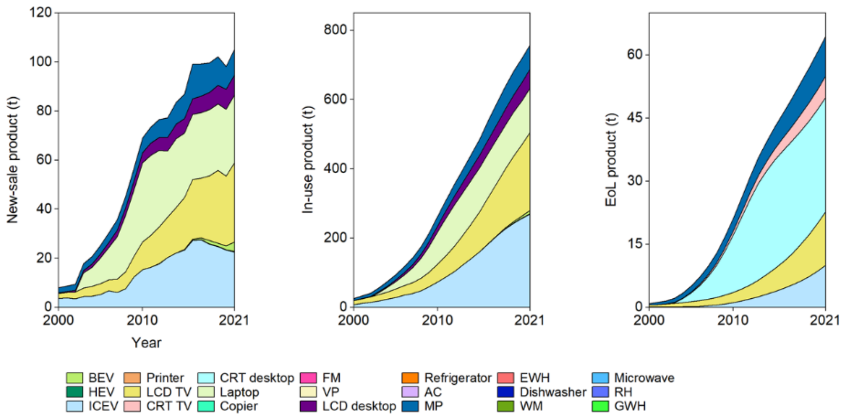
Characteristic	Indium (In) is a soft, ductile, malleable, lustrous metallic metal. Its color is silvery white. Indium is liquid over a wide range of temperatures, like gallium, that belongs to its same group. Indium is stable in air and water but dissolves in acids. Below the critical temperature of 3.41 K, indium becomes a superconductor[114]. Atomic number: 49; relative atomic mass: 114.818; density: 7.31 g/cm^3; melting point: 157 °C (430 K)[38]
General application[39]	Most indium (364 t of 662 t in 2011[115]) is used to make indium tin oxide, which is an important part of touch screens, flatscreen TVs, and solar panels. This is because it conducts electricity, bonds strongly to glass, and is transparent. Indium nitride, phosphide, and antimonide are semiconductors used in transistors and microchips[116].
Use in automobiles and EEE	 Indium in the new-sale products increased from 7.9 t to 105 t in 2000−2021. In this period, indium in in-use products increased 30 times to 758 t in 2021, and it in EoL products increased 74 times to 64 t. Essential carriers are ICEV, LCD TV, laptop, LCD desktop, and MP.
Recycling[52]	Indium recovery from spent indium tin oxide targets for conductive coatings. Recycling indium from dissipative applications such as flat panel displays and photovoltaics remains a very challenging process, especially in terms of economics. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature	Indium is one of the minor abundant minerals on Earth. It has been found uncombined in nature but is typically associated with zinc minerals and iron, lead, and copper ores. It is commercially produced as a by-product of zinc refining[39]. The leading refinery producers in 2020 were China (500 t), South Korea (200 t), Japan (65 t), and Canada and France (both have 50 t). Quantitative estimates of thallium reserves are not available[2].

Table 36. Nickel characteristics, applications, and recycling

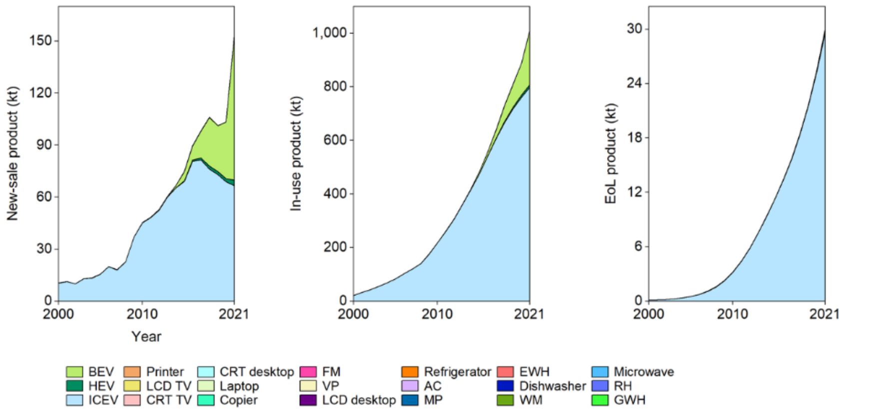
Characteristic	Nickel (Ni) is silvery-white. hard, malleable, and ductile metal. It is a fairly good conductor of heat and electricity. It also forms several complex compounds. Most nickel compounds are blue or green. Metallic nickel, nickel sulfide and nickel oxide are poorly soluble in water compared to soluble nickel salts (chloride, nitrate, sulfate)[117]. Atomic number: 28; relative atomic mass: 58.693; density: 8.912 g/cm^3; melting point: 1,455 °C (1,728 K)[38]
General application[39]	Nickel has a long history of being used in coins. Today, nickel is mainly used in making alloys such as stainless steel. Nickel is used in batteries, including rechargeable nickel-cadmium batteries and nickel-metal hydride batteries used in HEVs[118].
Use in automobiles and EEE	 Nickel in the new-sale products increased from 14 kt to 154 kt in 2000−2021 (with a sharp increase from 2020). In this period, nickel in in-use products increased 47 times to 1010 kt in 2021, and it in EoL products soared to 30 kt. The most essential carriers include BEV and HEV.
Recycling[119]	Nowadays, 57% of discarded nickel is recycled within the nickel and stainless steel industries, and 14% is lost to other metal markets where nickel is an unwanted constituent of carbon steel and copper alloy scrap. Overall EoL recycling ratio (from all applications): 57%, 58−63%[25]
Occurrence in nature	Most nickel is extracted from the mineral pentlandite. The large nickel deposit is believed to be the result of an ancient meteorite impact[120]. The largest reserve holders are Indonesia (21 Mt), Australia (20 Mt), and Brazil (16 Mt); the leading mine producers in 2020 were Indonesia (760 kt), Philippines (320 kt), and Russia (280 kt)[2].

Table 37. Lithium characteristics, applications, and recycling

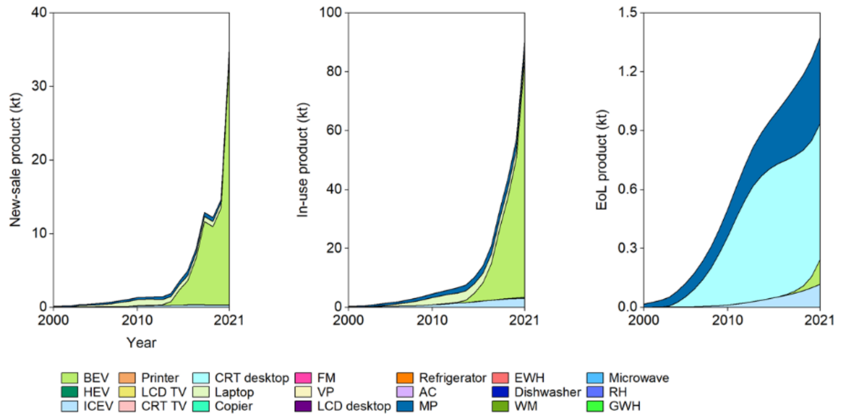
Characteristic	Lithium is the lightest solid metal, soft, silvery-white, low melting point, and reactive. Metallic lithium's reaction with water is extremely vigorous. It has the lowest density of all solid elements at room temperature[121]. Atomic number: 3; relative atomic mass: 6.941; density: 0.534 g/cm^3; melting point: 181 °C (454 K)[38]
General application[39]	The most important use of lithium is in rechargeable batteries for mobile phones, laptops, digital cameras, and EVs[122]. Lithium is also used in some non-rechargeable batteries for things like toys and clocks. A magnesium-lithium alloy is used for armor plating. Aluminum-lithium alloys are used in aircraft, bicycle frames, and high-speed trains[123]. Lithium oxide is used in special glasses and glass ceramics. Lithium hydride is used as a means of storing hydrogen for use as a fuel[124].
Use in automobiles and EEE	 Lithium in the new-sale products increased from 136 t to 36 kt in 2000−2021 (with a sharp increase from 2020). In this period, lithium in in-use products soared to 91 kt in 2021, and it in EoL products increased 82 times to 1.4 kt. The most essential carriers include BEV, MP, and computers.
Recycling[52]	Due to the abundance of lithium in nature, lithium recovery has not been a priority for many players in the lithium-ion battery, glass, or ceramic industries. The recent surge in demand for lithium from electric vehicles has highlighted the importance of recycling, as both pyrometallurgical and hydrometallurgical processes can now recover lithium from lithium-ion battery waste. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature	Lithium is not found free in nature and makes up only 0.0007% of the Earth's crust. Today, larger amounts of metal are obtained through lithium chloride electrolysis[38]. The largest holders are Chile (9.2 Mt), Australia (4.7 Mt), Argentina (1.9 Mt), and China (1.5); the leading mine producers in 2020 were Australia (40 kt), Chile (18 kt), China (14 kt), and Argentina (6.2 kt)[2].

Table 38. Cobalt characteristics, applications, and recycling

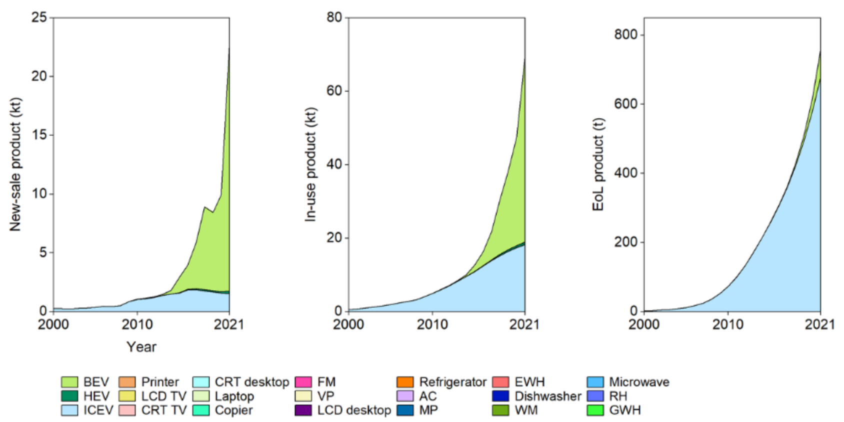
Characteristic	Cobalt (Co) is a hard ferromagnetic, silver-white, hard, lustrous, brittle element. Cobalt is active chemically, forming many compounds. Cobalt is stable in the air and unaffected by water but is slowly attacked by dilute acids. Like iron, cobalt can be magnetized, and it has a relative permeability of two-thirds that of iron[125]. Atomic number: 27; relative atomic mass: 58.933; density: 8.68 g/cm^3; melting point: 1,495 °C (1,768 K)[38]
General application[39]	Cobalt is alloyed with aluminum and nickel to make particularly powerful magnets[126]. Other alloys of cobalt are used in jet turbines and gas turbine generators, where high-temperature strength is important. Cobalt metal is sometimes used in electroplating because of its attractive appearance, hardness, and resistance to corrosion[127].
Use in automobiles and EEE	 Cobalt in the new-sale products increased from 238 t to 23 kt in 2000−2021 (with a sharp increase from 2020). In this period, cobalt in in-use products soared to 70 kt in 2021, and it in EoL products increased 82 times to 758 t. The most essential carriers include ICEV and BEV.
Recycling[52]	Most cobalt is recovered from manufacturers' production processes for applications such as cemented carbide and cemented carbide tools or rechargeable lithium-ion batteries. Cobalt can also be retrieved from end-of-life products such as spent rechargeable batteries, petrochemical catalysts, and alloys used in aerospace applications. Overall EoL recycling ratio (from all applications): 68%[25]
Occurrence in nature	Cobalt's primary ores are cobaltite and erythrite. Cobalt is usually recovered as a by-product of mining and refining nickel, silver, lead, copper, and iron[38]. The largest reserve holders are Congo (3.6 Mt), Australia (1.4 Mt), and Cuba (500 kt); the leading mine producers in 2020 were Congo (95 kt), Russia (6.3 kt), and Australia (5.7 kt). Reserve and production in China were 80 kt and 2.3 kt in 2020[2].

Table 39. Lead characteristics, applications, and recycling

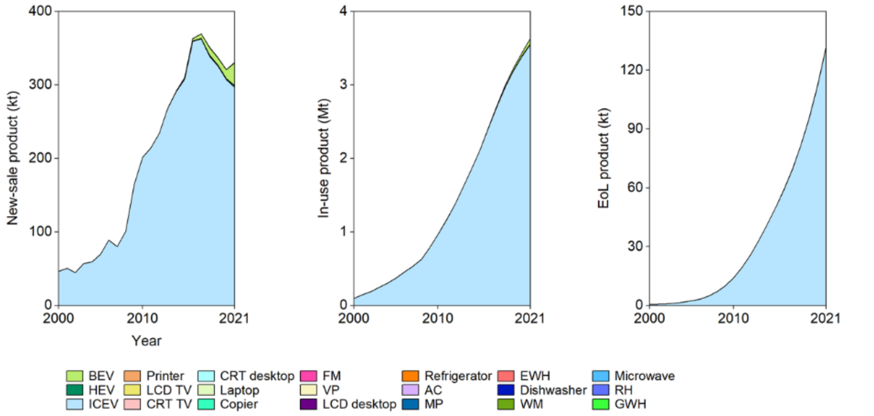
Characteristic	Lead (Pb) is soft and malleable and has a relatively low melting point. When freshly cut, lead is silvery with a hint of blue; it tarnishes to a dull gray color when exposed to air. The properties of lead include high density, flexibility, ductility, and high corrosion resistance due to passivation[128]. Atomic number: 82; relative atomic mass: 207.2; density: 11.342 g/cm^3; melting point: 327 °C (601 K)[38]
General application[39]	Lead is commonly used in automobile batteries, paint, ammunition, cable sheathing, weightlifting, diving weight belts, lead crystal glass, radiation shields, and some plumb bobs[129]. It is also sometimes used in architecture, roofing, and stained glass windows[130].
Use in automobiles and EEE	 Lead in the new-sale products increased from 46 kt to 331 kt in 2000−2021 (with a pick, 369 kt, in 2017). In this period, lead in in-use products increased 38 times to 3.6 Mt in 2021, and it in EoL products soared to 132 kt. The most essential carriers are ICEV and BEV.
Recycling[131]	Lead-acid batteries are the most recycled consumer product in the world. Over 99% of lead-acid batteries are recycled, even more than any other common daily waste (e.g., tires, paper, aluminum cans, glass). Some lead products are not recycled, either because it is not currently economical or because it is not practical at all. Overall EoL recycling ratio (from all applications): 52%, 68%, 95%, 99%[25]
Occurrence in nature	Lead is sometimes found free in nature but is usually obtained from the ores galena, anglesite, and cerussite. Although lead makes up only about 0.0013% of the earth's crust, it is not considered to be a rare element since it is easily mined and refined. Most lead is obtained by roasting galena in hot air, although nearly one-third of the lead used is obtained through recycling efforts[38]. The top three reserve holders are Australia (36 Mt), China (18 Mt) and Peru (6 Mt); the top three mine producers in 2020 were China (1.9 Mt), Australia (480 kt), and the USA (290 kt)[2].

Table 40. Silver characteristics, applications, and recycling

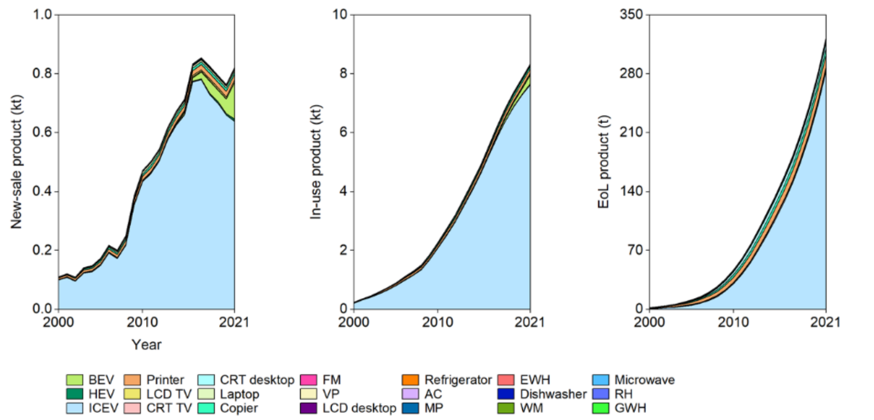
Characteristic	Pure silver (Ag) is nearly white, lustrous, soft, ductile, and malleable. It is an excellent conductor of heat and electricity. It is not a chemically active metal but is attacked by nitric acid (forming the nitrate) and hot concentrated sulfuric acid. It has the highest electrical conductivity of all metals, but its greater cost has prevented it from being widely used for electrical purposes. Silver is stable in water[132]. Atomic number: 47; relative atomic mass: 107.868; density: 10.501 g/cm^3; melting point: 962 °C (1,235 K)[38]
General application[39]	Sterling silver contains 92.5% silver[133]. It is used for jewelry and silver tableware, where appearance is important. Silver is used to making mirrors, as it is the best reflector of visible light known, although it does tarnish with time. It is also used in dental alloys, solder and brazing alloys, electrical contacts, and batteries. Silver paints are used for making printed circuits[134].
Use in automobiles and EEE	 Silver in the new-sale products increased from 111 t to 0.8 kt in 2000−2021 (with a pick, 0.9 kt, in 2017). In this period, silver in in-use products increased 35 times to 8.4 Mt in 2021, and it in EoL products soared to 323 t. The most essential carriers are ICEV, BEV, and etc.
Recycling	Silver is extracted from the tailings of copper, nickel, and lead refining processes because it is mainly present in the ore body along with these metals. Silver can also be recovered from jewelry, industrial waste, and EoL uses such as electronics and WEEE[135]. Overall EoL recycling ratio (from all applications): 30−50%, 58%, 97%[25]
Occurrence in nature	Silver occurs in unbound ores such as argentite and chalcopyrite (horn silver). However, it is mainly extracted from lead-zinc, copper, gold, and copper-nickel ores as a by-product of mining these metals. The metal is recovered either from the ore or during the electrolytic refining of copper[39]. The largest reserve holders are Peru (91 kt), Australia (88 kt), and Poland (70 kt); the leading mine producers in 2020 were Mexico (5.6 kt), Peru (3.4 kt), and China (3.2 kt)[2].

Table 41. Gold characteristics, applications, and recycling

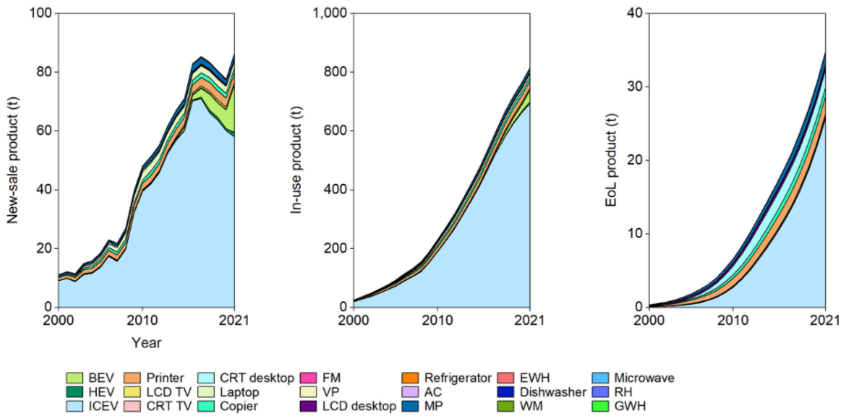
Characteristic	Gold (Au) is metallic, with a yellow color in a mass, but when finely divided, it may be black ruby or purple. It is the most malleable and ductile metal. It is a soft metal and is usually alloyed to give it more strength. It is a good conductor of heat and electricity and is unaffected by air and most reagents[136]. Atomic number: 79; relative atomic mass: 196.967; density: 19.282 g/cm^3; melting point: 1,064 °C (1,337 K)[38]
General application[39]	Gold metal is also used for coinage, art, decoration, and architectural ornamentation. Gold electroplating is used in gears for watches, artificial limb joints, cheap jewelry, and electrical connectors[137]. It is ideal for protecting electrical copper components because it conducts electricity well and does not corrode (which would break the contact). Thin gold wires are used inside computer chips to produce circuits[138].
Use in automobiles and EEE	 Gold in the new-sale products increased from 11 t to 87 t in 2000−2021. In this period, gold in in-use products increased 32 times to 816 t in 2021, and it in EoL products increased 97 times to 35 t. Essential carriers are ICEV, printer, MP, laptop, and recent BEV.
Recycling	The electrical contacts in cell phones, computers, or cars sometimes contain small amounts of gold, which improves conductivity. Factories, workshops, and houses are also golden carriers. 1 t old computer circuit boards can yield more than 200 g of precious metals. However, only about 15% of gold comes from WEEE[139]. Overall EoL recycling ratio (from all applications): 15−20%, 40%, 96%[25]
Occurrence in nature	Gold is one of the few elements to occur in a natural state. It is found in veins and alluvial deposits. Seawater contains about 4 g of gold in 1,000 kt of water. Overall, this is a considerable amount of gold stored in the oceans but because the concentration is so low, attempts to reclaim this gold have consistently failed[39]. The largest reserve holders are Australia (10 kt), Russia (7.5 kt), and The USA (3.0 kt); the leading mine producers in 2020 were China (380 t), Australia (320 t), and Russia (300 t)[2].

Table 42. Palladium characteristics, applications, and recycling

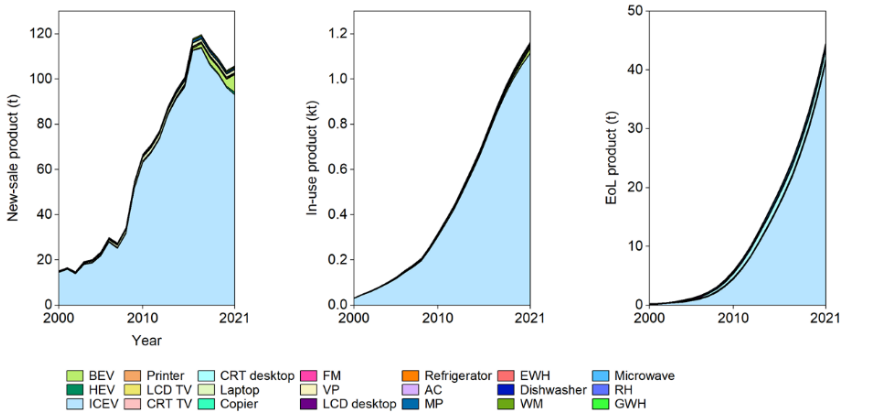
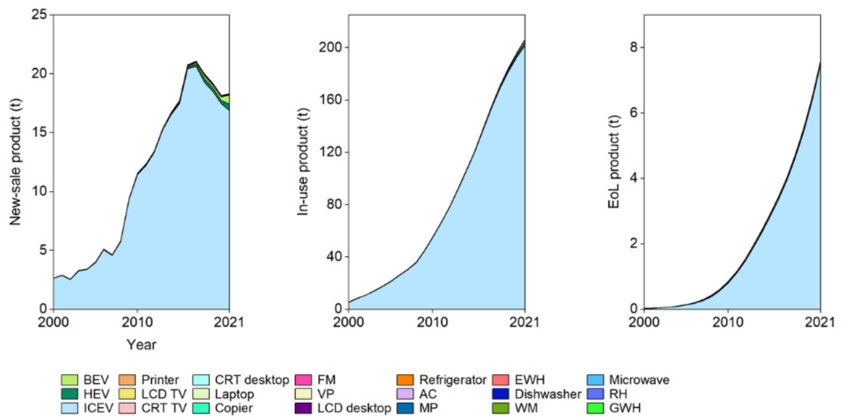
Characteristic	Palladium (Pd), together with rhodium, ruthenium, osmium, iridium, and platinum, form a group of elements referred to as the PGM. Palladium is a lustrous silver-white metal. At ordinary temperatures, it is strongly resistant to corrosion in air and the action of acids. It is attacked by hot acids, and it dissolves in aqua regia[140]. Atomic number: 46; relative atomic mass: 106.42; density: 12.0 g/cm^3; melting point: 1,555 °C (1,828 K)[38]
General application[39]	Most palladium is used in catalytic converters for automobiles. It is also used in jewelry and some dental fillings and crowns. Palladium is used in the electronics industry in ceramic capacitors, found in laptop computers and MPs[141].
Use in automobiles and EEE	 Palladium in the new-sale products increased from 15 t to 106 t in 2000−2021. In this period, palladium in in-use products increased 35 times to 1.2 kt in 2021, and it in EoL products soared to 45 t. The most essential carriers are ICEV and BEV.
Recycling	Palladium can be infinitely recycled without losing its intrinsic characteristics, and because of its high value, it is recycled quite readily. Most recycled volumes come from spent automotive catalysts and old jewelry, with electronics making up the remainder[52]. Overall EoL recycling ratio (from all applications): 60−70%[25]
Occurrence in nature	Palladium has been found uncombined in nature, but mostly occurs in sulfide minerals such as braggite. It is obtained commercially as a by-product of nickel refining. It is also obtained as a by-product of copper and zinc refining[39]. The top three reserve holders are South Africa, Russia, and USA; the top three producers are South Africa, Russia, and Zimbabwe[43]. China lacks palladium ore resources.

Table 43. Platinum characteristics, applications, and recycling

<table>
<tr><td>Characteristic</td><td>Platinum (Pt), a PGM, is a lustrous silvery-white, malleable, ductile metal. It has the third highest density, behind osmium and iridium. Platinum is unaffected by air and water, but will dissolve in hot aqua regia, in hot concentrated phosphoric and sulphuric acids, and molten alkali. It is as resistant as gold to corrosion and tarnishing[140].
Atomic number: 78; relative atomic mass: 195.084; density: 21.46 g/cm^3; melting point: 1,768 °C (2,042 K)[38]</td></tr>
<tr><td>General application[39]</td><td>Platinum is used extensively for jewelry. Its main use, however, is in catalytic converters for cars, trucks, and buses. This accounts for about 50% of demand each year[142]. Platinum is also used as a catalyst to improve the efficiency of fuel cells. The electronics industry uses platinum for computer hard disks and thermocouples. Platinum is also used to make optical fibers and LCDs, turbine blades, spark plugs, pacemakers, and dental fillings[143].</td></tr>
<tr><td>Use in automobiles and EEE</td><td>



Platinum in the new-sale products increased from 2.7 t to 18 t in 2000−2021 (with a pick, 21 t, in 2017). In this period, platinum in in-use products increased 37 times to 207 t in 2021, and it in EoL products soared to 7.6 t. The most essential carrier is ICEV.</td></tr>
<tr><td>Recycling</td><td>Because of its value, platinum is usually easy to recycle. Most of the recycling comes from used automotive catalysts, with the remainder from old jewelry and electronics. In addition to end-of-life recycling, large quantities of platinum are used in closed-loop production processes such as glass manufacturing, where old platinum equipment is recycled and converted into new equipment or used in the chemical and pharmaceutical sectors[52].
Overall EoL recycling ratio (from all applications): 60−70%, 76%[25]</td></tr>
<tr><td>Occurrence in nature</td><td>Platinum's primary occurrence is with other metal ores associated with basic igneous rocks. Platinum nuggets occur naturally as an uncombined metal, as does an alloy of platinum-iridium. Most commercially produced platinum comes from the mineral cooperite (platinum sulfide). Some platinum is prepared as a by-product of copper and nickel refining[37]. The largest reserve holders are South Africa, Russia, and the USA; the largest producers are South Africa, Russia, and Zimbabwe[43].</td></tr>
</table>

Table 44. Rhodium characteristics, applications, and recycling

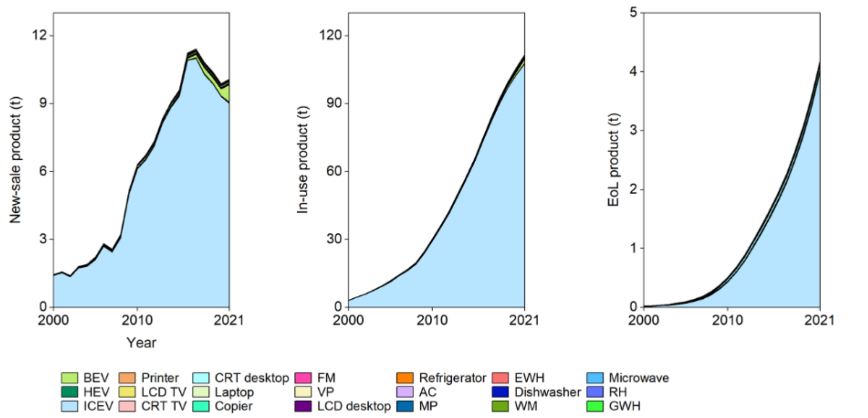
Characteristic	Rhodium (Rh), a PGM, has a high reflectance and is hard and durable. Sputtering targets of rhodium are used to make the reflective surface for automobile mirrors and other optical instruments. Rhodium is also used for a range of catalyst applications and as alloys and coatings for jewelry[140]. Atomic number: 45; relative atomic mass: 102.906; density: 12.4 g/cm^3; melting point: 1,964 °C (2,237 K)[38]
General application[39]	The major use of rhodium is in catalytic converters for automobiles (80%)[144]. It reduces nitrogen oxides in exhaust gases. Rhodium is used to coat optic fibers and optical mirrors, and for thermocouple elements and headlight reflectors. It is used as an electrical contact material as it has a low electrical resistance and is highly resistant to corrosion[145].
Use in automobiles and EEE	 Rhodium in the new-sale products increased from 1.5 t to 10 t in 2000−2021 (with a pick, 11 t, in 2017). In this period, rhodium in in-use products increased 36 times to 112 t in 2021, and it in EoL products soared to 4.2 t. The most essential carrier is ICEV.
Recycling	Rhodium is mainly recovered from spent auto-catalysts. It is used in so-called "closed loops" (and therefore also recycled, often in the glass industry) or in such small quantities in various applications that recycling is not technically and economically feasible. It rarely returns loops from other uses[52]. Overall EoL recycling ratio (from all applications): 50−60%[25]
Occurrence in nature	Rhodium is the rarest of all non-radioactive metals. It occurs uncombined in nature, along with other platinum metals, in river sands. It is also found in copper-nickel sulfide ores. Rhodium is obtained commercially as a by-product of copper and nickel refining. World production is about 30 t per year[39]. The largest reserve holders are South Africa, Russia, and USA; the leading producers are South Africa, Russia, and Zimbabwe[43].

Table 45. Lanthanum characteristics, applications, and recycling

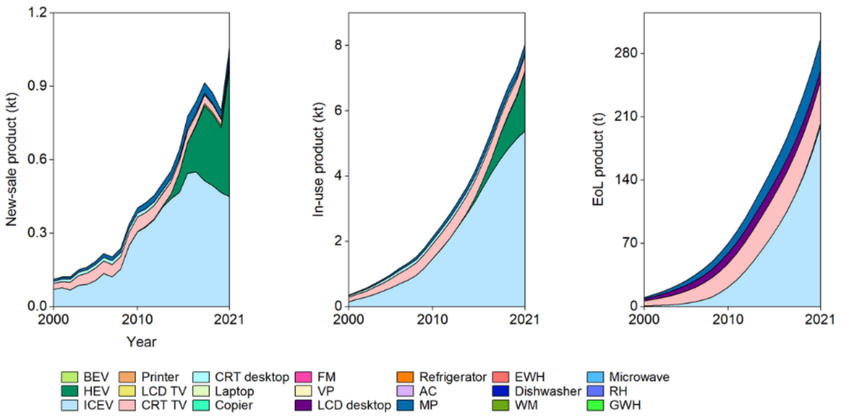
Characteristic	Lanthanum (La), a REE, is a soft, malleable, ductile, silver-white metal. Lanthanum is naturally found in sediments. It oxidizes rapidly in the air and reacts with water to form hydroxide[37]. Atomic number: 57; relative atomic mass: 138.905; density: 6.15 g/cm^3; melting point: 918 °C (1,191 K)[38]
General application[39]	Lanthanum metal has no commercial uses. However, its alloys have a variety of uses. A lanthanum-nickel alloy is used to store hydrogen gas in hydrogen-powered vehicles[146]. Lanthanum is also found in the anode of nickel metal hydride batteries used in HEVs[147]. REE compounds containing lanthanum are used extensively in carbon lighting applications, such as studio lighting and cinema projection. They increase the brightness and give an emission spectrum similar to sunlight.
Use in automobiles and EEE	 Lanthanum in the new-sale products increased from 111 t to 1.1 kt in 2000−2021. In this period, lanthanum in in-use products increased 23 times to 8.0 kt in 2021, and it in EoL products increased 30 times to 296 t. The most essential carrier is ICEV, HEV, and CRT TV.
Recycling[148]	REEs, including lanthanum, are very challenging to recycle commercially due to their very dispersed use. In lab scale, the recycling rate from spent nickel metal hydride batteries can reach over 90%[149]. Overall EoL recycling ratio (from all applications): <1%[25]
Additional information	
Occurrence in nature	Lanthanum is found in REE minerals, principally monazite (25% lanthanum) and bastnaesite (38% lanthanum). Ion-exchange and solvent extraction techniques are used to isolate the REE elements from the minerals. Lanthanum metal is usually obtained by reducing the anhydrous fluoride with calcium[39]. For REEs, the largest reserve holders are China, Russia, and USA; the leading producers are China, Russia, and Malaysia[43].

Table 46. Cerium characteristics, applications, and recycling

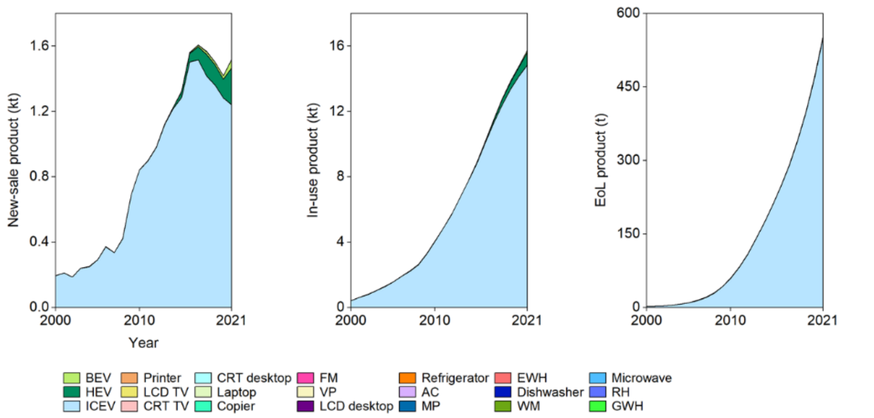
Characteristic	Cerium (Ce), a REE, is a soft, ductile, and malleable (about like tin) metal with a color going from the iron gray of the commercial grade to silvery when in a pure form. It is rarely used because it tarnishes quickly, reacts with water (slowly in cold water and very rapidly in hot water), and burns when heated[150]. Atomic number: 58; relative atomic mass: 140.116; density: 6.770 g/cm^3; melting point: 798 °C (1,071 K)[38]
General application[39]	Cerium metal is used as a core for the carbon electrodes of arc lamps and incandescent mantles for gas lighting. Cerium is used in aluminum and iron alloys in stainless steel as a precipitation-hardening agent to make permanent magnets[151]. Cerium oxide is part of the catalyst of catalytic converters used to clean up exhaust vehicles, and it also catalyzes the reduction of nitrogen oxides to nitrogen gas[144]. Cerium sulfide is likely to replace cadmium in red pigments for containers, toys, household wares, and crates since cadmium is now considered environmentally undesirable. In chromium plating, other uses of cerium are in flat-screen televisions, low-energy light bulbs, and magnetic-optic compact discs.
Use in automobiles and EEE	 Cerium in the new-sale products increased from 0.2 kt to 1.5 kt in 2000−2021 (with a pick, 1.6 kt, in 2017). In this period, cerium in in-use products increased 39 times to 16 kt in 2021, and it in EoL products soared to 553 t. The most essential carriers are ICEV and HEV.
Recycling[148]	REEs, including cerium, are very challenging to recycle commercially due to their very dispersed use. In lab scale, the recycling rate from spent nickel metal hydride batteries can reach over 90%[152]. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature[37]	Cerium is the most abundant of the rare earth elements. It makes up about 0.0046 % of the Earth's crust by weight. Cerium comes mainly from the major lanthanide ores but some are obtained from perovskite, a titanium mineral, and allanite, both of which can have enough cerium to make them viable sources. The global annual production amounts to 23 kt.

Table 47. Praseodymium characteristics, applications, and recycling

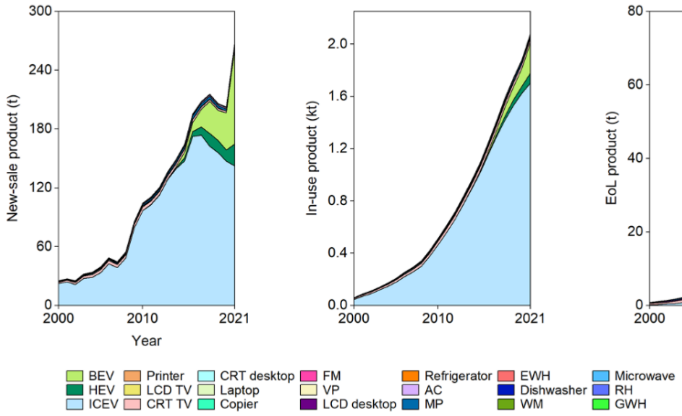
Characteristic	Praseodymium (Pr), a REE, is a soft malleable, silvery-yellow metal. It reacts slowly with oxygen: when exposed to air it forms a green oxide that does not protect it from further oxidation. It reacts rapidly with water[37]. Atomic number: 59; relative atomic mass: 140.908; density: 6.77 g/cm^3; melting point: 1,204 °C (931 K)[38]
General application[39]	Praseodymium is used in a variety of alloys. The high-strength alloy it forms with magnesium is used in aircraft engines[153]. Praseodymium is also used in alloys for permanent magnets[154]. Along with other lanthanide elements, it is used in carbon arc electrodes for studio lighting and projection. Praseodymium salts are used to color glasses, enamel, and glazes an intense and unusually clean yellow.
Use in automobiles and EEE	 Praseodymium in the new-sale products increased from 25 t to 269 t in 2000−2021. In this period, praseodymium in in-use products increased 35 times to 2.1 kt in 2021, and it in EoL products increased 87 times to 71 t. The most essential carriers are ICEV, BEV, and HEV.
Recycling[148]	REEs, including praseodymium, are very challenging to recycle commercially due to their very dispersed use. In lab scale, the recycling rate from spent neodymium magnets can reach approximately 89.2%[155]. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature[37]	The major commercial ores in which praseodymium is found are monazite and bastnasite. The main mining areas are China, the USA, Brazil, India, Sri Lanka, and Australia. Reserves of praseodymium are estimated to be around 2 Mt. The global production of praseodymium is about 2,5 kt per year.

Table 48. Neodymium characteristics, applications, and recycling

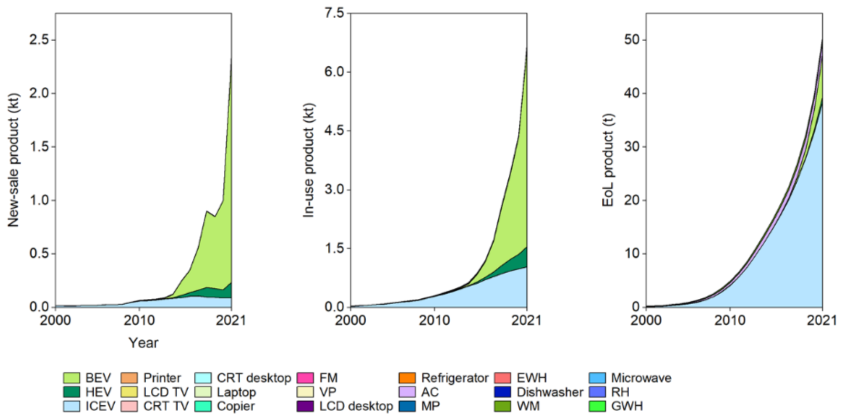
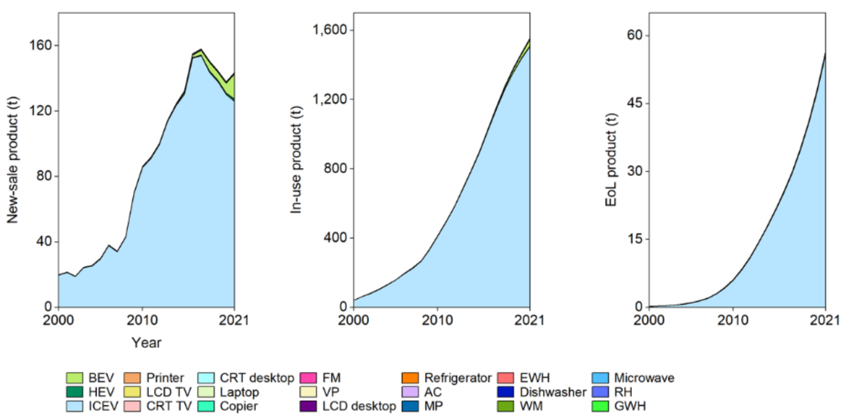
Characteristic	Neodymium (Nd), a REE, is a lustrous silvery-yellow metal. It is very reactive, and quickly tarnishes in air, and the coated formed does not protect the metal from further oxidation, so it must be stored away from contact with air. It reacts slowly with cold water and rapidly with hot[156]. Atomic number: 60; relative atomic mass: 144.242; density: 7.01 g/cm^3; melting point: 1,294 °C (1,021 K)[38]
General application[39]	The most important use for neodymium is in an alloy with iron and boron to make powerful permanent magnets[157]. Neodymium can be used to miniaturize many electronic devices, including mobile phones, microphones, loudspeakers, and electronic musical instruments. These magnets are also used in car windscreen wipers and wind turbines. Neodymium is a component, along with praseodymium, of didymium glass[158].
Use in automobiles and EEE	 Neodymium in the new-sale products increased from 14 t to 238 t in 2000−2021. In this period, neodymium in in-use products soared to 6.7 kt in 2021, and it in EoL products soared to 51 t. The most essential carriers are ICEV, BEV and HEV.
Recycling[148]	REEs, including neodymium, are very challenging to recycle commercially due to their very dispersed use. Although the current recycling rate is less than 1%, the recycling technologies, including leaching and molten salt extraction, is developed rapidly[159]. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature[37]	Neodymium is the second most abundant of the rare-earth elements (after cerium) and is almost as abundant as copper. It is found in minerals that include all lanthanide minerals, such as monazite and bastnasite. The main areas are Brazil, China, the USA, India, Sri Lanka, and Australia. Reserves of neodymium are estimated to be 8 Mt, and the world production of neodymium oxide is about 7 kt a year.

Table 49. Samarium characteristics, applications, and recycling

<table>
<tr><td>Characteristic</td><td>Samarium (Sm), a REE, is a moderately hard silvery metal that slowly oxidizes in air. It has no significant biological role, but it is slightly toxic[156]. Atomic number: 62; relative atomic mass: 150.36; density: 7.52 g/cm^3; melting point: 1,074 °C (1,347 K)[38]</td></tr>
<tr><td>General application[39]</td><td>Samarium-cobalt magnets are much more powerful than iron magnets; they remain magnetic at high temperatures and so are used in microwave applications[160]. Samarium-cobalt magnets enabled the miniaturization of electronic devices like headphones and the development of personal stereos. However, neodymium magnets are now more commonly used instead. Samarium is used to dope calcium chloride crystals for use in optical lasers. Similar to other lanthanides, samarium is used in carbon arc lighting for studio lighting and projection[161].</td></tr>
<tr><td>Use in automobiles and EEE</td><td>


Samarium in the new-sale products increased from 20 t to 144 t in 2000−2021 (with a pick, 158 t, in 2017). In this period, samarium in in-use products increased 38 times to 1.6 kt in 2021, and it in EoL products soared to 57 t. The most essential carriers are ICEV and BEV.</td></tr>
<tr><td>Recycling[148]</td><td>REEs, including samarium, are very challenging to recycle commercially due to their very dispersed use.
Overall EoL recycling ratio (from all applications): <1%[25]</td></tr>
<tr><td>Occurrence in nature[37]</td><td>Samarium is the fifth most abundant of the rare elements and is almost four times as common as tin. It is never found free in nature, but is contained in many minerals, including monazite, bastnasite, and samarskite. Samarium containing ores is found in the USA, China, Brazil, India, Australia, and Sri Lanka. World production of samarium oxide is about 700 t per year, and worldwide reserves are estimated to be around 2 Mt.</td></tr>
</table>

Table 50. Europium characteristics, applications, and recycling

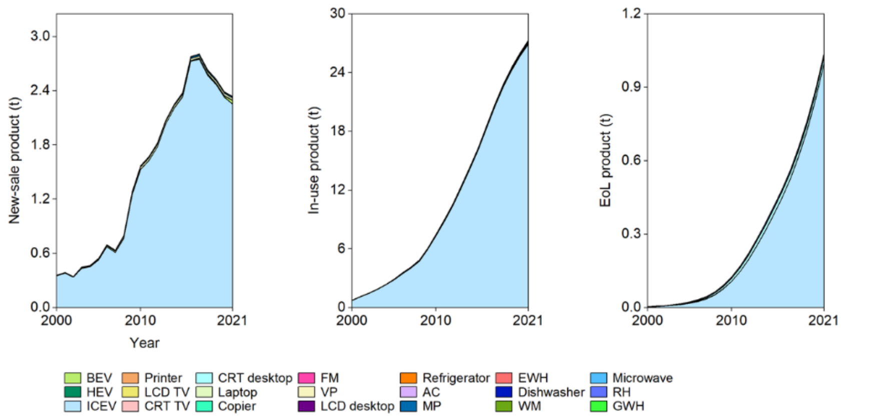
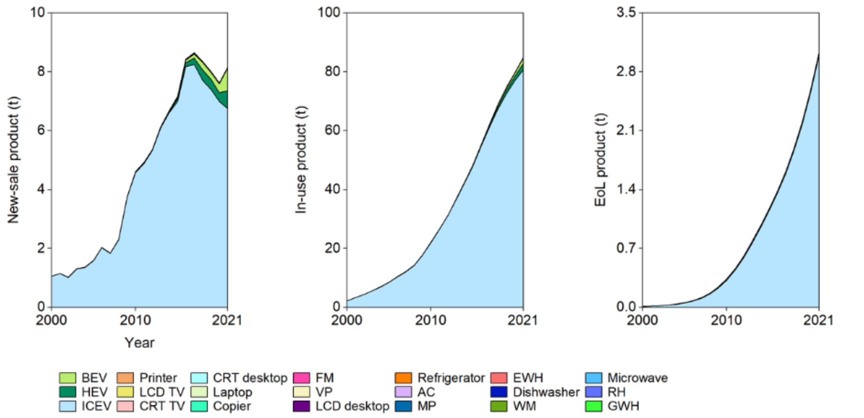
Characteristic	Europium (Eu), a REE, is a ductile metal with a hardness similar to that of lead. It has the second lowest melting point and the lowest density of all lanthanides[162]. Atomic number: 63; relative atomic mass: 151.964; density: 5.24 g/cm^3; melting point: 822 °C (1,095 K)[38]
General application[39]	Low-energy light bulbs contain a little europium to give a more natural light, by balancing the blue (cold) light with a little red (warm) light[163]. Europium-doped plastic has been used as a laser material. It is also used in making thin super-conducting alloys[164].
Use in automobiles and EEE	 Europium in the new-sale products increased from 357 kg to 2.3 t in 2000−2021 (with a pick, 2.8 t, in 2017). In this period, europium in in-use products increased 36 times to 27 t in 2021, and it in EoL products soared to 1.0 t. The most essential carrier is ICEV.
Recycling[148]	REEs, including europium, are very challenging to recycle commercially due to their very dispersed use. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature[37]	Europium is one of the less abundant rare-earth elements: it is almost as abundant as tin. It is never found in nature as a free element, but there are many elements containing europium. The main mining areas are China and USA. Reserves of europium are estimated to be around 150 kt, and the world production of the pure metal is around 100 t a year.

Table 51. Gadolinium characteristics, applications, and recycling

<table>
<tr><td>Characteristic</td><td>Gadolinium (Gd), a REE, is a silvery-white, malleable and ductile metal with low shear strength. At room temperature to about 1262 °C it crystallizes in the hexagonal, close-packed a form. Thus, gadolinium itself possesses good lubrication ability[165].
Atomic number: 64; relative atomic mass: 157.25; density: 7.90 g/cm^3; melting point: 1,313 °C (1,586 K)[38]</td></tr>
<tr><td>General application[39]</td><td>Gadolinium has useful properties in alloys. Gadolinium improves the machinability of iron and chromium alloys and their resistance to high temperatures and oxidation. It is also used to make alloys for magnets, electronic components, and data storage disks[166]. Gadolinium compounds can be used in magnetic resonance imaging, especially in the diagnosis of cancerous tumors[167].</td></tr>
<tr><td>Use in automobiles and EEE</td><td>



Gadolinium in the new-sale products increased from 1.1 t to 8.2 t in 2000−2021 (with a pick, 8.6 t, in 2017). In this period, gadolinium in in-use products increased 38 times to 85 t in 2021, and it in EoL products soared to 3.0 t. The most essential carriers are ICEV, HEV, and BEV.</td></tr>
<tr><td>Recycling[148]</td><td>REEs, including gadolinium, are very challenging to recycle commercially due to their very dispersed use.
Overall EoL recycling ratio (from all applications): <1%[25]</td></tr>
<tr><td>Occurrence in nature[37]</td><td>Gadolinium is one of the more abundant rare-earth elements. It is never found as a free element in nature, but it is contained in many rare minerals. The main mining areas are China, the USA, Brazil, Sri Lanka, India, and Australia, with reserves expected to exceed 1 Mt. The world production of pure gadolinium is about 400 t per year.</td></tr>
</table>

Table 52. Terbium characteristics, applications, and recycling

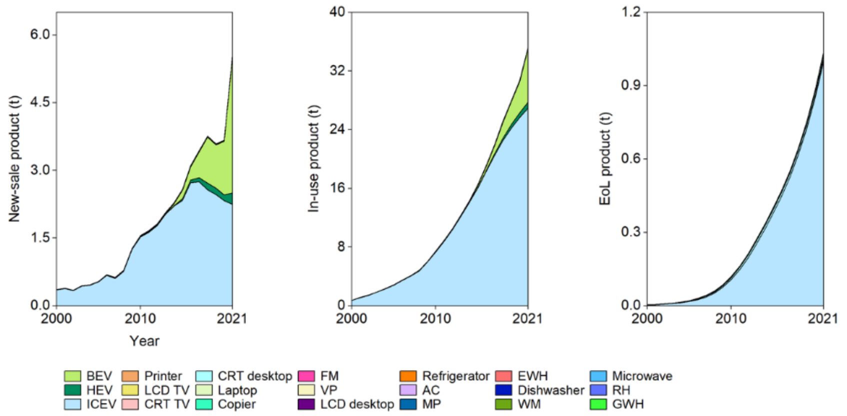
Characteristic	Terbium (Tb), a REE, is a silvery-white rare earth metal that is malleable, ductile, and soft enough to be cut with a knife. Terbium burns readily to form a mixed terbium(III, IV) oxide[168]. Atomic number: 65; relative atomic mass: 158.925; density: 8.23 g/cm^3; melting point: 1,356 °C (1,629 K)[38]
General application[39]	Terbium is used in low-energy lightbulbs and mercury lamps. Terbium salts are used in laser devices[169]. An alloy of terbium, dysprosium, and iron lengthens and shortens in a magnetic field, and this effect forms the basis of loudspeakers that sit on a flat surface, such as a window pane, which then acts as the speaker[170].
Use in automobiles and EEE	 Terbium in the new-sale products increased from 355 kg to 5.6 t in 2000−2021. In this period, terbium in in-use products increased 47 times to 35 t in 2021, and it in EoL products soared to 1.0 t. The most essential carriers are ICEV and BEV.
Recycling[148]	REEs, including terbium, are very challenging to recycle commercially due to their very dispersed use. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature[37]	Terbium is one of the rarer REEs, although it is twice as common in the Earth's crust as silver. It is never found in nature as a free element but is contained in many minerals. The most important ore are monazite, bastnasite and cerite. The main mining areas are China, the USA, India, Sri Lanka, Brazil, and Australia, and reserves of terbium are estimated to be around 300 kt. The world production is 10 t a year.

Table 53. Dysprosium characteristics, applications, and recycling

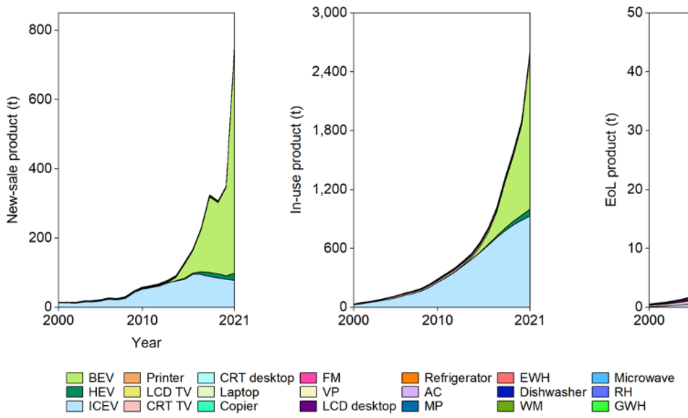
Characteristic	Dysprosium (Dy), a REE, has a metallic, bright silver luster, relatively stable in air at room temperature, but dissolving readily in dilute or concentrated mineral acids with the emission of hydrogen. Soluble dysprosium salts are slightly toxic, while insoluble salts are considered nontoxic[171]. Atomic number: 66; relative atomic mass: 162.500; density: 8.55 g/cm^3; melting point: 1,412 °C (1,685 K)[38]
General application[39]	Dysprosium's main use is in alloys for neodymium-based magnets, which is because it is resistant to demagnetization at high temperatures. This property is important for magnets used in motors or generators[172]. These magnets are used in wind turbines and electrical vehicles, so demand for dysprosium is growing rapidly. Dysprosium iodide is used in halide discharge lamps. The salt enables the lamps to give out a very intense white light[173].
Use in automobiles and EEE	 Dysprosium in the new-sale products increased from 14 t to 760 t in 2000−2021. In this period, dysprosium in in-use products increased 75 times to 2,620 t in 2021, and it in EoL products increased 77 times to 42 t. The most essential carriers are ICEV, BEV and CRT TV.
Recycling[148]	REEs, including dysprosium, are very challenging to recycle commercially due to their very dispersed use. Additionally, as much as 15% recycling rate were reported in some cases[174]. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature[37]	Dysprosium is one of the more abundant lanthanide elements and is more than twice as abundant as tin. Dysprosium is never encountered as a free element, but is found in many minerals. The most important ores are monazite and bastnasite. The world annual production is around 100 t.

Table 54. Erbium characteristics, applications, and recycling

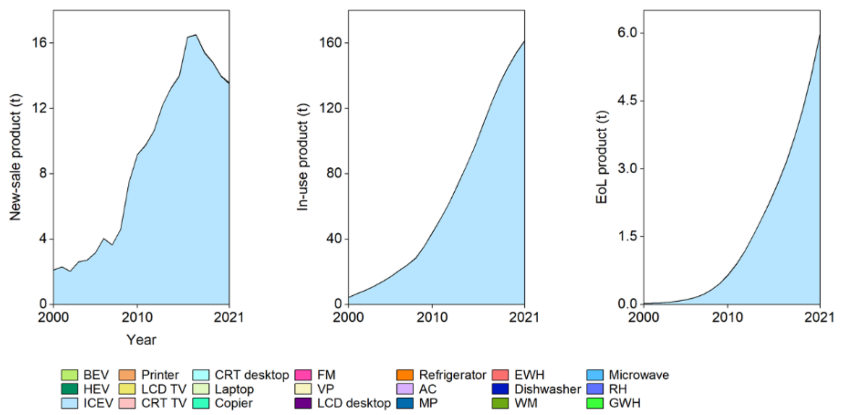
Characteristic	Erbium (Er), a REE, is a silvery-white solid metal when artificially isolated, natural erbium is always found in chemical combination with other elements on Earth[168]. Atomic number: 68; relative atomic mass: 167.259; density: 9.07 g/cm^3; melting point: 1,592 °C (1,802 K)[38]
General application[39]	Erbium oxide is occasionally used in infrared absorbing glass, for example, safety glasses for welders and metal workers. When erbium is added to glass, it gives the glass a pink tinge[175]. Broadband signals, carried by fiber optic cables, are amplified by including erbium in the glass fiber.
Use in automobiles and EEE	 Erbium in the new-sale products increased from 2.1 t to 14 t in 2000−2021 (with a pick, 17 t, in 2017). In this period, erbium in in-use products increased 37 times to 162 t in 2021, and it in EoL products soared to 6.0 t. The most essential carrier is ICEV.
Recycling[148]	REEs, including erbium, are very challenging to recycle commercially due to their very dispersed use. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature[176]	Erbium is primarily obtained through an ion exchange process from the minerals: xenotime and euxenite. It can be extracted by ion exchange and solvent extraction. The world production of erbium is 500 t per year[37].

Table 55. Scandium characteristics, applications, and recycling

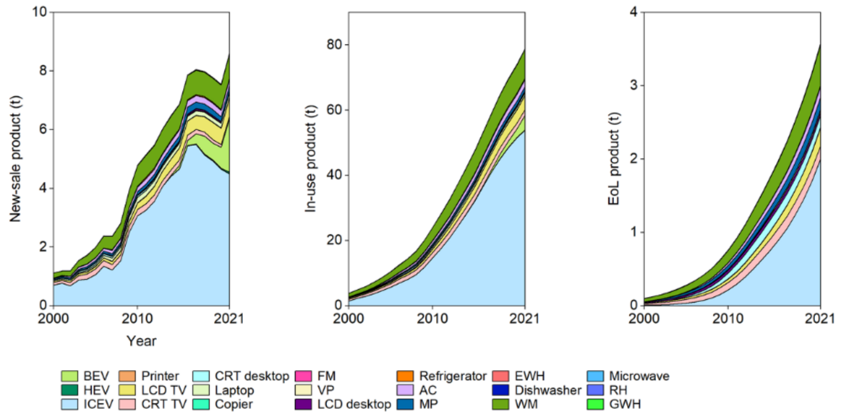
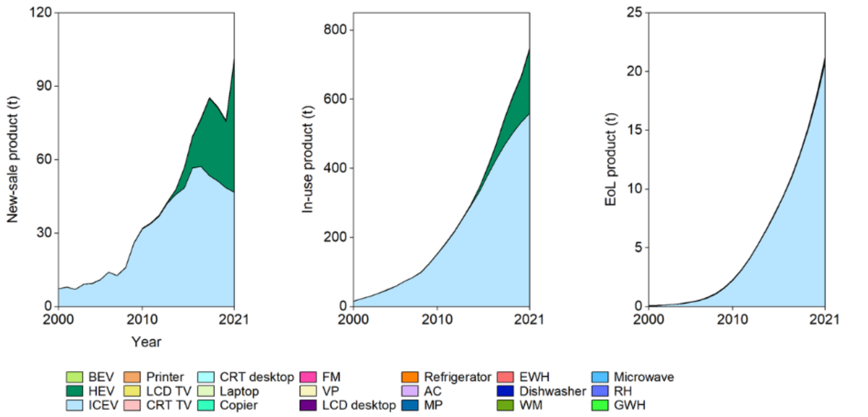
Characteristic	Scandium (Sc), a REE, is a silvery-white metallic d-block element, it has historically been classified as a rare-earth element, together with yttrium and the lanthanides[97]. Atomic number: 21; relative atomic mass: 44.956; density: 2.99 g/cm^3; melting point: 1,541 °C (1,814 K)[38]
General application[39]	Scandium is mainly used for research purposes. Aluminum-scandium alloys are used in high-end bicycle frames and baseball bats, etc[177]. Scandium iodide is added to mercury vapor lamps to produce a highly efficient light source similar to sunlight. These lights help TV cameras reproduce colors well when shooting indoors or at night[178].
Use in automobiles and EEE	 Scandium in the new-sale products increased from 1.1 t to 8.6 t in 2000−2021. In this period, scandium in in-use products increased 21 times to 79 t in 2021, and it in EoL products increased 36 times to 3.6 t. The most essential carriers are ICEV, HEV, BEV, LCD TV, etc.
Recycling[148]	REEs, including scandium, are very challenging to recycle commercially due to their very dispersed use. Overall EoL recycling ratio (from all applications): <1%[25]
Occurrence in nature[37]	Scandium can rarely be found in nature, as it occurs in very small amounts. Scandium is usually found only in two different kinds of ores. Thortveitite is the primary source of scandium, with uranium mill tailings by-products also being an important source. The world annual production amount to only 50 kg. There is no estimate of how much is potentially available.

Table 56. Yttrium characteristics, applications, and recycling

<table>
<tr><td>Characteristic</td><td>Yttrium (Y), a REE, is a soft, silver-metallic, lustrous, and highly crystalline transition metal. Yttrium is almost always found in combination with lanthanide elements in rare-earth minerals and is never found in nature as a free element[179].
Atomic number: 39; relative atomic mass: 88.905; density: 4.47 g/cm^3; melting point: 1,522 °C (1,795 K)[38]</td></tr>
<tr><td>General application[39]</td><td>Yttrium-aluminum garnet is used in lasers that can cut through metals. It is also used in white light-emitting diode lights[180]. Yttrium oxide is added to the glass used to make camera lenses to make them heat and shock-resistant. It is also used to make superconductors. Yttrium oxysulfide used to be widely used to produce red phosphors for old-style color television tubes[181].</td></tr>
<tr><td>Use in automobiles and EEE</td><td>

Yttrium in the new-sale products increased from 7.4 t to 102 t in 2000−2021. In this period, yttrium in in-use products increased 49 times to 479 t in 2021, and it in EoL products soared to 21 t. The most essential carriers are ICEV and HEV.</td></tr>
<tr><td>Recycling[148]</td><td>REEs, including yttrium, are very challenging to recycle commercially due to their very dispersed use.
Overall EoL recycling ratio (from all applications): <1%[25]</td></tr>
<tr><td>Occurrence in nature[37]</td><td>Yttrium never occurs in nature as a free element. It is found in almost all rare earth minerals and uranium ores. The yellow-brown ore xenotime can contain as much as 50% yttrium phosphate. The output of yttrium is about 600 t per year, measured as yttrium oxide, and world reserves are estimated to be around 9 Mt.</td></tr>
</table>

Table 57. Mass and value losses of target metals

Metal	Mass			Value		
	LS	HS	Mean	LS	HS	Mean
	Unit: t			Unit: US$		
Fe	4.17E+06	2.03E+06	3.10E+06	7.92E+08	3.87E+08	5.90E+08
Al	7.86E+05	2.20E+05	5.03E+05	1.67E+09	4.67E+08	1.07E+09
Cu	9.07E+05	2.19E+05	5.63E+05	5.36E+09	1.29E+09	3.32E+09
Cr	6.29E+04	2.49E+04	4.39E+04	6.20E+08	2.45E+08	4.33E+08
Zn	2.00E+05	2.04E+04	1.10E+05	5.07E+08	5.18E+07	2.79E+08
Sn	7.02E+03	5.50E+03	6.26E+03	1.32E+08	1.03E+08	1.17E+08
Mg	5.05E+04	1.16E+04	3.11E+04	1.17E+08	2.68E+07	7.17E+07
In	6.44E+01	2.33E+01	4.39E+01	1.41E+07	5.09E+06	9.57E+06
Ni	2.99E+04	4.87E+03	1.74E+04	3.65E+08	5.95E+07	2.12E+08
Li	1.38E+03	1.58E+02	7.67E+02	3.62E+07	4.16E+06	2.02E+07
Co	7.01E+02	6.24E+02	6.62E+02	3.05E+07	2.71E+07	2.88E+07
Pb	6.59E+04	4.67E+04	5.63E+04	1.35E+08	9.55E+07	1.15E+08
Ag	3.23E+02	1.66E+02	2.44E+02	1.99E+08	1.02E+08	1.50E+08
Au	2.12E+01	1.41E+01	1.76E+01	1.04E+09	6.89E+08	8.64E+08
PGM	2.91E+01	7.06E+00	1.81E+01	1.34E+09	3.40E+08	8.42E+08
REE	1.10E+03	1.10E+03	1.10E+03	3.10E+07	3.08E+07	3.09E+07
Other metals	8.83E+04	8.83E+04	8.83E+04	1.63E+08	1.63E+08	1.63E+08

Measuring the value of materials is an essential complement to mass-based metrics. Recycled value retention rates provide information on quality, price, and practical options for replacing new merchandise with recycled content. It also uncovers new revenue opportunities for the private sector and thus may spur innovation. For example, European public statistics are already improving, with indicators shifting from the proportion of sorted, recycled material to an indicator showing the value of recycled material produced, sold, or lost[182]. Thus, price and quality data would be an excellent addition.

Table 58. Raw material demands for target industries in China in 2021

Metal	Automobile	EEE
	Unit: t	
PGM	1.31E+02	4.42E+00
Ni	1.62E+05	1.19E+02
Cu	1.40E+06	1.98E+06
Li	3.62E+04	1.26E+03
In	2.81E+01	8.28E+01
Co	2.42E+04	8.29E-01
Au	7.67E+01	1.09E+01
Al	4.12E+06	1.27E+06
Ag	7.80E+02	5.11E+01
Pb	3.89E+05	9.80E+01
Mg	1.57E+05	6.96E+01
Zn	6.37E+05	2.49E+02
Sn	1.63E+04	3.91E+03
Fe	1.97E+07	8.68E+06
Cr	2.49E+05	1.78E+01
REE	6.89E+03	8.97E+01
Other metals	5.35E+05	2.07E+02
Total	2.74E+07	1.19E+07

Table 59. Sensitivity analysis

Parameter, x	Sensitivity, S(x)	
	When x +10%	When x -10%
Metal concentration	109.95%	90.00%
Product weight	110.00%	90.00%
Product new-sale number	110.02%	90.00%
Product lifespan distribution shape parameter	98.25%	101.94%
Product lifespan distribution scale parameter	86.62%	116.13%
Metal price	100.02%	99.98%
Economic threshold	101.57%	98.68%
Material separation ratio	104.74%	90.00%
Material recovery ratio	109.67%	90.00%

Note, dismantling ratio has an upper limit of 100%, therefore, when the collection level has reached 75–100%, it can only increase to 83–100%. The most sensitive parameter is product lifespan distribution scale parameter, which means that the lifespan data of products is essential for our estimation model. Other important parameters are product new-sale number, product weight, metal concentration, material recovery ratio, and material separation ratio. Parameter has the lowest sensitivity is metal price, because the AMB threshold of relative economic proportion (as a percentage) can offset the change in the input data when all metal prices go up or down. This is an advantage of our model, which can avoid errors caused by the statistical caliber of prices.

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