Supplementary Materials

Uncovering the germanium sustainability up to 2050 in China

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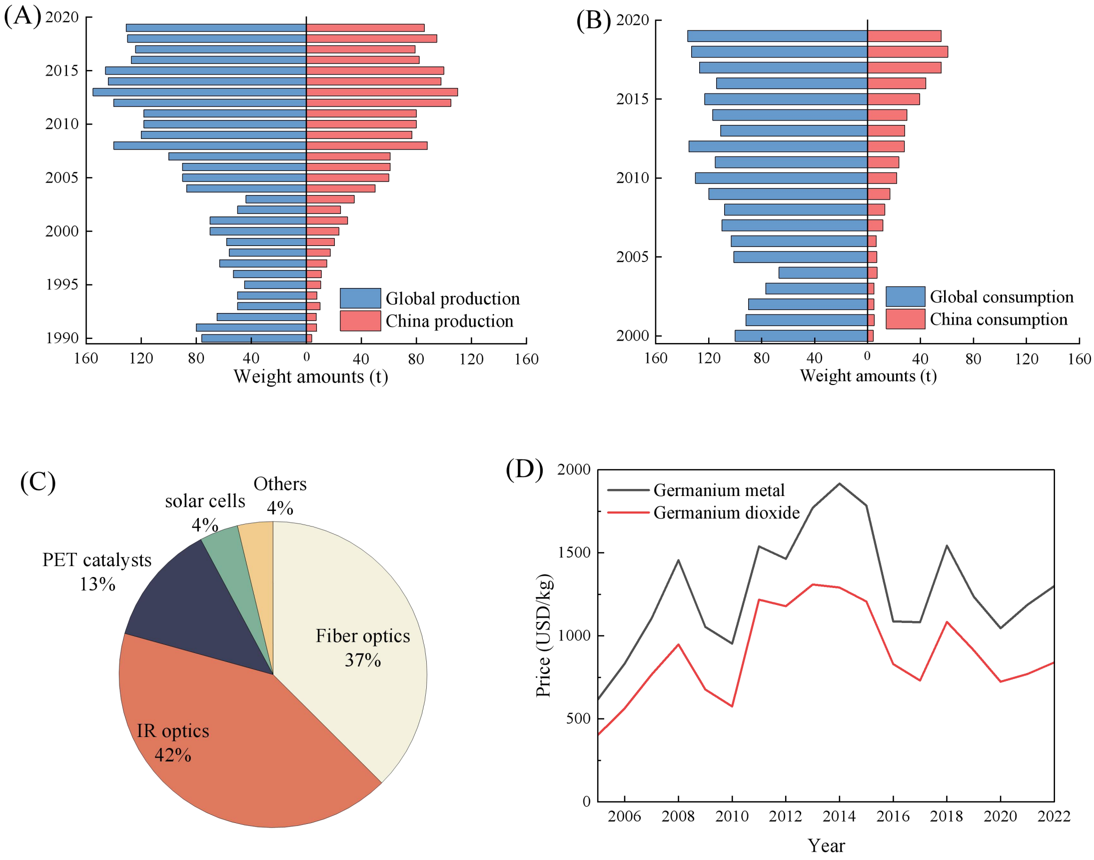


Figure S1 (A) Germanium amount of refinery production in the world and China for 1990-2019; (B) Germanium amount of consumption in the world and China for 2000-2019; (C) Germanium consumption share of end-use in China for 2010-2019; (D) Price of germanium metal and dioxide.

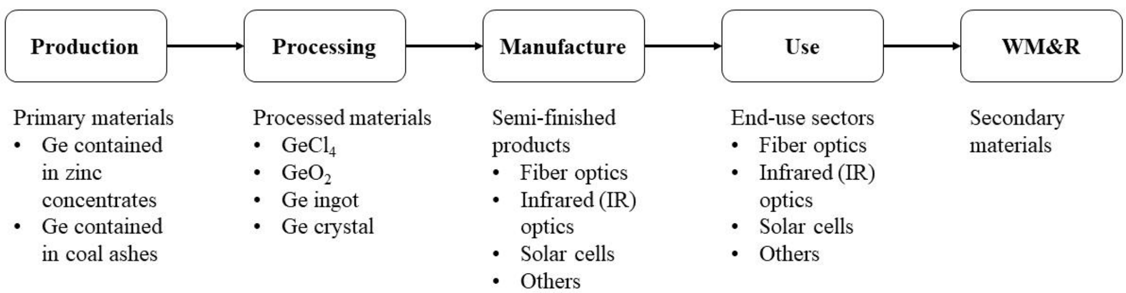


Figure S2 Substance flow modeling of germanium

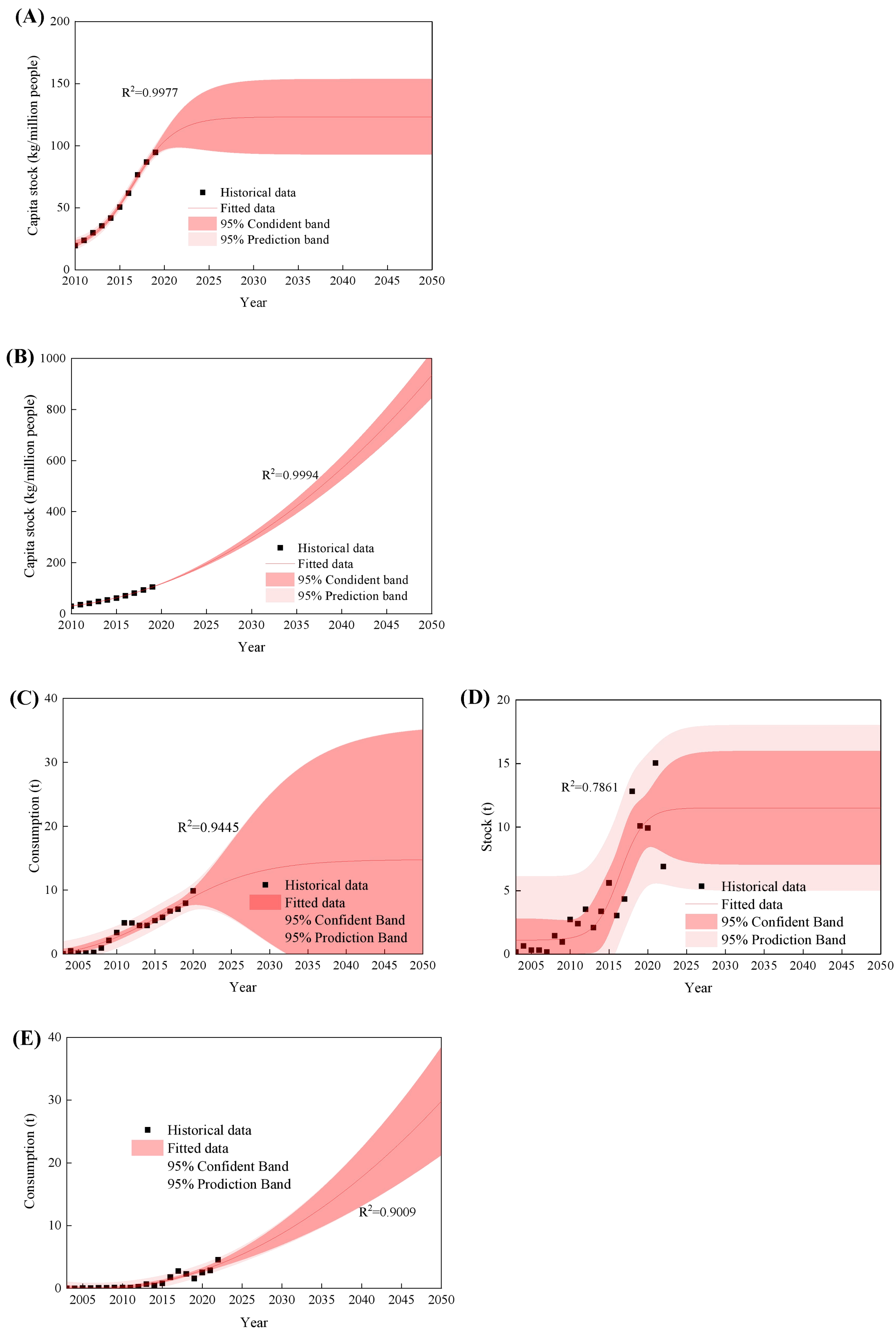
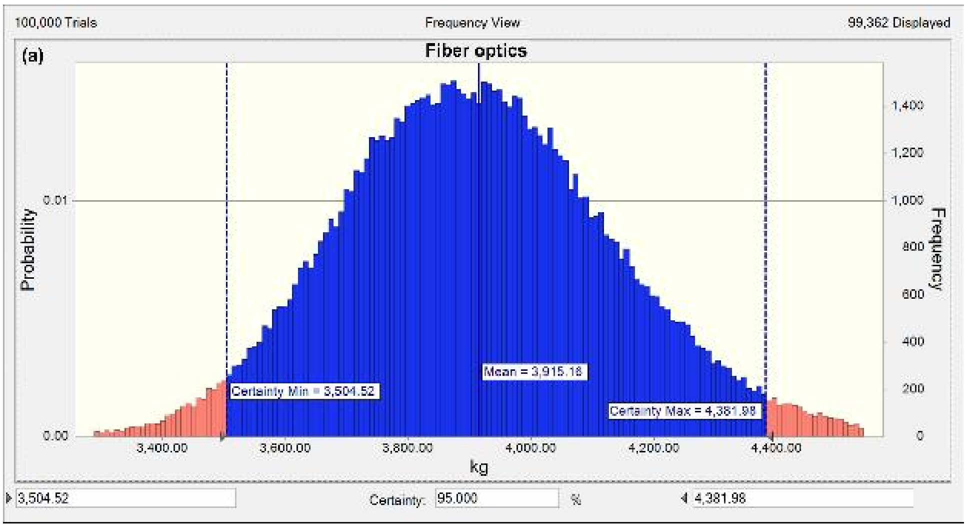
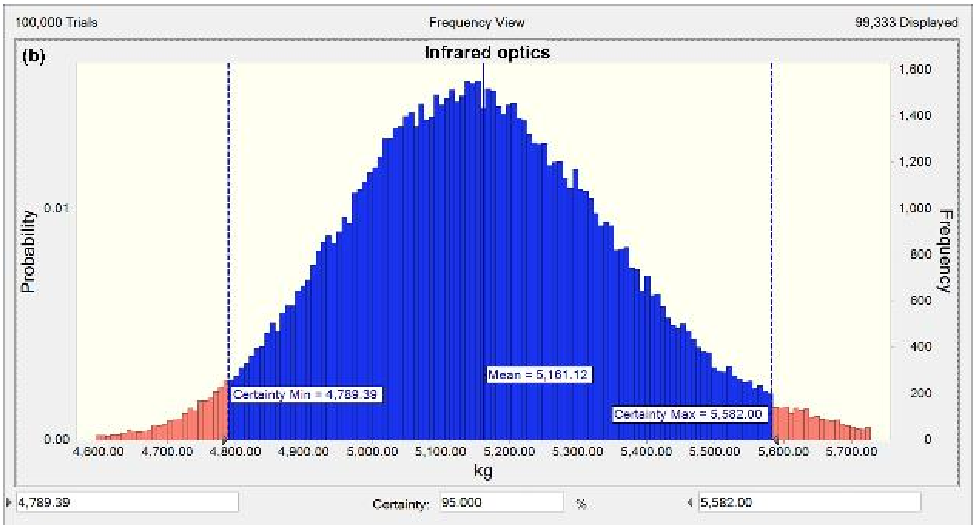
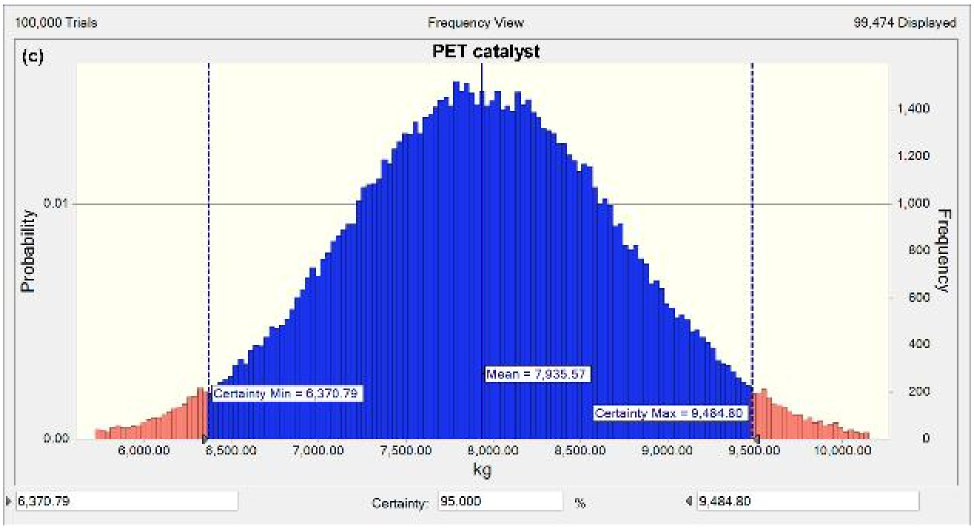
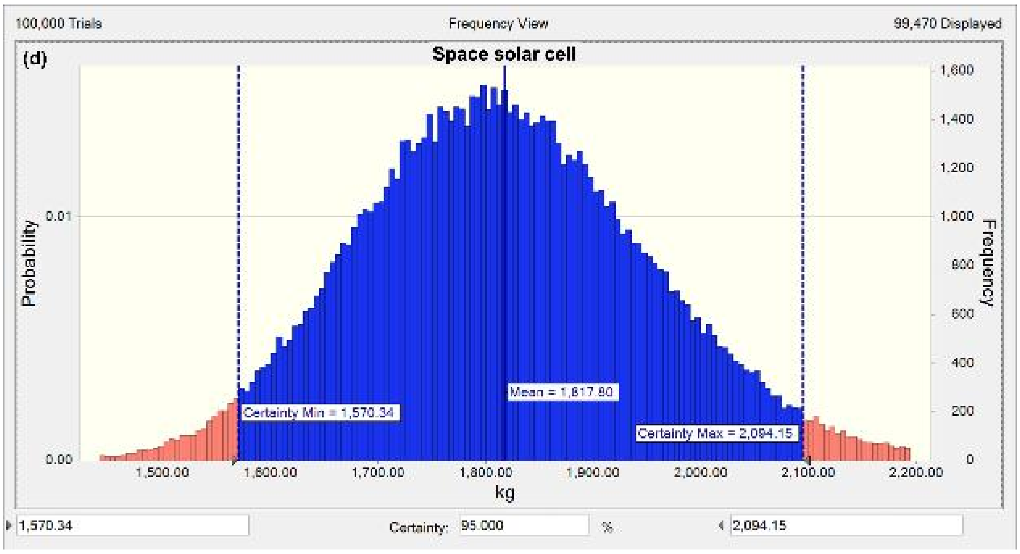


Figure S3 Germanium consumption of different products to 2050 in China: (A) fiber optics; (B) IR optics; (C) PET catalysts; (D) space solar cells; (E) terrestrial solar cells.


100,000 Trials
Frequency View
99,362 Displayed
(a)
Fiber optics
Probability
Frequency
Mean = 3,915.18
Certainty Min = 3,504.52
Certainty Max = 4,381.98
kg
3,504.52
Certainty: 95.000 %
4,381.98


100,000 Trials
Frequency View
99,333 Displayed
(b)
Infrared optics
Probability
Frequency
Mean = 5,161.12
Certainty Min = 4,789.39
Certainty Max = 5,582.00
kg
4,789.39
Certainty: 95.000 %
5,582.00


100,000 Trials
Frequency View
99,474 Displayed
(c)
PET catalyst
Probability
Frequency
Mean = 7,935.57
Certainty Min = 6,370.79
Certainty Max = 9,484.80
kg
6,370.79
Certainty: 95.000 %
9,484.80



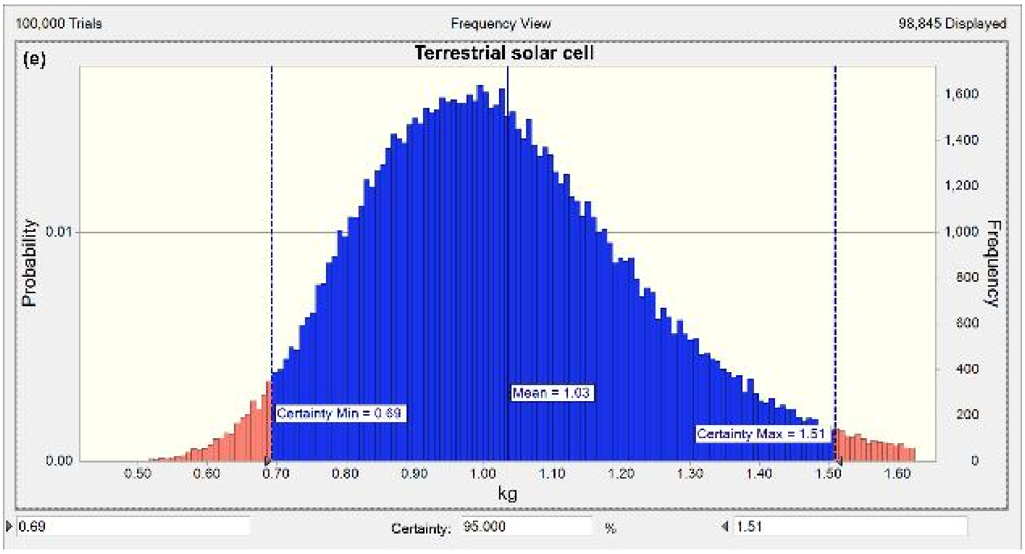


Figure S4 Uncertainty analysis of germanium scrap quantities in 2019. (A) fiber optics; (B) IR optics; (C) PET catalysts; (D) space solar cells; (E) terrestrial solar cells.

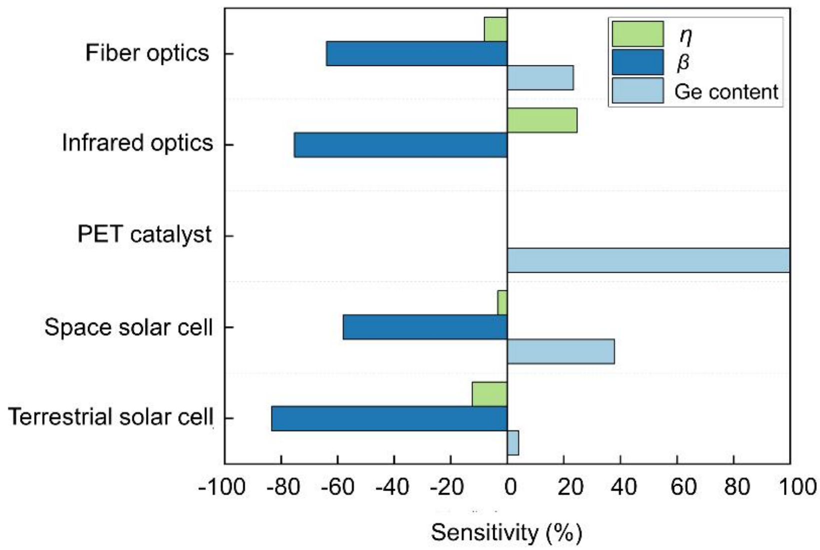


Figure S5 Sensitivity analysis of germanium scrap quantities in 2019.

Supplemental tables

Table S1 Germanium flow for China in 2019

Stage		Description	Value	Unit	Reference
	F01	*Extraction from zinc concentrates*	*53.00*	*t/a*	
	F01.1	Refinery Ge ratio from zinc concentrates	35.00	%	(Guberman, 2010)
	F02	*Extraction from coal ashes*	*113*	*t/a*	
	F02.1	Refinery Ge ratio from coal ashes	65.00	%	(Guberman, 2010)
	F03	*Refinery Ge production*	*87*	*t/a*	
	F04	*Losses in primary refining of coal ashes and zinc concentrates*	*79.00*	*t/a*	
	F04.1	Losses in primary refining of zinc concentrates	43.00	%	(Wardell and Davidson, 1987)
	F04.2	Losses in primary refining of coal ashes	50.00	%	(Arroyo et al., 2009)
	F05	*Import of metal, oxide, chloride*	*4.50*	*t/a*	
Production	F05.1	China imports of "Unwrought germanium waste and scraps" (HS CODE: 81129210)	4.99	t/a	(General Administration of Customs of the People's Republic of China, 2024)
	F05.2	China export of "Unwrought germanium waste and scraps" (HS CODE: 81129210)	0.49	t/a	(General Administration of Customs of the People's Republic of China, 2024)
	F6	*Export of metal, oxide, chloride*	*21.95*	*t/a*	
	F6.1	China imports of "Other germanium and articles thereof" (HS CODE: 81129910)	0.90	t/a	(General Administration of Customs of the People's Republic of China, 2024)
	F6.2	China export of "Other germanium and articles thereof" (HS CODE: 81129910)	22.84	t/a	(General Administration of Customs of the People's Republic of China, 2024)

	F7	*Exports of fiber optics*	*9.13*	*t/a*	
	F7.1	China export of "Preformed bars for drawing optical fiber " (HS CODE: 70022010)	904.00	t/a	(Trade statistics for international business development, 2024)
	F7.2	Share of germanium in performed bars	0.22	%	(Ministry of Commerce of the People's Republic of China, 2021)
	F7.3	China export of "Optical fiber bundles and cables" (HS CODE: 90011000)	3914.94	t/a	(Trade statistics for international business development, 2024)
	F7.4	Share of germanium in optical fiber bundles	0.10	%	(Ministry of Commerce of the People's Republic of China, 2021)
	F7.5	China export of "Optical fiber cables" (HS CODE: 85447000)	255.46	t/a	(Trade statistics for international business development, 2024)
F&M	F7.6	Share of germanium in optical fiber cables	12.60	millionth	(Lv, 2021)
	F8	*Import of fiber optics*	*3.40*	*t/a*	
	F8.1	China imports of "Preformed bars for drawing optical fiber" (HS CODE: 70022010)	922.00	t/a	(Trade statistics for international business development, 2024)
	F8.2	Share of germanium in performed bars	0.22	%	(Ministry of Commerce of the People's Republic of China, 2021)
	F8.3	China imports of "Optical fiber bundles and cables" (HS CODE: 90011000)	1295.00	t/a	(Trade statistics for international business development, 2024)
	F8.4	Share of in optical fiber bundles	0.10	%	(Ministry of Commerce of the People's Republic of China, 2021)
	F8.5	China imports of "Optical fiber cables" (HS CODE: 85447000)	3.73	t/a	(Trade statistics for international business development, 2024)

F8.6	Share of germanium in optical fiber cables	12.60	millionth	(Lv, 2021)
F09	*Export of PET*	*5.01*	*t/a*	
F9.1	China export of "Polyethylene terephthalate chips" (HS CODE: 390761, 390760)	2.90	million t/a	(Trade statistics for international business development, 2024)
F9.2	Share of germanium in PET	0.01	%	(Zimmermann and Goessling-Reisemann, 2014)
F10	*Import of PET*	*0.16*	*t/a*	
F10.1	China imports of "Polyethylene terephthalate chips" (HS CODE: 390761, 390760)	0.09	million t/a	(Trade statistics for international business development, 2024)
F10.2	Share of germanium in PET	0.01	%	(Zimmermann and Goessling-Reisemann, 2014)
F11	*Germanium dioxide and tetrachloride for fiber optics*	*25.00*	*t/a*	
F11.1	Domestic consumption of fiber optics (*F17*)	13.0	t/a	
F11.2	Export of fiber optics (*F7*)	9.13	t/a	
F11.3	Import of fiber optics (*F8*)	3.40	t/a	
F12	*Germanium metal and dioxide for IR optics*	*28.00*	*t/a*	
F12.1	Domestic consumption in IR optics	21.00	t/a	(CITIC Securities, 2018)
F12.2	Loss rate in the process of processing	25.00	%	(Jorgenson, 2006)
F13	*Germanium dioxide for PET*	*17.00*	*t/a*	
F13.1	Domestic consumption in PET bottle	5.75	million t/a	(Sha, 2021)
F13.2	Loss rate in the process of processing	25.00	%	(Jorgenson, 2006)
F13.3	China export of "Polyethylene terephthalate chips" (HS CODE: 390761, 390760)	2.90	million t/a	(Trade statistics for international business development, 2024)
F13.4	China imports of "Polyethylene terephthalate chips" (HS	0.09	million t/a	(Trade statistics for international business

		CODE: 390761, 390760)			development, 2024)
	F13.5	Share of germanium in PET	0.01	%	(Zimmermann and Goessling-Reisemann, 2014)
	F14	*Germanium metal for solar cells*	*15.53*	*t/a*	
	F14.1	New installed photovoltaic capacity	30.11	GW/a	(National Energy Administration of the People's Republic of China, 2024)
	F14.2	Share of germanium in photovoltaics	0.05	t/GW	(Yu, 2015)
	F14.3	Number of satellite launches	63.00	units/a	(Union of Concerned Scientists, 2024)
	F14.4	Share of germanium in satellite	0.16	t/units	(CITIC Securities, 2018)
	F14.5	Loss rate in the process of processing	25.00	%	(Jorgenson, 2006)
	F15	*Germanium for others*	*3.00*	*t/a*	
	F15.1	Domestic consumption in others	2.00	t/a	(Antaike, 2012-2022)
	F15.2	Loss rate in the process of processing	25.00	%	(Jorgenson, 2006)
	F16	*New scrap recycled*	*19.00*	*t/a*	(National Development and Reform Commission, 2021)
	F17	*Domestic consumption of fiber optics*	*13.00*	*t/a*	
	F17.1	Length of fiber optic cable lines increased	4.30	million km/a	(Nation Bureau of Statistics of the People's Republic of China, 2024)
	F17.2	Number of fiber optic cores	45.00	core	(Lv, 2021)
Use	F17.3	Germanium contained in fiber optics	0.07	core million km	(Ministry of Commerce of the People's Republic of China, 2021)
	F18	*Domestic consumption of IR optics*	*21.00*	*t/a*	
	F18.1	Total consumption	78.23	t/a	(Antaike, 2020)
	F18.2	Proportion of IR optics	45.00	%	(Antaike, 2012-2018)
	F18.3	Estimated export rate of	40.00	%	(Antaike, 2012-2018)

		IR optics			
	F19	*Domestic consumption of PET*	*8.00*	*t/a*	
	F19.1	Domestic consumption in PET bottle	5.75	million t/a	(Sha, 2021)
	F19.2	Share of germanium in PET	0.01	%	(Zimmermann and Goessling-Reisemann, 2014)
	F20	*Domestic consumption of solar panel*	*11.65*	*t/a*	
	F20.1	New installed photovoltaic capacity	30.11	GW/a	(National Energy Administration of the People's Republic of China, 2024)
	F20.2	Share of germanium in photovoltaics	0.05	t/GW	(Yu, 2015)
	F20.3	Number of satellite launches	63.00	units/a	(Union of Concerned Scientists, 2024)
	F20.4	Share of germanium in satellite	0.16	t/units	(CITIC Securities, 2018)
	F21	*Domestic consumption of others*	*2.00*	*t/a*	(Antaike, 2012-2022)
	F22	*Manufacturing scrap*	*2.00*	*t/a*	
WM&R	*SR1*	*Stock of fiber optics*	*134.32*	*t/a*	*1
	F23	*Loss of fiber optics*	*1.51*	*t/a*	*1
	SR2	*Stock of IR optics*	*148.66*	*t/a*	*1
	F24	*Loss of IR optics*	*3.58*	*t/a*	*1
	F25	*Loss of PET*	*8.00*	*t/a*	
	SR3	*Stock of terrestrial solar cells*	*11.07*	*t/a*	*1
	F26	*Loss of solar cells*	*10.86*	*t/a*	
	F26.1	Loss of terrestrial solar cells	0.78	*t/a*	*1
	F26.2	Loss of space solar cells	10.08	*t/a*	
	F27	*Loss of others*	*2.00*	*t/a*	*1

Notes: *1: Lifetime model - own assumptions on average lifetime and standard deviation

Table S2 Weibull distribution function parameters for main germanium-bearing products

Products	Average lifespan	Parameters	Lifespan distribution functions	Data source

Fiber optics	14.6	β =1.70， η =18.1	F(*t*)=1-exp[-(t/18.1)1.7]	(Incorporated Administrative Agency National Institute for Environmental Studies, 2024)
IR optics	13.1	β =1.79， η =16.1	F(*t*)=1-exp[-(t/16.1)1.79]	(Incorporated Administrative Agency National Institute for Environmental Studies, 2024)
Terrestrial PV panel	30.0	β =5.4， η =32.1	F(*t*)=1-exp[-(t/32.1)30]	(Weckend et al., 2016)

Table S3 Consumption of germanium applications in China from 2000 to 2019 (unit: t)

Year	Fiber optics*1	IR optics*2	PET catalysts*3	Solar cells*4	Others*5
2000	1	1	0	0	2
2001	2	1	0	0	2
2002	1	1	0	0	2
2003	1	2	0	0	2
2004	2	2	0	1	2
2005	2	3	0	0	2
2006	1	4	0	0	2
2007	5	4	0	0	2
2008	3	6	1	2	2
2009	5	7	2	1	2
2010	5	9	3	3	2
2011	6	8	5	3	2
2012	9	8	5	4	2
2013	8	11	4	3	2
2014	9	10	4	4	2
2015	13	13	5	6	2
2016	17	15	6	5	2
2017	22	18	7	7	2
2018	16	20	7	15	2
2019	13	21	8	12	2

Notes: *1: Germanium consumption in fiber optics was approximated by the length of new fiber optics cable lines added per year in China and germanium contained per unit of fiber optics. Given an assumption of 45 cores per kilometer of optical fiber, each kilometer comprises 0.2 tons of germanium tetrachloride, wherein the germanium content within the germanium tetrachloride is calculated at 33.68%(Lv, 2021; Ministry of Commerce of the People's Republic of China, 2021; Nation Bureau of Statistics of the People's Republic of China, 2024).

*2: Available data for infrared optics generally include export volumes, assuming an average export volume of 40% (Antaike, 2012-2018).

*3: Given a scenario where 5% of PET bottles are manufactured using a germanium catalyst in the market, with 0.004% germanium dioxide present within the PET bottles, and an internal composition of 69% germanium in the compound itself (Zimmermann and Goessling-Reisemann, 2014; Sha, 2021).

*4: Assuming a 1.3% market share of germanium substrate cells in terrestrial photovoltaics, each gigawatt of these cells consists of roughly 4 tons of germanium (Yu, 2015; National Energy Administration of the People's Republic of China, 2024). Considering an average of 20,000 germanium single crystal wafers per satellite, each wafer consumes 8 grams of germanium (CITIC Securities, 2018; Union of Concerned Scientists, 2024).

*5: The consumption of other germanium products is assumed to consistently remain at 2 tons (Antaike, 2012-2022).

Table S4 Net exports of germanium products in China (unit: t)

Year	Unwrought germanium	Other germanium	Performed bars of fiber optics	Fiber optics bundles	Fiber optics cables	PET chips
2002	-	-	-	-	-	-170
2003	-	-	0	0	0	-128
2004	-	-	0	0	4	-353
2005	-	-	0	0	13	396
2006	-	-	0	0	26	536
2007	-1	38	-1	0	40	690
2008	-2	41	-1	0	50	709
2009	-12	30	-2	-2	43	408
2010	-11	41	-2	-1	50	508
2011	-4	35	-2	0	68	818
2012	0	32	-2	-2	76	1162
2013	-1	25	-3	-1	101	1751
2014	-1	12	-2	0	116	1895
2015	-4	10	-1	1	133	1479
2016	-2	15	-1	-1	150	1872
2017	-1	19	0	0	178	2100
2018	-7	19	-1	3	231	2626
2019	-5	22	0	3	252	2812
2020	-25	28	0	3	319	2210
2021	-9	42	1	8	400	3081
2022	-7	42	2	17	406	4266

Notes: Includes HS codes 81129210 (unwrought germanium), 81129910 (other germanium), 70022010 (performed bars of fiber optics), 90011000 (Fiber optics bundles), 85447000 (Fiber optics cables); 390760, 390761 (PET chips).

Supplemental notes

Note S1 Flows and stocks accounting

The mass-balance principle is applied to the entire germanium cycle in this study, which means the mass of all input streams in each stage equal to the mass of all output streams of this stage, combined with the stock change, is applied to the entire germanium cycle, as explained in Equation (S1):

$$m_i^{input} + m_i^{import} + m_i^{recycling} = m_i^{output} + m_i^{export} + m_i^{loss} + m_i^{stock} \quad , \qquad (S1)$$

where *i* is the ith life stage, *j* denotes the jth year, m_i^{input} is the Ge contained in domestic feed-in flows from ith life stage, m_i^{import} is the Ge embedded in import of Ge-contained products from ith life stage, $m_i^{recycling}$ is the recycling Ge in the ith life stage, m_i^{output} is Ge contained in products consumed by domestic demand from ith life stage, m_i^{export} is exported Ge embodied in Ge-contained products from the ith life stage, m_i^{loss} is quantity loss during the ith life stage, m_i^{stock} is the Ge net addition to the stock of the ith life stage.

Note S2 Geology, resources, and reserves of germanium

Germanium is a rare and dispersed metal. The mean germanium content of the Earth's crust lies in the range of 1.0 to 1.7 parts per million (ppm) and is usually placed at 1.4 or 1.5 ppm. As is the case for many minor metals, germanium does not occur in its elemental state in nature, but is found as a trace metal in a variety of minerals and ores. Germanium is a byproduct of copper, gold, lead, silver, and zinc deposits and is associated with ores of the mineral sulfides, oxides, hydroxides, sulfates, and silicates. It is also found in coal mainly in the form of organic matter associated with it. Direct production of germanium from germanium minerals and deposits is not commercially viable because these minerals are rarely formed in economically sustainable quantities (Shanks et al., 2017; Nguyen and Lee, 2021).

Global resources and reserve data for germanium are difficult to obtain, because details related to trace-metal concentrations in many sulfide and coal deposits are not readily available, or are of poor quality. The available resources of germanium are associated with certain zinc and lead-zinc-copper sulfide ores, as well as coal ashes. The amount of germanium potentially recoverable from coal ash is unlimited, but the commercial recovery is currently not viable except for germanium-rich coals from Russia and China (U.S. Geological Survey, 2005).

Global known resources of germanium are estimated at 7-13 kt in zinc ores and 25-112 kt in coal (Patel and Karamalidis, 2021). The estimated Ge content of coal in the USA is estimated to be 1.7 Mt (Lin et al., 2018). China has the largest share of active Ge resources based on zinc and sulfide ores, with 4.2 kt Ge in 3 deposits, while Russia has the largest share of active and potential Ge resources based on coal, with 17.5 kt Ge in 7 deposits. Other active and potential sources of Ge are the Congo (3.75 kt Zn ore) and the USA (2.3 kt Zn), followed by Canada, Mexico, Namibia, Ukraine, and Uzbekistan (Melcher and Buchholz, 2012; Patel and Karamalidis, 2021). World known reserves for germanium are estimated at 8,600 t in 2012, including 3,500 t of proven reserves of germanium in China. The top germanium reserves are in the USA, at 3,870 t.

Three important terms used in this study are "resource", "reserve base", and "reserves". A dictionary definition of Resource, "something in reserve or ready if needed," has been adapted for mineral and energy resources to comprise all materials, including those only surmised to exist, that have presented or anticipated future value. The Reserve Base is "the in-place demonstrated resource from which reserves are estimated, encompasses parts of resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics". Finally, a "Reserve" refers to "a part of the reserve base which could be economically extracted or produced at the time of determination." The potential reserves of a metal are a dynamic property, changing with geological discoveries, new technologies and new applications. Nevertheless, in order to assess relative, if not absolute, availability, it is useful to obtain a periodic snapshot. Reserve base estimation serves this function, as reserve base includes current economic resources (reserves), marginal economic resources, and some current sub-economic resources. It is more effective than reserves and resources (Gordon et al., 2006). However, there is no published data on China's germanium reserve base, so we chose to use reserves as a benchmark to check supply risk (Ministry of Natural Resources of the People's Republic of China, 2022).

Note S3 Trend projection for germanium stock and scrap

Murakami et al. (Murakami et al., 2010) introduced different definitions of product lifespan. In this study, lifespan is considered as service lifespan, that is, the time span from entering the use phase to leaving. There are several approaches to estimating lifespan distribution (Murakami et al., 2010; Oguchi et al., 2010), here, we assume a particular statistical distribution for Weibull distribution. The shape and scale parameters of Ge products were determined through literature. The probability density function f(t) and distribution function F(t) of the double-parameter Weibull distribution can be expressed in the following Equations:

$$f(t) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} \cdot exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad , \qquad (S2)$$

$$F(t) = 1 - exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad , \qquad (S3)$$

$t \geq 0, \beta > 0$

Different temporal perspectives were applied to the year of Ge stock, defined as 't', and the year of scrap generation, defined as 'n'. η and β represent the shape and scale parameters, respectively. In this study, therefore, *f*(*n*) refers to the rate of scrap generation in year n and F(n) to the cumulative rate of scrap generation in year n. The probability of scrap generation throughout year n, F'(n), can be derived from *F*(n) to *F*(n−1).

$$F^{'}(n) = exp\left[-\left(\frac{n-1}{\eta}\right)^{\beta}\right] - exp\left(-\frac{n}{\eta}\right)^{\beta} \quad , \qquad (S4)$$

The amount of scrap generated in year n is defined as P(n), which can be calculated using T(t), the amount of total input to products in year t.

$$P(n) = \sum_{t=0}^{n-1} T(t) \cdot F^{'}(n-t) \quad , \qquad (S5)$$

The flow of Ge stock change in year n, R(n), can be calculated from the difference between the total Ge input to the products in year n and the scrap generation in year n.

$$R(n) = T(n) - P(n) \quad , \qquad (S6)$$

Note S4 Forecast of germanium-bearing products

The forecast of fiber optics (Figure S3a) was estimated using a logistic growth curve fitted to the historical data in use per capita. Germanium consumption in fiber optics was approximated by the length of new fiber optics cable lines added per year in China and germanium contained per unit of fiber optics.

Due to the difficult availability of the data, IR optics was estimated using a different methodology. Firstly, the available data of IR optics, which generally include the volume of exports, should be multiplied by a rate of 60% (Antaike, 2012-2022). Then, to obtain as much data as possible, estimates by experts also be used in this study. Existing gaps were filled by linear regression on the available data. Logistic regression is not suitable for predicting IR optics demand as it grows exponentially and far exceeds China's germanium reserve of germanium in 2050. Therefore, we use second-order polynomial regression to fit to the historical data on per capita consumption to obtain the best possible fit (Figure S3b).

For the PET catalyst sector, stocks were not used for fitting here as the lifetime of PET bottles is generally considered to be less than one year. Considering the competitive substitutes in the PET catalyst market and the scarcity of resources, germanium consumption in the PET industry is likely to be flat or even decreasing in the medium to long term, thus a logistic growth curve has been fitted based on historical consumption (Figure S3c).

Solar panel application scenarios are categorized into terrestrial and space. Germanium-based solar cells are primary used in space-based application in China. A logistic growth curve was used to fitted the historical data of space germanium substrates (Figure S3d). Satellite data were obtained from the UCS Satellite Database. Germanium-containing solar cells are not common in terrestrial applications as the cost of manufacture. Nevertheless, there are considerably that they can become economically competitive in the terrestrial applications market as the highest efficiency among all available PV technologies (Bleiwas, 2010; Shanks et al., 2017). The advancement in manufacturing technology and an increase in the scale of production can reduce the cost of germanium cells. Assuming that the proportion of germanium-containing solar cells among all types of solar cells in terrestrial PV is constant at 1.3% (Chen et al., 2021), and 1 GW of new installed PV capacity consumes 4 t of germanium (Yu, 2015). According to IRENA and IEA-PVPS (Weckend et al., 2016), solar PV deployment has grown at an unprecedented rate since the early 2000s, with global installed PV capacity expected to reach 4,500 GW by 2050, including 1,731 GW in China. Due to its singular tendency, logistic regression is not suitable for fitting and therefore second-order polynomial regression is used as the best fit (Figure S3e).

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