Supplementary Information for

Towards an equitable future of global photovoltaic waste recycling

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Table for Contents

Supplementary Note S1 Comparison of global PV waste projection

This study projects that cumulative global PV waste will reach approximately 93–115 Mt by 2050 (Figure 1). These values are higher than earlier projections reported in the International Renewable Energy Agency (IRENA) 2016 study (https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels), i.e. 60–78 Mt. The discrepancy is mainly due to the more conservative assumptions by IRENA on the annual growth rates of PV installation (2.5%–8.9% post-2015). In fact, the actual global PV capacity has grown at an average annual rate of around 26% over the past decade [1]. Consequently, earlier studies likely underestimated both the scale of future PV deployment and the resulting volumes of PV waste.

However, our projections are significantly lower than those in the latest IRENA 2022 report (https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022), which projects up to 212 Mt of cumulative PV waste by 2050 under a 1.5°C-compatible pathway, with global PV capacity reaching 14,036 GW. By contrast, our study projects a maximum of 13,334 GW by 2050. This lower capacity projection reflects the exclusion of 1.5°C-aligned energy transition scenarios, as numerous studies have suggested that achieving such a pathway remains highly unlikely globally. Therefore, the lower projected PV deployment in our analysis directly leads to a more conservative projection of PV waste volumes.

This also explains the lower economic benefits from PV recycling projected in this study than those under a 1.5°C scenario. Our study projects that by 2050, global PV recycling revenues will remain below USD 11 billion, whereas IRENA's 2024 webinar (Wired for Circularity – Securing the Power Grids of the Future[2]) presented projections as high as USD 20 billion under 1.5°C-aligned scenarios.

In summary, our study provides a more conservative projection of global PV waste generation and associated economic benefits, taking into account the current challenges in meeting the 1.5°C energy transition target.

Supplementary Note S2 Variance analysis of recycling benefits

To evaluate regional inequity in recycling benefits, we calculated the variance of economic and environmental benefits across 30 regions for each scenario. For a given scenario j. The variance σ_j^2 is computed as:

$$\sigma_j^2 = \frac{1}{n}\sum_i^n \left(B_{ij} - \overline{B_j}\right)^2 \tag{1}$$

where B_{ij} represents the benefit (economic or environmental) of region i, and $\overline{B_j}$ denote the average benefit across all n=30 regions.

To facilitate comparison across scenarios, these variances were normalized to the range [0, 1] using min-max normalization. The normalized variance σ_j^{2*} is computed as:

$$\sigma_j^{2*} = \frac{\sigma_j^2 - \sigma_{min}^2}{\sigma_{max}^2 - \sigma_{min}^2} \tag{2}$$

Where σ_{min}^2 and σ_{max}^2 represents the minimum and maximum variances among all scenarios, respectively. This normalized variance reflects the relative level of inequality in each scenario, where 0 represents the least variance (highest equity) and 1 represents the greatest variance (highest inequity).

In addition, to assess the impact of subsidy policies on reducing regional disparities in recycling benefits, we calculated the variance in unit net recycling benefits (e.g., US$/ton) across the 30 regions both before and after subsidy implementation. The variance in unit net recycling benefits is computed as:

$$\sigma_{pre}^2 = \frac{1}{n}\sum_i^n \left(N_i^{pre} - \overline{N^{pre}}\right)^2 \tag{3}$$

$$\sigma_{post}^2 = \frac{1}{n}\sum_i^n \left(N_i^{post} - \overline{N^{post}}\right)^2 \tag{4}$$

Where N_i^{pre} and N_i^{post} denote the unit net benefits in region i before and after subsidies, respectively, and N_i^{pre} and N_i^{post} denote their corresponding means.

Supplementary Note S3 Calculation of recycling subsidy in various scenarios

To promote stakeholder participation and avoid the spatial concentration of PV recycling industries, we designed four subsidy scenarios for photovoltaic (PV) waste recycling: (1) Continuous subsidy scenario, (2) Declining subsidy scenario, (3) Low-carbon price scenario, and (4) High-carbon price scenario. For the carbon pricing scenarios, we adopt the Stated Policies Scenario and the Announced Pledges Scenario from IEA's report (https://www.iea.org/reports/world-energy-outlook-2024) as proxies for low- and high-carbon price pathways, respectively.

S6.1 Continuous subsidy scenario

In this scenario, the government subsidizes a fixed proportion of the total recycling cost to reduce the initial financial burden on recycling companies and stimulate infrastructure investment.

$$Subsidy_{cont} = \alpha \times TC_{total} \tag{5}$$

Where α is the subsidy rate, randomly sampled from a uniform distribution between 0.01 and 0.15 in Monte Carlo simulations. TC_{total} is the recycling total cost (USD/ton). $Subsidy_{cont}$ is the subsidy received (USD/ton).

S6.2 Declining subsidy scenario

In this scenario, subsidies decrease gradually once the project breaks even. The annual reduction rate r starts at 0.1 in the first year after break-even and increases by 0.1 each year until it reaches 1.0, at which point the subsidy is phased out completely.

$$Subsidy_{decline,t} = \beta_t \times P_{price} \times Total\ PV \tag{6}$$

$$\beta_t = \begin{cases} \beta_0, if\ t \leq t_{break-even} \\ \beta_{t-1} \times (1 - r_t), if\ t > t_{break-even}, r_t \in \{0.1, 0.2, ..., 1\} \end{cases} \tag{7}$$

Where β_0 is the initial subsidy rate, randomly sampled from a uniform distribution between 0.15 and 0.20 in Monte Carlo simulations. β_{t-1} is the subsidy rate in year *t*. P_{price} is the sales price of PV modules (USD/ton). $Total\ PV$ refers to the volume of PV waste generated. r_t is the annual reduction rate in year t, increasing by 0.1 per year starting from 0.1. $t_{break-even}$ is the year when recycling reaches break-even.

S6.3 Carbon price subsidy scenario

These scenarios evaluate environmental benefits from recycling based on avoided carbon emissions, which are monetized using region-specific carbon prices (Extended Data Table 3).

$$Subsidy_{carbon} = \gamma \times E_{avoided} \tag{8}$$

Where γ is the regional carbon price (USD/tCO_2). $E_{avoided}$ is the amount of avoided carbon emissions from PV recycling (tCO_2-eq/ton).

Supplementary Table S1. Capacity factor in GCAM

GCAM Region	Utility-scale PV	Distributed PV
USA	0.2	0.17
Africa_Eastern	0.28236	0.24
Africa_Northern	0.28019	0.23816
Africa_Southern	0.27554	0.23421
Africa_Western	0.27357	0.23253
Australia_NZ	0.27252	0.23164
Brazil	0.24671	0.2097
Canada	0.12978	0.11031
Central America and Caribbean	0.25133	0.21363
Central Asia	0.21567	0.18247
China	0.23988	0.2039
EU-12	0.16551	0.14069
EU-15	0.18318	0.1557
Europe_Eastern	0.16287	0.13844
Europe_Non_EU	0.21953	0.1866
European Free Trade Association	0.1099	0.09341
India	0.24736	0.21025
Indonesia	0.23176	0.19699
Japan	0.18912	0.16075
Mexico	0.26843	0.22816
Middle East	0.27372	0.23266
Pakistan	0.25961	0.22067
Russia	0.13021	0.11068
South Africa	0.27614	0.23472
South America_Northern	0.24307	0.20661
South America_Southern	0.24065	0.20456
South Asia	0.25478	0.21656
South Korea	0.20922	0.17784
Southeast Asia	0.23772	0.20206
Argentina	0.23285	0.19792

Colombia	0.21884	0.18601

Note: The original regions in the GCAM model include EU-15 and EU-12. We combine them into a single region, EU-27.

Supplementary Table S2. Solar PV installed capacity in 2000-2005(unit: GW).

GCAM Region	2000	2001	2002	2003	2004	2005
Africa_Eastern	0.0	0.0	0.0	0.0	0.0	0.0
Africa_Northern	0.0	0.0	0.0	0.0	0.0	0.0
Africa_Southern	0.0	0.0	0.0	0.0	0.0	0.0
Africa_Western	0.0	0.0	0.0	0.0	0.0	0.0
Argentina	0.0	0.0	0.0	0.0	0.0	0.0
Australia_NZ	0.0	0.0	0.0	0.0	0.0	0.1
Brazil	0.0	0.0	0.0	0.0	0.0	0.0
Canada	0.0	0.0	0.0	0.0	0.0	0.0
Central America and the Caribbean	0.0	0.0	0.0	0.0	0.0	0.0
Central Asia	0.0	0.0	0.0	0.0	0.0	0.0
China	0.0	0.0	0.0	0.0	0.0	0.1
Colombia	0.0	0.0	0.0	0.0	0.0	0.0
EU-27	0.2	0.3	0.3	0.6	1.3	2.3
Europe_Eastern	0.0	0.0	0.0	0.0	0.0	0.0
Europe_Non_EU	0.0	0.0	0.0	0.0	0.0	0.0
European Free Trade Association	0.0	0.0	0.0	0.0	0.0	0.0
India	0.0	0.0	0.0	0.0	0.0	0.0
Indonesia	0.0	0.0	0.0	0.0	0.0	0.0
Japan	0.3	0.5	0.6	0.9	1.1	1.4
Mexico	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	0.0	0.0	0.0	0.0	0.0	0.0
Pakistan	0.0	0.0	0.0	0.0	0.0	0.0
Russia	0.0	0.0	0.0	0.0	0.0	0.0
South Africa	0.0	0.0	0.0	0.0	0.0	0.0
South America_Northern	0.0	0.0	0.0	0.0	0.0	0.0
South America_Southern	0.0	0.0	0.0	0.0	0.0	0.0

South Asia	0.0	0.0	0.0	0.0	0.0	0.0
South Korea	0.0	0.0	0.0	0.0	0.0	0.0
Southeast Asia	0.0	0.0	0.0	0.0	0.0	0.0
USA	0.2	0.2	0.3	0.3	0.4	0.5
Total	0.8	1.0	1.3	1.8	2.9	4.4

Note: The specific countries included in each GCAM region can be found in Supplementary Table S7.

Supplementary Table S3. Solar PV installed capacity in 2006-2011(unit: GW).

GCAM Region	2006	2007	2008	2009	2010	2011
Africa_Eastern	0.0	0.0	0.0	0.0	0.0	0.0
Africa_Northern	0.0	0.0	0.0	0.0	0.0	0.0
Africa_Southern	0.0	0.0	0.0	0.0	0.0	0.0
Africa_Western	0.0	0.0	0.0	0.0	0.0	0.0
Argentina	0.0	0.0	0.0	0.0	0.0	0.0
Australia_NZ	0.1	0.1	0.1	0.3	1.1	2.5
Brazil	0.0	0.0	0.0	0.0	0.0	0.0
Canada	0.0	0.0	0.0	0.1	0.2	0.6
Central America and the Caribbean	0.0	0.0	0.0	0.0	0.1	0.1
Central Asia	0.0	0.0	0.0	0.0	0.0	0.0
China	0.1	0.1	0.1	0.3	0.9	3.1
Colombia	0.0	0.0	0.0	0.0	0.0	0.0
EU-27	3.2	5.0	10.4	16.7	30.0	53.1
Europe_Eastern	0.0	0.0	0.0	0.0	0.0	0.2
Europe_Non_EU	0.0	0.0	0.0	0.0	0.0	0.0
European Free Trade Association	0.0	0.0	0.1	0.1	0.1	0.2
India	0.0	0.0	0.0	0.0	0.0	0.5
Indonesia	0.0	0.0	0.0	0.0	0.0	0.0
Japan	1.7	1.9	2.1	2.6	3.6	4.9
Mexico	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	0.0	0.0	0.0	0.0	0.1	0.2
Pakistan	0.0	0.0	0.0	0.0	0.0	0.0
Russia	0.0	0.0	0.0	0.0	0.0	0.0
South Africa	0.0	0.0	0.0	0.0	0.0	0.0
South America_Northern	0.0	0.0	0.0	0.0	0.0	0.0
South America_Southern	0.0	0.0	0.0	0.0	0.0	0.0
South Asia	0.0	0.0	0.0	0.0	0.0	0.0

South Korea	0.0	0.1	0.4	0.5	0.7	0.7
Southeast Asia	0.0	0.0	0.0	0.0	0.1	0.1
USA	0.7	1.0	1.2	1.6	2.9	5.2
Total	5.9	8.3	14.4	22.5	39.8	71.5

Note: The specific countries included in each GCAM region can be found in Supplementary Table S7.

Supplementary Table S4. Solar PV installed capacity in 2012-2017(unit: GW).

GCAM Region	2012	2013	2014	2015	2016	2017
Africa_Eastern	0.0	0.0	0.0	0.0	0.0	0.1
Africa_Northern	0.0	0.0	0.0	0.0	0.3	0.5
Africa_Southern	0.0	0.0	0.0	0.0	0.0	0.1
Africa_Western	0.0	0.0	0.0	0.0	0.1	0.2
Argentina	0.0	0.0	0.0	0.0	0.0	0.0
Australia_NZ	3.8	4.6	5.3	6.0	6.7	7.4
Brazil	0.0	0.0	0.0	0.0	0.1	1.2
Canada	0.8	1.2	1.8	2.5	2.7	2.9
Central America and the Caribbean	0.1	0.2	0.2	0.8	0.9	1.2
Central Asia	0.0	0.0	0.0	0.1	0.1	0.1
China	6.7	17.9	28.7	44.1	78.7	132.2
Colombia	0.0	0.0	0.0	0.0	0.0	0.0
EU-27	70.8	80.3	86.8	94.9	101.0	106.5
Europe_Eastern	0.4	0.7	0.8	0.8	1.0	1.3
Europe_Non_EU	0.0	0.1	0.1	0.3	0.9	3.5
European Free Trade Association	0.4	0.8	1.1	1.4	1.7	2.0
India	0.8	1.2	3.1	4.9	9.0	17.1
Indonesia	0.0	0.0	0.0	0.0	0.0	0.1
Japan	6.6	13.6	23.3	34.2	42.0	49.5
Mexico	0.1	0.1	0.2	0.3	0.6	1.1
Middle East	0.3	0.5	0.7	0.9	1.4	2.0
Pakistan	0.0	0.1	0.2	0.3	0.6	0.6
Russia	0.0	0.0	0.0	0.1	0.1	0.2
South Africa	0.0	0.3	1.1	1.3	2.0	3.1
South America_Northern	0.0	0.0	0.0	0.1	0.1	0.1
South America_Southern	0.1	0.1	0.3	0.8	1.3	2.3

South Asia	0.0	0.0	0.0	0.0	0.1	0.2
South Korea	1.0	1.6	2.6	3.8	4.9	6.4
Southeast Asia	0.4	1.0	1.6	2.0	3.8	4.3
USA	8.1	12.0	16.4	22.5	33.7	42.0
Total	100.7	136.1	174.5	222.0	293.8	388.2

Note: The specific countries included in each GCAM region can be found in Supplementary Table S7.

Supplementary Table S5. Solar PV installed capacity in 2020-2022(unit: GW).

GCAM Region	2018	2019	2020	2021	2022
Africa_Eastern	0.2	0.2	0.3	0.3	0.5
Africa_Northern	1.3	2.2	2.2	2.3	2.4
Africa_Southern	0.1	0.3	0.3	0.4	0.7
Africa_Western	0.3	0.4	0.4	0.5	0.7
Argentina	0.2	0.4	0.8	1.1	1.1
Australia_NZ	11.5	16.3	21.0	25.9	29.9
Brazil	2.4	4.6	8.3	14.2	24.1
Canada	3.1	3.3	3.6	4.6	5.3
Central America and the Caribbean	1.6	2.1	2.4	2.9	3.2
Central Asia	0.3	0.7	1.1	1.4	1.8
China	177.4	208.3	258.8	313.7	401.7
Colombia	0.0	0.0	0.1	0.2	0.4
EU-27	114.6	130.9	149.1	174.8	208.4
Europe_Eastern	2.2	6.1	7.5	8.2	8.4
Europe_Non_EU	5.2	6.1	6.9	8.1	9.9
European Free Trade Association	2.2	2.6	3.1	3.8	4.6
India	26.0	33.7	37.9	48.0	61.1
Indonesia	0.0	0.1	0.1	0.2	0.2
Japan	56.2	63.2	71.9	78.4	83.1
Mexico	2.6	4.7	6.7	8.2	9.3
Middle East	3.0	5.5	7.0	9.2	12.5
Pakistan	0.7	0.7	0.8	1.1	1.2
Russia	0.5	1.3	1.4	1.7	1.8
South Africa	4.4	4.4	5.5	5.8	5.8
South America_Northern	0.1	0.1	0.1	0.1	0.1
South America_Southern	2.8	3.3	3.9	5.1	6.9
South Asia	0.3	0.4	0.6	1.0	1.1

South Korea	8.9	12.7	17.3	21.3	24.1
Southeast Asia	4.9	10.5	23.1	24.1	26.6
USA	50.2	59.8	74.7	93.9	111.5
Total	483.0	585.2	716.7	860.4	1048.5

Note: The specific countries included in each GCAM region can be found in Supplementary Table S14.

Supplementary Table S6. Income groups and included regions according to World Bank's classification

Income group	Regions
High-income	Australia_NZ, Canada, Europe_Non_EU, USA, European Free Trade Association, EU-27, South Korea, Japan
Middle-income	Mexico, Central America and the Caribbean, Brazil, South America_Northern, South America_Southern, Colombia, Argentina, South Africa, Russia, Middle East, China, Southeast Asia
Low- income	Europe_Eastern, Africa_Eastern, Africa_Northern, Africa_Southern, Africa_Western, India, Indonesia, South Asia, Central Asia, Pakistan

Supplementary Table S7. The region classification used in the GCAM model

GCAM Region	Countries or sub-regions in the region
Australia_NZ	Australia, New Zealand
South Asia	Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Nepal
Japan	Japan
South Korea	South Korea
Southeast Asia	American Samoa, Brunei Darussalam, Cocos (Keeling) Islands, Cook Islands, Christmas Island, Fiji, Federated States of Micronesia, Guam, Cambodia, Kiribati, Lao Peoples Democratic Republic, Marshall Islands, Myanmar, Northern Mariana Islands, Malaysia, Mayotte, New Caledonia, Norfolk Island, Niue, Nauru, Pacific Islands Trust Territory, Pitcairn Islands, Philippines, Palau, Papua New Guinea, Democratic Peoples Republic of Korea, French Polynesia, Singapore, Solomon Islands, Seychelles, Thailand, Tokelau, Timor Leste, Tonga, Tuvalu, Viet Nam, Vanuatu, Samoa
Central Asia	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, Uzbekistan
India	India
China	China
Pakistan	Pakistan
Indonesia	Indonesia
Canada	Canada
USA	United States
Mexico	Mexico
Central America and Caribbean	Aruba, Anguilla, Netherlands Antilles, Antigua & Barbuda, Bahamas, Belize, Bermuda, Barbados, Costa Rica, Cuba, Cayman Islands, Dominica, Dominican Republic, Guadeloupe, Grenada, Guatemala, Honduras, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Montserrat, Martinique, Nicaragua, Panama, El Salvador, Trinidad and Tobago, Saint Vincent and the Grenadines

EU-27	Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovakia, Slovenia, Andorra, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Ireland, Italy, Luxembourg, Monaco, Netherlands, Portugal, Sweden, Spain, United Kingdom
Europe_Non_EU	Albania, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia, Turkey
European Free Trade Association	Iceland, Norway, Switzerland
Europe_Eastern	Belarus, Moldova, Ukraine
Russia	Russia
Africa_Eastern	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Sudan, Somalia, Uganda
Africa_Northern	Algeria, Egypt, Western Sahara, Libya, Morocco, Tunisia
Africa_Southern	Angola, Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe
Africa_Western	Benin, Burkina Faso, Central African Republic, Cote d'Ivoire, Cameroon, Democratic Republic of the Congo, Congo, Cape Verde, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Sao Tome and Principe, Chad, Togo
South Africa	South Africa
Argentina	Argentina
Brazil	Brazil
Colombia	Colombia
South America_Northern	French Guiana, Guyana, Suriname, Venezuela
South America_Southern	Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay
Middle East	United Arab Emirates, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Yemen

Supplementary Table S8. The region classification used in the GCAM model

Year	Weight-to-power ratio(t/GW)	Year	Weight-to-power ratio(t/GW)
2000	109863.0	2031	55393.7
2001	106660.9	2032	54043.5
2002	103769.5	2033	52801.7
2003	101188.9	2034	51640.1
2004	98919.0	2035	50554.0
2005	97000.0	2036	49543.4
2006	95672.7	2037	48608.4
2007	94977.2	2038	47736.2
2008	94767.7	2039	46850.6
2009	94169.9	2040	45939.0
2010	93038.0	2041	45001.3
2011	91372.0	2042	44037.5
2012	89171.9	2043	43061.0
2013	86437.8	2044	42152.1
2014	83392.3	2045	41324.0
2015	80258.4	2046	40576.8
2016	77036.0	2047	39910.5
2017	73725.1	2048	39325.1
2018	70325.8	2049	38820.6
2019	67333.5	2050	38397.0
2020	65244.0	2051	38397.0
2021	64057.2	2052	38397.0
2022	63773.1	2053	38397.0
2023	64218.4	2054	38397.0
2024	64352.8	2055	38397.0
2025	64003.0	2056	38397.0
2026	63168.9	2057	38397.0
2027	61850.7	2058	38397.0
2028	60122.8	2059	38397.0

2029	58433.4	2060	38397.0
2030	56857.0		

Supplementary Table S9. Input and output flows associated with the mechanical recycling processes of PV waste.

Phases	Input	quantity	Output	quantity
Transportation	module waste	1t	module waste	1t
	diesel fuel	21.49kg/km	NOx	574g
			SO_2	2068.5g
			CO_2	17.8275kg
			methane	136.5g
			total particulate matter	140g
Al frame removal	module waste	1t	Al frame	179kg
	electricity	5.3kwh	junction box	14.4kg
			copper wire	9.767kg
			laminate	745.833kg
			electricity	17.8448kwh
			solid waste	51kg
			chemical waste	30.29g
			total particulate matter	0.03g
Knife grinder cutting	laminate	745.833kg	fragment mixture	641.63kg
	electricity	48kwh	EVA	41kg
	water	20kg	general waste	56kg
			hazardous waste	7.2kg

			liquid waste	18.6kg
			NOx	108kg
			SO_2	71.4kg
			CO_2	144.5kg
Grinding and screening	fragment mixture	641.63kg	glass fragments	505.4kg
	electricity	3.45kwh	metal fragments	28.89kg
			solid waste	107.34kg
			liquid waste	10.11kg
			ammonia nitrogen	2.78g
			total nitrogen	113.72g
			total phosphorus	0.25g

Supplementary Table S10. Input and output flows associated with the chemical recycling processes of PV waste.

Phases	Input	quantity	Output	quantity
Transportation	module waste	1t	module waste	1t
	diesel fuel	21.49kg/km	NOx	574g
			SO_2	2068.5g
			CO_2	17.8275kg
			methane	136.5g
			total particulate matter	140g
Al frame removal	module waste	1t	Al frame	179kg
	electricity	5.3kwh	junction box	14.4kg
			copper wire	9.767kg
			laminate	745.833kg
			electricity	17.8448kwh
			solid waste	51kg
			chemical waste	30.29g
			total particulate matter	0.03g
Toluene soak	laminate	745.833kg	glass	635kg
	toluene	63.14kg	back panel	33.9kg
	water	173.2kg	cells	24.97kg

	electricity	56.76kwh	sludge	18.3kg
			electricity	41.16138 kwh
			liquid waste	236.34kg
			solid waste	38.92kg
			NOx	2kg
			dichloroe thylene	30.82kg
			CO_2	32.25kg
			methane	50.69kg
			total phosphor ous	0.32kg
			total nitrogen	6.6kg
Metal extraction	cells	24.97kg	silicon	21.6kg
	nitric acid	6.72kg	silver	0.46kg
	electricity	32.23kwh	copper	2.91kg
	water	175.76kg	liquid waste	173.71kg
			NO_x	108.54kg
			SO_2	71.4kg
			CO_2	144.5kg
			total particulat e matter	9.5g

Supplementary Table S11. Input and output flows associated with the thermal recycling processes of PV waste.

Phases	Input	quantity	Output	quantity
Transportation	module waste	1t	module waste	1t
	diesel fuel	21.49kg/km	NOx	382g
			SO_2	1379g
			CO_2	67kg
			methane	91g
			total particulate matter	140g
Al frame removal	module waste	1t	Al frame	179
	electricity	5.3kwh	junction box	14.4
			copper wire	9.767
			laminate	745.833
			electricity	17.8448kwh
			solid waste	51kg
			chemical waste	30.29g
			total particulate matter	0.03g
Heat decomposition	laminate	745.833kg	EVA	45.9kg
	electricity	35.7kwh	glass	665kg
	nitrogen gas	154.22m³	cells	38.91kg
	oxidant	165.98m³	backplan	14.5

			e	
	standard coal	80.92kg	solid waste	96.75kg
			CO_2	32.25kg
			methane	50.69kg
			NO_2	30.94kg
			SO_2	51.17kg
Metal extraction	cells	38.91kg	Al	2.6kg
	water	309.7kg	silicon	34.7kg
	electricity	56.8kwh	silver	0.53kg
	nitric acid	7.08kg	copper wire	1.08kg
	potassiu m hydroxid e	36.5kg	sludge	50.2kg
			liquid waste	306.1kg
			NO_2	30.23kg
			SO_2	24.04kg
			CO_2	30.82kg
			Nitric oxide	0.14kg
			Ammonia	

Supplementary Table S12. Unit recycling cost of mechanical recycling technology (Unit: US$/ton).

Recycling costs				
Stage-by-stage costs	Collection			110
	transportation	logistics		119.25
		emissions		1.86
	dismantling	energy and resource	water	0
			electricity	0.40
		storage		47.2
		loss		5.5
	processing	materials		0
		energy and resource	water	0.01
			electricity	3.96
	disposal	general solid waste		1.13
		hazardous solid waste		3.20
		liquid waste		0.03
		gas waste		379.95
Whole-process costs	labor			per capita Gross National Income (GNI)
	management	safety production expenses		3.5
		general management		30% of the labor cost
	depreciation of fixed assets			175
	operation and maintenance			3.5
	opportunity cost			8.75

Supplementary Table S13. Unit recycling cost of chemical technology (Unit: US$/ton).

Recycling costs				
Stage-by-stage costs	Collection			110
	transportation	logistics		119.25
		emissions		1.875
	dismantling	energy and resource	water	0
			electricity	0.41
		storage		47.25
		loss		5.5
	processing	materials	toluene	71.49
			nitric acid	1.73
		energy and resource	water	0.16
			electricity	6.85
	disposal	general solid waste		0.48
		hazardous solid waste		0
		liquid waste		0.66
		sludge		0.56
		gas waste		396.94
whole-process costs	labor			per capita Gross National Income (GNI)
	management	safety production expenses		4.25
		general management		30% of the labor cost
	depreciation of fixed assets			212.5
	operation and maintenance			4.25
	opportunity cost			10.63

Supplementary Table S14. Unit recycling cost of thermal technology (Unit: US$/ton).

Recycling costs				
Stage-by-stage costs	Collection			110.00
	transportation	logistics		119.25
		emissions		1.88
	dismantling	energy and resource	water	0.00
			electricity	0.41
		storage		47.25
		loss		5.50
	processing	materials	Nitrogen	12.43
			Oxidant	28.69
			nitric acid	1.83
			sodium hydroxide	10.98
		energy and resource	water	0.14
			standard coal	4.38
			electricity	7.12
	disposal	general solid waste		0.78
		sludge		1.54
		liquid waste		0.49
		gas waste		282.85
whole-process costs	labor			per capita Gross National Income (GNI)
	management	safety production expenses		5.25
		general management		30% of the labor cost
	depreciation of fixed assets			262.50
	operation and maintenance			5.25
	opportunity cost			13.13

Supplementary Table S15. Unit recycling benefits of three technologies (Unit: US$/ton).

Recycling benefits		
mechanical recycling	Aluminum	230.80
	Copper	55.97
	Glass	36.19
	Silicon	0.00
	Silver	0.00
	Metallic mixture	165.56
Chemical recycling	Aluminum	230.80
	Copper	72.65
	Glass	45.47
	Silicon	129.97
	Silver	263.61
	Metallic mixture	0.00
Thermal benefits	Aluminum	234.16
	Copper	62.16
	Glass	47.61
	Silicon	208.80
	Silver	303.73
	Metallic mixture	0.00

Supplementary Table S16. PV module learning rate

GCAM region	Learning rate
USA	0.264
Africa_Eastern	0.1
Africa_Northern	0.1
Africa_Southern	0.1
Africa_Western	0.1
Australia_NZ	0.233
Brazil	0.163
Canada	0.233
Central America and Caribbean	0.163
Central Asia	0.1
China	0.32
EU-12	0.202
EU-15	0.202
Europe_Eastern	0.1
Europe_Non_EU	0.202
European Free Trade Association	0.202
India	0.163
Indonesia	0.1
Japan	0.23
Mexico	0.163
Middle East	0.163
Pakistan	0.1
Russia	0.163
South Africa	0.163
South America_Northern	0.163
South America_Southern	0.163
South Asia	0.1
South Korea	0.233
Southeast Asia	0.163

Argentina	0.163
Colombia	0.163