Estimation of photovoltaic waste spatio-temporal distribution by 2060 in the context of carbon neutrality

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Abstract

In recent decades, large-scale deployment of photovoltaic (PV) power leads to management challenges for recycling PV module waste in China. With the growth of waste PV volumes, it is necessary to figure out the spatio-temporal distribution of PV waste at the provincial level. Based on China's carbon neutrality goal by 2060, six development pathways of PV installed capacity are proposed to identify in-use stocks of PV capacity. In particular, we developed the retired flow estimation model for PV modules that is constructed by three PV module degradation scenarios. The results show that a relatively large scale of PV waste will be started to emerge in China by 2030 and the cumulative waste is expected to reach 1100 $\sim$ 1450 GW by 2060. Our findings also indicate an unequal distribution of PV waste across regions and the highest PV waste volumes by 2060 is the East China region at 31.4%, with Shandong (8.99%) and Hebei(8.65%) ranking as the top provinces. This prospective research will help the PV industry plan the location and capacity of recovery facilities at an appropriate time to advance toward a more resource efficient and circular economy.

Keywords: Solar photovoltaic waste, Recycling, Spatio-temporal distribution, Sustainability, carbon neutrality, China

1 Introduction

In response to climate change, China has set a clear goal of achieving carbon neutrality before 2060 (Zhao et al., 2022). Renewable energy, especially solar energy, is anticipated to become the dominant source of electricity due to zero carbon dioxide emissions when generating electricity (Kök et al., 2018). Moreover, investment in solar energy is increasing rapidly in China, since the cost of solar power has dropped dramatically over the past decade (He et al., 2020; IRENA, 2021). By the end of 2021, China's new and total installed photovoltaic (PV) capacity ranked first in the world for nine and seven years, respectively (Muthusamy et al., 2022). Large-scale PV deployment also will generation substantial amounts of end-of-life (EOL) PV modules (Muthusamy et al., 2022; Walzberg et al., 2021). As a result, China will face significant obstacles on the path to carbon neutrality, that is how to deal with large volumes of PV modules at the end of their approximately 30-year lifespan emerges (Heath et al., 2020) as large-scale global PV deployment proceeds.

There's a need for China to recycle PV waste sooner or later, which not only reduces environmental problems but also avoids wastage of crucial resources (Salim et al., 2019). Because solar energy is China's most abundant renewable energy resource, particularly in western China (EF, 2015), the most noteworthy feature of China's PV waste management is the spatial heterogeneity. While planning EOL PV panels recovery, monitoring changes in the PV module design and regional trends in PV module deployment could assist the recycling industry in designing and adapting recycling infrastructure (Choi and Fthenakis, 2014; Goe et al., 2015). To manage those waste PV modules in China, a comprehensive and accurate estimation of waste spatio-temporal distribution is necessary.

There are two main points involved: one is that discarded PV modules are generally generated where the PV power station is installed. China's solar power deployment pattern is shifting from western to eastern regions, and from centralized to distributive form (Li and Huang, 2020). Furthermore, the majority of centralized PV power plants are located in northwest China, whereas distributed PV power generation is a more cost-effective option in central and eastern China (Wu et al., 2022). Previous research has highlighted the necessity of waste distribution for ease of collection and transport across the area to reduce resource waste (Hemmelmayr et al., 2014). Consequently, as an emerging waste type with a complicated composition and a broad spatial dispersion, waste PV's distribution data is critical for infrastructure considerations when proximity to the waste source is relevant (Goe et al., 2015).

Second, we recognize that the different pathways to achieve carbon neutrality lead to different targets for solar energy installed capacity (Zhao et al., 2022), which will directly affect the volume of PV waste generated. Additionally, solar energy deployment in China is highly reliant on unpredictable future market conditions and public policies, including but not limited to polices aimed at achieving the country's "dual carbon" goal (Wei and Xin-gang, 2022). Little attention has been paid to the impact of the context of carbon neutrality on PV waste flow in China (Wang et al., 2021). Therefore, considering potential PV development pathways in the context of carbon neutrality enables an accurate prediction of waste.

There are a large number of studies that have focused on waste PV recycling domains such as recovery technology (Azeumo et al., 2019; Cui et al., 2022), environmental impacts, and economic return of stakeholders (Faircloth et al., 2019; Liu et al., 2020). Many studies have provided insightful information on estimating the future generation of PV waste in several countries, including Italy, Mexico, Australia, America, India, and Spain (Dominguez and Geyer, 2019, 2017; Mahmoudi et al., 2019, 2021; Paiano, 2015; Santos and Alonso-Garcia, 2018; Gautam et al., 2022). Very few studies have emphasized the influence of the carbon-neutral target on newly added PV flows, in-use stocks, and retired flows of China, the world's largest solar power market (Xu et al., 2020).

Motivated by the research gaps, this study assesses the provincial cumulative waste generation to accurately grasp the spatio-temporal pattern of waste PV generation and provide a reasonable basis for recycling strategies in China. In the context of carbon neutrality, this study aims to: (1) investigate the development of the PV industry to propose PV installed capacity under three different scenarios with two classical growth patterns; (2) develop a methodology to forecast the input and output of PV power installed, including the timing and position of PV waste generation; (3) and estimate the PV waste volumes and its mid-long term waste distribution in China from 2022 to 2060. This study also provides a foundation for other nations with similar waste concerns to China, as well as related industries, to gain more insights.

The structure of this paper is organized as follows: In Section 2, the method and data of this paper are described in detail; the results and discussion are reported in Section 3; followed by the conclusions in the final section.

2 Research methods and data

2.1 Research framework

An analysis of how much, when, and where the PV systems will reach their EOL will aid in PV waste management planning (Dominguez and Geyer, 2019). According to the input and output theory, the relationship of the newly flows (annual newly installed PV capacity $N(t)$), in-use stocks (cumulative PV installed capacity $Q(t)$), and retired flows (yearly waste PV modules $W(t)$) in the year t can be represented as:

$$Q(t) = Q(t-1) + N(t) - W(t) \tag{1}$$

$$Q\left(t\right) = \sum_{i=1}^{31} Q(t)_i \tag{2}$$

$$W\left(t\right) = \sum_{i=1}^{31} W(t)_i \tag{3}$$

$$N\left(t\right) = \sum_{i=1}^{31} N(t)_i \tag{4}$$

where $Q(t)_i$ represents cumulative PV installed capacity in the year t in the province i, $W(t)_i$ represents yearly PV waste volumes in the year t in the province i, and $N(t)_i$ indicates the annual newly installed PV capacity in the year t in the province i.

Following that, we explains the PV waste estimation methodology (see Fig.1) and the source of data. Firstly, three development scenarios are constructed with two classical growth patterns for cumulative PV installed capacity forecasting. Secondly, considering the characteristics of PV power market development stages, the Weibull forecasting model is established to estimate the retired flows. As a result, based on historical data, this research assesses how much waste PV modules are discarded, as well as when and where those are available for collection.

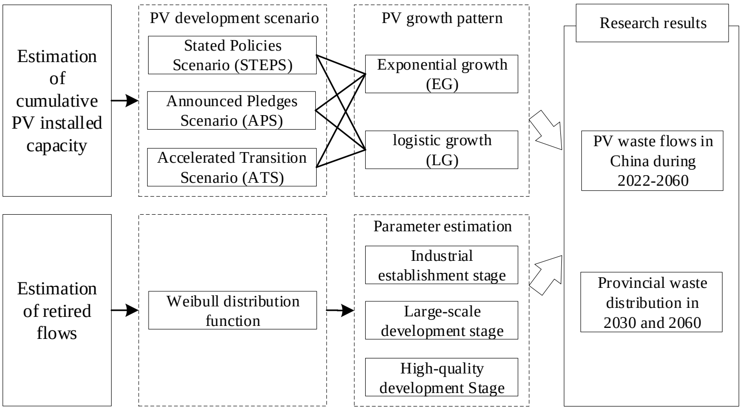


Fig. 1: PV waste estimation methodology

2.2 Estimation of cumulative PV installed capacity

There are two-stage to the projection of PV installed capacity in China, which will influence PV waste estimation. First, we construct three PV development scenarios by outlining the short-term and long-term development targets from government and authority organizations. Then, the trend of cumulative PV installed capacity is simulated by applying two PV growth patterns. Therefore, we have 6 (3 × 2) pathways to consider.

2.2.1 PV development scenario

Achieving carbon neutrality by 2060 in line with China's broader development goals (IEA, 2021b). It stands at the confluence of the strategic national objectives at some pointy stages, including a peak in CO_2 emissions before 2030 and becoming the top innovation-oriented country by 2035 (Xi, 2021). Based on well-recognized settings that were collected from the official report, three scenarios have been considered for the target goals of the PV installed capacity in the years 2035 or 2050, and 2060 in China (Table 1), which are the main input to cumulative PV installed estimation.

Table 1: The target PV installed capacity of different development scenarios

Abbreviation	Capacity in 2035 (GW)	Capacity in 2050 (GW)	Capacity in 2060 (GW)	Source
Stated Policies Scenario (STEPS)	1486	2157	——	CNREC (2018)
Announced Pledges Scenario (APS)	1470	——	4515	IEA (2021a)
Accelerated Transition Scenario (ATS)	1764	——	5418	IEA (2021b)

The first is the Stated Policies Scenario (STEPS), where data points are collected from the "Below 2 degrees" scenario that shows ambitious deployment targets for 2050. This provides a more conservative benchmark for the future because it does not take it for granted that governments will reach all announced goals (IEA, 2021c). Therefore, this energy scenario set specific PV installed targets for 2035 and 2050 to be around 1486 GW and 2157 GW, respectively.

The second scenario, the Announced Pledges Scenario (APS), reflects China's enhanced targets that it declared in 2020 in which emissions of CO_2 reach a peak before 2030 and net-zero by 2060, in line with China's stated goals. The solar energy sector's cumulative PV capacity is 1470 GW and 4515 GW in 2035 and 2060, respectively.

The third is the Accelerated Transition Scenario (ATS), which is an even faster transition and has the socio-economic benefits than APS. China has the technical capabilities, economic means, and policy experience to accomplish a faster clean energy transition than the APS. Therefore, in this scenario, PV installed capacity rises by about 15% above the level of the APS.

2.2.2 PV growth pattern

Given the PV development scenario, the growth patterns specify the annual development of solar power to reach the installed capacity target (Ren et al., 2021). Two commonly used growth patterns are employed to construct a concrete China's PV energy pathway toward 2060 (Ren et al., 2021).

One is the Exponential Growth (EG), which can reflect the rapid growth of new energy technology at the beginning phase or in the fast-growing phase (Hansen et al., 2017). History shows an exponential growth for the new renewable energy (RE) technologies (e.g. wind and solar energy) (Fell, Breyer, and Métayer, Fell et al.). The logistic function can be written as follows:

$$Q(t) = x_0(1 + r)^t \tag{5}$$

where $Q(t)$ is the cumulative PV installed capacity in the year t in China, x_0 is the PV installed capacity in the year t_0, and r is the fixed annual growth rate.

The second is the Logistic Growth (LG), which can reflect the mature phase of an energy technology during the study period. It has also been shown to adequately model energy demand and consumption (Cherp et al., 2021; Harris et al., 2018; Madsen and Hansen, 2019). Solar power production as a function of time can be well described by a logistic curve in Italy and China (Bianco et al., 2021; Madsen and Hansen, 2019). The logistic growth formula is shown as follows:

$$Q(t) = \frac{S}{(1 + e^{(-k(t-t_a))})} \tag{6}$$

where S is the asymptotic PV installed capacity, k is the diffusion rate, t_a is the inflection point where the maximum growth rate occurs.

2.2.3 Evolution of China's cumulative PV installed to 2060

As the previous section described, combined 3 deployment scenarios (Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), and Accelerated Transition Scenario (ATS)) and 2 types of growth patterns (Exponential Growth (EG) and Logistic Growth(LG)), we have 6 (3×2) pathways to take into account. Using historical cumulative PV installed data from the year 2009 to 2021 and the target value in the years 2035, 2050, and 2060, the estimation of parameters are listed in Table 2.

Then the six pathways are simulated in Fig.2. For example, the STEPS-LG is regarded as a China's PV development pathway under the STEPS development scenario with the LG growth pattern.

Table 2: Parameters estimation of PV development pathway

Pathway	Scenario	Growth pattern	Parameter
STEPS-LG	STEPS	LG	$S = 2228.5$; $k = 0.1808$; $t = 11.1634$
STEPS-EG	STEPS	EG	2021-2035: $r = 0.1195$; 2035-2060: $r = 0.0252$
APS-LG	APS	LG	$S = 4893.1$; $k = 0.1330$; $t = 21.3551$
APS-EG	APS	EG	2021-2035: $r = 0.1186$; 2035-2060: $r = 0.0459$
ATS-LG	ATS	LG	$S = 5722.2$; $k = 0.1475$; $t = 20.4783$
ATS-EG	ATS	EG	2021-2035: $r = 0.1333$; 2035-2060: $r = 0.0459$

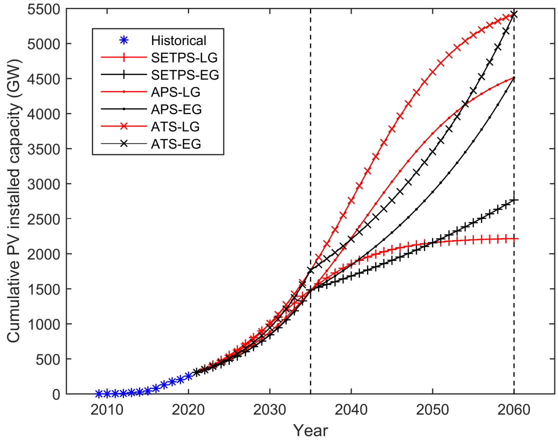


Fig. 2: Cumulative PV installed capacity in China under six pathways

2.3 Estimation of waste volumes

2.3.1 Weibull distribution function for waste generation

The reliable statistics on the waste quantity are limited because China's PV modules degradation tide has not yet reached its peak. Because of this uncertainty, a Weibull distribution function was chosen to determine the evolution of the failure probability for the PV capacity installed in China (Zhang and Fu, 2020). Its suitability to describe the PV module failure under real working conditions has been previously shown in previous research (Mahmoudi et al., 2019, 2021; Santos and Alonso-Garcia, 2018). Then the probability shows installed PV module degradation in the time interval between 0 and x, as shown in Eq.(7).

$$P(x) = 1 - e^{(x/T)^{\beta}}, x \geq 0 \tag{7}$$

Where $P(x)$ is the degradation probability in the time interval between 0 and x, x equals to module life in years, T is the average lifetime of PV modules, and β, called shape factor, is responsible for the typical S shape of the Weibull curve.

Accordingly, the annual retired waste PV flows in the year t can be represented as the sum of the annual newly capacity installed before year t times its failure probability in the year t. Therefore, the annual retired waste PV flows of the province i in the year t can be expressed as

$$W(t)_i = \sum_{k=t_0}^{t-1} [N(k)_i \times (P(t-k)_i - P(t-k-1)_i)], t > t_0 \tag{8}$$

where $N(k)_i$ represents the province i's annual newly installed PV capacity in the year k, $P(t-k)_i$ is the degradation probability of a PV module installed in province i after $(t-k)$ years of service. $P(t-k)_i - P(t-k-1)_i$ is the loss probability during the $(t-k)$th year of service.

2.3.2 Parameter estimation

To model the temporal evolution of losses in the PV modules, the shape parameter β, and the characteristic lifetime T, had to be previously specified (Santos and Alonso-Garcia, 2018). Based on previous literature, the assumption of β and T in both schemes was estimated based on the systematic review and expert judgment for the PV module loss probability model (IEA-PVPS, 2014; IRENA, 2016). In our research, based on the process of solar PV power market development, we analyze the value of parameters by defining the PV module degradation scenario, shown in Table 3.

Table 3: Parameters values of Weibull function

Stage	Scenario	β	T
Industrial establishment stage	Early-loss Scenario	2.4928	20
Large-scale development stage	Early-loss Scenario	2.4928	30
High-quality development Stage	Regular-loss Scenario	5.3759	30

Before 2008, China's PV power market had centered on off-grid rural electrification projects (Zhang et al., 2013), while the amount of consumption was less than 1% of the world's total consumption capacity compared with a total solar cell production amounted to 45% of world capacity in 2008 (Zhao et al., 2011). At this time, the PV industry was in the initial stage of the pilot, and PV installed capacity was very small (Hanfang et al., 2020; Huo and Zhang, 2012). Because of the limitation of data acquisition, the waste generated in this time is not into account in our research. And from 2009, we divide the process of PV power development into three stages and the characteristics of those stages are stated as follows.

(a) Industrial establishment stage (2009-2012): From 2009 to 2012, China implemented five phases of the "Golden Sun project" and "photovoltaic building" (Grau et al., 2012), which played an important role in initiating a domestic PV market (Sun et al., 2014) and resulted in concerns about the installation of low-quality PV projects. By the end of 2012, the gross installed capacity of the solar PV industry was about 6.5 GW. However, a report released by the China Compulsory Certification (CCC) showed that out of the 425 solar PV stations from 32 provinces investigated in 2014, 30% that were built more than three years or older exhibited various quality issues (Chen et al., 2019). In this stage, PV module failure during the early life stages, meaning early-loss, and its life cycle is shortened (Wu et al., 2019). The corrected shape factor and characteristic lifetime are listed in Table 3.

(b) Large-scale development stage (2013-2017): With the introduction of the national PV zone on-grid price system in 2013 (Ye et al., 2017), the annual newly installed capacity increased significantly from 12.92 GW in 2013 to 53.06 GW in 2017, with an average annual growth rate of more than 40%. At the same time, there are "abandoned light" problems in western China. This is because the majority new projects were installed in western China, which has a limited ability to absorb renewable energy and is located far from the load centres of eastern and central China (Ye et al., 2017). So PV module in this stage can be regarded as the early-loss and those parameter values are listed in Table 3.

(c) High-quality development Stage (Since 2018): Under significant pressure arising from the financial shortfall, the Chinese government issued the new "5.31" policy 2018, which promotes the transition of the PV market from a 'high-speed development' road to a 'high-quality development' path. Some proper operation and maintenance strategies are adopted by the power station owners to make solar power energy systems run as they are supposed to (Osmani et al., 2020). This stage can be seen as a regular-loss scenario and the parameters for scenario type are listed in Table 3.

2.4 Estimation of annual newly installed PV capacity

The distribution of the province i's annual newly installed PV capacity is determined according to the cumulative installed capacity of the previous year $(t-1)$, that is:

$$N(t)_i = N(t) * \frac{Q(t-1)_i}{Q(t-1)} \tag{9}$$

The data of each province from 2009 to 2021can be obtained according to the statistical annual report, new energy development plan, and Golden Sun installation plan of each province (NEA, 2022). The historical provincial solar photovoltaic (PV) installed capacity data are listed in Table 4.

3 Research results and Discussion

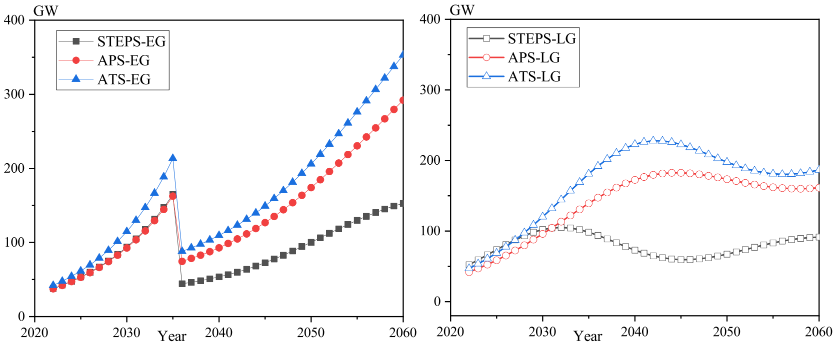
Table 4: Provincial solar photovoltaic (PV) installed capacity in 2009-2021 annually (GW)

Province	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity	Newly Installed capacity
Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Total	0.17	0.40	2.30	3.20	12.92	10.60	12.92	34.54	52.78	44.26	30.11	48.20	54.88
Beijing	-	-	0.03	0.06	-	0.05	-	0.08	0.01	0.15	0.11	0.10	0.19
Tianjin	-	-	-	0.04	-	0.08	-	0.47	0.08	0.60	0.15	0.21	0.14
Hebei	-	0.01	0.07	0.04	0.54	0.97	0.54	2.03	4.25	3.66	2.40	7.15	7.30
Shanxi	-	-	-	0.03	0.28	0.23	0.28	1.83	2.93	2.74	2.24	2.20	1.49
Inner Mongolia	-	-	-	0.38	1.18	1.64	1.18	1.48	1.06	2.02	1.53	1.57	1.74
Liaoning	-	-	-	0.02	0.08	0.05	0.08	0.36	1.71	0.79	0.41	0.57	0.78
Jilin	-	-	0.01	-	-	0.05	-	0.49	1.03	1.06	0.09	0.64	0.09
Heilongjiang	-	-	0.01	-	-	-	-	0.15	0.77	1.21	0.59	0.44	1.02
Shanghai	0.01	0.01	0.02	0.10	0.04	-	0.04	0.14	0.23	0.31	0.20	0.28	0.32
Jiangsu	-	0.09	0.31	0.04	0.88	1.52	0.88	1.23	3.61	4.25	1.53	1.97	2.32
Zhejiang	-	0.03	0.03	0.07	0.18	0.30	0.18	1.75	4.76	3.24	2.01	1.78	3.63
Anhui	-	0.01	0.03	0.06	0.05	0.43	0.05	2.25	5.43	2.30	1.36	1.20	3.37
Fujian	-	-	0.02	0.04	0.02	0.04	0.02	0.12	0.66	0.55	0.21	0.33	0.75
Jiangxi	0.01	0.04	0.01	0.04	0.09	0.26	0.09	1.85	2.21	0.87	0.93	1.46	1.35
Shandong	-	0.03	0.11	0.07	0.11	0.32	0.11	3.22	5.97	3.09	2.58	6.56	10.71
Henan	-	0.01	0.02	0.02	-	0.16	-	2.44	4.20	2.87	0.63	1.20	3.81
Hubei	-	-	0.01	0.02	0.07	0.09	0.07	1.38	2.26	0.97	1.11	0.76	2.55
Hunan	-	-	0.01	0.08	0.15	0.05	0.15	0.01	1.45	1.17	0.52	0.47	0.61
Guangdong	-	-	-	0.20	0.10	0.22	0.10	0.92	1.75	1.96	0.83	1.87	2.26
Guangxi	-	-	-	0.05	-	0.04	-	0.06	0.51	0.55	0.12	0.72	1.07
Hainan	-	-	0.03	0.07	0.06	0.07	0.06	0.10	-	1.02	0.04	-	0.26
Chongqing	-	-	-	-	-	-	-	-	0.13	0.30	0.22	0.02	0.07
Sichuan	-	-	-	0.01	0.03	0.03	0.03	0.60	0.39	0.46	0.07	0.03	0.05
Guizhou	-	-	-	-	-	-	-	0.43	0.91	0.41	3.40	5.47	1.47
Yunnan	-	0.02	0.01	0.02	0.15	0.15	0.15	1.44	0.26	1.09	0.33	0.14	0.63
Tibet	-	0.01	0.04	0.05	0.01	0.04	0.01	0.16	0.17	0.48	0.12	0.27	0.02
Shaanxi	-	0.02	0.03	0.05	0.03	0.42	0.03	2.17	1.90	1.92	2.23	1.47	2.30
Gansu	-	0.02	0.01	0.72	3.45	0.97	3.45	0.76	0.98	0.44	0.79	0.57	1.60
Qinghai	-	0.10	1.00	1.00	0.96	1.02	0.96	1.19	1.08	1.66	1.45	4.80	0.63
Ningxia	0.02	0.05	0.41	0.26	1.02	0.82	1.02	2.17	0.94	1.96	1.02	2.79	1.87
Xinjiang	-	-	0.04	0.24	2.32	0.42	2.32	3.29	0.46	0.45	0.88	1.80	0.50

"-" represents the data unavailable or is "0".

3.1 Newly installed PV capacity in China during 2022–2060

The annual newly installed PV capacity in China from 2022 to 2060 is derived by combining the historical data and estimation model (Fig.3). Clearly, we see that the new capacity shows different characteristics in the Exponential Growth (EG) and Logistic Growth (LG) patterns.



(a) Newly installed PV capacity in Exponential Growth (EG) pattern

(b) Newly installed PV capacity in Logistic Growth (LG) pattern

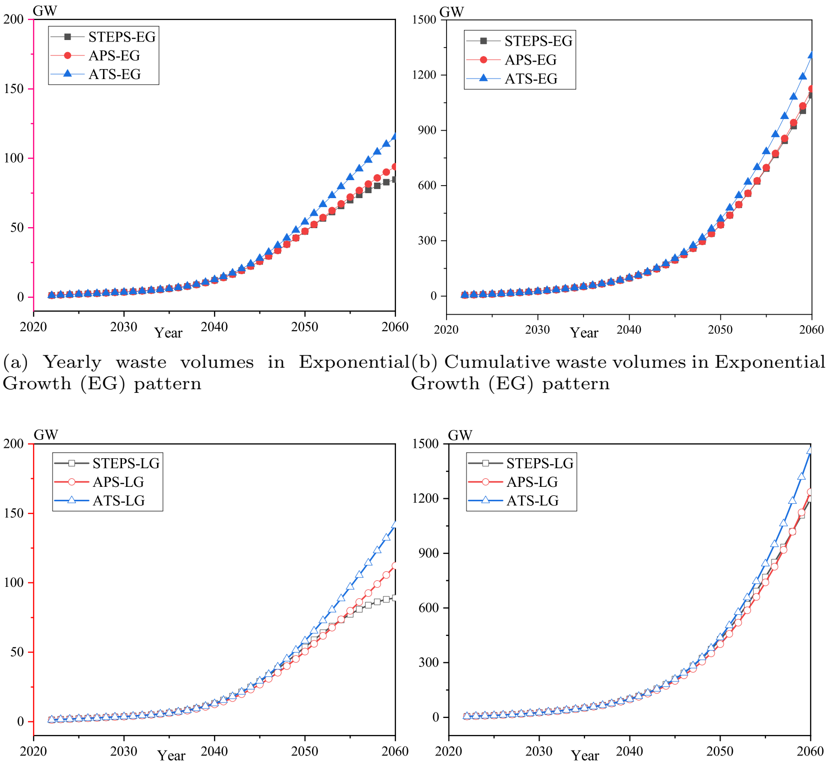
Fig. 3: Annual newly installed PV capacity in China from 2022 to 2060

In the EG pattern, the curve of annual newly installed PV capacity looks like a sawtooth (Fig.3(a)), which means that the annual newly capacity ramps upward from 2022 to 2035, sharp drops in 2036, and then rises during 2036-2060. In 2035, the newly installed PV capacity in the STEPS-EG, APS-EG, and ATS-EG pathways will be 164 GW, 162 GW, and 213 GW, respectively. Obviously, after 2035, the newly installed PV capacity under the three pathways in turn is ATS-EG, APS-EG, and STEPS-EG. As shown in Fig.3(a), in 2060, the capacity in the STEPS-EG, APS-EG, and ATS-EG pathways will be 153 GW, 292 GW, and 353 GW, respectively.

Compared to the EG pattern, the annual newly installed PV capacity in the LG pattern increases at first, peaks at some point, and then slowly drops down (Fig.3(b)). The annual newly installed PV capacity in STEPS-LG, APS-LG, and ATS-LG is expected to peak at about 105 GW in 2032, 182 GW in 2045, and 228 GW in 2042, respectively. Furthermore, it is demonstrated that after 2030, the annual newly installed PV capacity from high to low will be ATS-LG, APS-LG, and STEPS-LG. Even on the STEPS-LG pathway, the annual newly installed PV capacity would be 90 GW.

3.2 Waste PV volumes in China during 2022–2060

In this section, based on the Weibull distribution model, the yearly and cumulative waste PV volumes are estimated for the period 2022–2060 in China in the six pathways. There is a growing tendency among yearly waste PV volumes (Fig.4(a) and Fig.4(c)). From 2022 to 2030, the average growth rate of the yearly waste PV volumes will decrease from 25% to 10%, and the cumulative waste volume might reach 25 GW by 2030. However, beginning in 2030, the annual growth rate began to rise and will reach 17% in 2040, bringing the cumulative amount of PV waste to 100 GW. As a result, the increase in the average growth rate will result in a significant increase in PV waste after 2030. Between 2040 and 2050, although the annual growth rate decreases, it remains over 10%, causing the cumulative waste PV volume to increase rapidly and reach 400 GW by 2050. After 2050, although the annual growth rate decreases, about 70∼100 GW waste modules will be generated each year.



(a) Yearly waste volumes in Exponential Growth (EG) pattern

(b) Cumulative waste volumes in Exponential Growth (EG) pattern

(c) Yearly waste volumes in Logistic Growth (LG) pattern

(d) Cumulative waste volumes in Logistic Growth (LG) pattern

Fig. 4: PV waste volumes in China from 2022 to 2060

The cumulative waste is estimated to be 5 GW in 2022, increasing to 26 GW by 2030, then reaching 100 GW in 2040 and about 400 GW in 2050 (Fig.4(b) or Fig.4(d)). The cumulative waste grows faster and faster with time, reaching 1100∼1450 GW by 2060. Using an exponential model to fit the predicted data of cumulative PV waste from 2022 to 2060, we find that the exponential growth rate of the six pathways of STEPS-EG, APS-EG, ATS-EG, STEPS-LG, APS-LG, and ATS-LG is 13.75%, 13.79%, 14.20%, 14.11%, 14.01%, and 14.47%, respectively. As part of the results, the correlation coefficient reveals the "quality of fit," which is labeled as 0.9923, 0.9928, 0.9945, 0.9929, 0.9939, and 0.9955, indicating that the exponential model is a good fit to the predicted data. This observation implies that the exponential trend in PV power station decommissioning between 2022 and 2060 is inevitable, no matter which path is chosen for PV power generation development. Significantly, the exponential growth will become fast, even if it is slow now.

In order to understand the impact of the three development scenarios and two growth patterns on waste volumes in China, we undertake further work to explore this. As illustrated in Fig.4(b) and Fig.4(d), in the same growth pattern, there is no remarkable difference in PV waste flow between the STEPS, APS, and ATS scenarios until 2035. This is because the yearly PV waste volume differences across the three scenarios are less than 1% before 2035 (Fig.4(a) and Fig.4(c)). Then the gap between the amount of PV waste in the three scenarios is growing over time. After 2050, we can see that the cumulative waste in ATS is greater than that in APS, which is greater than that in STEPS. For example, in 2060, the cumulative waste in ATS-EG is 16% higher than the cumulative waste in APS-EG, which is 3% greater than in STEPS-EG. Further, in the same development scenario, we observe that the waste volumes in the LG pattern are always higher than those in the EG pattern and this gap increases over time. In 2060, the cumulative waste PV in the LG pattern is an average of 10% higher than that in the EG pattern.

3.3 Provincial waste PV volumes during 2022–2060

3.3.1 Yearly waste PV volumes distribution

Based on geographical characteristics, the 31 provinces can be divided into seven regions (Table 5). The highest average annual waste is observed in Northwest China (1.53 GW), followed by East China (1.42 GW), North China (1.24 GW), Central China (0.94 GW), South China (0.48 GW), Southwest China (0.46 GW), and Northeast China (0.44 GW). The PV waste generation is not only spatially associated with the distribution of solar resources in China, but also inextricably linked to the promotion of PV distributed generation. Specifically, Shandong will generate the most waste, followed by Hebei, Jiangsu, Qinghai, and Zhejiang, all of which will face greater PV waste burdens. In comparison, waste PV module growth in Beijing, Shanghai, Hainan, and Chongqing will be relatively smaller at the same time.

Fig.5 presents the changes of yearly waste PV volumes for 31 provinces in China. The yearly waste PV volumes distribution in 31 provinces shows increased changes from 2022 to 2060 under six pathways (STEPS-EG, APS-EG, ATS-EG, STEPS-LG, APS-LG, ATS-LG). We discover that the ATS scenario has the greatest yearly waste PV volumes, followed by the APS and

Table 5: The yearly waste PV volumes of 31 province, 2022–2060

Region	Province	Average annual waste (GW)	Average annual growth rate	Region	Province	Average annual waste (GW)	Average annual growth rate
Central China	Henan	1.46	13.50%	South China	Guangdong	0.99	13.48%
	Hunan	0.49	13.10%		Guangxi	0.26	14.43%
	Hubei	0.87	13.19%		Hainan	0.18	12.28%
North China	Beijing	0.08	11.11%	Northwest China	Shaanxi	1.35	13.52%
	Tianjin	0.21	13.37%		Gansu	1.24	9.00%
	Hebei	2.73	13.65%		Ningxia	1.52	11.08%
	Shanxi	1.63	13.60%		Qinghai	1.99	10.67%
	Inner Mongolia	1.57	11.10%		Xinjiang	1.56	10.53%
East China	Shandong	2.83	13.85%	Northeast China	Heilongjiang	0.39	15.83%
	Jiangsu	2.11	11.93%		Jilin	0.42	14.26%
	Anhui	1.72	13.02%		Liaoning	0.50	13.33%
	Shanghai	0.17	11.68%	Southwest China	Sichuan	0.24	12.34%
	Zhejiang	1.89	13.34%		Guizhou	1.31	18.52%
	Jiangxi	0.97	12.96%		Yunnan	0.49	12.15%
	Fujian	0.25	13.47%		Chongqing	0.08	17.70%
					Tibet	0.17	12.56%

STEPS. The PV waste produced in the ATS scenario corresponds to 1.03 times that generated in the APS scenario and 1.21 times that generated in the STEPS scenario. We can see that, in the seven regions, the province at greater risk of PV waste management is Henan, Hebei, Shangdong, Guangdong, Qinghai, Liaoning, and Guizhou, respectively. Therefore, if the PV waste is collected by region, the recycling facility should be located in the province where the most waste is produced in order to save transportation costs and enhance efficiency. For example, the recycling facility in central China may be established in Henan province rather than Hunan or Hubei province. Hence, the yearly waste PV volumes might serve as a valuable reference for capacity planning and expansion to improve the recycling rate.

3.3.2 Cumulative waste PV volumes distribution

Considering the provincial spatial distribution, we analyzed the distribution of cumulative waste PV volumes in each province in 2030 and 2060. The results are presented in Fig.6 and Fig.7, which indicate that the spatial and temporal distributions exhibit evident differences across regions.

Analysis of the forecasting data of provincial cumulative waste PV volumes in 2030, we can find that:

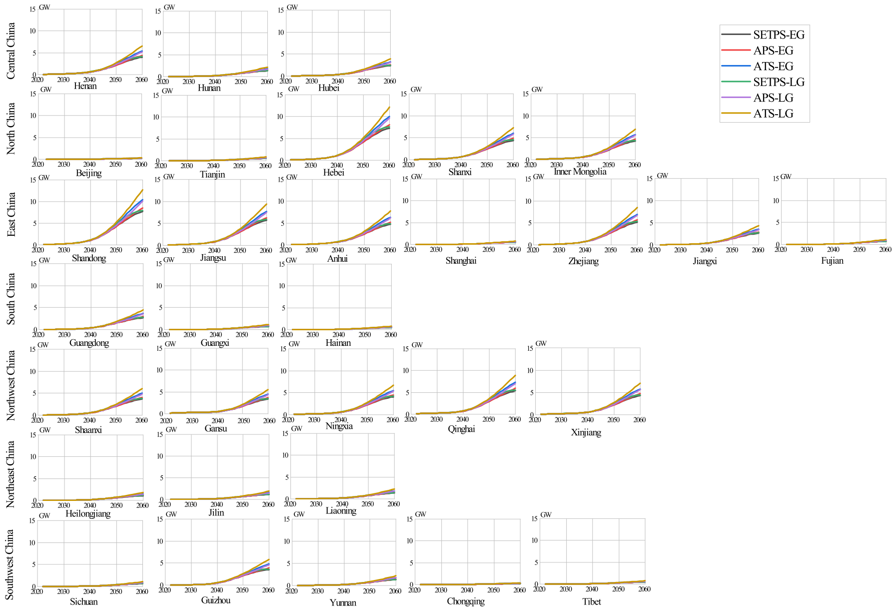


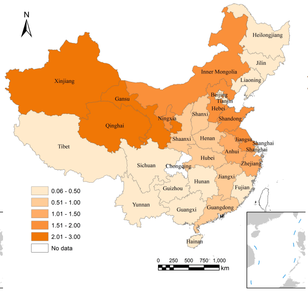
Fig. 5: Yearly waste PV volumes of 31 provinces

(a) Until 2030, there are no significant disparities in the cumulative waste PV volumes of the six pathways at the provincial level (Fig.6).
(b) Provinces or municipalities with large cumulative waste PV volumes included Gansu (10.47%), Qinghai (9.56%), and Xinjiang (8.31%), where the cumulative waste will exceed 2 GW (Fig.6). In comparison, the cumulative waste PV volumes in Yunnan, Liaoning, Hunan, Jilin, Guizhou, Sichuan, Shanghai, Fujian, Heilongjiang, Hainan, Tianjin, Tibet, Guangxi, Beijing, and Chongqing will less than 0.5 GW.
(c) For the sake of further analysis, we divided the country into seven regions. The region with the largest PV waste volumes in 2030 is the Northwest at 38.1%. East China comes in second, accounting for more than 27.3% of total garbage creation, followed by North China (17.4%). The region of Central China, Southwest China, South China, and Northeast China will generate 7.4%, 3.9%, 3.2%, and 2.7% of PV waste, respectively.

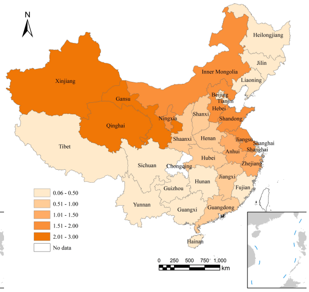
Furthermore, analyzing the forecasting data of provincial cumulative waste PV volumes in 2060 (Fig.7), we can find that:

(a) There is a gap in the cumulative waste PV volumes in different provinces under different pathways.
(b) Two provinces provide the highest figures, including Shandong (8.99%) and Hebei (8.65%) (Fig.7(g)). The region with the highest PV waste volumes by 2060 is the East at 31.4%. The next is Northwest China, which accounts

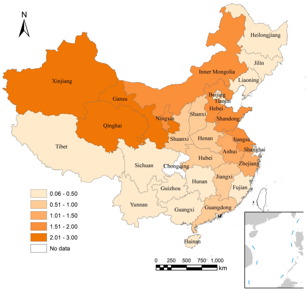
(a) STEPS-EG



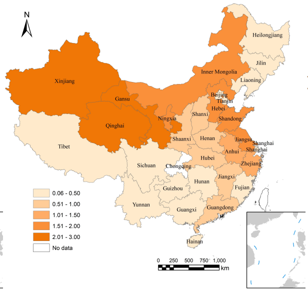
(b) APS-EG



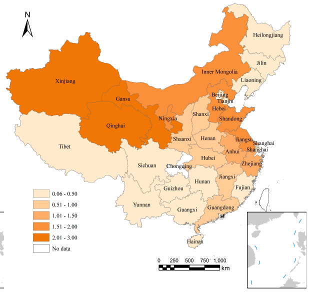
(c) ATS-EG



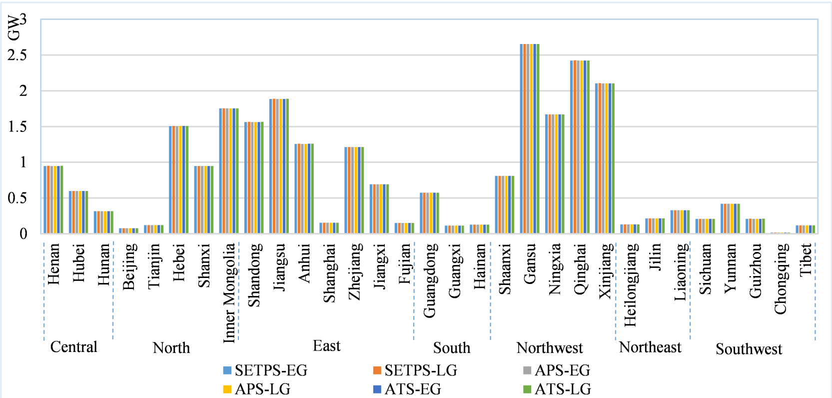
(d) STEPS-LG



(e) APS-LG



(f) ATS-LG

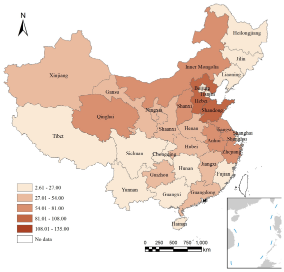


(g) Cumulative PV waste volumes in 2030 at the provincial level

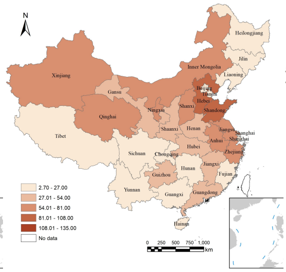
Fig. 6: Cumulative PV waste volumes in 2030 (GW)

for over 24.2% of total waste, followed by North China (19.6%). The waste generated in Central China, Southwest China, South China, and Northeast China regions will account for 8.9%, 7.2%, 4.5%, and 4.1%, respectively.

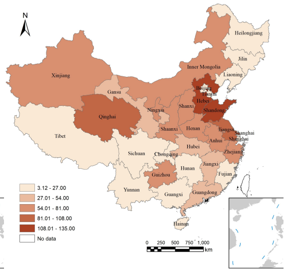
(c) The ATS scenario generates the most waste, followed by the APS and STEPS scenarios. Under the PV growth pattern of EG, compared with the STEPS-EG pathway, the cumulative amount of waste in APS-EG and



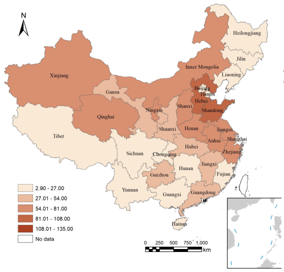
(a) STEPS-EG



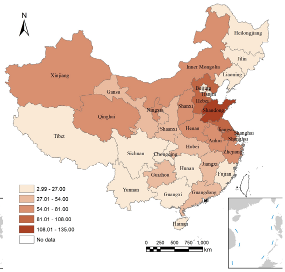
(b) APS-EG



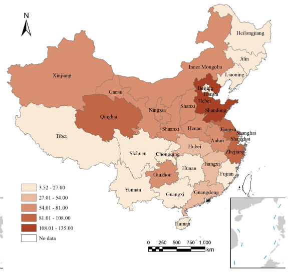
(c) ATS-EG



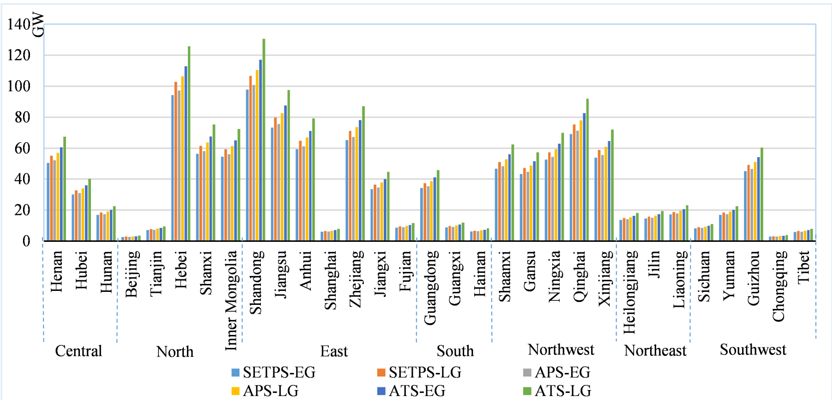
(d) STEPS-LG



(e) APS-LG



(f) ATS-LG



(g) Cumulative PV waste volumes in 2060 at the provincial level

Fig. 7: Cumulative PV waste volumes in 2060 (GW)

ATS-EG will increase by 3.14% and 19.71%, respectively. Under the PV growth pattern of LG, compared with the STEPS-LG pathway, the cumulative amount of waste in APS-LG and ATS-EG will increase by 3.46% and 22.24%, respectively.

(d) Waste volumes in the LG pattern are higher than those in the EG pattern. In the STEPS, compared with the EG path, the cumulative waste amount of each province under the LG path increases by 9.16%. In APS, the cumulative waste of each province in the LG scenario is 9.51% higher than that in the EG scenario. In the ATS scenario, the cumulative scrap amount of each province in the LG scenario is 11.47% higher than that in the EG scenario.

3.4 Discussion

The goal of carbon neutrality provides a bright future for the photovoltaic industry, and green manufacturing has been implemented in the PV business. The significance of waste recycling, which every industry must deal with during the development process, cannot be ignored (Zhang et al., 2022). We extend the research to 2060 and predict the development scenario of PV in the context of carbon neutrality. Simultaneously, based on historical data from China, we developed PV module degradation scenarios that are more in line with the real situation. Further, combined with the renewable energy development pathway, the spatio-temporal distribution of waste PV modules in China is estimated, which is consistent with IEA's findings (IRENA, 2016).

Previous studies have identified that recycling this waste offers significant economic and environmental advantages (Sica et al., 2018). Recycling 1 t of waste PV modules enables a reduction of about 8-12 t CO_2 eq (Cucchiella et al., 2015) and the unit benefit for recyclable material in China is about 340 USD (Liu et al., 2020). According to our research, more than 20 million t of PV waste will be generated in 2060, equating to 6800 million USD worth of recyclable material, a valuable resource for China, and will reduce around 160-240 million t CO_2 eq throughout the recycling process. As a result, it is critical that materials used in solar modules may be recycled or repurposed for future use, which is beneficial to the photovoltaic industry's cost-cutting and profit-increasing efforts.

The spatio-temporal distribution of waste PV modules may provide the reference for when, and where is available for recycling facility setup. On the one hand, there are variances between each province or municipality in waste spatial distribution. Therefore, in the early stage of PV recycling, we can first start recovery business in those regions with substantial volumes of PV waste, for instance, Northwest and East China. For the region with less waste volumes, it may be a good choice to carry out cross-regional cooperation with the leading regions. On the other hand, the changes in PV waste volumes in the temporal dimension may aid the pre-planning, expansion, and shifting of recycling facilities' capacity. When demand changes, some classic methodologies, such as Mixed-Integer Programming (MIP), can be applied to solve the dynamic facility location and capacity planning problem in order to minimize environmental and socioeconomic impacts.

The issue of how to deal with increasing PV waste has been put on the agenda of China's waste management plan (NDRC, 2021; PRC, 2021; MIIT, 2022). This study fills current data gaps to create a solid foundation for good policymaking. The following policy implications are suggested:

(a) It appeared that technology and infrastructure would need to be developed soon in order to deal with the increasing waste volumes. The infrastructures can be launched initially as pilot projects, on a regional or provincial basis. Simultaneously, the government must define responsibility, structure, and standards for recycling waste modules through regulatory measures.

(b) Moreover, in order to improve resource efficiency and incentivize the transition to a circular economy, the PV industry could be encouraged to replace traditional material inputs derived from virgin resources with recovered materials, reducing demand for virgin resource extraction. Taxes, subsidies, and tradable permit schemes can be utilized by the government to enhance resource efficiency.

(c) Further, alternative PV module materials with ecodesign but higher recyclability might be a future option. It is especially appealing for PV module manufacturers that undertake their recycling and benefit from the improved recyclability. Therefore, the government should promote manufacturers to increase the performance criteria for PV modules in terms of quality, durability, and recyclability. This research result has direct reference significance to similar emerging waste streams, such as wind energy and lithium-ion batteries.

4 Conclusion

The rapid growth of solar PV installation will result in a serious PV waste issues. In the context of carbon neutrality, we analyze six PV industry pathways to estimate PV installed capacity. Considering the PV degradation characteristics of the different development stages, we estimate the spatio-temporal distribution of waste volume in China from 2022 to 2060, offering valuable insights for the design and construction of recycling facilities. The research conclusions are as follows:

(a) It has been demonstrated that cumulative waste in China increased exponentially between 2022 and 2060, and large volumes of yearly waste are anticipated in China after 2030. The cumulative waste is expected to be 5 GW in 2022, 26 GW by 2030, and 1100 $\sim$ 1450 GW by 2060.

(b) The PV waste distribution is uneven in different regions or provinces. The highest average annual waste generation is observed in Northwest China (1.53 GW), followed by East China (1.42 GW), North China (1.24 GW), Central China (0.94 GW), South China (0.48 GW), Southwest China (0.46 GW), and Northeast China (0.44 GW). In 31 provinces, the highest average annual waste will produce in Shandong, followed by Hebei, Jiangsu, Qinghai, and Zhejiang, while Beijing, Shanghai, Hainan, and Chongqing will generate the least.

(c) The distribution of PV waste changes over time. By 2030, the majority of cumulative waste will be distributed in the Northwest, accounting for 38.1%. The provinces or municipalities with the greatest cumulative waste PV volumes are Gansu (10.47%), Qinghai (9.56%), and Xinjiang (8.31%). By 2060, the East, which stands for 31.4% of all garbage, will have the greatest volumes of cumulative PV waste. The biggest percentages come from two provinces, Shandong (8.99%) and Hebei (8.65%).

(d) Different PV development pathways have various effects on PV waste volumes. Additionally, the effect increases over time. In the same growth pattern, the PV waste in the ATS scenario is greater than that in the APS scenario, which is larger than that in the SETPS scenario; In the same development scenario, the waste in the LG pattern is higher than that in the EG pattern.

The waste assessment conducted in this study provides a strong foundation for the construction of recovery facilities in China, which will promote the long-term sustainable development of the PV industry. Our study also offers a research framework for other countries that should carry out spatio-temporal analyses of waste distribution, particularly those that are implementing large solar or wind energy installations. Due to data availability, the type of PV module is not taken into account in this study.

Declarations

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- **Authors' contributions:** All authors have contributed the creation of this manuscript. Caijie Liu and Qin Zhang designed the model. Data collection and analysis were performed by Caijie Liu. Caijie Liu and Lingxuan Liu discussed the results and conclusion.
- Ethics approval: Not applicable
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- Code availability: Not applicable

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