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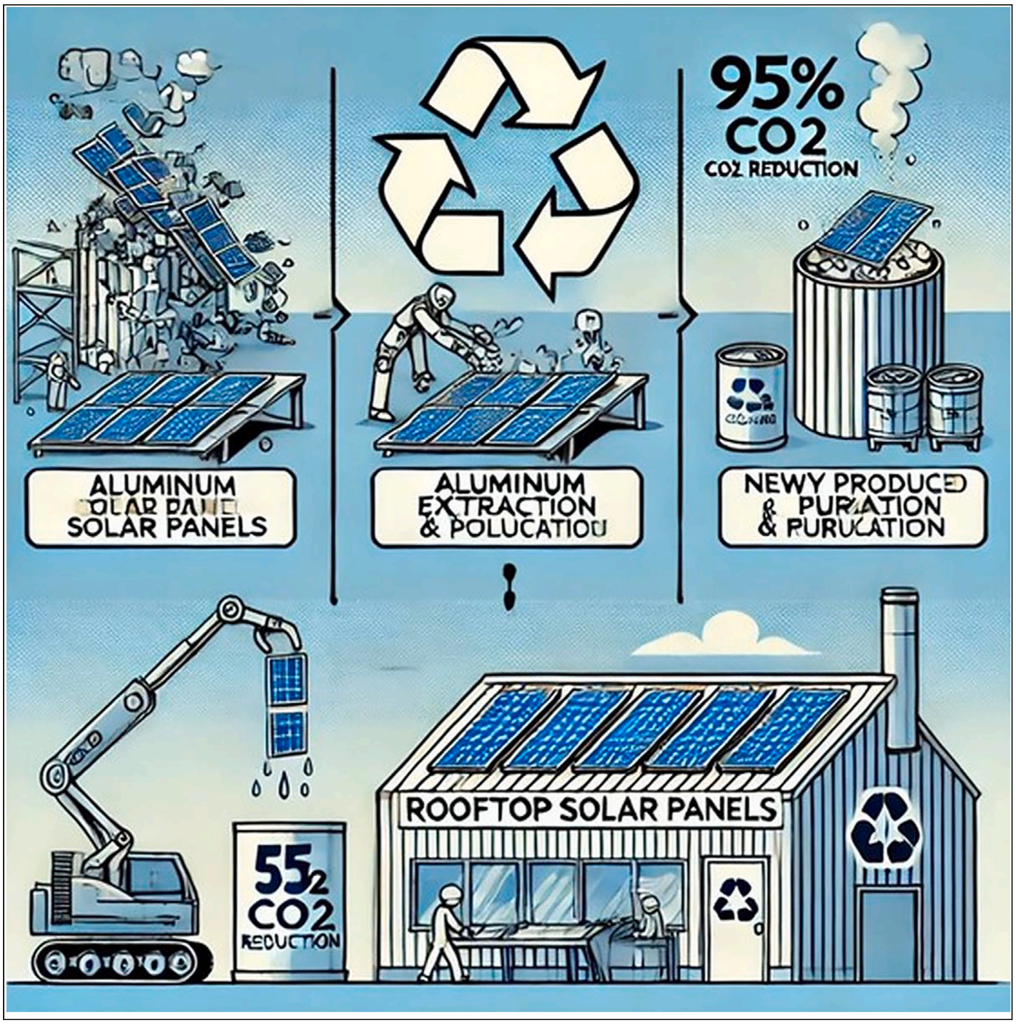

Bin Zhang,
Yingnan Zhang,
Yuantao Yang,
Zhaohua Wang

zynan083@163.com (Y.Z.)
wangzhaohua@bit.edu.cn
(Z.W.)

Highlights

The volume of waste rooftop photovoltaic (RPV) in China toward carbon neutrality

Combining the GCAM and Weibull distribution function

RPV waste recycling can alleviate RPV primary aluminum supply gap

Recycling Al from waste RPV could reduce CO_2 emissions

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Aluminum saving and CO_2 emission reduction from waste recycling of China's rooftop photovoltaics under carbon neutrality strategy

Bin Zhang,[1,2,3] Yingnan Zhang,[1,2,6,*] Yuantao Yang,[4] and Zhaohua Wang[2,3,5,*]

SUMMARY

Rooftop photovoltaics (RPVs) are crucial for decarbonizing the power sector and achieving carbon neutrality, with expected future capacity increases. The growth of RPVs necessitates substantial aluminum (Al) resources, contributing significantly to carbon dioxide (CO_2) emissions from Al production. Given China's bauxite shortage, recycling Al from waste RPV panels presents an effective solution to enhance resource security and mitigate CO_2 emissions. We developed a framework to project waste RPV quantities and assess the recycling potential of Al and its impact on CO_2 emissions from 2020 to 2060. Our findings indicate potential waste flows of 95–221 million tonnes (Mt) and recycled Al ranging from 5 to 28 Mt, with a primary Al supply gap of 25–43 Mt. Recycling could reduce CO_2 emissions by 35–207 Mt over the period. This research underscores the importance of Al resource security and sustainable RPV industry development in China's pursuit of carbon neutrality.

INTRODUCTION

The global climate change caused by excessive greenhouse gas emissions[1,2] has been tackled by various countries in the world through extensive cooperation.[3,4] China, the world's top CO_2 emitter, has committed to achieving the targets of carbon peak before 2030 and carbon neutrality before 2060,[5] and has taken a series of carbon mitigation measures.[6] Solar photovoltaic system has been viewed as a key technology for decarbonizing the power sector and achieving carbon neutrality,[7,8] with an expectation to fulfill 32% of the world's total electricity demand by 2050.[9] Compared with centralized photovoltaics, rooftop photovoltaics (RPVs) can reduce the user's dependence on the grid of power supply and reduce energy loss during transmission.[10] Meanwhile, they can provide electricity for rural households[11] and are suitable for installation in cities. China's RPV installations were 21.5 GW (GW) in 2021, with its share in the national photovoltaics system installation showing a significant increase from 13% in 2016 to 40% in 2021.[12] In 2022, the world's installed RPV capacity reached 118 GW,[13] in which about 50% were contributed by China.[14,15] China's rapid urbanization in recent decades has led to substantial construction stocks, creating favorable conditions for RPV system development. RPV would be a major driver for decarbonizing the electricity grid and achieving carbon neutrality.[16,17] Although the installed potential of RPV in China is about 5,000 GW, less than 1% have been developed in 2020,[3] which shows tremendous potential for market expansion toward the carbon neutrality target.

676 pilot counties were chosen by the Chinese government in 2021 to develop RPV projects.[18] Centralized photovoltaics is usually large in scale and has considerable economic benefits but is greatly affected by the terrain and site. The dispersion and flexibility of RPV prevent it from being limited by nearby topography and allows it to be developed close to power consumption areas as an important supplement to energy supply.[19] According to the study, the installation of RPV in old residential buildings in Nanjing City, China, has the potential to supply about 17.7–20% of the residential electricity demand.[20] End-of-life photovoltaics panels in photovoltaics plants can be centrally collected and then transported to the relevant companies for recycling, which is less costly. The demand for RPV is growing rapidly, but the cost and difficulty of recycling end-of-life RPV is high due to the specificity of their installation locations.

The fast expansion of RPV will pose a massive demand for significant mineral resources in related industries.[21–25] Aluminum (Al) is extensively employed in RPV panel manufacturing[26] due to its high conductivity and exceptional corrosion resistance (Figure 1). Specifically, the Al shares in valuable metals are 92.62% for crystalline silicon (c-Si), 94.90% for amorphous silicon (a-Si), 2.69% for cadmium telluride (CdTe), and 89.24% for copper indium gallium diselenide (CIGS) (Figure 2),[27,28] showing that Al holds the largest shares among the valuable metals used in RPV panels except CdTe. China has become the world's largest primary Al producer and consumer, and its production and consumption have been increasing annually.[29] Bauxite resource reserves in China account for only 3% of the world's total, but its production occupies about a

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[1] School of Management, Beijing Institute of Technology, Beijing 100081, China
[2] Digital Economy and Policy Intelligentization Key Laboratory of Ministry of Industry and Information Technology, Beijing Institute of Technology, Beijing 100081, China
[3] Tangshan Research Institute, Beijing Institute of Technology, Hebei 063099, China
[4] School of Economics and Management, Beijing University of Technology, Beijing 100124, China
[5] School of Economics, Beijing University of Technology, Beijing 100124, China
[6] Lead contact
*Correspondence: zynan083@163.com (Y.Z.), wangzhaohua@bit.edu.cn (Z.W.)
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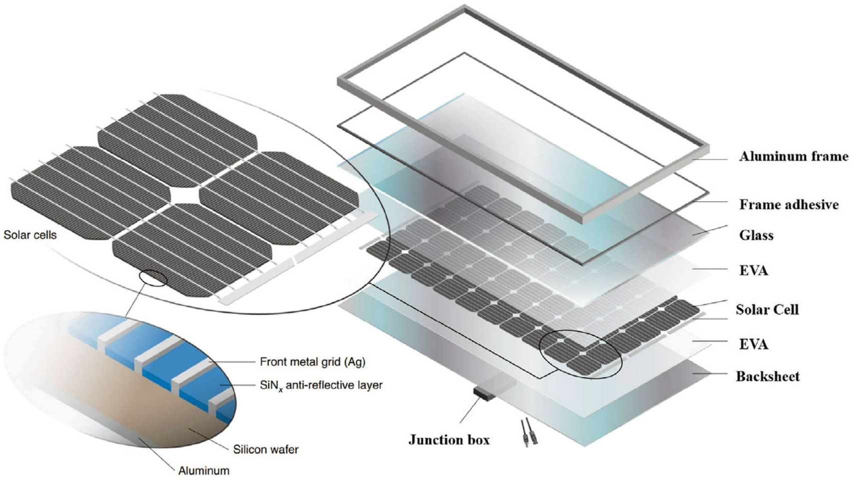

Figure 1. General structure of an RPV panel

Due to its technical capabilities, ease of fabrication, easy transportation, recyclability, and corrosion resistance. Al is a metal broadly used in RPV panels, because the frame of panels is made of Al alloys, accounting for 9–42% of mass. Light weight, high strength, and proper corrosion resistance are such interesting properties of Al that make it an inseparable part of solar power systems. In RPV panels, Al is mainly used in the cells and frames. The cells are produced by RPV cell manufacturer. Al frame is assembled with the cells and other materials during the production of RPV panels. Moreover, high surface reflectivity, excellent electrical and thermal conductivities, as well as special optic properties of its anodic coating make Al a material that is widely used in concentrating solar power and concentrating solar power. What's more, Al frames are found in panels c-Si, a-Si and CIGS. The thin film CdTe solar modules do not have an Al frame.

quarter of the world, showing high dependence on imports with the import rate increasing from 35% in 2015 to 60% in 2022 (Figure 3).[30,31] Furthermore, the service life of China's bauxite reserves is only 14 years, far below the world average of 102 years[32] Approximately 75% of all Al produced is currently in use,[33] with end-of-life recycling rates ranging from 34% to 63%.[34] Significant Al resources will be needed to satisfy the escalating demand for manufacturing RPV panels in the future. Approximately 72–134 Mt of waste photovoltaics panels will be cumulatively generated in China up to 2050,[27] so it is crucial to recycle Al from waste RPV panels.

In particular, the recycling system of RPV panels emerges as a way to reduce the demand for primary Al and the environmental pressure of the RPV industry,[35] while ensuring the future resource security of Al. Compared to steel or copper, the production of primary Al is both emission- and energy-intensive, and its continuous production intensifies greenhouse gas emission and energy consumption issues.[36,37] With the rapid Al demand in manufacturing RPV panels, carbon dioxide (CO_2) emissions of Al production cannot be ignored. Recycling is attractive because recycled Al production generates only 3–5% of the emissions of primary production,[34,38] which could reduce massive CO_2 emissions.[29] Tang et al.[39] illustrated that China's current Al recycling ratio is low although the corresponding greenhouse gas emission can be reduced by 93.73% if all the primary Al can be replaced by secondary Al. Pedneault et al.[40] emphasized that improvement in the recycling system must be made to promote using recycled aluminum, reduce the overall environmental impacts of the industry, and move toward a circular economy. Currently, effective recycling modes have been established with the support of industrial, government, and academic agencies, which provides new opportunities for the effective management of RPV waste. With a national RPV waste market regulated, annual Al demand for manufacturing RPV panels could be satisfied through both primary and recycled Al production methods.

Previous studies have investigated the recycling of materials from waste photovoltaics panels, but the Al recycling potential of RPV and CO_2 emission reduction of replacing primary Al with recycled Al during manufacturing RPV panels are still unclear under China's carbon neutrality target. First, some have predicted the annual installed photovoltaics capacity using the approaches by simple linear assumptions,[41] machine learning,[42] and the optimization model with a set of objective functions.[43] However, these approaches only consider the photovoltaics system itself and do not consider the possible impact of other systems on the photovoltaics. RPV systems may also be affected by other power subsystems. Considering the future transition to a cleaner power system, other forms of power generation such as nuclear, wind. The share of nuclear power will grow in the future as a mode with high power generation potential. The market share of these power generation methods will have an impact on the amount of installed RPV capacity.[44,45] Second, current research focused on the electricity generation potential[46,47] and CO_2 emission reduction potential of RPV,[3,48] with fewer predictions on the annual installed RPV capacity. Third, although some studies have explored the sustainability of rare metals from waste photovoltaics panels,[27] the importance of recycled Al from waste photovoltaics panels has received less attention. Fourth, the amounts of reduction in primary Al demand and CO_2 emissions through recycling waste RPV panels have not been explored yet. Recycled Al from waste RPV panels can reduce the demand for primary Al and CO_2 emissions by substituting primary Al when producing RPV panels since emission intensities between primary and recycled Al production vary.[26]

To fill these research gaps, we highlight the role of recycled Al from waste RPV panels in the reduction of primary Al consumption and CO_2 emissions for manufacturing RPV panels given China's carbon neutrality target. First, the annual installed RPV capacity and weights of waste RPV panels have been quantified by combining the Global Change Assessment Model (GCAM) with the Weibull distribution function.

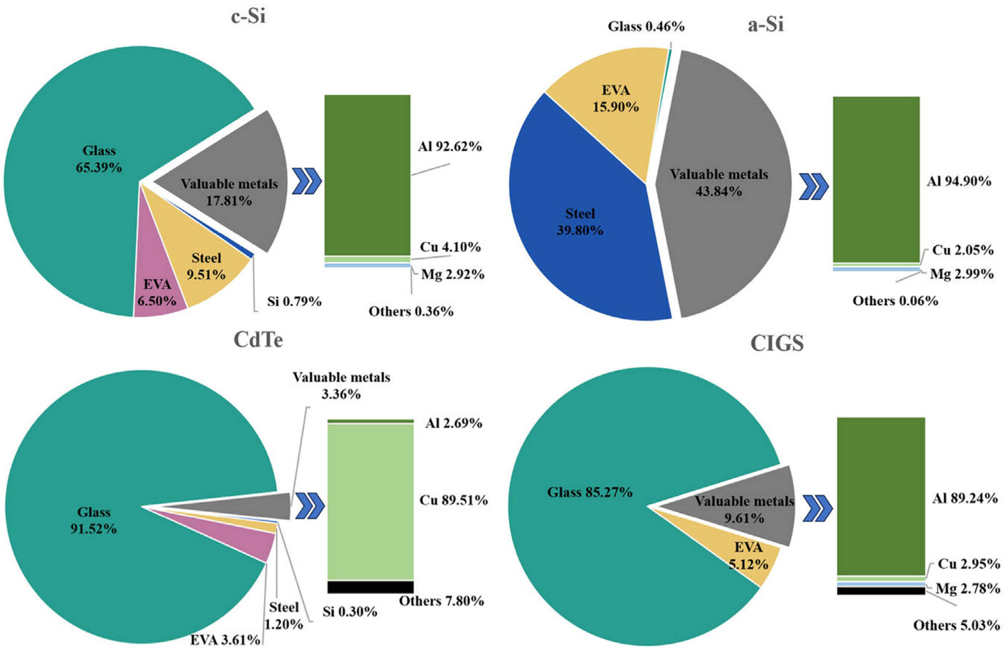

Figure 2. Al composition of each RPV technology

The Al share in valuable metals is taken as 92.62% for c-Si, 94.90% for a-Si, 2.69% for CdTe, and 89.24% for CIGS. Although the shares of valuable metals vary in different RPV technologies, Al holds the largest share among the valuable metals used in RPV panels, except for CdTe.

Second, the weight of Al demand and total CO_2 emissions of Al production for manufacturing RPV panels have been forecasted. Third, the amounts of reduction in primary Al demand and CO_2 emissions through the recycling of waste RPV panels have been assessed. This study provides the research framework to quantify the recycled materials from waste RPV panels, and the emission reduction by recycling and management of waste RPV panels. Our findings could provide policymakers with implications on the recycling and management of Al from waste RPV panels, which can be utilized in other nations facing similar issues.

RESULTS

RPV installation and waste quantification

Under the various scenarios of lifespan and failure rate of installed RPV panels, the annual RPV installation and the RPV in operation are shown in Figure 4A. Large-scale deployment of RPV panels will emerge in the future. The RPV in operation is expected to increase annually to 1425 GW by 2060, which is almost 22 times larger than that in 2020. China's RPV still has a large installed potential for development under China's carbon neutrality target.

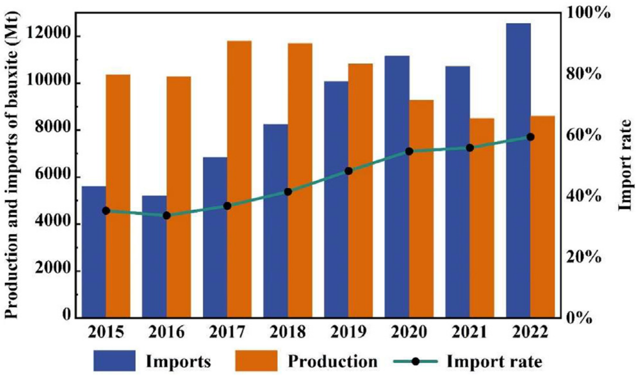

Figure 3. The production and imports of bauxite in China and the import rate during 2015–2022

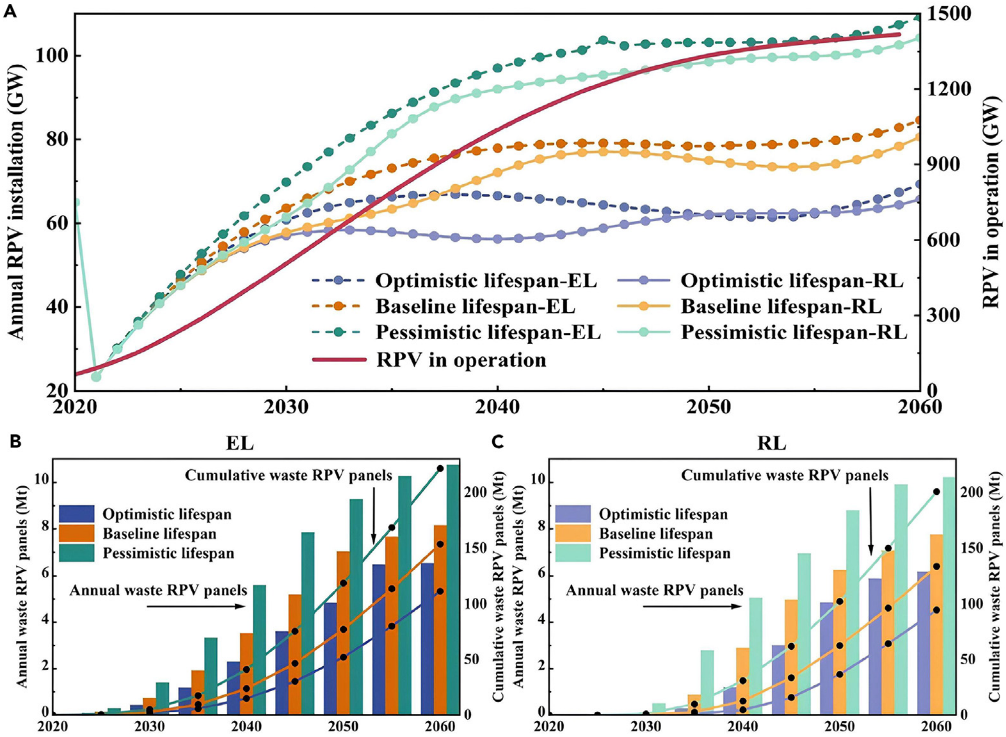

Figure 4. Annual RPV installation and waste RPV panels during 2020–2060

(A) Annual RPV installation and RPV in operation. Dot-solid line and dot-dashed line indicate early loss (EL) and regular loss (RL) scenarios, respectively; the red solid line indicates the installation of RPV in operation that can satisfy electricity demand. Compared to failure rates of RPV panels, the lifespan of RPV panels affects annual RPV installation significantly.

(B and C) illustrate the annual and cumulative weight of waste RPV panels under EL and RL scenarios, respectively. The bars and solid lines show the annual and cumulative weight of waste RPV panels, respectively. A longer lifespan of installed RPV panels could contribute to fewer annual RPV installations and the cumulative weight of waste RPV panels. More failures of RPV panels in the early usage phase could lead to an earlier increase in cumulative weight for waste RPV panels.

The annual capacity of RPV installations is 23–109 GW in 2020–2060 under various scenarios. The main reasons for the high annual installations after 2030 are improvements in RPV technology, expanded installed capacities, and increased electricity demand under the carbon neutrality target. RPV installations in 2020 are significantly larger than in 2021–2025. Since the RPV generation data in the GCAM model starts in 2020, the calculated RPV installations in 2020 include those that have been installed before 2020. Additionally, the annual installations under the optimistic lifespan-early loss (EL) scenario are higher than those in the optimistic lifespan- Regular loss (RL) scenario (The detailed description of the scenarios is presented in Table 1). The longer the lifespan of installed RPV panels, the lower the annual capacity of the RPV it installs. Compared to avoiding failure during the early usage phase, increasing the lifespans of RPV panels has a greater impact on reducing annual RPV installations.

The annual weights of the waste RPV panels would be 6.54–10.75 Mt and 6.17–10.22 Mt in 2060 under EL and RL scenarios, respectively. In the EL scenario, the waste RPV panels are on an upward trend, beginning with a fast pace of growth and then becoming stable during the next decade (Figure 4B). In the RL scenario, the annual weight of the waste RPV panels is low in the initial decade but increases gradually over time (Figure 4C). More specifically, the waste RPV panels would reach only 34 kt in 2030, but show a clear upward trend after 2045 under the optimistic lifespan-RL scenario. The growth turning years for EL and RL scenarios are 2025 and 2035, respectively, showing that the cumulative weight of waste RPV panels grows slowly initially, but rapidly after 2035. Under the optimistic lifespan scenario, the cumulative weight of waste RPV panels would be 95–112 Mt, 134–154 Mt and 201–221 Mt during 2021–2060 under the baseline, and pessimistic lifespan scenarios, respectively.

Annual Al demand and CO$_2$ emissions

The annual Al demand for producing RPV panels shows an upward trend overall, beginning with fast growth and then becoming stable (Figure 5A), ranging from 391 to 1,762 kt during 2020–2060. The demand reaches its peak around 2030 under the optimistic lifespan scenario and around 2045 under the baseline and pessimistic lifespan scenarios. The growth in demand accounts only for RPV installation, omitting the additional anticipated consumption of Al in various clean energy technologies, as well as its ongoing application in infrastructure construction

Table 1. Description of the scenarios

Scenario dimension	Description
Lifespan of RPV panels[49]	
Optimistic lifespan	The lifespan of RPV panels is assumed to be 25 years. High-quality panels and regular maintenance would decrease the failures of panels.
Baseline lifespan	The lifespan of RPV panels is assumed to be 20 years. The panel quality and maintenance status are considered average.
Pessimistic lifespan	The lifespan of RPV panels is assumed to be 15 years. Poor quality panels and neglecting maintenance could shorten the lifespan of panels.
Failure rate of RPV panels[27]	
Early loss (EL)	Higher likelihood of panel failure during the early usage phase.
Regular loss (RL)	The failure rates increase quickly during the middle and late phases of panel usage.
Recycling rate (RR) of recycled Al from waste RPV panels	
Low recycling rate (Low-RR)	The RR remains constant at 34% during 2020–2060.[26]
Medium recycling rate (Medium-RR)	The RR is 34% in 2020, gradually increasing linearly to 75% in 2060.[26]
High recycling rate (High-RR)	The RR is 34% in 2020, gradually increasing linearly to 100% in 2060.

and transportation. Therefore, this estimate could be considered a lower bound of the real demand, and the demand for Al might have to be fulfilled through a combination of domestic and imported Al. The cumulative Al demand for manufacturing RPV panels is 38–58 Mt by 2060 (Figure S1). Under the pessimistic lifespan scenario, the cumulative Al demand would be 1.2 and 1.4 times larger than that under baseline and optimistic lifespan scenarios, respectively. Compared to avoiding failure during the early usage phase, increasing the lifespan of RPV panels could create great potential to decrease the annual Al demand.

The annual CO_2 emissions from Al production for producing RPV panels display an upward trend overall as well, beginning with a fast increase and then a decrease (Figure 5B), with a range of 5–17 Mt during 2021–2060. The annual CO_2 emissions peak around 2030 and 2037 under the optimistic and pessimistic lifespan scenarios, respectively. However, different failure rates lead to asynchronous peaks under the baseline lifespan scenario. The emissions peak around 2033 under the EL scenario and around 2030 under the RL scenario. The CO_2 emissions decrease gradually after the peaks result from the decreasing emissions intensity of primary Al production.

The cumulative CO_2 emissions of Al production for producing RPV panels exhibit an upward trend during 2020–2060 because of the annual emissions from Al production. The cumulative CO_2 emissions under pessimistic lifespan-EL and -RL scenarios are 548 (~5.6% of China's total CO_2 emissions in 2020) and 516 Mt by 2060, respectively, 35% and 36% larger than that under the optimistic lifespan-EL and -RL scenarios, respectively (Figure S2). The CO_2 emissions under the EL scenario would be about 30 Mt more than that under the RL scenario for the same lifespans of RPV panels.

Recycled Al and CO_2 emission reduction

The amount of recycled Al from waste RPV panels varies due to different recycling rates (RR) of Al from the panels and continuously grows from 2020 to 2060 (Figure 6A). The annual recycled Al would be 333–1,047 kt, 411–1,209 kt, and 536–1,658 kt in 2060 under the optimistic, baseline, and pessimistic lifespan scenarios, respectively. Under high RR scenarios, the annual recycled Al would be triple those under low RR scenarios. Cumulative recycling Al from waste RPV panels is expected to reduce the use of primary Al by 5–28 Mt during 2020–2060 (Figure S3). The recycled Al from RPV waste holds the potential to offset the shortage of Al materials for the RPV industry. However, there still exists a gap of approximately 25–43 Mt that needs to be satisfied by primary Al. The demand for Al resources in the manufacturing process of RPV panels is met by primary Al and recycled Al. There is still a large gap between the Al demand (Figure 5A) and recycled Al when we assume that recycled Al is obtained only from the recycling of waste RPV panels, and recycled Al from other industries is not considered. High recycling rates will reduce these gaps, but they cannot fully alleviate the supply gap.

The proportion of recycled Al from waste PRV panels to total Al demand denotes the reuse rate of recycled Al when manufacturing RPV panels, which could rise close to 31% under the low-RR scenario and 94% under the high-RR scenario, respectively (Figure 6B). In terms of changes in trends, in the early loss (EL) scenarios, the reuse rates of recycled Al begin to grow significantly earlier, compared to regular loss (RL) scenarios. Overall, the lifespan and failure rate of installed RPV panels have not exerted significant impacts on the reuse rate of recycled Al. However, in terms of changing trends, the reuse rates of recycled Al begin to grow significantly after 2030 under the EL scenario. By contrast, under the RL scenario, such a phenomenon would appear after 2035. Additionally, under the low RR scenarios, the reuse rates of recycled Al would peak in 2057 and then decrease to 2060. Under high RR scenarios, the reuse rates of recycled Al would be 1.3 and 3 times larger than those under medium and low RR scenarios, respectively. The higher the RR, the higher the reuse rates of recycled Al will appear, which means that more recycled Al would be used for manufacturing RPV panels and better utilization of recycled Al. If the recycling system has yet to be improved and the RR is low, the RPV industry would still require a large amount of primary Al. The low reuse rate of recycled Al

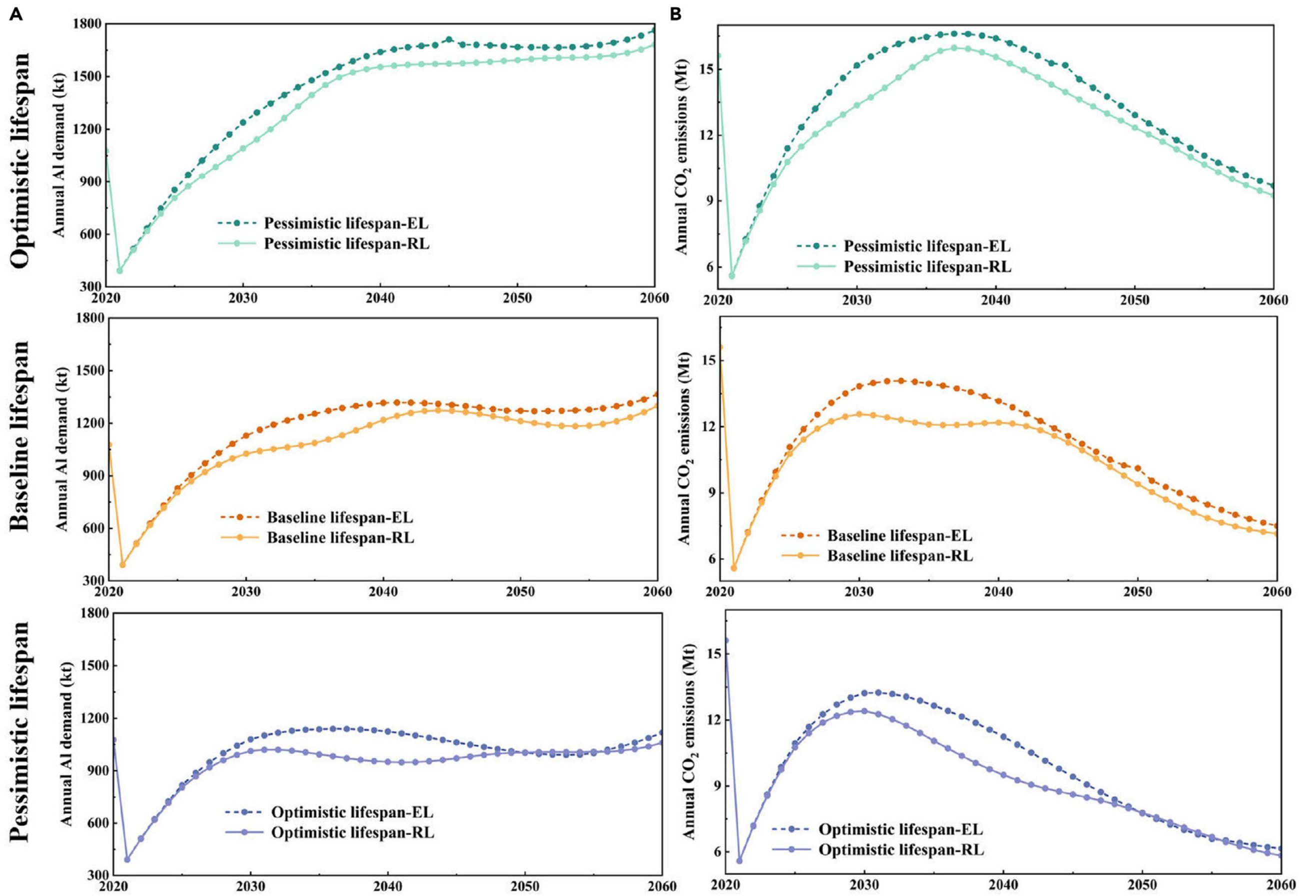

Figure 5. Annual Al demand and CO$_2$ emissions of Al production

(A) Annual Al demand for producing RPV panels. Compared to failure rates of RPV panels, the lifespan of RPV panels affects annual Al demand significantly.

(B) Annual CO$_2$ emissions of Al production for producing RPV panels. The annual CO$_2$ emissions present here exclude that from recycled Al use. The CO$_2$ emissions show an upward trend and then a downward trend, with different peak years under the 6 scenarios.

may cause a substantial shortage of Al materials for China's RPV industry in the future. Further improving the recycling rate and recycling technology could reduce the risk of material shortage, and such improvements should be taken more seriously.

Considering that recycled Al is being used for producing RPV panels, the cumulative CO$_2$ emissions would be 290–457 Mt during 2020–2060 (Figure S4). Under the high RR scenarios, the cumulative CO$_2$ emission reduction of Al production would be 88–207 Mt by 2060 (Figure 6C). The cumulative reduction would be 68–163 Mt and 35–90 Mt by 2060 under the medium and low RR scenarios, respectively. Increasing recycling rates of Al would contribute to CO$_2$ emission reduction with 35–207 Mt. Nevertheless, the cumulative CO$_2$ emission reduction under the EL scenario is approximately 8–19 Mt more than those under the RL scenario for the same lifespans of RPV panels and recycling rates scenarios. What's more, short lifespans of RPV panels mean faster circularity, resulting in more CO$_2$ emission reduction.

DISCUSSION

The rapid development of RPV demands large amounts of Al, and as the highest share among valuable metals in RPV panels, the production of Al emits large CO$_2$ emissions, posing potential resource security issues and CO$_2$ emissions, and curbing the advancement toward carbon neutrality. The recycling of Al from waste RPV panels is crucial to reduce the primary Al demand and related emissions.

In this research, we estimate the potential of recycling Al from waste RPV panels and CO$_2$ emission reduction of Al production in China under the 2060 carbon neutrality target, which is different from existing studies that focus on the recycling of other rare metals (e.g., silver) from RPV waste. To meet the high demand for Al for the development of the RPV industry in the future, it is vital to advance RPV recycling, not only focusing on the primary Al production.

The RPV industry is growing rapidly under the carbon-neutral target, which will generate huge amounts of waste RPV panels. The results indicate that approximately 1425 GW of RPV capacity will be operating and the waste RPV panels would be 95–221 Mt by 2060 in China. The advancement of RPV technology and rising electricity demand as a result of the high annual installations after 2030. To meet the need for

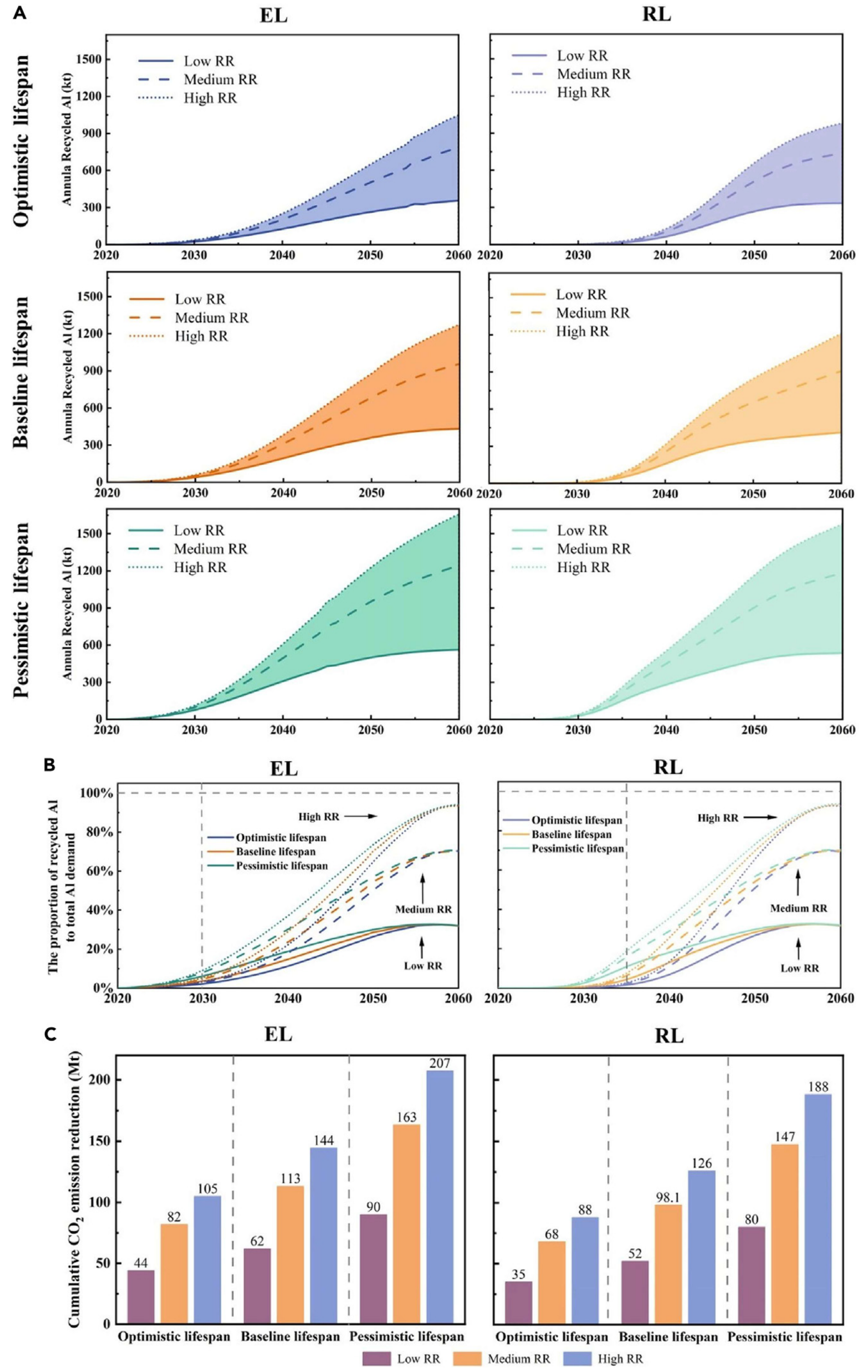

Figure 6. The recycled Al from waste RPV panels and cumulative CO_2 emission reduction of Al production for producing RPV panels during 2020–2060 under various scenarios

(A) The weight of annual recycled Al under various scenarios. The annual recycled Al would be 333–1,658 kt in 2060.

(B) The proportion of recycled Al to total Al demand. It could rise close to 31% under the low-RR scenario and 94% under the high-RR scenario, respectively.

(C) Cumulative CO_2 emission reduction by 2060. Replacing primary Al by recycling Al from waste RPV during manufacturing RPV panels, the cumulative CO_2 emission reduction is 35–207 Mt under the 18 scenarios (Table 1).

carbon neutrality, the cumulative demand of primary Al in RPV panels would be 38–58 Mt by 2060. There are no discernible distinctions in Al demand under two failure rate scenarios of installed RPV panels. In this context, the CO_2 emissions of Al production for manufacturing RPV panels is 378–548 Mt. The main reason for the reduction in annual CO_2 emissions after 2035 is the reduction in the carbon intensity of Al production and the stabilization of aluminum demand. Extending the lifetime of the RPV panels is the first of these options that should be considered. Extending the lifespan of installed RPV panels could decrease Al demand and CO_2 emissions during manufacturing RPV panels.

The import rate of China's bauxite resources was 60% in 2022, and even the service life of China's bauxite reserves is only 14 years. The cumulative recycled Al would be about 5–28 Mt by 2060, replacing the demand for primary Al by the recycled Al from waste RPV panels could directly relieve the supply pressure of primary Al. The proportion of recycled Al to total Al demand could rise to nearly 31% under the low-RR scenario, and it would reach nearly 94% in 2060 if the recycling rate increases to become the high recycling rate scenario. Differences in turning points for reuse rates of recycled Al are mainly due to different recycling rates. The higher reuse rates of recycled Al imply the fewer primary Al gaps, and the better the utilization of recycled Al. High recycling rates will increase reuse rates of recycled Al, but recycled Al couldn't fully meet the demand for Al. It merits noting that increasing the utilization of recycled Al could reduce reliance on imported bauxite and heighten the self-sufficiency rate.

By using recycled Al during the manufacturing of RPV panels, due to the different emission intensities between primary and recycled Al, the cumulative CO_2 emission reduction of Al production would be 35–207 Mt during 2020–2060. The promotion and application of Al recycling can effectively reduce carbon emissions during the manufacturing process of RPV panels, contributing to China's goal of carbon neutrality. At the same time, the recycling Al also fits in with China's policy objectives of promoting the development of a circular economy, resource conservation, and environmental protection, further promoting sustainable development.

In order to analyze the impact of future changes in the composition of Al in the four technologies on the results of the study, we set up two scenarios: a gradual increase in the composition of Al and a gradual decrease in the composition of Al to perform sensitivity analysis in the discussion. By reducing the proportion of Al in each technology, cumulative aluminum demand and CO_2 emissions are reduced by 50% and 40%, respectively. the reuse rate of recycled Al will reach 100% during 2047–2055. However, there still exists a gap of approximately 10–21 Mt that needs to be satisfied by primary Al. Supply gap and emission reductions both reduced by 50%. By increasing the proportion of Al in each technology, Primary Al supply gap becomes 3–7 times larger. Considering the continuous progress of technology, a smaller composition of Al in each technology is more conducive to the development of RPV systems.

Recycled Al from waste RPVs could meet a large fraction of future Al demand for manufacturing RPV panels, thereby recycling waste RPV panels and decreasing the demand for primary Al could relieve the resource pressure and reduce primary Al-related emissions. The potential of recycled Al from waste RPVs may decrease the demand for the primary Al, but they could not eliminate the primary Al demand for producing RPV panels under the carbon neutrality strategy. Developing new recycling technology for Al and improving the RR can reduce such demands. Future research that incorporates realistic waste RPV panels and recycling rates is necessary to accurately estimate the recycled Al potential for manufacturing new RPV panels. Comprehensive methods are needed to comprehend the environmental impacts of production, such as life cycle assessment. Additionally, an analysis that studies the impact of RPV technology development and the substitution of Al materials for RPV panels would add to this research.

The benefits of recycling Al from RPV systems may vary depending on the region. RPV panels can be expensive to recycle due to their size, weight, mounting position, and geographic dispersal. There are significant spatial differences in solar energy resources and social and economic development in China. Eastern coastal regions such as Guangdong and Jiangsu have greater potential for RPV installations, due to the high demand for industrial electricity due to their abundant rooftop resources and high policy support. Central and western regions such as Xinjiang and Inner Mongolia are rich in solar energy resources, but the relatively low level of economic development has led to slower development of RPV.[50] RPV panels are often manufactured and utilized in different cities. Recycling end-of-life PV panels across regions will increase transportation costs. Therefore, it is necessary to consider the rate of rooftop PV development between regions and then optimize the location of targeted recycling sites. To implement more tailored strategies, such as logistic optimization, for the collection and management of RPV waste.[27] In addition, the multi-scale RPV yield characteristics can be estimated more accurate and in real-time using the estimation model developed in this paper.

Recycling routes are mainly categorized into mechanical, thermal and chemical treatments. The chemical processes are used to recover the module metal fraction and use solvents and other reagents. It is more expensive to perform these methods, but the purity of the final output materials is higher than what is obtained through mechanical methods, especially when it comes to high value metals. In spite of the negative effects of the recycling of photovoltaic panels, such as the expenditure of reagents and gas emissions, these processes are still convenient and can be remedied with gas emission filters, reagent reuse, and wastewater treatment. In comparison to the manufacture of a new panel, recycling consumes less energy.[51]

It is possible to create a non-profit organization (NPO) to gather all pertinent data about the RPV industry. This database should be used to track three types of data on a regular basis: installed capacity, RPV characteristics, and RPV waste management. Supporting the green design of RPV products means looking at the recycling problem from the standpoint of product design and material selection. The supply chain system for recycling RPV modules needs to be reinforced in terms of green credit, land security, full process control, and subsidies. Rather of using the current e-waste management system, a Chinese RPV waste recycling fund has to be developed based on the PV Cycle, an industry organization for photovoltaics recycling established by the EU.

Limitations of the study

Our work provides valuable insights into recycling Al from RPV waste, not only for China and the RPV industry but also for any regional or industry quantifying recycled materials. Some uncertainties are acknowledged here. First, Al's share of RPV panels remains unchanged and is assumed to remain unchanged in the future, ignoring changes in material proportions due to technological advances. Second, we only considered the total CO_2 emissions of Al production for manufacturing RPV panels, so we may underestimate the emission level because emissions caused by other production processes were not taken into account, such as the transportation and recycling process of RPV waste. Third, it is assumed that recycled Al is obtained only from recycling waste RPV panels, and recycled Al from other industries is not considered. New RPV panels are manufactured with priority to use recycled Al, and when recycled Al is not sufficient, primary Al is used for production.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for code may be directed to the lead contact, Y.Z. (zynan083@163.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.
- This manuscript did not generate new data or code.
- All data reported in this paper will be shared by the lead contact upon request.

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AUTHOR CONTRIBUTIONS

B.Z. conceived the study, conducted the modeling and was the primary author of the manuscript. Y.Z. performed most of the experiments. Y.Y. and Z.W. conceived the concept. All authors contributed to the manuscript structure and proofreading.

DECLARATION OF INTERESTS

The authors declare no competing financial interest.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
Microsoft Office 2022	Microsoft	https://www.microsoft.com/zh-cn/microsoft-365/microsoft-office
Origin Pro 2023	OriginLab	https://www.originlab.com/

METHOD DETAILS

System definition and framework modeling

This study tends to quantify the recycling potential for Al from waste RPV panels and CO_2 emission reduction by using recycled Al under China's carbon neutrality target (Figure S5). It requires modeling and estimation of (i) RPV installed capacity and the amount of waste to the year 2060, (ii) the Al demand and CO_2 emissions of Al production, and (iii) recycled Al and CO_2 emission reduction of Al production. We assume that the Al required for producing RPV panels is obtained through both recycled Al from waste RPV panels and primary Al.

Future recycling potential for Al from waste RPV panels and CO_2 emission reduction are examined through scenario analysis. Table 1 illustrates the scenario dimensions, including three scenarios on the lifespan of RPV panels (Optimistic lifespan, Baseline lifespan, and Pessimistic lifespan), two on the failure rate of installed RPV panels (RL and EL), and three on recycling rate (RR) of recycled Al from waste RPV panels (Low-RR, Medium-RR, and High-RR). So, a total of 18 (=3×2×3) scenarios are obtained. Further descriptions of data, modeling approach, and key assumptions are provided in subsequent sections.

Prediction of RPV installed capacity and waste quantification

GCAM is a multisector, multiregion, and human-earth system model, which links global energy, water, agriculture, and land use to the economy and climate system. GCAM has been used to investigate the interconnections between complex systems and acquire long-term trends from different sectors. Here, we use the version 6.0 of GCAM accessible from a public source (https://github.com/JGCRI/gcam-core/releases) to obtain the electricity generation of RPV in China during 2020–2060 by constructing China's carbon-neutral scenario (Table S1).[52] The electricity generation from RPV is converted to the annual installation of RPV in operation during 2020–2060.

New RPV panels will be installed to satisfy the demand for electricity every year in China. Meanwhile, the RPV panels already installed will experience failures gradually and require replacement as time goes on. Therefore, by combining the GCAM and Weibull distribution function, the capacity of RPV installations as well as the waste RPV panels distribution and flow are projected through analyzing the annual new installations and replacements during 2020–2060 in China. Based on the above two models' results, the lifespan and failure rate of installed RPV panels[53] are the two decisive factors of the annual installed RPV capacity and the weight of waste RPV panels.[49] The above-mentioned four PV technologies, one traditional panel (c-Si), and three thin-film RPV panels (a-Si, CdTe, and CIGS)[54] are considered in our model (Table S2). Details of the models are shown in the Text S1.

The GCAM[52] is used to simulate annual energy (EJ) generated by RPV in a carbon-neutral scenario with a five-year step. To obtain continuous data from 2020 to 2060, we perform 4th-degree polynomial curve fitting ($R^2 = 0.994$). Then, the annual energy can be converted into power generation (P_i^{power}) from RPV. The correlation between the RPV power generation and the installation of RPV in operation can be expressed as follows:

$$G_i^D = \frac{P_i^{power}}{K \times h} \quad \text{(Equation 1)}$$

where G_i^D is the installation of RPV in operation that can generate electricity in year i, P_i^{power} is the electricity generation (GWh) from RPV in year i, K is the overall efficiency of the RPV system, which is assumed as 80%,[3,46,48] h is the average effective light duration (h) in China in 2020, which is equal to 1526. It merits noting that the installation of RPV in operation will be less than the cumulative installed RPV capacity in a given year. Because previously installed RPV panels will become waste in the future, and these RPVs waste are unable to generate electricity.

RPV panels may turn into waste prematurely due to a range of failures, not reaching their expected end-of-life targets. The annual waste RPV panels are quantified by applying the Weibull distribution function under China's carbon neutrality target, which is a widely employed statistical model to evaluate machinery lifespans. We simulate the probability of obsolescence of RPV panels at different times using the Weibull distribution function. The Weibull function of RPV lifespans[49] and the failure probability of the RPV panels are shown as Equations 2 and 3.,[27] respectively:

$$F(\varepsilon) = \int_0^{\varepsilon} f(\varepsilon)d(\varepsilon) = 1 - exp\left\{-\left(\frac{\varepsilon}{a}\right)^{\beta}\right\} \quad \text{(Equation 2)}$$

$$d(\varepsilon) = F(\varepsilon) - F(\varepsilon - 1) \quad \text{(Equation 3)}$$

where $d(\varepsilon)$ is the failure probability of the RPV panels used for ε years, ε is the lifespans of RPV panels from the time of installation (years), a is a scale factor that is determined by the lifespans of RPV panels, β is the shape factor and determined through simulation of real failure data from RPV panels.

RPV is more difficult to maintain than centralized PV.[55] RPV modules are more likely to suffer damage from unprofessional installation, unsound support-roof connections, and severe weather conditions, including strong winds. Influenced by various factors, the service lifespans of RPV modules may be shorter than those of centralized PV, but some RPV modules may even have lifespans of about 15 years. Installations of RPV, especially for anti-poverty projects, are quite geographically dispersed in remote rural areas. It is difficult to centralise management and to conduct even simple regular maintenance, thus further reducing the lifespans. Moreover, by June 2020, the total installed capacity of the currently operating anti-poverty PV power stations reached 26.49 GW and will continue to grow rapidly in the long term. Anti-poverty PV power plants will also be an indispensable portion of future waste PV modules. So, the lifespan of RPV is shorter than the 30-year lifespan of centralized photovoltaics,[49] which leads to higher cumulative end-of-life RPV panels and recycled Al. Considering the uncertainty of RPV maintenance, we set up three lifetime scenarios in order to better describe the real operation of RPV. Recycled Al estimates hinge on the lifespans of RPV panels. When the amount of RPV waste is generated significantly, recycled Al would grow. This situation is associated with the end-of-life of the RPV panels, and the optimistic, baseline, and pessimistic lifespans of RPV panels are assumed to be 25, 20, and 15 years, respectively (Table 1).[49]

Considering the failure time of RPV, we use the early loss (EL) and regular loss (RL) scenarios[53] to quantify the failure rates of the RPV panels. Due to the operating environment and maintenance conditions of RPV, the failure rates of RPV are highly uncertain. By setting two failure rates, the actual operation of RPV can be better described. The shape factors in the EL and RL scenarios are assumed to be 2.4928 and 5.3759,[27,49] respectively (Table 1). Generally, the EL tends to have problems with failure earlier and faster, while RL has failure problems relatively later and grows more quickly in the later phase (Table S3). The failure probability distribution function is shown in Figure S6.

It can be noted that over 90% of RPV panels have failed when they operate longer than (T+10) years. T is the expected lifespans of the RPV panels. We assume that RPV panels operating for more than (T+10) years will be compulsorily recycled, considering RPV operation efficiency. The capacity of the waste RPV panels[49] in year j for those installed in year i is as follows:

$$G_{ij} = \begin{cases} G_i \times d_{ij}(T) & j < 10 + T \\ G_i \times \left(1 - \sum_{i}^{j} d_{ij}(10 + T)\right) & j = 10 + T \end{cases} \quad \text{(Equation 4)}$$

where G_{ij} represents the capacity of the waste RPV panels in year j for those installed in year i, G_i represents the annual installed RPV capacity (GW) in the year i and is determined by Equation 5, $d_{ij}(T)$ represents the failure probability of the RPV panels that are installed in year i and being wasted in year j. G_j represents the total capacity of the waste RPV panels in year j, shown as Equation 6:

$$G_i = {G_i}^D - {G_{i-1}}^D + G_j \, (i = j) \quad \text{(Equation 5)}$$

$$G_j = \sum G_{ij}, i, j = 2020, 2021, ..., 2060 \quad \text{(Equation 6)}$$

However, RPV has been in development for more than a decade and its cumulative installed capacity is already 78.3 GW by 2020, and it was not installed until 2020 as shown in the GCAM model. It could be noted that RPV installed more panels and generated fewer waste panels during 2017–2020. The installed capacity of the RPV calculated in the GCAM model and the actual cumulative installed capacity was similar by 2021. Consequently, it is assumed that RPV was installed starting from 2020 in this research of RPV installation estimation. RPV systems may also be affected by other power subsystems. Considering the future transition to a cleaner power system, other forms of power generation such as nuclear, wind. The market share of these power generation methods will have an impact on the amount of installed RPV capacity. According to model predictions, nuclear, wind and solar power account for 26% and 28%, respectively, of total electricity generation in 2060. The share of photovoltaic power in total electricity generation increases gradually from 20% in 2020 to 30% in 2060. RPV will account for half of total solar power generation. The output of GCAM model is a dynamic equilibrium result.

Finally, the capacity of the waste RPV panels (GW) is transformed into weight units in tonnes, utilizing the weight-to-power ratio (WPR) of the RPV panels.[56,57] The market share of RPV by technology is shown in Table S3, including RPV panels of crystalline silicon (c-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). Recently, the latter three are thin-film RPV panels that have improved significantly in the world RPV market,[27] and their market share is expected to expand continuously. We assume that these four categories of RPV technologies would mainly be used in the future,[54] and details are displayed in Table S4.

This method considers the conversion factor that is dependent on time.[56,57] The trend of the WPR (w_i) of the RPV panels over time is shown in Equation 7. The WPR of different RPV panel technologies is shown in Equation 8. Due to further advancements in RPV technology, the WPR (t/MW) of four RPV panel technologies (w_{ik}) is steadily decreasing over time (Figure S7).

$$w_i = A \times e^{-i/B} \quad \text{(Equation 7)}$$

$$w_{ik} = \left| w_{2020,k} - w_i \right| \quad \text{(Equation 8)}$$

where w_{ik} is the weight-to-power ratio of RPV panel technology k in year i, A is 1.11×10^{20} (tonnes/MW), and B is 48.24 years, $w_{2020,k}$ is the weight-to-power ratio of RPV panel technology k in the year 2020 (Table S2). The average weight-to-power ratio (w_i^{A}) in the year i is determined by the market share of the four RPV panel technologies, which is shown in Equation 9. The annual weights of the waste RPV panels in year j are as follows:

$$w_i^{AV} = \sum_k w_{ik} \times MS_{ik} \quad \text{(Equation 9)}$$

$$M_j = \sum_i \left(w_i^{AV} \times G_{ij}\right) \quad \text{(Equation 10)}$$

where w_i^{AV} is the average weight-to-power ratio in the year i is determined by the market share of the four RPV panel technologies, MS_{ik} is the market share of RPV technology k in year i (Tables S3 and S4), M_j is the annual weights of the waste RPV panels in year j.

Al demand and CO_2 emissions of Al production

To meet the development of RPV under the carbon-neutral goal, it is important to assess the Al demand during its manufacturing process. The weight of Al demand for manufacturing RPV panels is calculated by Equation 11:

$$M_{i,d}^{Al} = \sum_k G_i \times w_{ik} \times MS_{ik} \times MS_k^{Al} \quad \text{(Equation 11)}$$

where $M_{i,d}^{Al}$ represents the weight of Al demand for manufacturing RPV panels in year i, G_i shows the annual installed RPV capacity in year i, w_{ik} is the weight-to-power ratio of RPV panel technology k in year i, MS_{ik} means the market share of RPV technology k in year i (Tables S3 and S4), MS_k^{Al} tells the percentage of Al (The component material refers specifically to the material of the RPV module itself, such as the battery and Al alloy frame, excluding the ancillary equipment such as support structures) in the RPV technology k in year i (Table S5). Moreover, quantifying the Al content of waste RPV panels will help to measure their recycling potential. The weight of Al in the waste RPV panels is estimated by Equation 12:

$$WM_j^{Al} = \sum_i \sum_k G_{ij} \times w_{ik} \times MS_{ik} \times MS_k^{Al} \quad \text{(Equation 12)}$$

where WM_j^{Al} represents the weight of Al from the waste RPV panels in year j, and G_{ij} represents the capacity of the waste RPV panels in year j for those installed in year i.

The CO_2 emissions studied in this paper are only those generated during the Al production process and not the total CO_2 emissions under the full life cycle of RPV. The primary Al production is energy- and emission-intensive, the total CO_2 emissions of Al production for producing RPV panels are as Equation 13:

$$C_{i,1}^{Al} = M_{i,d}^{Al} \times EI_{i,1} \quad \text{(Equation 13)}$$

where $C_{i,1}^{Al}$ is the total CO_2 emissions of Al production for producing RPV panels in year i, assuming that only primary Al is used and no recycled Al; $EI_{i,1}$ is the CO_2 emissions intensity of producing primary Al in year i, which is assumed to decrease linearly from 14.5 t CO_2e/t Al in 2020 to 5.5 t CO_2e/t Al in 2060.[26]

Recycled Al and CO_2 emission reduction of Al production

Recycling Al from waste RPV panels could be reused in producing new RPV panels, which could reduce the dependence on primary Al. It is essential to accurately estimate of recycling potential of RPV waste in China since the recycling system of RPV is imperfect. The recycled Al from waste PRV panels can be quantified by Equation 14:

$$M_{j,r}^{Al} = WM_j^{Al} \times RR_j^{Al} \quad \text{(Equation 14)}$$

where $M_{j,r}^{Al}$ is the quantity of recycled Al from waste PRV panels in year j, WM_j^{Al} represents the weight of Al from the waste RPV panels in year j, RR_j^{Al} is the recycling rate (RR) of Al from waste PRV panels in year j. However, the recycling system of waste photovoltaic panels is still in the initial stage with a relatively low RR of Al from the panels. Previous studies have not considered the effect of differences in the RR on recycled Al, which is critical to evaluating the Al recycling potential of RPV under China's carbon neutrality target.

The proportion of recycled Al to the total Al demand denotes the reuse rate of recycled Al (RRA) when producing RPV panels in a given year. The annual quantity of recycled Al and Al demand are employed to establish an indicator for the recycling potential of Al (RRA_i). Higher RRA_i implies a higher self-sufficiency potential of Al, fewer primary Al gaps, and better utilization of recycled Al, and vice versa. The RRA_i in the current study refers to the approach applied in the assessment of the supply potential of recycled material for wind energy systems,[27,58] and can be obtained by Equation 15:

$$RRA_i = \frac{M_{j,r}^{Al}}{M_{i,d}^{Al}} \times 100\% \; (i = j) \quad \text{(Equation 15)}$$

It is equal to the quantity of recycled Al from waste PRV panels divided by the weight of Al demand for manufacturing RPV panels. The demand for Al is independent of the recycling rate and is determined by the amount of installed RPV. The recovery rate will have an effect on recycled Al from waste PRV panels. The Al demand for producing RPV panels can be satisfied through both primary Al and recycled Al production. We explore the CO_2 emission reduction potential due to the differences in emission intensities between the primary and recycled Al production for producing RPV panels. The total CO_2 emissions and CO_2 emission reduction of Al production are quantified by Equations 16 and 17, respectively.

$$C_{i,2}{}^{Al} = M_{j,r}{}^{Al} \times EI_{i,2} + \left(M_{i,d}{}^{Al} - M_{j,r}{}^{Al}\right) \times EI_{i,1} \quad (i = j) \tag{Equation 16}$$

$$CR_i = C_{i,1}{}^{Al} - C_{i,2}{}^{Al} \tag{Equation 17}$$

where $C_{i,2}{}^{Al}$ is the total CO_2 emissions of Al production for producing RPV panels by using both primary and recycled Al in year i; $EI_{i,2}$ is the CO_2 emissions intensity in the production of recycled Al in year i, which is assumed to decrease linearly from 0.65 to 0.5 t CO_2e/t Al in 2050[26,59] and then remains constant until 2060. So, the first term represents the CO_2 emissions of RPV panel production using recycled Al, while the second term shows those using primary Al. In this paper, the Al used to produce RPV panels is divided into primary and recycled Al. The carbon emission intensity of Al production is mainly referred to the study by Lennon et al.[26] In the GCAM model, the CO2 emission intensity of primary and recycled Al cannot be separated. The data does not meet the requirements of the study. So, we refer to the study of Lennon et al.[26] for parameter setting. Moreover CR_i is the total CO_2 emission reduction of Al production in year i.