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News & Views

Navigating the future: China's photovoltaic roadmap challenges

Moisés Gómez [a], Guochang Xu [a], Yan Li [a,b], Jinhui Li [a], Xi Lu [a,b], Kebin He [a,b], Xianlai Zeng [a,*]

[a] State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China
[b] Institute for Carbon Neutrality, Tsinghua University, Beijing 100084, China

Carbon neutrality aims to transform the global renewable energy industry [1]. Solar photovoltaic (PV) generation has grown exponentially over the last decade, from 0.84 GW (solar installed capacity) in 2000 to 843 GW in 2021, faster than other renewable energy industries [2]. Its technology has significant advantages such as safety, non-pollution, high efficiency, reliability, and convenient installation and maintenance. Over the past decade, China has seen a substantial increase in installed solar power capacity, accounting for nearly 36% (306 GW) of the world's new solar capacity in 2021, leading solar PV investment and deployment [3]. Additionally, solar power is expected to gain momentum due to several factors, including reduced capital costs, enhanced technology lifespan, and improved efficiency of solar panels. Notably, between 2011 and 2018, the capital cost of utility-scale solar PV projects per kilowatt of electricity in China dropped by an impressive 63%, making it more economical than coal power [4].

To reduce carbon emissions, China has set ambitious goals of carbon emissions and neutrality. To achieve this, China has pledged to install 880–890 GW of solar power by 2030 and 3070–3845 GW by 2060, representing about 45%–50% of China's electricity production by 2060 [5]. Historically, China has witnessed remarkable and consistent growth in its solar photovoltaic installed capacity. Simultaneously, the global solar installed capacity has also been experiencing exponental growth. To date, the PV industry has showcased its ability for rapid growth in annual production capacity, achieving an average two-fold increase every three years [6], and material demand for its deployment has been met. However, there are serious concerns about the availability of raw materials for the manufacture and development of the photovoltaic industry, which could seriously affect and delay the transition to renewable energy if future demand for materials does not meet their supply. The COVID-19 pandemic has a major impact on the global economy, leading to a deep global recession and inflation. It has also affected mining and raw material imports and exports. These uncertainties and contingencies raise questions about whether China and the world's will be able to meet the demand for materials in its future photovoltaic zero-emissions roadmap. What materials and how many tonnages would such a transition require?

We are attempting to answer these questions in line with the goals of China's carbon neutrality roadmap. To improve accuracy and minimize uncertainty, different solar cell sub-technologies and the future dominance of these sub-technologies were considered (Fig. S1 online). A total of 11 materials were considered (Fig. 1a), representing the key materials used in the manufacture of photovoltaic cells (see the Supplementary materials online for details). The main materials used in the production of PV components are aluminum, silicon, and copper. These three elements account for more than 95 wt% of the total material demand. Other metals such as lead, tin, cadmium, silver, indium, selenium, and tellurium account for nearly 1% of solar panels.

Just as alarming as missing the Paris Agreement target of 1.5 °C is the China PV roadmap results (Fig. 1b and Figs. S2, S3 online), if things continue as they have been. The cumulated material intensities of most of these 11 crucial elements will overcome their Chinese metal reserves in 2060 (Fig. S2 online), leading to serious imbalances and resource constraints in the medium and long term, threatening not only the goal of net zero emissions but also humans and the environment. Although mineral reserves are dynamic over time, i.e., they can increase or decrease—it is a serious concern as not only are these materials used in solar panels, but they are also used in other low-carbon technologies like wind turbines, electric vehicles, high-tech technologies, etc. Indeed, out of the 11 elements considered, only lead (<1% annual metal pressure, Fig. S3g online) was found to present minimal risk to meet its future demand; however, aluminum, cadmium, copper, tin, and silicon revealed high constraints to meet their future demand. The rest of the elements analyzed (e.g., silver, gallium, indium, selenium, and tellurium) will not meet the future demand with the current Chinese primary production. It is important to note that materials with the highest supply pressure (Fig. S3 online) are produced as a by-product since their concentration in the earth's crust is economically unfeasible, and they are mostly produced as coproducts from host metals such as aluminum, zinc, and copper [7]. Increasing the production of these by-product metals (e.g., indium, gallium, tellurium, and selenium) can have indirect impacts on their host metals demand as oversupply could reduce their prices and discourage recycling.

This scenario becomes even more concerning when considering that China is the largest producer of solar panels globally, with a share of over 75% of the entire global PV industry. In 2022, China exported 154 GW of modules, 24 GW of solar cells, and 41 GW of wafers. Furthermore, it is estimated that these exports could surge to reach a remarkable 379 GW by 2026, encompassing shipments of modules, cells, and wafers [8]. With China anticipated to maintain its leading role in the PV industry, the material intensity

* Corresponding author.
E-mail address: xlzeng@tsinghua.edu.cn (X. Zeng).

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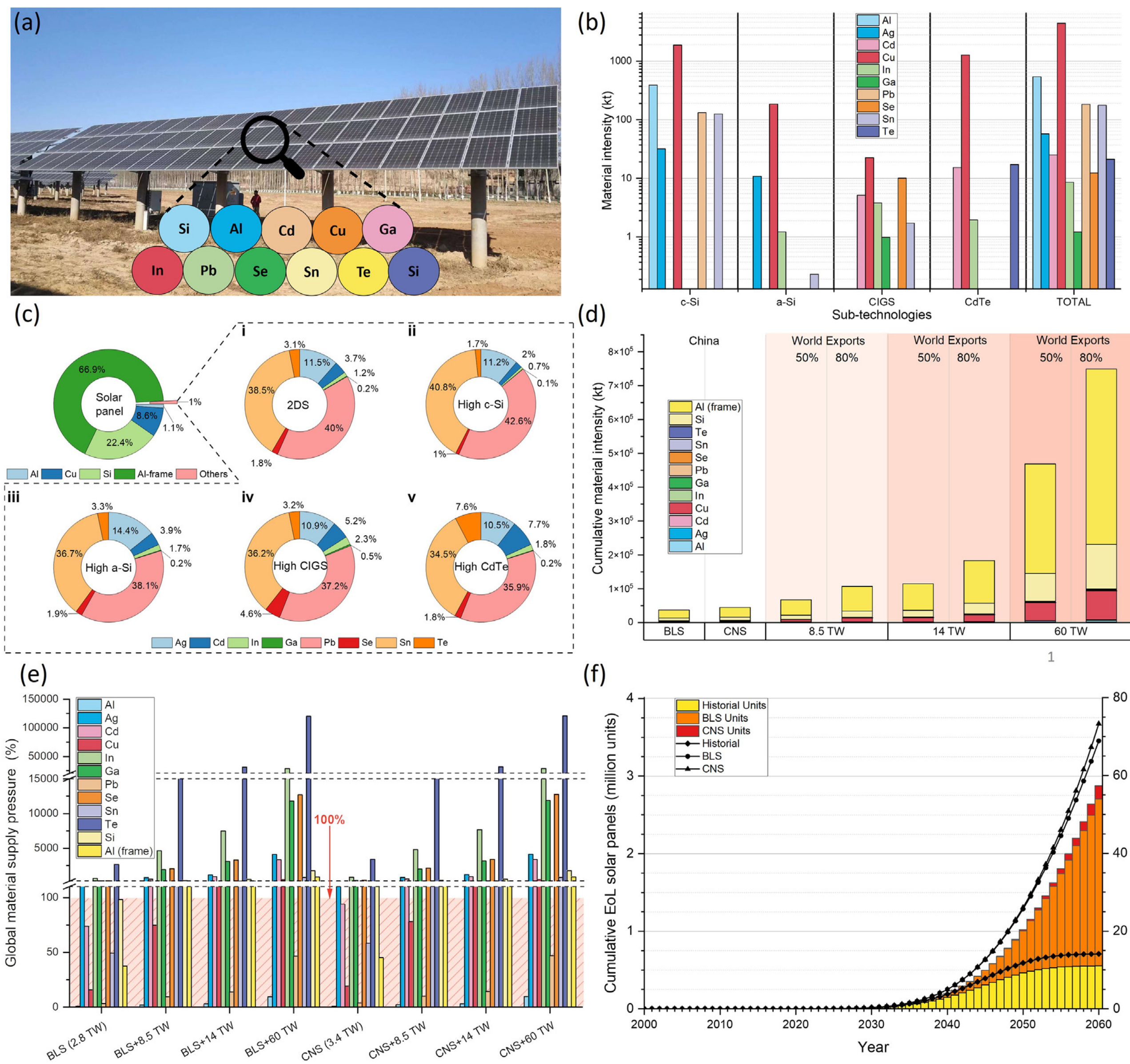

Fig. 1. (a) Materials studied in solar panels. (b) Cumulate material intensity in China by 2060 in the 2DS scenario (other scenarios are presented in the Supplementary materials online). (c) Material distribution in EoL solar panels and zoom of the metal distribution from solar panels (others) in different dominant sub-technology: (i) 2DS, (ii) high c-Si, (iii) high a-Si, (iv) high CIGS, and (v) high CdTe. (d) Cumulative material intensity considering the production of China and the World by 2050 under the net-zero emissions pledges in different scenarios. (e) Global material supply risk for the production of solar panels in 2050 considering the global mineral production of 2020. (f) Projected cumulated units and weight of EoL solar panels in China. BLS: baseline scenario; CNS: carbon neutral scenarios.

is projected to rise significantly by 2050, when most countries have pledged to reach their net-zero emissions. If China is responsible for producing 50% of the total solar modules by 2050, its material intensity will surge from 25% to 800% (Fig. 1d and Tables S3 online). Furthermore, if China produces 80% of global PV modules, the material intensity could increase by 100% to a staggering 1400% (Fig. 1d and Table S4 online). By 2050, the production of solar panels will necessitate an astounding quantity of materials, surpassing the global production levels of 2020 (Fig. 1e). Notably, even for China alone, the demand for certain materials like silver, indium, gallium, selenium, and tellurium will exceed the global production levels of these materials in 2020. In any scenario where 50% or 80% of the global PV panel production is exported by China, the availability of these materials poses a significant challenge to achieving global solar power goals.

Solar panels have a long lifespan (~25–30 years), which produces a notorious gap between the put-in operation and end-of-life (EoL). From the historical data (2000–2020), approximately 555,000 PV modules were put in operation, reaching a maximum withdrawal of nearly 34,500 units in 2046, declining thereafter (Fig. 1f). By 2060, PV modules installed between 2000 and 2020 will be completely retired, accounting for approximately 14 kt of e-waste, close to the reported data in one previous study [9]. In the case of future installed solar panels, their retirement will take off in 2025, showing rapid and almost exponential growth. By 2060, the cumulated retirement of China PV components is expected to reach 2.7–2.9 million units (69–73 kt), equivalent to 1142–1208 GW of capacity and in need of replacement. The decommissioning of this continuous photovoltaic assembly also means an increase in the accumulation of materials encapsulated in these components (Fig. 1c and Fig. S4 online). The bulk materials in EoL PV modules are aluminum, copper, and silicon, where only ~1% corresponds to other metals used in solar cells, and their amount varies according to the dominant sub-technology.

Is there any solution? Based on our calculations, different scenarios need different material intensities. Among the five sub-technology developments, the crystalline silicon (c-Si) scenario stands out as the least material-intensive option. While it demands significant quantities of silicon, it exhibits lower material intensities for metals such as cadmium, indium, gallium, tellurium, and selenium (Figs. S2 and S3 online). With crystalline silicon cells already dominating the global market, accounting for over 90% of production, this mature technology allows for large-scale production. Consequently, it presents the most favorable scenario in terms of material requirements both in China and globally.

According to our results (Figs. S2 and S3 online), the cumulative demand by 2060 will exceed the current proven reserves for eight resources that have a high supply risk: silver, cadmium, copper, gallium, indium, selenium, tellurium, and aluminum. Thin-film technologies tend to put more pressure on rare metals such as cadmium, gallium, and indium. In contrast, crystalline silicon technologies consume more base and precious metals such as aluminum, copper, and silver. The sole development of any one technology will lead to supply risks for some resources. The market needs to diversify the application scenarios of various technologies based on their advantages (such as the lightweight feature of thin-film technologies) to avoid resource supply risks.

An alternative to alleviate the high metal demand is the implementation of a circular economy strategy through the development of an e-waste management and recycling process for PV modules. Reshoring silicon PV manufacturing can contribute to decarbonization and climate change mitigation [10]. EoL PV modules will generate large quantities of materials available, which can be potentially exploited as feedstocks for new PV modules. China is the world's largest producer of most of the materials used in the solar PV industry as well as the main PV modules manufacturer, having the greatest potential for recycling and promoting circularity. If China were able to achieve a 100% recycling rate for its solar panels, it could result in a significant reduction in material demand of nearly 25% (Fig. S4 online). Nevertheless, even with the total recycling of EoL solar panels, the demand for gallium, indium, selenium, and tellurium will not meet its supply if only Chinese production is considered. Recycling alone cannot completely solve the supply and supply crisis. It must require the joint efforts of multiple methods, such as reducing the demand for materials per unit of power generation by technological advancement and process optimization while ensuring efficient recycling (i.e., broaden sources of income downstream and reduce expenditure upstream).

China has implemented regulations on the recycling of e-waste since 2011, but PV components are not considered e-waste, and therefore there is no specific legislation for the sound management of EoL PV modules [11]. Monitoring and managing EoL PV modules is paramount and urgently needed, where robust systems and legislative directives for collection, storage, and recycling targets are necessary before EoL PV modules pile up and become an environmental problem. This problem affects not only China but also several developed and developing countries. Europe is the only continent that has specific regulations on the collection and recycling of solar PV modules [11]. In addition to the EU and the UK, USA has recently implemented a regulation on the recycling of PV modules, requiring solar PV modules manufacturers to finance and manage the collection and processing at their EoL, a scheme known as extended producer responsibility (EPR), which is also applied in Europe. Other countries such as Australia, India, and Japan, although with no legal regulations, are working, and legislation is under development [12]. Interesting views and lessons can be learned from those experiences and legislation.

Reduction of the material intensity in the sub-technologies will certainly be reached by the continued innovation and optimization of solar cells, which has shown promising results on a laboratory scale [13]. Nevertheless, most of these technologies are not yet ready for commercial applications, and it will be a long time before they enter the market. Recycling more materials is crucial, including from existing dumping tailings, smelting residues, or product waste, but this simply would not meet the increasing demand for at least a decade owing to the poor collection and insufficient processing [14,15].

China has led the PV modules industry in both manufacturing and installed capacity worldwide. As the energy sector reduces its dependency on fossil fuels, not only solar energy but also other renewable forms of energy, such as wind and hydropower, will increase their metal intensities. China should strengthen its international relations, develop strong trade connections, promote secondary material production, and build global cooperation with multiple countries to diversify and safeguard its material supply for future booming demand. As solar power will be one of the largest sources of energy in China and worldwide, it will be favored by specific regulations requiring targets for collection, recycling, and recovery rates.

A viable solution pathway is underway. During the Thirteenth Five-Year Plan (2016–2020), China placed a strong emphasis on specific developments and objectives within the solar energy sector. This included setting ambitious capacity targets, enhancing grid integration, fostering research and development in solar technology, gradually reducing subsidies for solar panels to promote market competitiveness, prioritizing environmental protection and sustainability in solar industry practices, and strengthening international collaborations within the solar energy field. These directives and commitments have been further refined and expanded upon in China's Fourteenth Five-Year Plan (2021–2025), which places a heightened focus on accelerating the expansion of renewable energy, fostering innovation, and advancing technological development. Nevertheless, further approaches are needed. As a first step, China should incorporate EoL PV modules into its e-waste regulations and promote a circular economy for PV modules. A robust circular economy strategy for EoL PV modules is essential to achieve China's solar PV roadmap to zero-carbon emissions. Urgent legislative guidance for the solar power industry and e-waste management is needed to address material supply challenges promptly. Acting now is crucial to prevent further escalation of this issue.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary materials

Supplementary materials to this news & views can be found online at https://doi.org/10.1016/j.scib.2023.08.022.

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Moisés Gómez is a postdoctoral fellow and a recipient of the prestigious Shuimu Scholar award at the School of Environment, Tsinghua University, China. He earned his Ph.D. degree from Imperial College London in 2022. With a passion for environmental sustainability, his research interest encompasses e-waste management, recycling, circular economy, mass flow analysis, and life cycle analysis. His recent research focuses on material intensities, end-of-life management, and recycling of solar panels and wind turbines, contributing to the preparedness for renewable energy technologies reaching their end-of-life, ensuring sustainable practices, and minimizing environmental impacts.

Xianlai Zeng is currently an associate professor at the School of Environment, Tsinghua University, China. He obtained his Bachelor's (2002) and Master's (2005) degrees from Northwest A&F University, and Ph.D. degree (2014) from Tsinghua University. He worked as a technical advisor for the United Nations Development Programme (2015), visiting staff at Coventry University (2012), visiting professor at Macquarie University (2017), and Fulbright fellow at Yale University (2018–2019). His areas of specialization and interest include waste recycling and circular economy.