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Environmental Pollution 320 (2023) 121066

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Review

Green or not? Environmental challenges from photovoltaic technology☆

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ARTICLE INFO

Keywords:
Photovoltaic solar energy
Environmental benefits
Negligible effects
End-of-life PV panels
Sustainable development

ABSTRACT

The booming demands for energy and the drive towards low-carbon energy sources have prompted a worldwide emerging constructions of photovoltaic (PV) solar energy facilities. Compared with fossil-based electrical power system, PV solar energy has significantly lower pollutants and greenhouse gases (GHG) emissions. However, PV solar technology are not free of adverse environmental consequences such as biodiversity and habitat loss, climatic effects, resource consumption, and disposal of massive end-of-life PV panels. This review highlights the benefits and potential environmental impacts of implementing PV technologies. To the end, some proposals are recommended to improve this new technology's sustainability.

1. Introduction

Hitherto, global electricity generation relies fundamentally on fossil fuels which have been posing significant environmental and climatic problems. The transition from carbon-intensive fossil fuels to mixed energy by including more renewables (e.g., solar, wind, hydro) is crucial for humanity sustainable development. International Energy Agency (IEA) forecasted that annual additions to global renewable electricity capacity were expected to be averaged around 305 GW (GW) annually, between 2021 and 2026, with an acceleration of almost 60% (IEA, 2021).

Photovoltaic (PV) solar energy is generated directly by sunlight, which is the most promising and the fastest-growing renewable. According to International Energy Agency's Net Zero Scenario, by 2050, the global net electricity generation by solar power would have reached more than 10 trillion kWh (EIA, 2021) (Fig. 1a). China has been the most significant contributor (20%–36%) since 2015; besides, the USA, Germany, Japan, and India have been the top countries in electricity generation from PV solar energy (BP, 2022) (Fig. 1b). In particular, the Chinese government has scheduled a comprehensive plan to expand the scale of solar power generation and accelerate the construction of solar farms from 2021 to 2030 (Xinhuannet, 2021). By 2030, the installed wind and solar power generation capacity in China would have reached over 1200 GW (Xinhuannet, 2021). Meanwhile, solar energy would have been account for nearly 50% according to the 2020 data (NBSC, 2021).

Solar PV technology is widely promoted as a "clean" zero-emission energy production system. However, the adverse effects of PV solar technology application have not been sufficiently considered and even ignored. If to consider the whole life cycle of the PV industry, PV power generation is not a wholly zero-emission or zero-pollution industry. There is enormous resource consumption, non-negligible ecological impact, and massive pollutant emissions attributed to the production, operation, and scrap treatment of disposed PV devices (Fig. 2). The potential ecological and environmental costs of the rapid development of the PV industry need public attention urgently.

In this review, both advantages and potential negative effects of PV technologies were summarized from the view of the environmental impact, and further, some suggestions were given. We called for a comprehensive environmental impact assessment of PV solar application to improve the sustainability of this technology.

2. Environmental benefits from PV technologies

The lifecycle greenhouse gas (GHG) and pollutant emissions for

☆ This paper has been recommended for acceptance by Dr. Da Chen.
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https://doi.org/10.1016/j.envpol.2023.121066
Received 5 October 2022; Received in revised form 7 December 2022; Accepted 10 January 2023
Available online 10 January 2023
0269-7491/

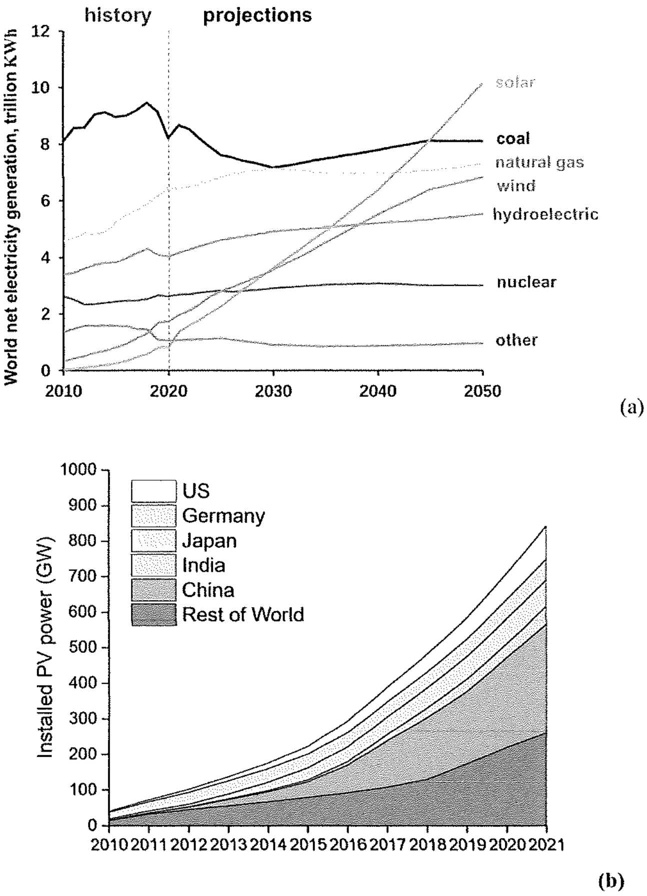

Fig. 1. (a) World net electricity generation by source (data from International Energy Outlook 2021) (EIA, 2021); (b) Growth trend of the global installed generating capacity of PV solar energy during 2010–2020 (data from Statistical Review of World Energy, 2021) (BP, 2022).

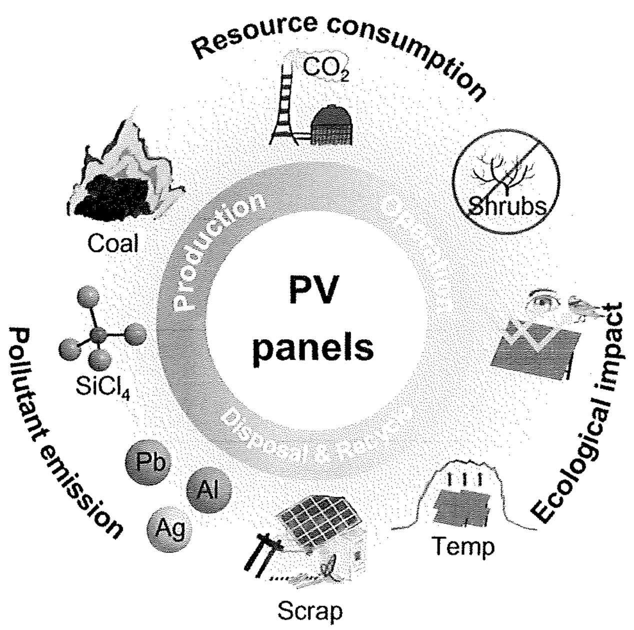

Fig. 2. Environmental problems are caused by production, operation, and disposal of PV devices.

different ways of generating electricity are shown in Fig. 3. It has been clearly shown that PV power generation is a lower-carbon and greener technology compared with fossil-fueled electricity. Typically, the lifecycle GHG emission factors for electricity generation from coal-fired power plants and natural gas-fired power plants are 753–1095 g CO_2 eq./kWh and 403–513 g CO_2 eq./kWh, respectively (UNECE, 2022). Whereas GHG emission factors from solar PV system ranges from 7.4 to 83 g CO_2 eq./kWh, which are significantly lower than those of fossil-fueled power sectors. Among different PV systems, GHG emission factors from thin-film technology (7.4–35 g CO_2 eq./kWh) are sensibly lower-carbon than those of silicon-based PV (23–83 g CO_2 eq./kWh) (UNECE, 2022). The global average lifecycle GHG emissions is 52–53 g CO_2 eq./kWh (ground-/roof-mounted), while the European Union (EU) region shows lower lifecycle GHG emissions: about 37 g CO_2 eq./kWh (NECE, 2022).

In addition, coal-fired electric power plants are accounted for about 70% of sulfur dioxide (SO_2) emissions and also important sources of nitrogen oxides (NOx) (Dincer, 1999). These emissions are, consequently, hazardous to ecological environments and harmful to human health. Both SO_2 and NOx contribute to acid precipitation which may cause respiratory and heart diseases (Hosenuzzaman et al., 2015). Acid rain has also negative impacts on plants and animals. NOx also

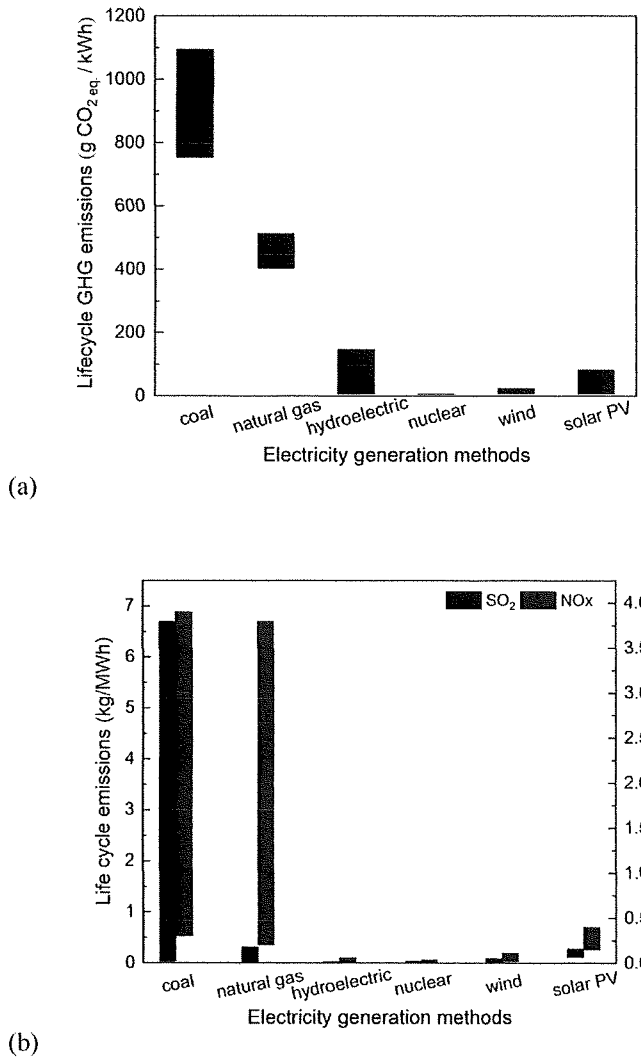

Fig. 3. Lifecycle emission ranges of the assessed electricity sources. (a) GHG emission (data from UNECE, 2022); (b) SO_2 and NOx emissions (Turconi et al., 2013).

contributes to smog and asthma attacks (Nomura et al., 2001). It was estimated that PV systems could save 0.53 kg CO_2 emission for each Kilowatt-hour of electricity generated, and therefore, reduce 69–100 million tonnes of CO_2, 126,000–184,000 tonnes of SO_2 and 68,000–99,000 tonnes of NOx by 2030 (Shahsavari and Akbari, 2018). Moreover, coal combustion emits other air pollutants, like fine particulate matter ($PM_{2.5}$), which contribute to thousands of premature deaths annually (Kelly & Fussell, 2015). A life cycle assessment indicated that, in China, the environmental impact of a PV system was equivalent to 4.5% of that of the current coal-based electrical power system (Xie et al., 2018). Therefore, PV power generation could significantly reduce GHG and pollutant emissions, as one of the most promising renewables. Indeed, PV technologies have shown considerably more environmental benefits in terms of climate change, ecotoxicity and human health, with respective to fossil fuel technologies.

3. Potential negative effects from PV technologies

3.1. Toxic chemicals involved in PV materials production

Semiconductor materials in PV cells are mostly made from monocrystalline silicon (Si) and polycrystalline Si, with their global market share of about 95% in 2021 (Philipps and Warmuth, 2022). The source of silicon, mining metallurgical grade silica, could generate silica dust, leading to severe lung diseases of miners. Subsequently, the extraction and purification of Si are essential process in semiconductor production. The Siemens chemical vapor deposition method using the trichlorosilane ($SiHCl_3$) precursor dominated more than 90% of the market for polysilicon production, followed by the fluidized bed reactor (FBR) method using the monosilane (SiH_4) precursor (3%–5% market share) (Woodhouse et al., 2020). The Siemens processes typically include hydrochloric acid (HCl) chlorination and H_2 reduction. A mass of toxic pollutants including silicon tetrachloride (STC), hydrogen fluoride, nitric acid, volatile organic pollutants (VOCs), dust, and other by-products, would be produced in these processes. According to Zhang et al. (2015), the production of one ton of polysilicon materials would generate at least four tons of highly toxic STC waste.

In addition, most solar cell technologies require heavy metals or rare metals to achieve higher photovoltaic conversion efficiency. The amount of the metals in PV panels depends on the type of cells being made. The metal contents in different type of PV cells are listed in Table 1. Notably, the content of cadmium (Cd) in CdTe (cadmium telluride) PV cell is significantly higher than that in crystalline silicon (c-Si), amorphous silicon (a-Si), and copper-indium-gallium-selenide (CIGS) PV cells, while lead (Pb) content in c-Si is relatively high. The highly toxic elements, such as Pb and Cd, are carcinogens and hazardous at even low doses (Haq, 2003). If not properly disposed, they would cause serious environmental hazards. For example, the precipitation percolated through broken modules dumped in an open area or landfill, if without proper control measures, would bring down metals in modules, and release them into the leachate, then contaminate nearby soil and water (Nain and Kumar, 2020). Similarly, many other hazardous chemicals used as solvents, such as acetone and toluene, to clean dust and dirt from the solar panels could be released into environments. Detailed potential health and environmental impacts from the toxic compounds involved in PV panel production were summarized in Table 2.

At the same time, the manufacture of PV products from quartz mining is highly energy consuming. Polysilicon production through the Siemens and FBR processes would have to consume about 50–80 kWh/kg equivalent of electricity and steam, and 30–40 kWh/kg equivalent including electricity and natural gas, respectively (Frischknecht et al., 2020; Woodhouse et al., 2020). Besides, the petrol burned during shipping of PV-supporting materials were also colossal. For a 30 MW PV-utility, 1500 t of steel for the mountings, 800 t of module glass, and 200 t of copper cable were needed and shipped to connect its modules to the nearest high-voltage line, in addition to the massive loads of concrete for fixing the mountings (Chen et al., 2022). With an increasing demand of PV, the environmental impacts from the increasing production and use of these materials should be also considered.

3.2. The PV operations affect vulnerable lands, ecological functions, and climatic environments

The application of PV devices occupies a large area (for example, a system with 1 MW capacity need 1.6 ha of land) (Ravichandran and Panneerselvam, 2022), most of which is cropland, followed by arid land and grassland, and thus significantly changes the land use (Kruitwagen et al., 2021). The construction of PV power stations would modify the landscape, including vegetation removal, soil compaction, and construction of access roads, not only leading to soil erosion and the loss of soil nutrients, resulting in habitat fragmentation or even failure, and the

Table 1
Metal content (weight %) in c-Si, a-Si, CdTe and CIGS PV cells.

	Toxic metals						Base or critical metals						References
	Pb	Cd	Cr	Al	Ni	Sn	Cu	Zn	Mg	Ga	In	Te	
c-Si	0.06					0.12	0.57	0.12					Paiano (2015)
	<0.1			10.00			0.60	0.12					Aman et al. (2015)
	4.69E-03			16.5	1.06E-03	5.86E-05	7.31E-01	7.81E-06	0.52				Dominguez and Geyer (2017)
	<0.01			16.9	<0.01	0.07	0.77	<0.01	0.58				Maani et al. (2020)
a-Si						0.043	0.9				0.50		Paiano (2015)
	<0.1			10.00				<0.1					Aman et al. (2015)
		5.13E-03	5.65E-04	41.6			8.99E-01	3.72E-04	1.31		1.16E-02	6.42E-03	Dominguez and Geyer (2017)
CdTe		0.07					1.00	0.01				0.07	Paiano (2015)
	<0.01	0.07		<0.01			1.00	0.01				0.07	Aman et al. (2015)
	4.22E-03	0.12	1.81E-02	9.04E-02		1.39E-06	3.01	1.81E-07				0.12	Dominguez and Geyer (2017)
		0.08				0.02	0.03					0.07	Sica et al. (2018)
	<0.01	0.12	0.02	0.05		<0.01	0.68	<0.01				0.12	Maani et al. (2020)
CIGS	0.05	5.00E-04					0.80	0.12		0.01	0.02		Paiano (2015)
	<0.1			12.00			0.85	0.12			0.02		Aman et al. (2015)
		1.71E-01		8.58		5.68E-02	2.84E-01	5.68E-02	2.67E-01	5.68E-02	2.84E-02		Dominguez and Geyer (2017)
							0.01	0.04		0.01	0.01		Sica et al. (2018)

Note: c-Si: crystalline silicon; a-Si: amorphous silicon; CdTe: cadmium telluride; CIGS: copper indium gallium selenide.

Table 2
Toxic chemicals involved in PV cells manufacturing (Aman et al., 2015; Hosenuzzaman et al., 2015; Tawalbeh et al., 2021).

Chemicals		Purpose	Environmental and health impacts
Acid	Hydrochloric acid (HCl)	Production of electrical grade silicon, etching and cleaning of semiconductor.	Irritate eyes, skin, nose, mouth, throat and even cause infection, affecting digestive system and respiratory system.
	Nitric acid (HNO_3)	Cleaning and removing dopants from wafers and reactors.	Cause chemical burns.
Solvent	Acetone	Clean out tiny dirt and dust-off chips from PV components.	Irritation or even damage to eyes, nose and throat, and damage to kidney, liver, nervous system and reproductive system.
	Iso-propanol	Separating, purifying and cleaning solar cell raw materials.	Flammable, corrosive, toxic, and carcinogenic.
	Toluene	Clean out tiny dirt and dust-off chips from PV components.	Headache, hearing loss, confusion, memory impairment and stunting.
	Xylene	Clean out tiny dirt and dust-off chips from PV components.	Irritate eyes, skin, nose and throat, cause infection and damage to liver and kidney, and affect normal pregnancy.
	Iso-propanol	Clean out tiny dirt and dust-off chips from PV components.	Irritate eyes and skin; Causes depression, dermatitis, nausea, respiratory failure.
	1,1,1-Trichloroethane	Clean out tiny dirt and dust-off chips from PV components.	Dizziness, decreased blood pressure, coma, causing heart problems.
Toxic gas	Ammonia (NH_3)	Separating, purifying and cleaning solar cell raw materials.	Flammable, corrosive, toxic, and carcinogenic
	Selenium hydride	Separating, purifying and cleaning solar cell raw materials.	Flammable, corrosive, toxic, and carcinogenic.
	Sulfur dioxide (SO_2)	Emissions from raw material extraction and processing.	Acid precipitation; risks heart attacks and asthma.
	Nitrogen oxide (NO_x)	Emissions from raw material extraction and processing.	Acid precipitation; contributes to smog; risks of heart attacks and asthma.
Metals	Lead (Pb)	Wiring and welding of photovoltaic electrical components.	Carcinogenic; damage to brain, kidney and nervous system, causing osteoporosis, anemia, abortion, etc.
	Cadmium (Cd)	Critical material of cadmium telluride (CdTe).	Carcinogenic; Damage to kidney, prostate, respiratory system, blood system, etc.

decline of biodiversity, but also further threatening the ecosystem stability (Dhar et al., 2020). The PV facilities across the landscape may disrupt the seasonal migration of wildlife species, probably as well as other activities, and increase bird mortality (Walston et al., 2016). The present and planned PV power stations sometimes overlap with many natural protected areas or ecologically fragile zones, undermining global biodiversity and ecological protection. However, there is still lacking relevant research progress on the environmental impacts and implementation of policies and laws on the site selection of the PV construction (Rehbein et al., 2020). In addition, the intense light reflection via the surface glasses of a large area laying of PV panels can lead to visual impact, e.g., temporary visual reduction or loss, and may even bring people both psychological trauma and physiological injury (Spellman, 2014).

Moreover, large-scale PV power plants may have consequences on microclimate. The photoelectricity conversion efficiency of new-generation modules is typically in the range 17.4%–22.7%, while more than 77% of solar power is lost in form of heat (Ballif et al., 2016; Battaglia et al., 2016). The physical shielding and the absorption of solar radiation by PV panels would cause a "PV heat island effect" by cooling down the land surface of solar parks and heating the ambient air adjacent to PV panels (Chang et al., 2018; Michalek et al., 2001). Besides, the massive deployment of PV panels could change the surface albedo and radiation balance, indirectly affecting regional weather patterns such as wind field, evaporation, and precipitation (Millstein & Menon, 2011; Armstrong et al., 2016).

3.3. *The disposal of an end-of-life PV system is challenging*

It was estimated that more than 68,000 PV solar energy facilities (PV generating stations over 10 kW nameplate capacity) had been installed worldwide at the end of 2018 (Kruitwagen et al., 2021). Commonly, the operation lives of those facilities were from 25 to 30 years. According to the prediction by the International Renewable Energy Agency (IRENA) and IEA, there would be 60–78 million tonnes of end-of-life PV modules by 2050 (IRENA, 2016). These retired PV modules would have contained Si wafers and auxiliary materials, e.g., glass, plastic, other polymers, and highly toxic heavy metals. Proper end-of-life management of PV modules could offer a sustainable solution to resource availability, economic feasibility and manageable potential environmental risks (Choi and Fthenakis, 2014). The EU has pioneered several PV waste regulations, including collection of end-of-life PV modules, recovery, and recycling targets. However, in many other countries, there are currently not enough indications on policies to handle these issues (Chowdhury et al., 2020). There are various issues involved in the economics of the recycling of end-of-life PV panels. For example, the shipping distances of the waste, variation of its locations, and the amount of PV waste collected are all important factors of the profitability of the recycling process (Ardente et al., 2019). In addition, it is also technically challenging to disposal that emerging solid waste from massive obsolete PV facilities.

The recycling/disposal of end-of-life PV involves many potential environmental, health, and safety hazard materials. For instance, potentially toxic air pollutants such as hydrogen fluoride (HF) could be emitted during the thermal treatments process. A considerable amount of flammable, corrosive, and poisonous chemicals are used throughout the separation, extraction, and purification during chemical treatments processes in PV recycling (Tao & Yu, 2015). Toxic metals utilized in the PV cell materials such as Pb and Cd could be released, if end-of-life panels were not adequately treated, resulting in toxic risks and threats to freshwater ecology and human health (Li et al., 2018; Maani et al., 2020; Lisperguer et al., 2020). A study found the leached Cd, Pb and other metals from end-of-life solar PVs might have exceeded their daily intake thresholds, posing health risks, especially to children, via soil-dermal exposure (Nain and Kumar, 2020). At the same time, there are valuable and relatively scarce metals such as indium and gallium in CIGS solar cells. Therefore, recycling GIGS material is vital in both economic and environmental perspectives (Tao and Yu, 2015).

4. Positive changes brought by technological and strategic innovation

Globally, the life-cycle carbon footprint and electricity energy consumption of the PV industry have been on a downward trend in the past decade (Anctil, 2021). About half of GHG emission can be attributed to silicon manufacturing (from primary production to solar-grade refining) (NECE, 2022). Due to the different technologies employed, the national average carbon footprint for manufacturing c-Si panels of the same scale PV industry in China is approximately 1.44 times as much as that in the United States in 2020 (Anctil, 2021). The module efficiency and improvements in the manufacturing process are the key of reducing energy consuming and GHG emissions. In the case of the rooftop residential PV system application in Switzerland using mono-crystalline technology, the GHG emission decreased from 121 g CO_2 eq./kWp in 1996 to 43 g CO_2 eq./kWp in 2021, while the module efficiency increased from 13.6% in 1996 to 20.0% in 2021 (Frischknecht, 2021). The technological innovation such as improvements in internal jar reflective coatings and increases in reactor size also bring down the cost and energy requirements for Siemens process (Ballif et al., 2016).

Upgrading of the materials used in PV production can improve the environmental friendliness. Compared with polysilicon, upgraded metallurgical grade silicon (UMG-Si) as feedstock for multi-crystalline silicon (multi-Si) production can reduce of over 20% for GHG emission (Méndez et al., 2021). The second generation of PV technologies, such as CdTe based thin film PV panel, carry the less environmental life cycle impact than the first generation, including multi-Si and mono-Si technology, does (Rashedi and Khanam, 2020). More cutting age and more sophisticated soldering materials in the third generation solar PVs such as concentrator photovoltaic (CPV) solar panels, dye-sensitized solar panels, organic solar panels, and hybrid panels would considerably reduce the amount of use and release of toxic metals (Nain and Kumar, 2020; Wang et al., 2022).

Multiple novel forms of PV systems spring up. Floating photovoltaic (FPV) can be installed on waterbodies, such as lakes, reservoirs, hydroelectric dams, and other often under-utilized water. FPV can solve the land occupation, shading and soiling problems (Liu et al., 2018), giving more possibilities of wide application. Thin-film PV panels with amorphous silicon have been used for the offshore environment. The thin film-based offshore floating PV systems can increase the annual energy yield by 13% and 14% compared to that of pontoon-mounted and that of ground-mounted systems, respectively, while reduce about 14% more GHG emission than other systems could (Ravichandran and Panneerselvam, 2022). Mirror or lens-based high concentration photovoltaic (HCPV) systems could reach a module efficiency between 36.7% and 41.6%. The environmental footprint of HCPV (16.4–18.4 g CO_2 eq./kWh) is three times lower than that of crystalline photovoltaic solutions (Payet and Greffe, 2019).

Research and development (R&D) investment is a key driver of PV technological innovation. Appropriate government subsidies for R&D can exert a significantly positive promoting effect on technological innovation in PV enterprises (Cai et al., 2022; Jiang et al., 2021). On the other hand, the policy orientation of governments and the regulations set by relevant administrations can also play essential roles. In 2012, Europe revised the Waste Electrical and Electronic Equipment (WEEE) regulation and established the requirements for recycling waste PV panels (European Parliament, 2012). Effective recycling silicon, metals (e.g. Cu, Ag, Al) and other valuable materials in PV waste can reduce 42% of GHG emission during the PV production, and ~78% of human toxicity and freshwater ecotoxicity (Klugmann-Radziemska and Kuczyńska-Łazewska, 2020; Daniela-Abigail et al., 2022).

5. Conclusion and recommendations

PV solar energy is one of the most promising sources and can potentially make a significant contribution to both carbon emission reduction and future energy demand. PV power generation is a lower-carbon and greener technology compared with fossil-fueled electricity. However, the potential ecological and climatic environmental effects of large-scale application PV solar technology have not yet been considered sufficiently. The recycling/disposal of end-of-life PV panels involves many potential environmental, health, and safety hazard materials. To minimize potential adverse environmental effects brought by the large-scale development of PV power generation, we should act progressively to ensure the sustainable development of the PV industry. Some proposals are as follows.

(1) To strengthen fundamental research on the environmental impacts of large-scale PV power development. The impact of PV power parks on the ecological environment and climate is a complex process, requiring further understanding of the environmental and climatic impact of PV power plants in local, and even in regional scale. Assessment methods and indicative systems of impacts of solar parks on the ecological and climatic environment should be comprehensively studied. There is a critical need to establish a network carrying out long-term monitoring and assessment on multiple aspects of settings, such as micro soil environment, biomass productivity, biological community, radiation balance, and energy balance.
(2) To make an optimized spatial arrangement planning and realize multi-energy complementary and coordinated development. Careful preparation in planning, site selection, and resource evaluation are needed, in addition to a full demonstration of construction conditions. To minimize adverse impacts, PV plant installations should be avoided in ecologically sensitive areas and locations of historical value. Additionally, PV development plans need to adapt to regional heterogeneity. An ecological spatial layout should be improved according to the local landform, climate characteristics, and energy endowment to maximize land use efficiency and minimize adverse environmental effects, supporting an orderly and healthy development of new energy technology.
(3) To assess resource consumption, energy consumption, carbon footprint, and harmful substance emissions of PV power generation through the whole life cycle. On the one hand, to maximally reduce emissions of hazardous materials in PV module production and waste disposal processes, it is essential to use rigorous control measures and establish strict regulations. On the other hand, to guide PV enterprises to develop in a greener and low-carbon fashion technologies, it is also necessary to build information management and certification systems which index the whole life cycle of the PV industry with a "green degree."

In particular, we should improve the recycling and reuse of waste PV modules and accelerate the establishment of a management system for related secondary resources. Recycling is considered increasingly important, given the coming surge in PV module wastes soon, and regarding potential harm from hazardous substances released from disposed of PV products and the risk of supply shortages of related mineral resources. It is urgent to study the innumerous utilization pathways and recycling measures. The governments need to formulate policy measures to manage end-of-life PV modules, including laws and regulations.

Credit author statement

Haiyan Zhang: Data curation, Formal analysis, Writing - original draft. Zhigang Yu: Data curation, Validation, Formal analysis. Chengcheng Zhu: Data curation, Formal analysis. Ruiqiang Yang: Conceptualization, Formal analysis, Funding acquisition, Writing - review & editing. Bing Yan: Supervision, Writing - review & editing. Guibin Jiang: Conceptualization, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This study was financially supported by the National Natural Science Foundation of China (22076204).

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