RSC Sustainability

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Cite this: *RSC Sustainability*, 2025, **3**, 2286

Reducing the environmental impact of large-scale photovoltaic systems through technological progress and effective management†

Xingyong Li,[a] Fanran Meng, *[b] Alan Dunbar, [b] Lixiao Zhang,*[a] Yan Hao,[a] Tong He,[a] Na Yang,[a] Junnan Mao,[a] Fanxin Meng[a] and Gengyuan Liu[a]

Photovoltaics (PVs), the fastest-growing renewable energy source, play a crucial role in decarbonizing global energy systems. However, the intermittent nature of solar PV and transmission line constraints pose challenges to its integration into electricity systems. Previous studies on PV systems often lack methodological consistency, limiting comparative insights into understanding their environmental impacts. This study conducts a comprehensive life cycle analysis of various PV technologies using primary data within a unified framework and explores different scenarios to assess the impact of technology and management on greenhouse gas (GHG) emissions and energy payback. The results indicate that transitioning from multi-crystalline to monocrystalline silicon reduces PV-related GHG emissions by 7.9–40.5% and improves energy payback by 1.5–52.5%. Additionally, effective management and technological advancements decrease GHG emissions by 29.6–34.3% compared to the current scenario. Integrating these factors into grid decarbonization efforts would reduce emissions to less than 7.2 gCO_2-eq per kW per h, shorten the energy payback time to less than 2.0 years, and boost energy returns by more than 18.4 times. These findings reveal that the potential of effective management in reducing GHG emissions is comparable to that of technological advancements. To maximize PV's decarbonization benefits, stakeholders should prioritize electricity system optimization, implement policies to boost grid-connected PV generation, reduce losses, and extend PV lifespan.

Received 6th December 2024
Accepted 13th March 2025

DOI: 10.1039/d4su00778f

rsc.li/rscsus

Sustainability spotlight

At the G20 Leaders' Summit in Brazil in 2024, it was proposed that the global installed capacity of renewable energy sources be tripled by 2030. As the most promising renewable energy source, photovoltaics (PVs) are pivotal in mitigating global climate change. In the context of the UN Sustainable Development Goals (SDGs) for clean energy (SDG 7), responsible consumption and production (SDG 12), and climate action (SDG 13), we present a comprehensive analysis of the environmental impacts associated with the life cycle of technological progress and the effective management of PV systems. This study assesses the positive effects of grid decarbonization, coupled with technological progress in PV module manufacturing and improved management, on the environmental impacts of PV systems, which could accelerate the global transition to net-zero emissions.

1. Introduction

In light of the increasingly severe global climate crisis, the reduction of greenhouse gas (GHG) emissions has emerged as a pivotal global challenge for countries worldwide. The electricity generation sector, currently the largest source of CO_2 emissions globally, is emerging as a key force for change in the drive towards net-zero emissions, with the rapid development and expansion of renewable energy technologies such as solar and wind.[1] Since 2014, solar energy has been a principal driver of the expansion of renewable energy, with an average annual growth rate of 25.9%.[2] By the end of 2023, the global photovoltaic (PV) power generation industry had a cumulative installed capacity of 1411 GW.[3] In addition, PV has a positive impact on increasing incomes,[4] alleviating poverty,[5,6] creating jobs,[7] strengthening energy security[8] and restoring vegetation.[9] The expansion of large-scale PV systems, defined as PV systems with an installed direct current capacity of more than 1 MW, is driven by increasing energy demand, lower PV costs and government incentives.[10] Their high electricity generation capacity and contribution to the decarbonization of the electricity grid are paving the way towards larger and more efficient PV technology.

[a]State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, 100875, China. E-mail: zhanglixiao@bnu.edu.cn

[b]School of Chemical, Materials and Biological Engineering, The University of Sheffield, Sheffield, S1 3JD, UK. E-mail: f.meng@sheffield.ac.uk

† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d4su00778f

The Solar Eco-Electric Park in Gonghe, Qinghai Province, China, is the world's largest PV electricity park, with 15.5 GW installed and 18.7 GW planned over a total area of 609.6 square kilometers.[11] There are hundreds of large-scale PV systems in the park, and since the construction of the PV park in 2011, these systems have undergone a technological evolution from multi-crystalline silicon (Multi-Si) to mono-crystalline silicon (Mono-Si) PV modules due to the improvement in the efficiency of Mono-Si modules.[12] However, due to problems such as insufficient transmission line capacity and irregularities in the operation and maintenance of PV systems, the electricity generation of the PV park has not met expectations, which has subsequently increased the environmental impact of PV systems and reduced their profitability.[13]

Given the future dominance of these PV technologies in the global power sector and the importance of decarbonization, it is particularly important to quantify their GHG impact and Energy Payback Time (EPBT) over their life cycle. The Life Cycle Assessment (LCA) methodology has been employed over the past decade to evaluate the environmental impacts and cumulative energy consumption of PV systems.[14,15] A summary of the principal parameters and LCA results for large-scale PV systems derived from previous studies is presented in Table S1.† Overall, the GHG and EPBT of large-scale PV systems range from 23.6–81.0 gCO_2-eq per kW per h and 1.2–5.3 years, respectively (can be seen in Fig. 3).

The broad ranges in GHG and EPBT are due to three principal differences: technological options, management efficiency, and the delineation of boundaries and methodologies. Firstly, diversity at the technological scale represents a pivotal factor. The efficiency of the PV module (14.1%,[16] 16.8% (ref. 17) and 17.5% (ref. 18)), the PV module type (Multi-Si[19,20] and Mono-Si[21,22]) employed, and the mounting structure (fixed support bracket[21,23] and floating bracket[24]) utilized all exert a direct influence on the performance of PV systems. Secondly, the performance ratio (0.750 (ref. 25), 0.796 (ref. 26) and 0.800 (ref. 24)) and the optimization of lifetime (*e.g.*, 25 (ref. 27) and 30 (ref. 10) years) are contingent upon the implementation of efficacious management strategies. Furthermore, the location of the installation (*e.g.*, China,[28,29] Brazil[17] and Germany[30]), solar irradiation (*e.g.*, 1797 (ref. 31), 1800 (ref. 32) and 2017 (ref. 18) kW h per m per year), system boundaries (*e.g.*, cradle to gate[18,33] and cradle to grave[25,34,35]), type of analysis software (*e.g.*, GaBi,[32,36] OpenLCA[37] and SimaPro[21,38]), sources of inventory data (primary, secondary and hypothetical data), LCA databases (*e.g.*, Ecoinvent,[20,39,40] literature[34] and Chinese Life Cycle Database[26]), and LCIA methods (IPCC2007,[16,26] CML2001 (ref. 28) and ReCiPe[10]) all have a notable impact on the assessment of GHG emissions and the energy payback of PV systems over their life cycle.

Direct quantitative comparisons of GHG impact and energy payback are challenging, as most studies focus on single PV systems and are constrained by differences in system boundaries, geographic contexts, and methodological approaches. This study develops a cradle-to-grave LCA model with consistent system boundaries and a unified methodological framework to compare the impact of technology selection and management strategies on GHG emissions and energy payback in large-scale PV systems over ten years. The assessment quantifies the impact of varying technology choices and management levels. Additionally, scenarios are constructed to simulate the evolutionary path of technology iteration, systematic management, and grid decarbonization on the GHG emissions and energy payback of future PV systems. Comprehensive primary data are collected from module manufacturers, power plant developers, and operators. Although this study focuses on six large-scale PV systems located on the Tibetan Plateau, the findings have global relevance. The results can guide stakeholders in the PV industry to understand how technological innovations can reduce material use and GHG emissions during production. Furthermore, plant and grid operators will gain insights into how optimal management strategies can enhance operational efficiency and electricity generation. This, in turn, will contribute to both the environmental sustainability and economic viability of large-scale PV systems.

2. Methods

The present study is based on the LCA methodology established by the International Organization for Standardization (ISO) 14040 and 14044 standards.[14,15] Process-based LCA comprises four phases: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The goal and scope phase of this work defines the study objectives, the functional unit of the PV systems, the system boundary, and the overall system description. The LCI phase involves raw data collection, data validation, and correlation of data to unit processes and the functional unit. In the LCIA phase, the LCI data are converted into indicators of GHG emissions and energy payback for the study. The final phase, interpretation, involves further evaluation of the LCIA results through various analytical methods, including contribution analysis, uncertainty analysis, sensitivity analysis, and scenario analysis. This process culminates in the formulation of conclusions and recommendations derived from the study's findings. The subsequent subsections provide detailed explanations of these processes.

2.1 Goal and scope

This LCA study aims to evaluate the impact of technology selection and management levels on the GHG emissions and energy performance in electricity generation using ground-mounted large-scale PV systems installed on the Tibetan Plateau in China. Various scenarios are formulated to imitate the evolutionary trajectory of technology iteration, systematic management, and grid decarbonization in terms of their impacts on GHG emissions and the energy payback in future PV systems. The system under investigation is electricity generation using large-scale PV systems, with a functional unit of '1 kW h of electricity generation'. The inventory data are obtained from primary sources. The LCA model was developed using the Ecoinvent V3.9.1 database[41] and implemented using SimaPro V9.5 software.[42]

2.2 System boundary

The system boundary defining the entire life cycle stages of the large-scale PV system is illustrated in Fig. 1a. It includes PV modules, mounting structures, inverters, box transformers, boosters and substation equipment before delivery to the national grid. Additionally, control and protection equipment ensuring the safety of the PV system, energy storage systems (ESSs), ventilation and fire-fighting equipment are also included. A cradle-to-grave approach is applied considering the production, transportation, construction & installation (C&I), operation and management (O&M), and End of Life (EoL) stages. The impact of PV module degradation is also considered, along with PV plant management factors such as curtailment rate, performance ratio and lifetime when determining electricity generation over the system's lifetime.

2.3 escription of PV systems

This study is based on six grid-connected large-scale ground-mounted PV systems located in the Gonghe Basin of the Tibetan Plateau, China, as shown in Fig. S1.† The key parameters of the six large-scale PV systems, including installed capacity, PV module efficiency, mounting angle, curtailment rate, performance ratio, system lifetime, and average annual electricity generation, are presented in Table 1. The six large-scale PV systems, with a lifetime of 25 years and a curtailment rate of 8%, are located in the world's largest PV industrial park, the Hainan Solar Power Park in Qinghai Province, China, where the average annual solar irradiation is 1830.64 kW h m^{-2}. The process of grid-connected electricity generation from six large-scale PV systems is shown in Fig. 1d. The structure of the PV module, mounting structure and site images of the large-scale PV systems are depicted in Fig. 1b and c and S2.† The electricity generated on the grid over the lifetime of the six PV systems can be seen in Table S2.† More details on the selection criteria for the six PV systems and data validation for primary data can be seen in Section 2.3 in the ESI.†

2.4 Life cycle inventory

The LCI and detailed descriptions of six large PV systems are shown in Tables S3–S8† and categorized into six main components: (1) PV module, (2) balance of system (BOS), (3) ESS, (4) transportation, (5) O&M, and (6) EoL. The foreground data are derived from primary data, collected from real, electricity-generating large-scale PV systems, including data from equipment manufacturers, power plant constructors, and system operators. The background data are sourced from the Ecoinvent 3.9.1 databases. In this study, the LCI modeling principle is based on the attributional approach, utilizing the economic allocation method.

The manufacturing processes for the PV module are presented in Fig. S3.† The first four PV systems installed in 2013 and 2016 are Multi-Si PV modules, and the later systems P50MW2021 and P500MW2023 are Mono-Si PV modules. The BOS encompasses the mounting structure, combiner & inverter & transformer (C&I&T). It also includes the Electric Transmission Line (ETL), Other Auxiliary Systems (OASs), which include the Boost Voltage Substation System, Control and Protection System, Firefighting and Ventilation systems, as well as Civil Works (including C&I). The transportation distances and manufacturing locations for PV modules, C&I&T and other equipment are shown in Table S9.† The specifications and quantities of the combiner, inverter, box transformer, and

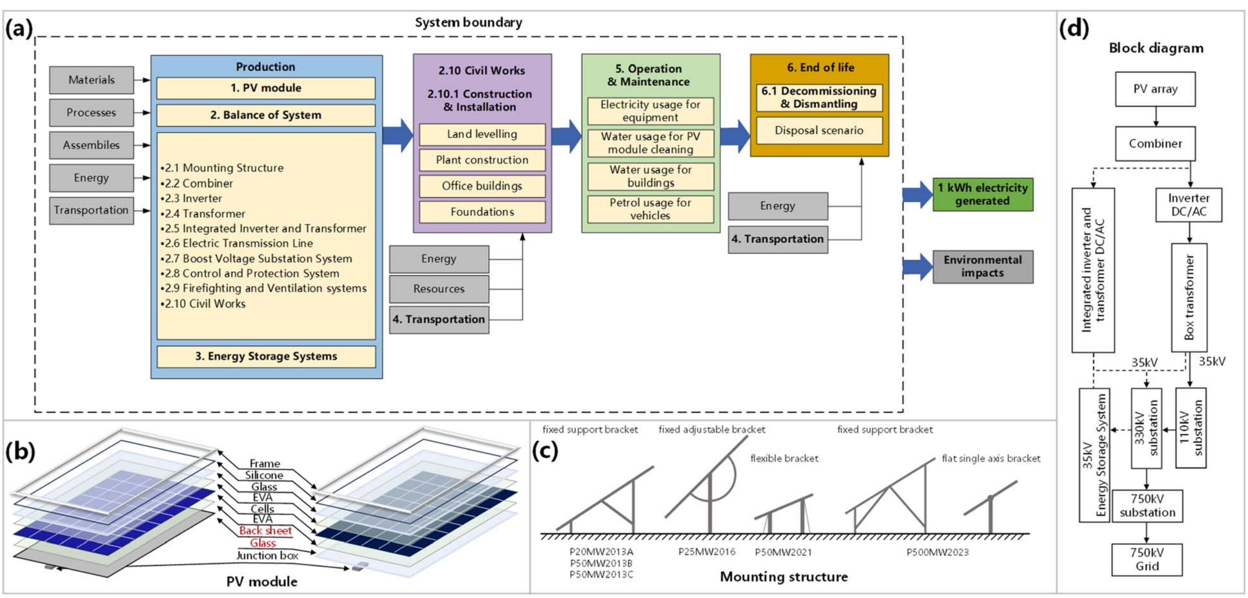

Fig. 1 The critical information for this study of large-scale PV systems, (a) system boundary; (b) PV module structure; (c) mounting structure; and (d) block diagram for grid connection. (see Section 2.4 in the ESI† for the detailed description of the large-scale PV systems, and the site images in Fig. S2†).

Table 1 Key parameters of the large-scale PV systems. P20MW2013A = the grid-connected 20 MW of a PV system in 2013, and the same for the rest of the PV systems

System parameter	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023
Grid-connected time/year	2013	2013	2013	2016	2021	2023
Installed capacity (alternating current side)/MWp	2019	50.73	50.67	24.98	49.93	500.01
PV module types	Multi-Si (245 Wp)	Multi-Si (245 Wp)	Multi-Si (245 Wp)	Multi-Si (265 Wp)	Mono-Si (540 Wp)	Mono-Si (540 Wp)
PV module efficiency/%	14.98	14.98	14.98	16.20	20.89	21.10
PV module average annual degradation rate/%	0.80	0.80	0.80	0.80	0.61	0.51
Mounting angle/°	39	39	39	58, 30, 6, 41	30	30
Curtailment rate/%	8	8	8	8	8	8
Performance ratio	0.80	0.80	0.80	0.80	0.83	0.82
System lifetime/years	25	25	25	25	25	25
Average annual solar irradiation/(kW h m^{-2})	1833	1833	1833	1820	1820	1820
Average annual utilization hours/h	1548.98	1548.98	1548.98	1628.30	1695.48	1780.04
Average annual electricity generation/GW h	28.77	72.29	72.20	37.41	77.88	1018.27

integrated inverter and transformer for PV systems are presented in Table S10.†

Since the PV systems in this study are located in China, the municipal solid waste scenario specific to China (MSWS of CN) is applied (details can be seen Section 2.4 in the ESI†). Additionally, two alternative disposal scenarios are established for comparison: the Recycling Scenario (RS) and the Non-recycling Scenario (NRS). The RS assumes a 100% recycling rate[43] of the metals and plastics that are recycled in the MSWS of CN, while the NRS assumes a 0% recycling rate of these materials. All other disposal processes remain the same across scenarios.

2.5 Life cycle impact assessment method

The study identified four indicators, including energy-related and GHG emissions indicators: Cumulative Energy Demand (CED), Energy Payback Time (EPBT), Energy Return on Investment (EROI) and GHG. The IPCC 2021 GWP100 method is employed to assess the life cycle GHG impacts of the PV system, considering a 100-year timeframe.[44] In addition to GHG impacts, the Cumulative Energy Demand V1.11 method is utilized to evaluate the primary energy consumption over the life cycle of the PV system.[45]

CED is the total primary energy consumption of all components of the PV system at each life cycle stage per unit of installed capacity, as shown in eqn (1).

$$\mathrm{CED} = \frac{\mathrm{CED_{total}}}{\text{installed capacity}} = \frac{\mathrm{CED_{PV\,module}} + \mathrm{CED_{BOS}} + \mathrm{CED_{transportation}} + \mathrm{CED_{O\&M}} + \mathrm{CED_{EoL}}}{\text{installed capacity}} \tag{1}$$

where the unit of CED is TJ/MW, $\mathrm{CED_{total}}$ is the total energy consumption for the PV system in TJ, and installed capacity is the actual installed capacity of the PV system in MWp. $\mathrm{CED_{PV\,module}}$, $\mathrm{CED_{BOS}}$, $\mathrm{CED_{transportation}}$, $\mathrm{CED_{O\&M}}$, and $\mathrm{CED_{EoL}}$ refer to the primary energy consumption for the PV module, BOS, transportation, O&M, EoL in TJ, respectively.

EPBT indicates the duration required for the electricity generated by the PV system to offset its lifecycle energy consumption, as shown below:

$$\sum_{1}^{\mathrm{EPBT}} E_n = \mathrm{CED_{total}} \tag{2}$$

where the unit of EPBT is years and E_n is the electricity generation of the PV system in the n-th year, in TJ.

EROI reflects how many times the energy is returned based on the energy that has been invested throughout the PV system's lifetime, as shown below:

$$\mathrm{EROI} = \frac{\sum_{1}^{25} E_n}{\mathrm{CED_{total}}} \tag{3}$$

where 25 means that the lifetime of the PV system is 25 years.

GHG represents the total GHG emissions from all components at each life cycle stage of the PV system per unit of electricity generation, as expressed below:
where the GHG emissions are expressed in gCO_2-eq per kW

$$\text{GHG emissions} = \frac{\text{GHG}_{\text{total}}}{E_{\text{lifetime}}} = \frac{\text{GHG}_{\text{PV module}} + \text{GHG}_{\text{BOS}} + \text{GHG}_{\text{transportation}} + \text{GHG}_{\text{O\&M}} + \text{GHG}_{\text{EoL}}}{E_{\text{lifetime}}} \tag{4}$$

per h and GHG_{total} represents the total GHG emissions over the life cycle of the PV system in gCO_2-eq. $GHG_{PV\ module}$, GHG_{BOS}, $GHG_{transportation}$, $GHG_{O\&M}$, and GHG_{EoL} refer to the GHG emissions associated with the PV module, BOS, transportation, O&M, EoL stages in gCO_2-eq., respectively. $E_{lifetime}$ refers to the total electricity generation of the PV system over its 25-year lifetime, measured in kW h.

2.6 Contribution analysis

The contribution analysis categorizes the total GHG impacts and energy consumption into six main components: PV modules, BOS, ESS, transportation, O&M, and EoL. The BOS is further subdivided into five sub-categories: mounting structure, C&I&T, ETL, OAS, and civil works. The analysis examines the share and percentage contribution of each component to overall energy consumption and GHG impacts, helping to identify components with the highest energy consumption and GHG contributions.

2.7 Uncertainty analysis

In this study, the LCA results are calculated using linked uncertainty in SimaPro V9.5, employing Monte Carlo simulation with random sampling[46] and 1000 iterations at a 95% confidence interval. Based on this, the uncertainty ranges for the GHG impacts and energy consumption of the PV system are determined, providing a robust understanding of the variability and reliability of the results based on the uncertainty analysis.

2.8 Sensitivity analysis

In this study, sensitivity analyses of GHG impacts and energy payback are conducted across three categories: technological pathways, disposal scenarios and management levels. The technological pathways include variations in PV module efficiency (ranging from 15% to 27%), wafer thickness (140 to 210 μm), PV module silver usage (reduced by 50% to 0%), low alloy steel usage for mounting structures (reduced by 50% to 0%), and concrete usage (reduced by 50% to 0%). The disposal scenarios evaluated are NRS, MSWS of CN, and RS. For management levels, the sensitivity analysis examines the curtailment rate (0% to 10%), performance ratio (0.76 to 1), and system lifetime (25 to 40 years). This analysis helps assess how variations in these factors influence the overall GHG impacts and energy payback of large-scale PV systems. The assumptions and justification of the parameter ranges can be found in Section 3.3 of the ESI.†

2.9 Scenario analysis

The scenario analysis is based on two Mono-Si PV systems, P50MW2021 and P500MW2023. This is achieved by varying certain materials and PV system parameters in the baseline scenario; the scenario assumptions are presented in Table 2.

Currently, the average GHG emissions factor for electricity in China is 0.594 kg CO_2-eq per kW per h, excluding market-traded non-fossil energy electricity.[47] Subsequently, four prospective grid decarbonization processes are established, based on previous studies,[48,49] with values of 0.5, 0.4, 0.3, and 0.2 kg CO_2-eq per kW per h. In addition to the baseline scenario (S0), four future scenarios are considered in this study: the technological progress scenario (S1), the effective management scenario (S2), the integrated optimization scenario (S3), and the ideal condition scenario (S4). The S0 scenarios refer to the 50 MW and 500 MW PV systems in this study, *i.e.*, P50MW2021 and P500MW2023. The S1 scenario is based on the S0 scenario, where only technological

Table 2 Future PV system scenarios based on China's ongoing electricity grid decarbonization efforts. The scenarios assume Mono-Si PV modules produced with grid carbon emission factors of 0.594 (China's average electricity GHG emissions factor in 2021), 0.5, 0.4, 0.3, and 0.2 kg CO_2-eq per kW per h, respectively

		Technology parameter			Management parameter			
Scenarios	No.	PV module efficiency/%	Silicon wafer/μm	Silver/%	Low alloy steel/%	Curtailment rate/%	Performance ratio	Lifetime/years
Baseline	S0	20.89 (50 MW) 21.10 (500 MW)	170 (50 MW) 150 (500 MW)	0	0	8	0.834 (50 MW) 0.823 (500 MW)	25
Technological progress	S1	27	140	−50	−50	8	0.834 (50 MW) 0.823 (500 MW)	25
Effective management	S2	20.89 (50 MW) 21.10 (500 MW)	170 (50 MW) 150 (500 MW)	0	0	4	0.900	35
Integrated optimization	S3	27	140	−50	−50	4	0.900	35
Ideal condition	S4	27	140	−50	−50	0	0.950	40

advances are considered and the management level remains unchanged. For example, increasing the PV module efficiency, reducing the thickness of silicon wafers, and reducing the usage of silver and low alloy steel. The S2 scenario is based on the S0 scenario and considers only management improvements with no changes in technical parameters. For example, a reduced curtailment rate, improved performance ratio and longer lifetime. The S3 scenario builds upon the S0 scenario, where technological advances are considered, as well as management improvements. The S4 scenario is based on the S3 scenario with further improvements in management capabilities.

3. Results

The GHG impacts and energy payback of each component of the PV system are first assessed through contribution analysis, which examines the contribution of each component to the overall environmental impacts. Following this, overall trends and key influencing factors are analyzed over a ten-year period, providing insights into the long-term performance and sustainability of the PV system. Subsequently, a sensitivity analysis is conducted to quantify the impacts of technological changes, disposal methods and management optimization on the GHG emissions and energy payback of PV systems. To account for the decarbonization process of the national grid, a series of prospective scenarios is developed to explore the potential GHG reductions and energy payback improvements achievable through technological advancements and effective management strategies in PV systems.

3.1 Contribution analysis of PV system components

As shown in Fig. 2a and Table S11,† the total CED of PV systems shows a decreasing trend in the last decade, from 20.0–26.3 TJ MW^{-1} for Multi-Si PV systems to 18.9–22.9 TJ MW^{-1} for Mono-Si PV systems. In contrast, the CED of PV modules shows an increasing trend, and PV modules have the largest contribution to the CED, accounting for more than half of the total CED, ranging from 54.8% to 84.2%.

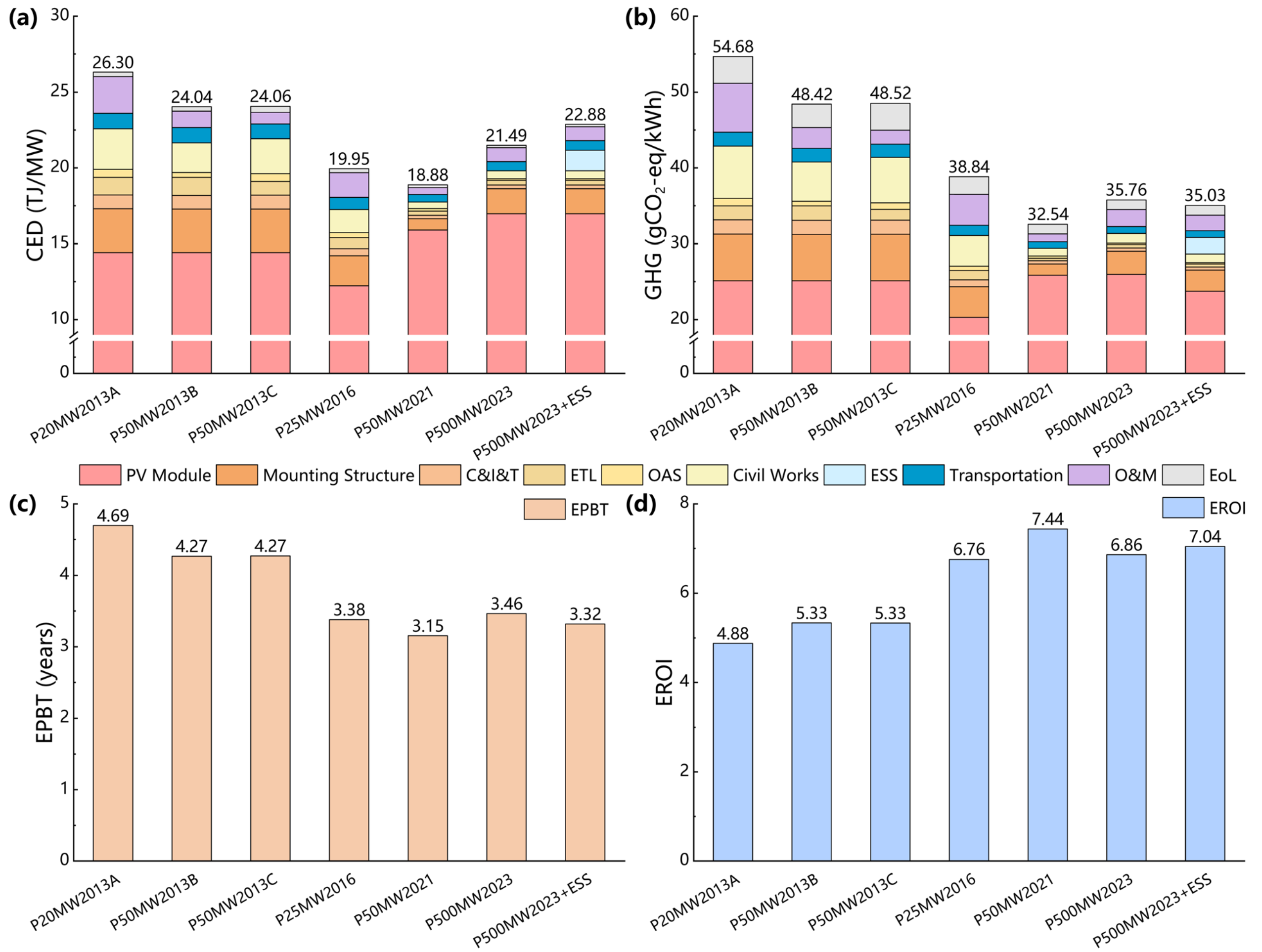

Fig. 2 Comparisons of the different lifecycle results for each of the large-scale PV systems. (a) The CED per MW for life cycle components of the PV systems. (b) The GHG impacts per kW per h for life cycle components of the PV systems. (c) The lifecycle EPBT of the PV systems. (d) The lifecycle EROI of the PV systems. P20MW2013A refers to the grid-connected 20 MW of a PV system in 2013, P500MW2023 + ESS refers to the grid-connected 500 MW of PV system in 2023 considering ESS, and the same for the rest of the PV systems. The four PV systems in 2013 and 2016 are Multi-Si PV systems, while the two PV systems in 2021 and 2023 are Mono-Si PV systems. The BOS includes the mounting structure, C&I&T, ETL, OAS and civil works.

The two disparate trends are attributed to technological advances. Firstly, the increase in the CED of PV modules, resulting from the transition from Multi-Si to Mono-Si technology, is a contributing factor. The energy consumption per MW of Mono-Si PV modules is found to be higher, ranging from 10.2% to 38.9% higher CED than Multi-Si PV modules in this study. It takes more energy to make a Mono-Si PV module compared to a Multi-Si PV module, but the Mono-Si PV modules convert sunlight into electricity more efficiently.

Secondly, technical progress over the past decade has led to improvements in equipment material utilization, coupled with a reduction in the use of materials, which has consequently lowered the CED per MW. The most significant reduction in BOS has a direct impact on the overall downward trend in the total CED of the PV systems. In comparison to Multi-Si PV systems, Mono-Si PV systems have exhibited a reduction in CED per MW for BOS, ranging from 43.4% to 77.3%. In particular, the mounting structure has resulted in a reduction in the

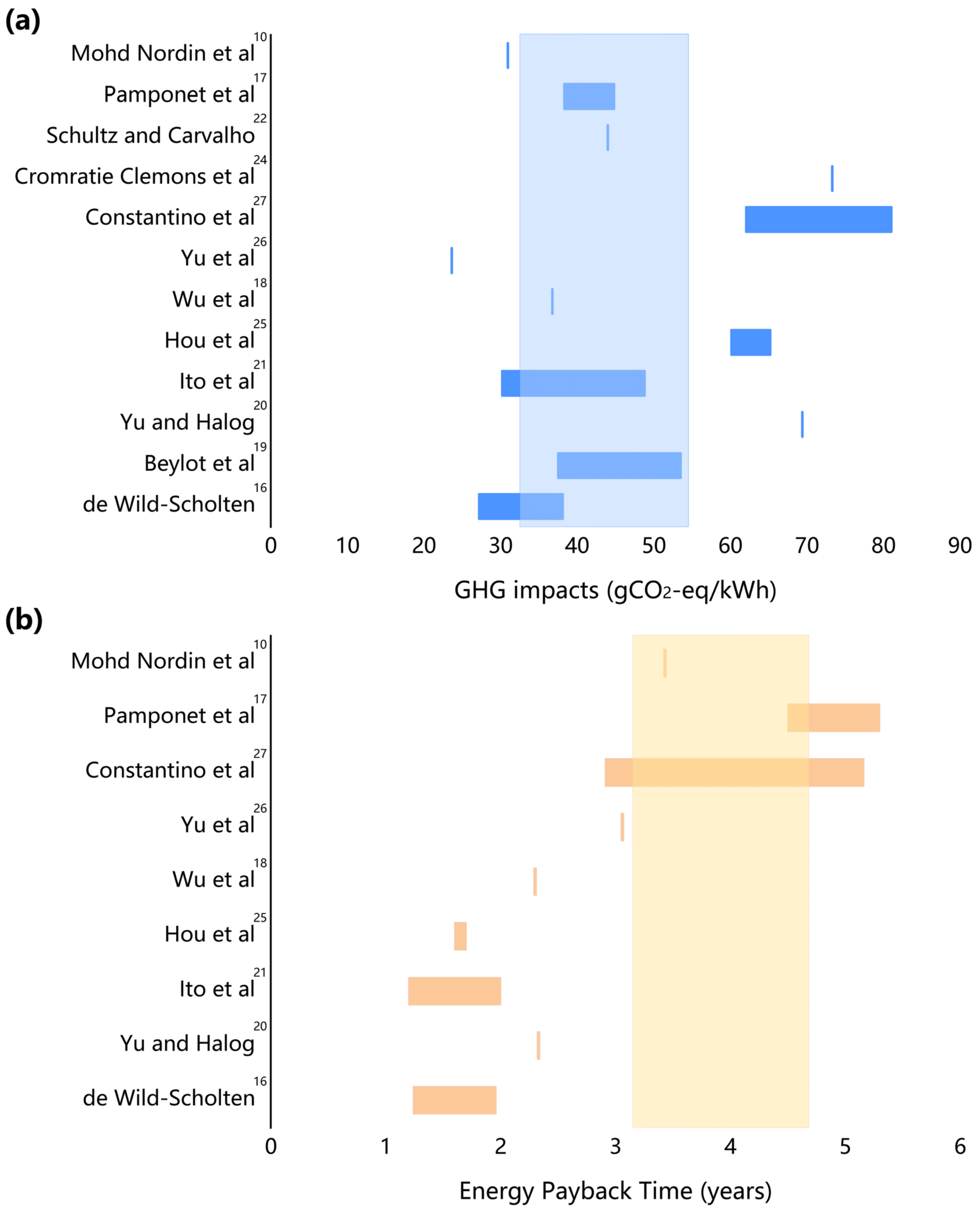

Fig. 3 Comparison of the LCA results for large-scale PV systems in this and the previous studies. (a) GHG impacts comparison of PV systems. (b) EPBT comparison of PV systems. The rectangles illustrate the range of GHG impacts and EPBT of the PV systems as reported in previous studies. The large, light, transparent rectangles represent the results of this study.

quantity of low-alloy steel employed per MW, with a corresponding decrease in CED per MW of between 17.1% and 74.0%. The integrated inverter and transformers in P50MW2021 and P500MW2023 reduce the CED per MW by more than 50% in comparison to the transformer and inverter combinations. Furthermore, this finding is supported by the evidence of a 46.9–83.5% reduction in CED for ETL, OAS and civil works. The 30.8–61.5% decline in the CED of EoL further indicates that less energy is required for disposal because fewer materials are used in the equipment.

The GHG emissions of PV systems show a decreasing trend over the past decade, as illustrated in Fig. 2b and detailed in Table S12.† This trend aligns with the GHG emission ranges (23.6 to 81.0 gCO_2-eq per kW per h) reported in other comparable studies, as summarized in Fig. 3a. The GHG emissions of Mono-Si PV systems range from 32.5 to 35.8 g CO_2-eq per kW per h, which is lower than that of Multi-Si PV systems, whose emissions range from 38.8 to 54.7 gCO_2-eq per kW per h. The GHG emissions from PV module manufacturing are generally increasing; the impact of Mono-Si PV modules is 2.9–27.9% higher than that of Multi-Si PV modules when ESS is excluded. The downward trend in GHG emissions from PV systems is primarily driven by technological advancements, such as the transition from Multi-Si to Mono-Si PV modules and improved management practices. Additionally, the reduction in material usage due to more efficient equipment and material utilization further contributes to this downward trend.

Firstly, the improvement in PV module efficiency is one of the main reasons for the decline in the GHG impacts of PV systems. Driven by technological progress in the shift from Multi-Si to Mono-Si, Mono-Si PV modules are more efficient and generate more electricity. Therefore, although the CED of Mono-Si PV modules is much higher than that of Multi-Si PV modules (see Table S11†), the substantial increase in electricity generation reduces its own GHG impacts while reducing that of other components of the PV systems. Secondly, improved material utilization due to technological changes and reduced energy consumption, which in turn reduces GHG emissions during the production phase of the equipment, is also one of the main reasons for the decline in GHG emissions of the PV system. As seen in Fig. 2b, the GHG impacts of BOS of Mono-Si PV systems show a significant downward trend of between 50.1% and 80.0% reaching 3.6–5.4 gCO_2-eq per kW per h, which is the direct cause of the downward trend of GHG impacts of PV systems during the decade.

Subsequently, efficient management reduces the GHG impacts of the PV system by increasing grid-connected generation. It can be seen from Table 1 that the performance ratio improved from 0.799 in 2013 to 0.834 in 2021 and 0.823 in 2023. The increase in the performance ratio reflects efforts in management optimization of the PV systems. For example, timely cleaning of PV panels reduces the loss of electricity generated by PV modules due to dust; regular inspections to replace or repair damaged parts reduce equipment electricity losses. The management optimization reduces the electricity loss of the PV systems and improves the electricity generation, thus reducing the GHG impacts. Utilizing ESS is also a management method to increase the electricity production of a PV system. The addition of an ESS allows better matching of electricity supply and demand and therefore reduces the GHG emissions of P500MW2023 by 0.7 gCO_2-eq per kW per h and mitigates the GHG impacts of the life cycle components except EoL. In this study area, there is still space for management optimization due to grid capacity and operating time constraints, so this paper will subsequently continue to explore the potential for precision management.

The energy payback capacity of the PV systems is shown in Fig. 2c and d. The EPBT shows a decreasing trend from 4.69 to 3.15 years, lying within the range of EPBTs of previous studies summarized in Fig. 3b (1.2–5.3 years), and the EROI increases from 4.88 to 7.44. This further validates the ability of Mono-Si PV modules to generate electricity more efficiently, with faster payback of lifecycle energy consumption and higher return on energy investment than Multi-Si PV modules. In addition, ESS can accelerate the EPBT of the P500MW2023 PV system by 0.14 years, increasing the EROI by 2.6%.

3.2 Uncertainty analysis

The results of the uncertainty analysis for CED and GHG are presented in Fig. S4 and Tables S13, S14.† A greater dispersion and a lower accuracy of the mean are observed for the Mono-Si PV systems when compared to the Multi-Si PV systems across the six systems over the ten years. In particular, the values of the standard deviation (SD), coefficient of variation (CV), and standard error of the mean (SEM) are all relatively larger for the Mono-Si PV systems. This is because the manufacturing technology of Mono-Si PV modules is currently not as mature as that of Multi-Si PV modules, resulting in a wider uncertainty range. Within the upper and lower ranges of uncertainty for CED, the Mono-Si PV systems have a relatively shorter EPBT and a relatively higher EROI compared to the Multi-Si PV systems. In P500MW2023 + ESS, the ESS results in a more concentrated data distribution of GHG for P500MW2023 in the uncertainty analysis, *i.e.*, relatively lower SD, CV, and SEM.

3.3 Sensitivity analysis

Following the findings of the contribution analysis and the prevailing PV system manufacturing technologies and management practices, the sensitivity analysis in this study can be classified into three categories: technological pathways, disposal scenarios, and management levels. The base case values of sensitivity analysis can be seen in Table S15.† The description, data and fitting results of the sensitivity analysis are presented in Tables S16–S38.†

Technological pathways encompass a sensitivity analysis of PV module efficiency and material usage. The sensitivity analysis for PV module efficiency is illustrated in Fig. 4a and b. The enhancement of PV module efficiency markedly diminishes the GHG of the PV systems by 20.7–34.8%, shortens the EPBT by 20.6–35.4%, and elevates the EROI by 26.1–53.3%. In conducting a sensitivity analysis of material usage, the reduction in the mass of material used can result in a reduction in the GHG and CED of the components. Furthermore, the thinning of silicon

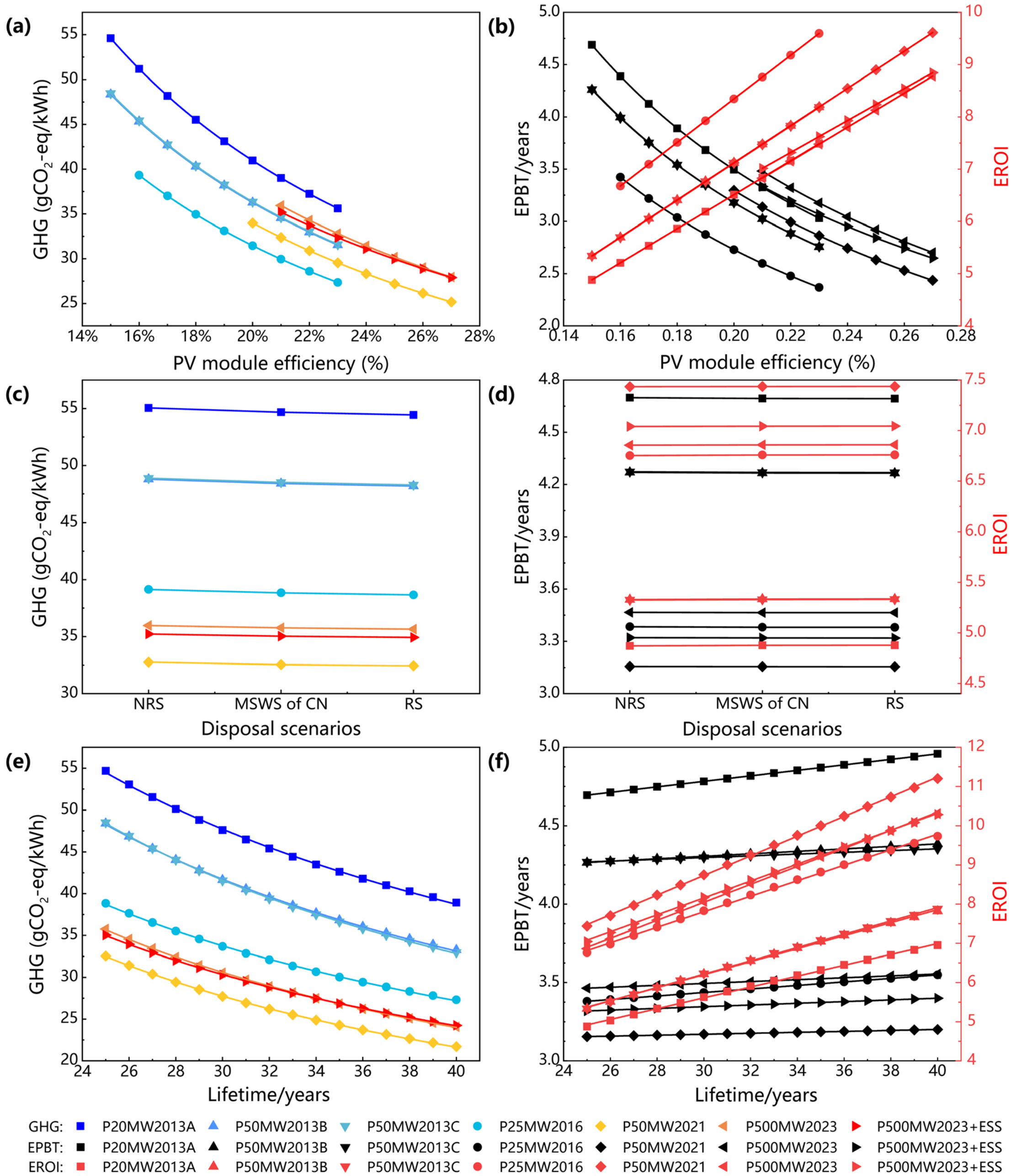

Fig. 4 The sensitivity analysis results on PV module efficiency for (a) GHG impacts, (b) EPBT and EROI of the PV system lifecycle. The sensitivity analysis results on disposal scenarios for (c) GHG impacts, (d) EPBT and EROI of the PV system lifecycle. The sensitivity analysis results on lifetime for (e) GHG, (f) EPBT and EROI of the PV system lifecycle. P20MW2013A refers to a grid-connected 20 MW PV system in 2013, P500MW2023 + ESS refers to a grid-connected 500 MW PV system in 2023 considering ESS, and the same for the rest of the PV systems. The four PV systems in 2013 and 2016 are Multi-Si PV systems, while the two PV systems in 2021 and 2023 are Mono-Si PV systems.

wafer thickness can lead to a notable reduction in the GHG by 10.1–17.3% and CED by 10.4–18.0% of the PV modules, as shown in Fig. S5a and b.† The alterations in the mass of silver employed in the PV modules, the mass of low alloy steel utilized for the mounting structures, and the mass of concrete used for the civil Works have relatively minor impacts on the GHG and CED of the components, as shown in Fig. S5c, d and S6.† The relatively minor impact of silver, low-alloy steel, and concrete in the GHG and CED sensitivity analyses can be attributed to two key factors. First, the GHG emissions and energy requirements associated with their production and manufacturing processes are relatively low. Second, their overall contribution to the total material demand of PV systems is comparatively small. As a result, reductions in these materials have a limited effect on the overall environmental impact of the PV systems.

In the sensitivity analysis of the six PV system disposal scenarios (see Fig. 4c and d), RS demonstrates a relative reduction in GHG of 0.1–0.2 gCO$_2$-eq per kW per h, with minor alterations in both EPBT and EROI, in comparison to MSWS of CN. Furthermore, RS exhibits a relative reduction in GHG of 0.3–0.6 gCO_2-eq per kW per h, with slight modifications in EPBT and EROI, in contrast to NRS. RS does not result in a notable decrease in the life cycle GHG of the PV systems, a finding supported by a previous study.[50]

The management levels include a sensitivity analysis of the curtailment rate, performance ratio and lifetime of PV systems. An increase in the lifetime of PV systems from 25 to 40 years results in a considerable reduction in the GHG emissions by 28.8–33.3% of the system over the entire life cycle, accompanied by a significant increase in EROI by 42.6–50.6%. Due to the extended lifetime, the energy consumption associated with O&M also increases, leading to an increase in EPBT by 1.4–5.6%, as illustrated in Fig. 4e and f. Reducing the curtailment rate and improving the performance ratio can result in a 9.2–24.0% reduction in GHG emissions, a 9.1–24.5% reduction in EPBT, and a 10.1–31.6% increase in EROI over the life cycle of PV systems, as shown in Fig. S7.†

3.4 Scenario analysis

The results presented in Fig. 5a and c illustrate the life cycle GHG of the PV systems under various scenarios. Using the current grid carbon emission factor for China of 0.594 kg CO_2-eq per kW per h, for the two Mono-Si PV systems of 50 MW and 500 MW, the GHG impacts are reduced by 34.3% and 29.6% in the S1 scenario, respectively, and are reduced by 33.8% and 34.2% in the S2 scenario, respectively, as compared to the S0 scenario. It can be seen that the S1 and S2 scenarios are of equal importance in the reduction of the life cycle GHG of PV systems. This indicates that the electricity generation of the PV systems is increased in the S2 scenario by management optimization strategies (reducing curtailment rate, improving performance ratio, and extending lifetime), thereby reducing GHG, in the same way as improving PV module efficiency and reducing material usage (such as silicon wafers, silver, low-alloy steel) decrease GHG in the S1 scenario through production technology progress, which not only increases electricity generation of the PV system but also reduces life cycle GHG emissions.

In the S1 and S2 scenarios, the GHG impacts of the large PV systems in this study (21.37–25.17 gCO_2-eq per kW per h) have been lower than the results of the most previous studies shown in Fig. 3a. This comparison verifies that technological advancement (S1) and effective management (S2) have significant GHG reduction effects. Furthermore, it can be observed that the GHG impacts can be reduced by an additional 29.4–34.2% in the S3 scenario, which integrates the S1 and S2 scenarios. In contrast, the GHG impacts in Fig. 3a cannot be quantitatively compared due to inconsistencies in boundary delineations and methodological choices in previous studies. In the S3 scenario, the GHG impacts can be reduced to a level

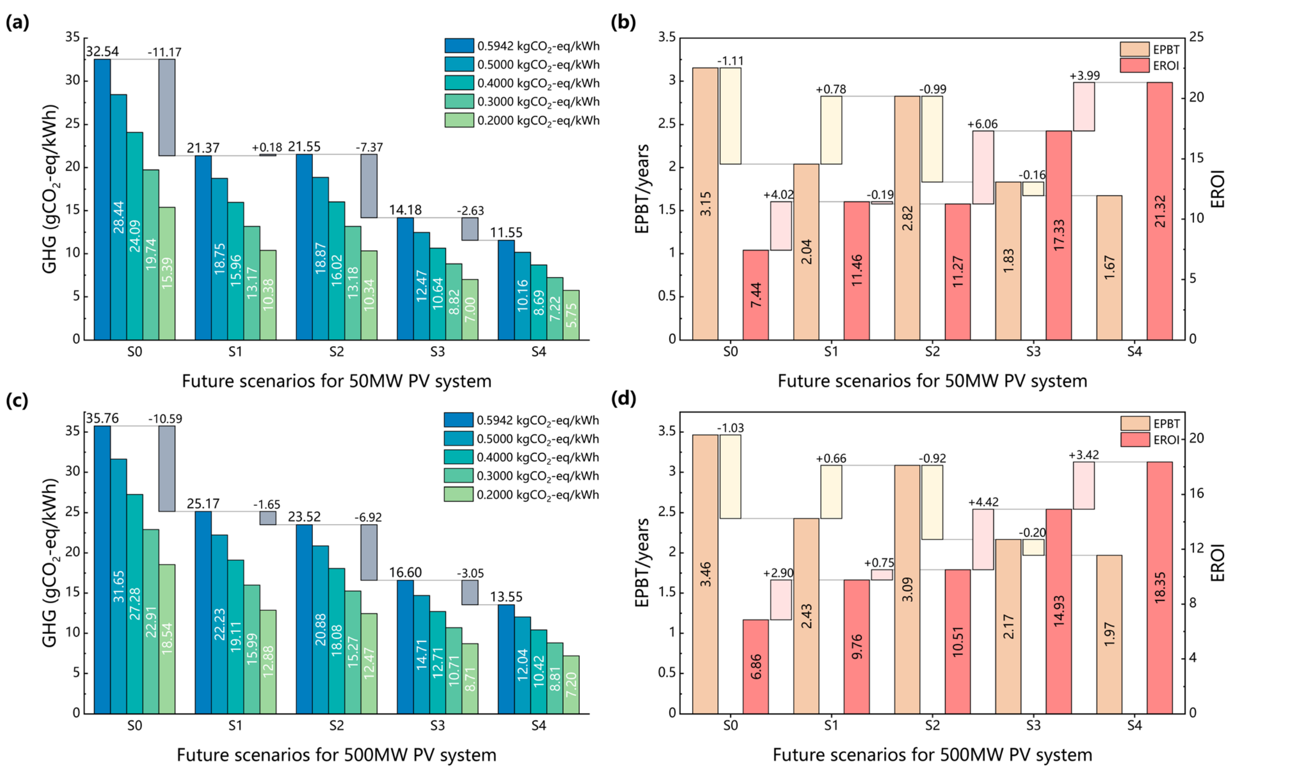

Fig. 5 LCA results for future scenario analysis of PV systems in the background of China's grid decarbonization. The GHG emissions of 50 MW and 500 MW PV systems with different electricity CO_2 emission factors and different scenarios are presented in (a) and (c). EPBT and EROI for 50 MW and 500 MW PV systems under different scenarios are illustrated in (b) and (d). 0.5942 kg CO_2-eq per kW per h is the electricity CO_2 emission factors. The S0 is the baseline scenario, and the other four scenarios are the technological progress scenario (S1), the effective management scenario (S2), the integrated optimization scenario (S3), and the ideal condition scenario (S4).

below 17 gCO_2-eq per kW per h for both 50 MW and 500 MW PV systems. This illustrates that to achieve cleaner electricity from renewable sources, apart from technological progress in the production of PV modules by PV module manufacturers, more efficient management of PV systems by grid operators around the world is required. In the S4 scenario, 2.6–3.1 gCO_2-eq per kW per h is reduced in comparison to the S3 scenario.

The grid decarbonization process in China has the potential to significantly reduce the life cycle GHG of PV systems across a range of scenarios. When considering a lower carbon emission factor of China's grid at 0.4 kg CO_2-eq per kW per h, the life cycle GHG of PV systems can be reduced to less than 19 gCO_2-eq per kW per h in S1 and S2 scenarios, and to less than 13 gCO_2-eq per kW per h in the S3 scenario. In the case of a carbon emission factor of 0.2 kg CO_2-eq per kW per h for China's grid and the ideal condition scenario (S4), the life cycle GHG of the 50 MW and 500 MW PV systems are 5.8 and 7.2 gCO_2-eq per kW per h, respectively.

As shown in Fig. 5b and d, the PV systems in the S1 and S2 scenarios have a higher energy payback capability compared to the S0 scenario. Specifically, in the S1 and S2 scenarios, the EROI of PV systems is improved by 42.3–54.0% compared to the S0 scenario. The EPBT of the PV systems is advanced by 1.0–1.1 years in the S1 scenario compared to the S0 scenario, while it is improved by only 0.3–0.4 years in the S2 scenario. This suggests that technological advances are more effective in improving EPBT than sound management. This is because the S1 scenario increases both the electricity generation of the PV systems and mitigates the life-cycle energy consumption through advancements in production technology by enhancing the efficiency of the PV modules and reducing the mass of materials utilized. Therefore, technical progress is more effective in reducing EPBT in the S1 scenario compared to S2, which merely decreases the EPBT by enhancing electricity generation through management optimization. The S3 scenario results in a further reduction of the EPBT by 0.2–1.0 years and an improvement in the EROI by 42.1–53.8% in comparison to the S1 and S2 scenarios. In the S4 scenario, the EPBT is shortened to less than 2 years and the EROI is improved to more than 18.

4. Discussion

Solar PV is a key technology driving the rapid growth of renewables, with the potential to accelerate the decarbonization of the global electricity supply. In the International Energy Agency's Net Zero Emissions by 2050 (NZE) scenario, solar PV is projected to exceed 18 000 GW of installed capacity and generate over 30 000 TW h of electricity globally by 2050.[51] With the integration of low-carbon renewables into the grid, the CO_2 intensity of global electricity is decreasing and is expected to reach 400 gCO_2-eq per kW per h in 2026.[48] The role of solar PV systems in reducing GHG emissions is becoming increasingly significant in this global decarbonization effort.

In this study, we conduct a cradle-to-grave LCA study using primary data from six different PV systems with varying technologies and management practices, located in the world's largest PV power park. Although this study focuses on six large PV systems located on the Tibetan Plateau, the findings are applicable to PV systems worldwide. Our findings show a decrease in GHG emissions from 38.8–54.7 gCO_2-eq per kW per h for Multi-Si PV systems to 32.5–35.8 gCO_2-eq per kW per h for Mono-Si PV systems in the past decade, aligning with previous studies. However, despite this progress, current efforts to reduce the life cycle GHG emissions of PV systems are insufficient to meet global net-zero goals. Therefore, how to further reduce the lifecycle GHG of PV systems remains critical to addressing the climate change challenge and achieving the net-zero emissions targets.

Technological progress of PV modules is an effective way to reduce the GHG emissions from PV electricity generation globally. Crystalline silicon (C-Si) PV modules (including Multi- and Mono-crystalline Si modules) accounted for 95% of the PV market in 2020 and are projected to become the world's primary electricity source by 2040–2050.[52] Mono-Si PV modules are gradually dominating the C-Si PV module market due to their higher efficiency and stability. Based on this trend, it is expected that Mono-Si PV modules will play a key role in future global energy decarbonization. Over the last decade, the GHG emissions of Mono-Si PV systems have been reduced by 7.9–40.5% and the EROI has improved by 1.5–52.5% compared to Multi-Si PV systems.

China's dominance in the PV market, producing 74.7% (ref. 53) and 77.8% (ref. 54) of the global PV modules in 2021 and 2022, respectively, means that China's manufacturing standards largely reflect global production levels. China's advancements in Mono-Si PV technology have been driven by policies like the 14th Five-Year Plan[55] and the Action Plan for the Smart Photovoltaic Industry (2021–2025).[56] According to our contribution analysis, Mono-Si PV modules made in China account for 74.2–84.2% of CED and 67.8–79.5% of GHG over the life cycle of the PV systems. It is therefore important to monitor the GHG emissions and energy payback capability of PV modules produced in China to achieve a global net-zero electricity system.

As new PV module technologies emerge, it is critical to periodically assess their GHG impacts and energy payback. This study relies on primary data from PV modules produced in China, which may introduce biases when applied to modules from other countries. However, given that China supplies 79.4% of polysilicon, 96.8% of wafers, and 85.1% of solar cells globally,[53] the findings remain broadly applicable, provided similar raw material supply chains and quality management systems are used elsewhere. Our sensitivity analysis shows that technological choices—such as module efficiency and silicon wafer thickness—significantly affect GHG impacts. Future studies should conduct comprehensive assessments of PV modules with varying production technologies and material usage on a global scale to better understand their life cycle impacts.

The intermittent nature of solar PV electricity generation requires precision management strategies for both PV plants and the electricity sector. Strategies such as timely panel cleaning, regular equipment inspections, replacing damaged components, and expanding transmission grid capacity can increase electricity generation and extend PV system lifetimes.

The PV systems in this study, located on the Tibetan Plateau of China, face issues such as "abandoned electricity" due to limited transmission capacity, which leads to wasted electricity.

The deployment of an ESS offers a solution to reduce electricity wastage. China's 14th Five-Year Plan includes recommendations for new energy storage development,[57] and our study shows that when a PV system is equipped with an ESS, the GHG emissions can be reduced by 0.7 gCO_2-eq per kW per h, the EPBT is shortened by 0.1 years, and the EROI improves from 6.8 to 7.0. However, incorporating an ESS alone is not enough to achieve significant GHG reductions; effective management, such as reducing the curtailment rate, improving the performance ratio, and prolonging the system's lifetime, is also required.

In this study, we explored different scenarios for technological changes, management strategies and grid decarbonization. In light of the uncertainties in the scenarios of the case PV plants and the simplifying assumptions based on key parameters, the prospect of optimizing PV systems in different regions will be examined in future studies. The results show that both technological progress (S1) and effective management (S2) scenarios contribute equally to reducing GHG emissions and improving the EROI over the life cycle of PV systems. The S3 scenario integrating both S1 and S2 reduces the GHG to 14.2–16.6 gCO_2-eq per kW per h, shortens the EPBT to 1.8–2.2 years, and improves the EROI to 14.9–17.3. This highlights the importance of technological developments and sound management in reducing GHG emissions and maximizing energy payback. However, it is noted that PV technology choice is locked in at the time of installation putting increased emphasis on the importance of management strategies.

By establishing consistent boundaries and methodological frameworks, this study enables cross-system comparisons of technologies and management strategies. Scenario analyses further show that technological innovation, optimized management, and grid decarbonization collectively reduce the GHG impacts of PV systems to below 14.7 gCO_2-eq per kW per h, outperforming historical results in Fig. 3a. These findings highlight the importance of standardized methodologies for assessing PV system sustainability and emphasize the global significance of reducing PV-related GHG emissions.

While technological advances in PV systems will help developing countries move away from traditional energy path dependency, further unlocking the decarbonization potential of PV systems will require a global focus on their management strategies. As PV penetration rises and the grid transitions to net-zero, challenges such as grid limitations, curtailment, and management inefficiencies are becoming major barriers to the development and competitiveness of the PV industry.[7] To overcome these barriers, local governments, PV owners, and grid operators must collaborate to explore cost-efficient management strategies that enhance PV system performance and lifetime. Additionally, global stakeholders must promote grid upgrades and expansion through policy incentives and investments to support the growing share of PV generation. Innovations in demand-side management will also be crucial for balancing supply and demand, further unlocking the potential of PV electricity generation.

As the share of global energy demand met by renewables continues to increase, the carbon emission factor of electricity supply will decrease, further reducing GHG emissions associated with PV module manufacturing. Our findings demonstrate that grid decarbonization, coupled with technological advancements in PV module manufacturing and improved management of PV systems, can accelerate the global transition to net-zero electricity.

5. Conclusion

In this study, we conduct a cradle-to-grave LCA study using primary data from six different PV systems with varying technologies and management practices, located in the world's largest PV power park. Over the last decade, the GHG emissions from Mono-Si PV systems have been reduced by 7.9–40.5% and the EROI has improved by 1.5–52.5% compared to Multi-Si PV systems. Effective management and technological advancements decrease GHG emissions by 29.6–34.3% compared to the current scenario. The technological progress (S1) and effective management (S2) scenarios contribute equally to reducing GHG emissions and improving the EROI over the life cycle of PV systems. The S3 scenario integrating both S1 and S2 reduces the GHG to 14.2–16.6 gCO_2-eq per kW per h, shortens the EPBT to 1.8–2.2 years, and improves the EROI to 14.9–17.3. This highlights the importance of technological developments and precision management in reducing GHG emissions and maximizing energy payback. It is important to monitor the GHG emissions and energy payback capability of PV modules to achieve a global net-zero electricity system. As PV penetration rises and the grid transitions to net-zero challenges, stakeholders must collaborate to explore cost-efficient management strategies that overcome grid limitations, curtailment, and management inefficiencies.

Data availability

The data supporting the findings of the study are available within the paper and its ESI.†

Author contributions

Xingyong Li: conceptualization, methodology, investigation, data curation, visualization, formal analysis, writing – original draft, writing – review & editing. Fanran Meng: conceptualization, methodology, investigation, formal analysis, supervision, funding acquisition, writing – original draft, writing – review & editing. Alan Dunbar: formal analysis, writing – review & editing. Lixiao Zhang: methodology, data curation, formal analysis, funding acquisition, writing – review & editing. Yan Hao: methodology, investigation, data curation. Tong He: investigation, data curation, visualization. Na Yang: investigation, formal analysis. Junnan Mao: investigation, data curation. Fanxin Meng: formal analysis, supervision. Gengyuan Liu: data curation, supervision.

Conflicts of interest

The authors declare no competing interest.

Abbreviations

PV	Photovoltaic
Multi-Si	Multi-crystalline Silicon
Mono-Si	Mono-crystalline Silicon
LCA	Life Cycle Assessment
GHG	Greenhouse Gas
CED	Cumulative Energy Demand
EPBT	Energy Payback Time
EROI	Energy Return On Investment
BOS	Balance Of System
ESS	Energy Storage Systems
O&M	Operation & Maintenance
EoL	End Of Life

Acknowledgements

This research received financial support from the National Key Research and Development Program of China (no. 2022YFB4202101), the National Natural Science Foundation of China (no. 2241200098, 52225902, and 7211101067), the Royal Society ISPF – International Collaboration Awards (ICA\R1\231046), and the Strategic Research and Consulting Project of the Chinese Academy of Engineering (2025-GD-04).

References

1 Electricity market report, 2023, available: https://www.iea.org/reports/electricity-market-report-2023.

2 Renewable energy statistics, 2024, available: https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024.

3 The 2024 Statistical Review of World Energy, available: https://www.energyinst.org/statistical-review.

4 Y. Wang, R. Wang, K. Tanaka, P. Ciais, J. Penuelas, Y. Balkanski, J. Sardans, D. Hauglustaine, *et al*, Accelerating the energy transition towards photovoltaic and wind in China, *Nature*, 2023, **619**, 761–767, DOI: 10.1038/s41586-023-06180-8.

5 Y. Zhou, H. Wang, Z. Liu, N. Bhattarai, J. Paudel and H. G. Qiu, Can Solar Photovoltaic Poverty Alleviation Policies Reduce Carbon Emissions and Increase Income in China?, *Environ. Sci. Technol.*, 2023, **57**, 20583–20594, DOI: 10.1021/acs.est.3c06342.

6 A. Bilich, K. Langham, R. Geyer, L. Goyal, J. Hansen, A. Krishnan, J. Bergesen and P. Sinha, Life Cycle Assessment of Solar Photovoltaic Microgrid Systems in Off-Grid Communities, *Environ. Sci. Technol.*, 2017, **51**, 1043–1052, DOI: 10.1021/acs.est.6b05455.

7 Trends in PV applications 2023, available: https://iea-pvps.org/trends_reports/trends-2023/.

8 M. Shafiullah, S. D. Ahmed and F. A. Al-Sulaiman, Grid Integration Challenges and Solution Strategies for Solar PV Systems: A Review, *IEEE Access*, 2022, **10**, 52233–52257, DOI: 10.1109/access.2022.3174555.

9 X. Li, Z. He, S. Xia and Y. Yang, Greenness change associated with construction and operation of photovoltaic solar energy in China, *Renewable Energy*, 2024, **226**, 120461, DOI: 10.1016/j.renene.2024.120461.

10 A. H. Mohd Nordin, S. I. Sulaiman, S. Shaari and R. F. Mustapa, Energy and environmental impacts of a 37.57 MW dc ground-mounted large-scale photovoltaic system in Malaysia: A life-cycle approach, *J. Cleaner Prod.*, 2022, **335**, 130326, DOI: 10.1016/j.jclepro.2021.130326.

11 J. White, World Biggest Solar Plant: What Are The Biggest Solar Plants In The World, https://www.sunvalue.com/posts/biggest-solar-panel, (accessed Jun 7, 2023).

12 Qinghai Gonghe Photovoltaic Tracker Project in 2017, https://en.zenithund.com/news/ns_3263.html, (accessed 27 June, 2023).

13 Q. F. Tan, Z. Y. Zhang, X. Wen, G. H. Fang, S. Xu, Z. Nie and Y. L. Wang, Risk control of hydropower-photovoltaic multi-energy complementary scheduling based on energy storage allocation, *Appl. Energy*, 2024, **358**, 16, DOI: 10.1016/j.apenergy.2023.122610.

14 International Organization for Standardization (ISO), *ISO 14040:2006 Environmental Management — Life Cycle Assessment — Principles And Framework*, International Organization for Standardization (ISO), Geneva, Switzerland, 2006, Available: https://www.iso.org/standard/37456.html.

15 International Organization for Standardization (ISO), *ISO 14044:2006 Environmental Management — Life Cycle Assessment — Requirements And Guidelines*, International Organization for Standardization (ISO), Geneva, Switzerland, 2006, Available: https://www.iso.org/standard/38498.html.

16 M. J. de Wild-Scholten, Energy payback time and carbon footprint of commercial photovoltaic systems, *Sol. Energy Mater. Sol. Cells*, 2013, **119**, 296–305, DOI: 10.1016/j.solmat.2013.08.037.

17 M. C. Pamponet, H. L. Maranduba, J. A. D. Neto and L. B. Rodrigues, Energy balance and carbon footprint of very large-scale photovoltaic power plant, *Int. J. Energy Res.*, 2022, **46**, 6901–6918, DOI: 10.1002/er.7529.

18 P. Wu, X. Ma, J. Ji and Y. Ma, Review on Life Cycle Assessment of Greenhouse Gas Emission Profit of Solar Photovoltaic Systems, *Energy Procedia*, 2017, **105**, 1289–1294, DOI: 10.1016/j.egypro.2017.03.460.

19 A. Beylot, J. Payet, C. Puech, N. Adra, P. Jacquin, I. Blanc and D. Beloin-Saint-Pierre, Environmental impacts of large-scale grid-connected ground-mounted PV installations, *Renewable Energy*, 2014, **61**, 2–6, DOI: 10.1016/j.renene.2012.04.051.

20 M. Yu and A. Halog, Solar Photovoltaic Development in Australia-A Life Cycle Sustainability Assessment Study, *Sustainability*, 2015, **7**, 1213–1247, DOI: 10.3390/su7021213.

21 M. Ito, S. Lespinats, J. Merten, P. Malbranche and K. Kurokawa, Life cycle assessment and cost analysis of

very large-scale PV systems and suitable locations in the world, *Prog. Photovoltaics*, 2016, **24**, 159–174, DOI: 10.1002/pip.2650.

22 H. S. Schultz and M. Carvalho, Design, Greenhouse Emissions, and Environmental Payback of a Photovoltaic Solar Energy System, *Energies*, 2022, **15**, 24, DOI: 10.3390/en15166098.

23 B. Zhang, R. H. Zhang, Y. Li, S. W. Wang and F. Xing, Ignoring the Effects of Photovoltaic Array Deployment on Greenhouse Gas Emissions May Lead to Overestimation of the Contribution of Photovoltaic Power Generation to Greenhouse Gas Reduction, *Environ. Sci. Technol.*, 2023, **57**, 4241–4252, DOI: 10.1021/acs.est.3c00479.

24 S. K. Cromratie Clemons, C. R. Salloum, K. G. Herdegen, R. M. Kamens and S. H. Gheewala, Life cycle assessment of a floating photovoltaic system and feasibility for application in Thailand, *Renewable Energy*, 2021, **168**, 448–462, DOI: 10.1016/j.renene.2020.12.082.

25 G. Hou, H. Sun, Z. Jiang, Z. Pan, Y. Wang, X. Zhang, Y. Zhao and Q. Yao, Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China, *Appl. Energy*, 2016, **164**, 882–890, DOI: 10.1016/j.apenergy.2015.11.023.

26 Z. Q. Yu, W. H. Ma, K. Q. Xie, G. Q. Lv, Z. J. Chen, J. J. Wu and J. Yu, Life cycle assessment of grid-connected power generation from metallurgical route multi-crystalline silicon photovoltaic system in China, *Appl. Energy*, 2017, **185**, 68–81, DOI: 10.1016/j.apenergy.2016.10.051.

27 G. Constantino, M. Freitas, N. Fidelis and M. G. Pereira, Adoption of Photovoltaic Systems Along a Sure Path: A Life-Cycle Assessment (LCA) Study Applied to the Analysis of GHG Emission Impacts, *Energies*, 2018, **11**, 28, DOI: 10.3390/en11102806.

28 Y. Fu, X. Liu and Z. Yuan, Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China, *J. Cleaner Prod.*, 2015, **86**, 180–190, DOI: 10.1016/j.jclepro.2014.07.057.

29 W. Chen, J. L. Hong, X. L. Yuan and J. R. Liu, Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China, *J. Cleaner Prod.*, 2016, **112**, 1025–1032, DOI: 10.1016/j.jclepro.2015.08.024.

30 M. Graebig, S. Bringezu and R. Fenner, Comparative analysis of environmental impacts of maize–biogas and photovoltaics on a land use basis, *Sol. Energy*, 2010, **84**, 1255–1263, DOI: 10.1016/j.solener.2010.04.002.

31 N. Stylos and C. Koroneos, Carbon footprint of polycrystalline photovoltaic systems, *J. Cleaner Prod.*, 2014, **64**, 639–645, DOI: 10.1016/j.jclepro.2013.10.014.

32 F. Grubišić Čabo, S. Nižetić, E. Giama and A. Papadopoulos, Techno-economic and environmental evaluation of passive cooled photovoltaic systems in Mediterranean climate conditions, *Appl. Therm. Eng.*, 2020, **169**, 114947, DOI: 10.1016/j.applthermaleng.2020.114947.

33 D. Yang, J. Liu, J. Yang and N. Ding, Life-cycle assessment of China's multi-crystalline silicon photovoltaic modules considering international trade, *J. Cleaner Prod.*, 2015, **94**, 35–45, DOI: 10.1016/j.jclepro.2015.02.003.

34 B. Huang, J. Zhao, J. Chai, B. Xue, F. Zhao and X. Wang, Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process, *Sol. Energy*, 2017, **143**, 132–141, DOI: 10.1016/j.solener.2016.12.038.

35 A. Sagani, J. Mihelis and V. Dedoussis, Techno-economic analysis and life-cycle environmental impacts of small-scale building-integrated PV systems in Greece, *Energy Build.*, 2017, **139**, 277–290, DOI: 10.1016/j.enbuild.2017.01.022.

36 E. Santoyo-Castelazo, K. Solano-Olivares, E. Martinez, E. O. Garcia and E. Santoyo, Life cycle assessment for a grid-connected multi-crystalline silicon photovoltaic system of 3 kWp: A case study for Mexico, *J. Cleaner Prod.*, 2021, **316**, 24, DOI: 10.1016/j.jclepro.2021.128314.

37 W. M. Soares, D. D. Athayde and E. H. M. Nunes, LCA study of photovoltaic systems based on different technologies, *Int. J. Green Energy*, 2018, **15**, 577–583, DOI: 10.1080/15435075.2018.1510408.

38 X. Jia, F. Lv, P. Li and W. Wang, Life-cycle assessment of p-type multi-Si back surface field (BSF) solar module in China of 2019, *Sol. Energy*, 2020, **196**, 207–216, DOI: 10.1016/j.solener.2019.12.018.

39 L. Liu, W. J. Liu, J. Yao, T. J. Ia, Y. Zhao and Y. J. Dai, Life cycle energy, economic, and environmental analysis for the direst-expansion photovoltaic-thermal heat pump system in China, *J. Cleaner Prod.*, 2024, **434**, 17, DOI: 10.1016/j.jclepro.2023.139730.

40 W. Luo, Y. S. Khoo, A. Kumar, J. S. C. Low, Y. Li, Y. S. Tan, Y. Wang, A. G. Aberle, *et al*, A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies, *Sol. Energy Mater. Sol. Cells*, 2018, **174**, 157–162, DOI: 10.1016/j.solmat.2017.08.040.

41 *Ecoinvent V3.9.1 databse*, available: https://support.ecoinvent.org/ecoinvent-version-3.9.

42 *Patent SimaPro V9.5 software Number*, available: https://simapro.com/.

43 R. Geyer, J. R. Jambeck and K. L. Law, Production, use, and fate of all plastics ever made, *Sci. Adv.*, 2017, **3**, e1700782, DOI: 10.1126/sciadv.1700782.

44 Climate change 2021: the physical science basis, available: https://www.ipcc.ch/report/ar6/wg1/.

45 R. Frischknecht, F. Wyss, S. B. Knöpfel, T. Lützkendorf and M. Balouktsi, Cumulative energy demand in LCA: the energy harvested approach, *Int. J. Life Cycle Assess.*, 2015, **20**, 957–969, DOI: 10.1007/s11367-015-0897-4.

46 C. F. Blanco, S. Cucurachi, J. B. Guinée, M. G. Vijver, W. J. G. M. Peijnenburg, R. Trattnig and R. Heijungs, Assessing the sustainability of emerging technologies: A probabilistic LCA method applied to advanced photovoltaics, *J. Cleaner Prod.*, 2020, **259**, 120968, DOI: 10.1016/j.jclepro.2020.120968.

47 CO_2 emission factor for electricity in 2021, available: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202404/t20240412_1070565.html.

48 Electricity, 2024, available: https://www.iea.org/reports/electricity-2024.
49 R. D. Chen, P. P. Xu and H. N. Yao, Decarbonization of China's regional power grid by 2050 in the government development planning scenario, *Environ. Impact Assess. Rev.*, 2023, **101**, 13, DOI: 10.1016/j.eiar.2023.107129.
50 C. Lamnatou, N. Guignard, D. Chemisana, C. Cristofari and V. Debusschere, Photovoltaic power plants with hydraulic storage: Life-cycle assessment focusing on energy payback time and greenhouse-gas emissions - a case study in Spain, *Sustain. Energy. Techn.*, 2023, **60**, 103468, DOI: 10.1016/j.seta.2023.103468.
51 World energy outlook, 2023, available: https://www.iea.org/reports/world-energy-outlook-2023.
52 C. Ballif, F. J. Haug, M. Boccard, P. J. Verlinden and G. Hahn, Status and perspectives of crystalline silicon photovoltaics in research and industry, *Nat. Rev. Mater.*, 2022, 7, 597–616, DOI: 10.1038/s41578-022-00423-2.
53 Solar P. V. global supply chains, available: https://www.iea.org/reports/solar-pv-global-supply-chains.
54 Distribution of solar photovoltaic module production worldwide in 2022, by country, available: https://www.statista.com/statistics/668749/regional-distribution-of-solar-pv-module-manufacturing/.
55 Outline of the 14th five-year plan for the national economic and social dvelopment of the People's Republic of China and vision 2035, available: https://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.
56 Action plan for the innovative development of the smart photovoltaic industry(2021-2025), available: https://www.gov.cn/zhengce/zhengceku/2022-01/05/content_5666484.htm.
57 China's "14th five-year plan" implementation programme for the development of new energy storage, available: https://www.gov.cn/zhengce/zhengceku/2022-03/22/content_5680417.htm.

