Sustainable Production and Consumption 49 (2024) 236–248

Contents lists available at ScienceDirect

Sustainable Production and Consumption

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

How will manufacturing capacity additions in China and North America affect the carbon footprint of silicon photovoltaics?

Luyao Yuan, Angela Farina, Annick Anctil *

Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824, United States

ARTICLE INFO

Editor: Prof. Ronggang Cong

Keywords:
Crystalline silicon
Low-carbon solar
Life cycle assessment
China
North America

ABSTRACT

Global annual PV installation is expected to increase from 150 GW in 2021 to 820 GW in 2030 to reach net zero emissions by 2050. Electricity production from PV generates almost zero carbon emissions, but the emissions from the manufacturing phase are nonnegligible. While most installed PV modules in the US are imported from China, manufacturers are expanding the manufacturing capacity in North America to reduce reliance on Chinese PV modules. Although it has been commonly perceived that the North American modules would have a lower environmental footprint than Chinese ones, the effect of capacity expansions and regional impact considering where each component is produced has yet to be fully understood. This study aims to compare the carbon footprint and cumulative energy demand of PERC modules manufactured in China and North America based on the expected 2024 manufacturing capacity additions. We develop PV manufacturing scenarios to perform life cycle assessment (LCA) for the first time considering the regional manufacturing capacity, partnerships between suppliers and manufacturers, and regional electricity grids, while previous PV LCA studies evaluated the national average production. The carbon footprint of China's PERC modules for monofacial and bifacial designs, when using the national average grid, is 517 and 412 kg CO_2eq/kWp, respectively. In comparison, the GWP of modules produced in North America is 22.0–22.2 % lower than in China, a difference attributed to the lower carbon footprint of electricity grids. When considering where each component is made, the GWP increases by 1.5 % in China compared to the national average. This difference arises because most of China's solar manufacturing facilities are in regions with higher carbon intensity grids than the national average. Solar manufacturers can reduce the carbon footprint of their products by changing manufacturing locations or increasing the share of renewable sources for manufacturing. We find that both China- and North America-made PERC modules meet the Electronic Product Environmental Assessment Tool (EPEAT) low carbon solar criteria (630 kg CO_2eq/kWp). However, to meet the ultra-low carbon solar criteria (400 kg CO_2eq/kWp), a significant share, approximately 60 % for China and 15 % for North America, of the total electricity supply must be sourced from renewable energy in addition to the existing grid. This study identifies the significant impact of manufacturing locations on the overall carbon footprint of PV modules. It is important to consider production locations by stage and the regional electricity supply when developing the carbon assessment methodology of PV modules. Otherwise, manufacturers may take advantage of assessing carbon footprint using the country's average grid while producing products in dirty grid regions.

1. Introduction

The United States Department of Energy (DOE) recognizes electricity decarbonization as critical to meet the nation's net-zero greenhouse gas (GHG) emissions goal by 2050 (USDOE, 2023a; United States Executive Office of the President, 2021). To decarbonize the grid and reach 100 % clean electricity, massive deployment of solar photovoltaics (PV) is happening in the US and globally, driven by solar's declining costs, federal and subnational policies, and consumer demand (United States Executive Office of the President, 2021).

While solar PVs have advantages over fossil fuels in terms of carbon emission reduction, not all PV modules are created equal, which means their manufacturing does not have the same environmental impact (Ultra Low-Carbon Solar Alliance, 2023a). All PV module manufacturing stages, from raw material to final module assembly, generate greenhouse gases and require energy and resources. As we move towards

* Corresponding author.
E-mail address: anctilan@msu.edu (A. Anctil).

https://doi.org/10.1016/j.spc.2024.06.014
Received 30 December 2023; Received in revised form 11 June 2024; Accepted 12 June 2024
Available online 18 June 2024

large-scale deployment, installing modules meeting the ultra-low carbon criteria compared to the reference could save 4094 megatonnes of CO_2eq globally and potentially more if we encourage manufacturers to reduce their carbon emissions. Life cycle assessment (LCA) is a well-developed method to quantify the potential environmental impact of a product or service through its entire life cycle (ISO, 2006). Carbon footprint is the quantity of greenhouse gases emitted into the atmosphere directly and indirectly by an individual, organization, process, product, or event (Pandey et al., 2011). Performing a life cycle assessment of PV modules to calculate the carbon footprint is the accepted method for comparing PV technologies (Müller et al., 2021; Gibon et al., 2017). Particularly for business-to-business (B2B) products such as PV modules, cradle-to-gate footprints are commonly measured from the extraction of raw materials to product manufacture up to the factory gate (Carbon Trust, 2020). In addition to carbon footprint, cumulative energy demand (CED), also called embodied energy, is often assessed in PV LCA studies since the ultimate goal of PV deployment is to meet the global energy demand (Gerbinet et al., 2014; Ludin et al., 2018). CED refers to the total amount of energy required through a product's life cycle (Kapur and Graedel, 2004).

1.1. Carbon footprint criteria and certifications worldwide for PV

PV module's carbon footprint can be verified by internationally recognized certification organizations. In the US, the Electronic Product Environmental Assessment Tool (EPEAT), managed by the Green Electronics Council (GEC), is a global ecolabel that develops environmental criteria and measures a product's environmental attributes for electronics (GEC, 2023). The new EPEAT criteria for solar were released in March 2023 and set thresholds on the carbon footprint of PV modules (630 and 400 kg CO_2eq/kWp for low and ultra-low carbon solar, respectively) (Global Electronics Council, 2023). Other globally acknowledged certifications, such as the Environmental Product Declaration (EPD) (EPD, n.d.), International Standard Organization (ISO) 14040 (ISO, 2006), and ISO 14067 (ISO, 2018), can be earned through third-party verification to validate the life cycle assessment and quantify a product's carbon footprint. While EPD and ISO certifications do not rank different PV products, they provide important references for PV project developers to evaluate the return on energy or carbon emissions mitigation.

Globally, regulations are coming into force, requiring carbon assessment and setting limits for the carbon footprints of PV modules installed for utility-scale PV projects (Rayner, 2022). For instance, France and South Korea set carbon footprint requirements for public solar PV projects (Polverini et al., 2023). The French tender mechanism requires a simplified carbon assessment (ECS – Évaluation Carbone Simplifiée), which is obligatory for PV manufacturers bidding for projects over 100 kWp (Ultra Low-Carbon Solar Alliance, 2021a). Modules with carbon footprints below 550 kg CO_2eq/kWp can be granted the ECS certificate. The carbon footprint accounts for 30 % of the final score of the tender application (Rayner, 2022; Ultra Low-Carbon Solar Alliance, 2021a), thus encouraging manufacturers to lower their carbon footprint to secure new solar projects. Similarly, in South Korea, PV modules are rated and classified into three grades based on their carbon footprint, representing 10 % of the tender application's evaluation criteria (Ultra Low-Carbon Solar Alliance, 2021b). Further, the European Commission is developing regulations to set up carbon footprint requirements for PV modules within the framework of the Ecodesign Directive (Polverini et al., 2023; European Commission, 2022). Overall, the prevalence of solar carbon criteria, certifications, and regulations has incentivized manufacturers to reduce the carbon footprint of their products and allow solar purchasers to identify low-carbon PV modules.

Manufacturers are increasing renewable energy use during manufacturing to reduce PV products' carbon footprint. For instance, JinkoSolar, Longi, and First Solar joined RE100, a global initiative led by Climate Group (RE100, 2023), and are committed to using 100 % renewable energy (First Solar, 2020; JinkoSolar, 2019; Longi, 2020). Not only module manufacturers but also suppliers, such as Sungrow, an inverter supplier, joined RE100 and committed to using 100 % renewable electricity (Sungrow, 2020). Manufacturers or suppliers can achieve the 100 % renewable electricity target by installing behind-the-meter (BTM) PV systems or purchasing renewable electricity through a power purchase agreement (PPA). For example, JinkoSolar's Malaysian and Chinese factories in Leshan and Chuxiong are fully powered by renewable sources, by external procurement through PPA and on-site solar rooftop installation (JinkoSolar, 2022a; JinkoSolar, 2022b). However, it is worth noting that only 25 % of purchased renewable electricity is allowed for the EPEAT verification to protect against misrepresentation (Global Electronics Council, 2023), so the effect of PPA may be limited regarding receiving EPEAT certifications. As the PV industry increases the share of renewable electricity, it is essential to determine its impact on the carbon footprint of PV manufacturing and further investigate the share of renewable electricity needed to fulfill low-carbon solar criteria.

1.2. PV manufacturing in China and North America

Global annual PV installations are expected to increase from 150 GW in 2021 to 820 GW in 2030 to reach net zero emissions by 2050 (IEA, 2023). Due to China's low labor and energy costs, global PV production has moved from Europe, Japan, and the US to China over the last decade (IEA, 2022a; IEA, 2022b). Currently, China produces >80 % of worldwide PV modules, and most installed PV modules in the US are imported from China (EIA, 2022a). However, the PV supply chain concentration in China increases vulnerabilities, posing risks of meeting the US's domestic PV demand (IEA, 2022b; Basore and Feldman, 2022). To reduce reliance on Chinese PV modules, the US subsidizes domestic solar manufacturing and imposes restrictions and tariffs on Chinese PV imports (USDOE, 2022; Liang and You, 2023; US CBP, 2021). Moreover, the US is pursuing friend-shoring and incentivizing investment in North America under the free trade agreement with Canada and Mexico (USDOE, 2023b). As a result, unprecedented announcements of solar manufacturing capacities have been made in North America. Although various sources attempted to gather information on existing or announced solar manufacturing capacity (Basore and Feldman, 2022; Ultra Low-Carbon Solar Alliance, 2023b), there are limitations in the existing data. For example, existing mappings consider the solar supply chain from polysilicon to module assembly while neglecting the upstream materials such as silica sand and metallurgical-grade silicon. On the data level, there is no aggregated information on the total expected capacity, considering both existing operations and newly announced additions. Moreover, there is no up-to-date data on solar manufacturing capacity in China, considering the most recent reference year in the literature is 2020 (Basore and Feldman, 2022).

Due to different electricity generation structures in China and North American countries, it has been commonly perceived that the North American modules would have a lower environmental footprint than Chinese ones (Yue et al., 2014). However, the effect of capacity expansions and regional impact considering where each component is produced has yet to be fully understood. Several studies compared the life cycle impacts of silicon module manufacturing in various countries, mainly China, the US, and Europe (Müller et al., 2021; Liang and You, 2023; Yue et al., 2014; Liu and van den Bergh, 2020). These investigations showed that China-made modules have a higher carbon footprint and embodied energy than modules made in the US and Europe, mainly due to China's higher carbon- and energy-intensive electricity grid. However, there are significant limitations in the existing literature. For instance, the inventory data of electricity mixes used in previous LCA studies are based on the Ecoinvent datasets (Müller et al., 2021; Liang and You, 2023; Yue et al., 2014; Lunardi et al., 2018; Fthenakis and Leccisi, 2021; Leccisi et al., 2016; Yang et al., 2015; Krebs-Moberg et al., 2021), which provide single-year data and do not reflect the situation of the investigated time frame. Besides, these studies disregard the differences between regional electricity supply in large countries such as China and the US while only evaluating and comparing the national average PV production. Moreover, the EPEAT criteria for solar allows manufacturers to use sub-national or regional level electricity emission factors based on facility locations when calculating the GWP of PV modules (Global Electronics Council, 2023). Thus, for a more accurate carbon assessment of PV modules, developing a regional life cycle inventory for PV manufacturing that considers geographical distributions of solar components' production and local electricity generation profiles is essential. However, no available study has comprehensively assessed the environmental impact of producing solar PV components on regional levels.

Another vital aspect to note is that most earlier PV LCA studies focused on multicrystalline, monocrystalline (buried contact cells), or ribbon silicon technologies (Liang and You, 2023; Fthenakis and Leccisi, 2021; Yang et al., 2015; Luo et al., 2018; Fu et al., 2015) that are no longer the leading technology. In 2022, Passivated Emitter and Rear Contact (PERC) on p-type monocrystalline silicon was the mainstream technology, accounting for about 80 % of the worldwide market share. Mono PERC is predicted to remain dominant until 2025 (VDMA, 2023), thus requiring a better understanding of the carbon footprint of PERC modules. Aside from cell technologies, the existing literature often ignores new module designs, considering the conventional monofacial module instead of the bifacial design, which is currently taking most of the market share and is expected to increase (VDMA, 2023). Thus, an LCA study considering new PV technologies and module designs using regional electricity inventory is required to have a better outlook on the environmental impacts of PV. These assessments are timely since China is the largest crystalline silicon PV manufacturer (IEA, 2022b), and the US plans to increase the PV manufacturing capacity domestically in the coming years.

This work aims to compare the global warming potential (GWP) and cumulative energy demand of solar module production in China and North America in 2024. The objectives are: i) mapping the existing and expected solar supply chains in China and North America in 2024, ii) estimating and comparing the GWP and CED of producing mono PERC glass-backsheet (G-BS) module and framed glass-glass (G-G) module from silica sand to module production considering average and local electricity grid in China and North America, and iii) evaluating the influence of increasing renewable electricity supply on the carbon footprint of PV module manufacturing. The present work is the first to evaluate the environmental impact of PV modules by considering the regional-level electricity grid mixes and production locations for each component, while previous studies only conducted national-level analysis. The existing and announced solar manufacturing capacity for China and North America, from silica sand production to module assembly, is considered. In contrast, silica sand and MG-Si have not been included in the existing capacity mappings. It is also the first study attempting to translate ultra-low carbon solar target (kg CO_2eq/kWp) into additional renewable energy requirement (% of total electricity consumption) and PV installation capacity (watt/watt) for PV manufacturing.

2. Materials and methods

2.1. Solar supply chains in China and North America in 2024

This study aims to compare the carbon and energy impact of silicon PV manufacturing in China and North America using a national and regional approach towards 2024 based on the expected manufacturing capacity. To achieve this goal, first, the existing and announced production locations and capacity for each solar component are collected. The quality of silica sand for each country is summarized in Table 1. Additional information, including the quartz quality and mining locations, is provided in Section S1 in the Supplementary Information (SI). Information on processes, such as mining and beneficiation, for extracting silica sand from quartz is based on a previous study (Heidari and Anctil, 2022). For other PV components, including metallurgical-grade silicon (MG-Si), solar-grade silicon (SoG-Si), ingots, wafers, cells, and modules, facility locations and manufacturing capacity are researched online in news announcements, manufacturers' websites, and public statistics. Announcements on new facilities or capacity additions made by September 2023, which are expected to be operating in 2024, are collected.

Table 1
Silica sand quality in China and North America.

Country	Silica sand quality	References
China	No domestic resources of high-quality (>98 % silica) and industrial-grade (95 % silica) quartz. Silica sand is imported from multiple countries.	(Heidari and Anctil, 2022)
US	High-quality (>98 % silica) and industrial-grade (95 % silica) quartz.	(Heidari and Anctil, 2022)
Canada	High-quality (>98 % silica) and industrial-grade (95 % silica) quartz.	See Section S1
Mexico	Low-quality (65 % silica) quartz.	See Section S1

2.2. Life cycle assessment

2.2.1. LCA goal and scope

The primary objective of this study is to evaluate and compare the GWP and CED for manufacturing PV components and modules in 2024 for China and North America. This is attained by considering different PV manufacturing scenarios based on capacity in various regions and existing partnerships between suppliers and module manufacturers. We consider monocrystalline silicon PERC technology manufacturing with G-BS and framed G-G designs. The LCA is done using the software SimaPro 9.3 (PR´e Sustainability, 2021). The impact categories GWP and CED are calculated using IPCC 2021 and Cumulative Energy Demand, respectively.

2.2.2. Functional unit and system boundary

The functional unit (FU) of this study is 1 kWp of nominal power of mono PERC modules. The system boundary is shown in Fig. 1, illustrating the manufacturing chain of crystalline silicon modules, starting from silica sand extraction to module assembly. The transportation of chemicals and components between each stage is considered by train or truck for domestic shipment and by sea for overseas shipment. The installation, operation, and end-of-life treatment are excluded since existing solar carbon assessment criteria only consider the manufacturing stage.

2.2.3. Life cycle inventory

The production process and life cycle inventory (LCI) are based on IEA PVPS datasets (Frischknecht et al., 2020a; Frischknecht, 2022) and PV industry reports (VDMA, 2023; VDMA, 2022). The inventory of important parameters and assumptions of solar component and module production is summarized in Table S2. Background data are based on public inventory databases Ecoinvent v3.8 (Ecoinvent, 2021) and Datasmart 2021 (LTS, 2021). Foreground material and energy consumption data are based on the PV inventory reports (Frischknecht et al., 2020a; Frischknecht, 2022) and literature (Müller et al., 2021). Detailed processes used in SimaPro are provided in Table S3. The electricity generation mixes by source in China and North America in 2024 are compiled (see Section 2.2.4) and then used for estimating the GWP and CED of PV manufacturing. Transportation inventory, including mass and distance, is calculated depending on the consumed materials and considered locations in different scenarios. Detailed assumptions for transportation are included in Section S2.2 in the SI.

2.2.4. Electricity supply for PV manufacturing

This section considers electricity mixes of different production

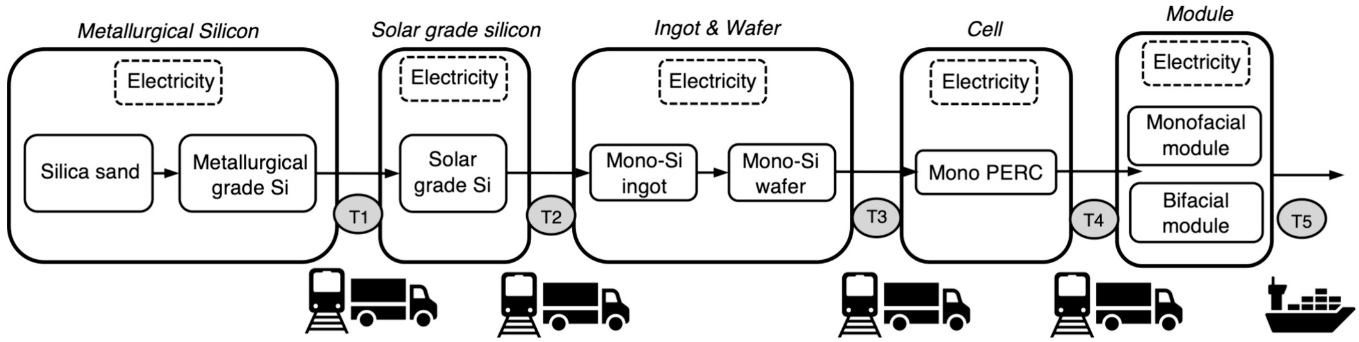

Fig. 1. The system boundary, including transportation (T1-T5) and electricity that are adjusted in different scenarios.

locations in 2024 to develop a regional-level life cycle inventory for PV module manufacturing. The reference years of electricity processes in Ecoinvent v3.8 for China, the US, Canada, and Mexico are 2012, 2019, 2019, and 2018, respectively (Ecoinvent, 2021), which cannot reflect the ongoing decarbonization of electricity grids. Thus, it is necessary to model the electricity generation mixes in 2024 to better estimate the impact of PV manufacturing.

The electricity market is divided into subregions in large countries like the US and China (see Table 2). Additional information is provided in Section S3 in the SI. Meanwhile, in Canada, each province has its electricity generation profile. Considering Mexico's small solar manufacturing capacity, only electricity generation on an average national level is considered in this LCA. The forecasted electricity mixes for North American countries (the US (EIA, 2022b), Canada (Canada Energy Regulator (CER), 2023), and Mexico (Secretariat of energy (SENER), 2018)) for 2024 are collected from national statistics. Due to unavailable forecasted data for China's regional grid, national statistics on electricity generation for the year 2021 are used (National Bureau of Statistics, 2023). Further, the electricity generation mix data are input for the LCA model to calculate the GWP and CED of the national and regional grid.

2.3. Scenario analysis

In this section, different scenarios for solar manufacturing are considered based on i) capacity in various regions and ii) existing partnerships between suppliers and module manufacturers. For China and North America, the carbon footprint and CED for solar manufacturing are evaluated per four scenarios (Table 3). Production's electricity mixes and transport distances are adjusted in each scenario depending on the manufacturing locations. In the "Reference" scenario, the national average electricity grid is considered for all solar component stages. In Scenario 1 (S1), the weighted average of the electricity grid considering the manufacturing capacity in each electricity subregion is used. In Scenario 2 (S2), integrated supply chains representing the facility locations of leading manufacturers and their suppliers in China and North America are considered. In Scenario 3 (S3), regions with the lowest carbon intensity grid are considered for each production stage to assess the potentially lowest carbon footprint of solar manufacturing in China and North America. In Scenario 4 (S4), the impact of increasing the use of renewable electricity by installing BTM solar or signing PPA is evaluated. The assumed locations in S4 are the same as in S2.

Table 2
Electricity grid subregions in China and North America.

Country	Electricity grid subregion divisions	References/ Comments
China	7 electric power supply operation subregions.	(Ecoinvent, 2022) See Fig. S1
US	26 Emissions & Generation Resource Integrated Database (eGRID) subregions.	(EPA, 2022) See Fig. S2
Canada	Each province is considered a subregion in this study.	–
Mexico	Country average electricity is considered in this study.	–

Table 3
LCA scenarios and descriptions.

Scenario	Considered electricity
Reference	National average electricity grid.
S1. PV market	Weighted average electricity grid based on the regional manufacturing capacity for each stage.
S2. Integrated supply chain	Regional electricity grid of representative manufacturers' supply chains and facility locations.
S3. Lowest carbon footprint	Regional electricity grid with the lowest carbon emissions for each stage.
S4. EPEAT criteria	Increase renewable (solar) electricity to meet the EPEAT criteria (630 kg and 400 kg CO_2eq/kW$_p$ for low-carbon solar and ultra-low-carbon solar, respectively).

In Scenario 4, extra renewable electricity supply from PV systems is considered. An analysis of the carbon footprint of PV modules with electricity from renewables is presented in Section 3.3. The extra solar electricity is assumed to be generated from mono PERC modules in a monofacial G-BS design. The carbon footprint of manufacturing these solar modules is calculated based on the national average electricity grid, as considered in the "Reference" scenario, for China and North America. The impact of the balance of system (BOS) is estimated based on the literature (Fthenakis and Leccisi, 2021). The lifetime yield of solar electricity is calculated based on the IEA PVPS guidelines, which provide guidance on the methodology of LCA of PV electricity (Frischknecht et al., 2020b). The total electricity generated E_{total} can be calculated using the following equation (Müller et al., 2021):

$$E_{total} = \sum_{y}^{LT} (1 - DR)^{y} \times I \times A \times \eta \times PR \tag{1}$$

where LT is the module lifetime; DR is the mean annual degradation rate; I is the local average annual solar irradiation; A is the module surface area; η is the module efficiency under standard test conditions (STC), and PR is the performance ratio. Similarly, the IEC 61853 Standard series "Photovoltaic (PV) module performance testing and energy rating" provides models for calculating the yearly PV energy output for given conditions, which may integrate climate conditions datasets with high time and spatial resolution (IEC, 2018). By comparison, Eq. (1) considers average and consistent irradiation at the specific location.

When DR is included in PR (Frischknecht et al., 2020b), Eq. (1) is adjusted to Eq. (2):

$$E_{total} = I \times A \times \eta \times PR \times LT \tag{2}$$

Thus, the GWP of solar electricity generation (GWP_{solar}, per kWh) is given by the following equation:

$$GWP_{solar} = \frac{GWP_{system} \times A}{E_{total}} = \frac{GWP_{system}}{I \times \eta \times PR \times LT} \quad (3)$$

where GWP_{system} is the GWP of the solar system (including module and BOS) (per square meter).

Table 4 provides details of different parameters. The module efficiency of mono PERC modules in 2024 is considered based on the industry trend report (VDMA, 2023). In LCAs of PV, IEA PVPS recommended a lifetime of 30 years for silicon modules (Frischknecht et al., 2020b). It is also recommended to use a default performance ratio value of 0.75 for roof-top mounted installations, which includes degradation over time (Frischknecht et al., 2020b). Since the PV components production and module assembly are located in different regions, the solar irradiations of various provinces or states are considered to calculate the PV electricity generation (World Bank, 2024). As the lifetime PV electricity yield and the associated environmental impact depend on various parameters, the effect of the assumptions on the final results is discussed in Section 3.4.

3. Results and discussion

3.1. Regional solar manufacturing capacity

The collected data on manufacturing capacities in China for the year 2024 are detailed in Table S10 to S12. This analysis reveals a significant geographic shift in SoG-Si production from Xinjiang towards the provinces of Inner Mongolia, Qinghai, and Gansu, as depicted in Fig. 2. Projections indicate that Inner Mongolia is set to become the predominant hub for China's SoG-Si production in 2024, expected to account for 30.6 % of the nation's total output, thereby overtaking Xinjiang in production volume (see Table S12). Historically, in 2020, Xinjiang was the epicenter of more than half of China's solar-grade silicon production (Basore and Feldman, 2022). The absence of new capacity announcements in Xinjiang, as evidenced in Fig. S3b, is potentially influenced by forced labor concerns. In 2021, the US government banned imports from silicon producers in that region, and a large volume of solar panel shipments between June and October 2022 was detained at the border under the Uyghur Forced Labor Prevention Act (UFLPA) (Groom, 2022). Then, in December 2022, the shipments were released after the Chinese solar companies proved they were in compliance (Kennedy, 2022). Meanwhile, the EU Commission proposed a ban on products made with forced labor in the EU market in 2022. The European Solar Manufacturing Council (ESMC) advocates a legislative mechanism against forced labor in the PV industry (Skujins, 2023). Due to global solar manufacturers and purchasers' concerns about forced labor, Chinese manufacturers might have to move production facilities to non-Xinjiang provinces since the US and Europe prefer SoG-Si to be produced outside of Xinjiang.

For China, it is worth noting that Inner Mongolia has attracted a lot of solar investment since 2021, not only in the SoG-Si production but also in the complete production line of modules, benefiting from abundant mineral resources, low power prices, and local policies that support the development of clean energy industries (Department of Science and Technology of Inner Mongolia Autonomous Region, 2023; Securities Times, 2022). In addition, the Inner Mongolian government's proactive promotion of PV deployment, attributed to the region's rich solar radiation, positions it as an advantageous hub for manufacturers looking to enhance product sales (The State Council, 2023). Similarly, China's northwestern provinces have witnessed a PV deployment surge due to abundant land resources and low labor and materials costs (Xia et al., 2022). The rapid growth in PV installations in the North and Northwest regions cultivates new markets for PV manufacturers due to significant demand. Moreover, the increasing renewable energy sources in the electricity grids foster the potential to reduce the carbon footprint of PV manufacturing. As a result, PV manufacturers have been expanding capacity in Inner Mongolia, Shaanxi, Gansu, and Qinghai (Fig. 2a). Further, the results reveal a concentration of cell and module production in the East, specifically in Jiangsu and Zhejiang provinces, a trend expected to persist in 2024. The regional concentration is attributed to the southeast coast's historical prominence in China's manufacturing landscape, characterized by its strategic geographic advantages and cost-effective transportation for imports and exports. Consequentially, as China identified the strategy to develop the PV industry in the mid-2000s, manufacturers in Jiangsu and Zhejiang naturally took on leadership roles.

An examination of the distribution of solar manufacturing capacities across North America, as illustrated in Fig. 2b, reveals a concentration primarily within the United States, with Canada and Mexico hosting only minimal module assembly operations. This situation might be due to the competitive advantages of the US in attracting investment in PV manufacturing facilities, given the substantial incentives under the Inflation Reduction Act (IRA) that favor domestic manufacturing (ARC Energy Research Incentives, 2023). Most SoG-Si is produced in Michigan and Tennessee, housing Hemlock Semiconductor and Wacker Polysilicon, respectively (Hemlock, 2023; Wacker, 2023). Moreover, the landscape of solar manufacturing witnessed the reopening of REC Silicon's facility in Washington in 2023 (REC, 2023; Hall, 2022), indicating a strategic revival in domestic production.

As presented in Fig. S4, the geographic clustering of solar manufacturing within the US is prevalent along the southeast and west coasts, with strategic plans underway for expansion into states such as Texas, Georgia, Arizona, Ohio, and New York. These states actively promote renewable energy growth and offer business-friendly policies (SEIA, 2023a; SEIA, 2023b; SEIA, 2023c; SEIA, 2023d; SEIA, 2023e). When selecting sites for manufacturing facilities, manufacturers appear to consider local electricity generation mixes to some extent, with New York standing out for its relatively cleaner grid (EIA, 2022b). However, it indicates that the primary determinants influencing the decision-making process for facility locations lean more towards economic incentives and regulatory landscapes rather than environmental considerations or the advantages of cleaner energy sources.

Since the enactment of the IRA, new manufacturing capacities have been announced across the solar supply chain in North America. However, a noteworthy aspect is that the majority focuses on solar modules, with a comparatively smaller emphasis on cells, ingots, wafers, and polysilicon, exposing gaps in the onshoring and nearshoring supply chains. This unbalanced distribution is because the module assembly process is cheaper and faster to scale than others (Basore and Feldman, 2022). In light of this, North American manufacturers are likely to continue sourcing upstream materials from other countries, especially China, due to its sufficient supply and competitive pricing. In May 2023, the Internal Revenue Service (IRS) released initial guidance for green energy project owners on how to qualify for the domestic content bonus (IRS, 2023). It would be possible to meet the Domestic Content Requirement for utility-scale PV projects by installing US-made PV modules using US-made cells. Thus, there may be more cell manufacturing announcements in the US in the near future. Despite the capacity addition announcements, the construction phase might encounter delays, influenced by factors such as obtaining local permits in adherence to state policies or facing opposition from the public concerned about unrecognized solar plant risks (Speaks, 2023; Sud and

Table 4
Parameters for solar electricity generation.

Parameter	Description
Installed module	Monocrystalline PERC, glass-backsheet design
Module efficiency (***η***)	21.5 % (VDMA, 2023)
Lifetime (***LT***)	30 years (Frischknecht et al., 2020b)
Degradation rate (***DR***)	Included in PR (Frischknecht et al., 2020b)
Performance ratio (***PR***)	0.75 (Frischknecht et al., 2020b)
Irradiation (***I***)	See Tables S6 and S7 in the SI
GWP_{system}	GWP of the PV system, including module and BOS

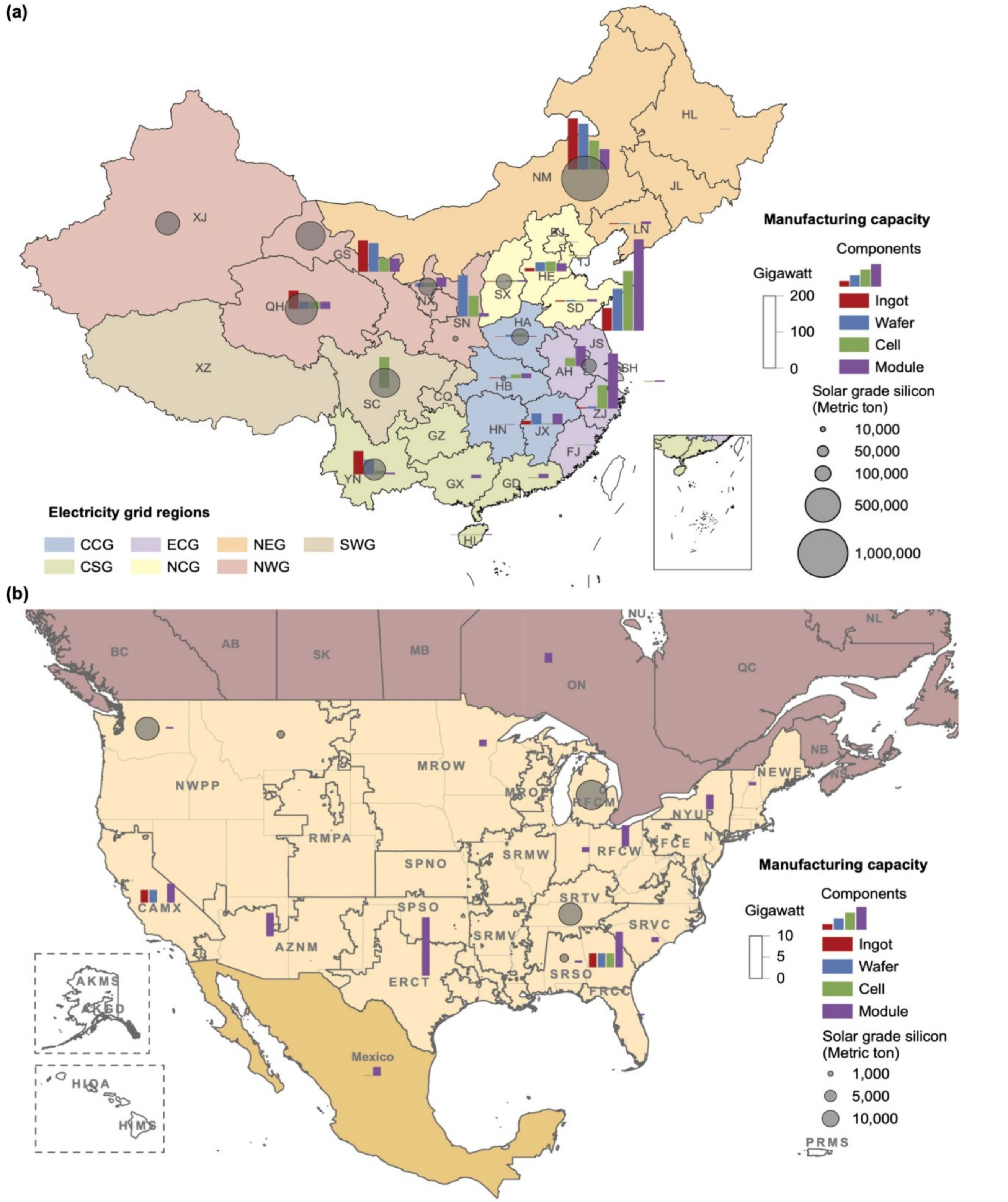

Fig. 2. Solar manufacturing capacity by stage for 2024 and electricity grid regions in (a) China and (b) North America. Abbreviations are used for China's electricity subregions and Canadian provinces. China subregions: Southwest China Grid (SWG), China Southern Power Grid (CSG), Central China Grid (CCG), Northwest China Grid (NWG), East China Grid (ECG), Northeast China Grid (NEG), and North China Grid (NCG). Canadian provinces: British Columbia (BC), Alberta (AB), Saskatchewan (SK), Manitoba (MB), Ontario (ON), Quebec (QC), New Brunswick (NB), Nova Scotia (NS), and Prince Edward Island (PE).

Patnaik, 2022; Susskind et al., 2022). Consequently, in the short term the North American solar market will likely continue to rely on China imports.

3.2. Impact of silicon solar module manufacturing

3.2.1. Electricity generation mixes in China and North America in 2024

The results reveal that the national and regional electricity generation profiles of China, the US, Canada, and Mexico vary greatly by location (Fig. 3 and Table S8). Coal, hydro, and natural gas are the predominant sources of electricity generation in China, Canada, and Mexico, respectively. In comparison, the US relies on natural gas and nuclear power for electricity generation. The divergence in energy sources directly impacts the carbon intensity of each nation's grid. With its substantial reliance on coal power, China has the highest carbon intensity in its national grid, followed by Mexico, the US, and Canada. The regional analysis shows that China's NCG and NEG regions exhibit the highest carbon-intensive grids due to significant shares of coal power. In contrast, the SWG region stands out with the cleanest grid attributed to a substantial proportion of hydropower. In the US, the regions (states) with the dirtiest and cleanest grids are RFCM (Michigan) and NYUP (New York), respectively. The different national and regional electricity generation profiles of these large nations generate different GHG emissions, which will influence the environmental footprint of silicon PV manufacturing. As PV manufacturing expands, particularly domestically in the US, these regional disparities in the electricity grid become crucial considerations for manufacturers aiming to optimize their environmental impact of supply chains.

The share of regional manufacturing capacity and the corresponding weighted average carbon footprint of the electricity grid for each stage is presented in Fig. 4, representing assumptions for Scenario 1. According to Fig. 4a, for China, solar components and module manufacturing are located mostly in regions with higher carbon intensity grids than the national average. The analysis reveals the potential of China's PV manufacturing to lower carbon emissions by adjusting the manufacturing locations or electricity generation sources. For North America, most SoG-Si is produced in Michigan, which has the highest carbon-intensive grid in the US. Manufacturing ingots, wafers, and cells are concentrated in Georgia and South Carolina, while module manufacturing has more diverse distributions (Fig. 4b).

3.2.2. Silicon manufacturing in China and North America

The SoG-Si production process requires significant electricity consumption (see Table S2), so the carbon footprint of SoG-Si is likely to be highly influenced by the local electricity grid. Thus, investigating the regional electricity impacts on the carbon footprint for silicon production is necessary to better understand the overall impacts of solar PV production. The present section compares silicon production for China and North American countries, including silica sand, MG-Si, and SoG-Si. The LCA results of silica sand show that in China, the imported industrial-grade silica sand has a carbon footprint of 88.5 g CO_2eq/kg, 51 % and 55 % higher than that in the US and Canada, respectively (Fig. 5a). This is mainly due to the high carbon intensity of electricity and fuels used for mining operations. The GWP of silica sand production in the US using high-purity and industrial-grade quartz is 36.14 g CO_2eq/kg and 49.75 g CO_2eq/kg, respectively (Fig. 5a). By comparison, the LCA results show that silica sand produced from these two quartz grades in Canada has a GWP of 6.57 % and 8.20 % lower than that in the US. The impact of silicon sand production in Canada changes when the regional electricity grid is considered instead of the national average grid (Fig. S5). Due to the higher share of hydropower (>93 %) in Manitoba and Quebec (see Fig. 3), the impact of producing silica sand is 2 % lower than the national average. In Mexico, the impact of producing low-purity sand is 48.68 g CO_2eq/kg (Fig. 5a).

Fig. 5b shows the carbon footprint of MG-Si production from high-purity, industrial-grade, and low-purity sand in China, the US, Canada, and Mexico for 2024, using each country's respective average electricity grid. In China, MG-Si produced from imported industrial-grade silica sand has a GWP of 13.22 kg CO_2eq/kg, indicating a 26 % and 102 % increase compared to production in the US and Canada, respectively. In Canada, MG-Si impacts are 38 % lower than in the US (with consistent reductions for both high-quality and industrial-grade) and 42 % lower than in Mexico (11.19 kg CO_2eq/kg) due to distinct electricity grid mixes. Notably, regardless of sand quality or production origin, the contribution of silica sand to the total carbon emissions of MG-Si production remains within the range of 1–2 %. Conversely, electricity accounted for 28 %, 55 %, and 63 % of the total impact for Canada, the US, and China, respectively. Recognizing electricity as the primary contributor, we further calculate the impact of MG-Si production by region, using specific regional electricity grids (see Figs. S6 and S7). The results reveal that MG-Si produced in Quebec and Ontario

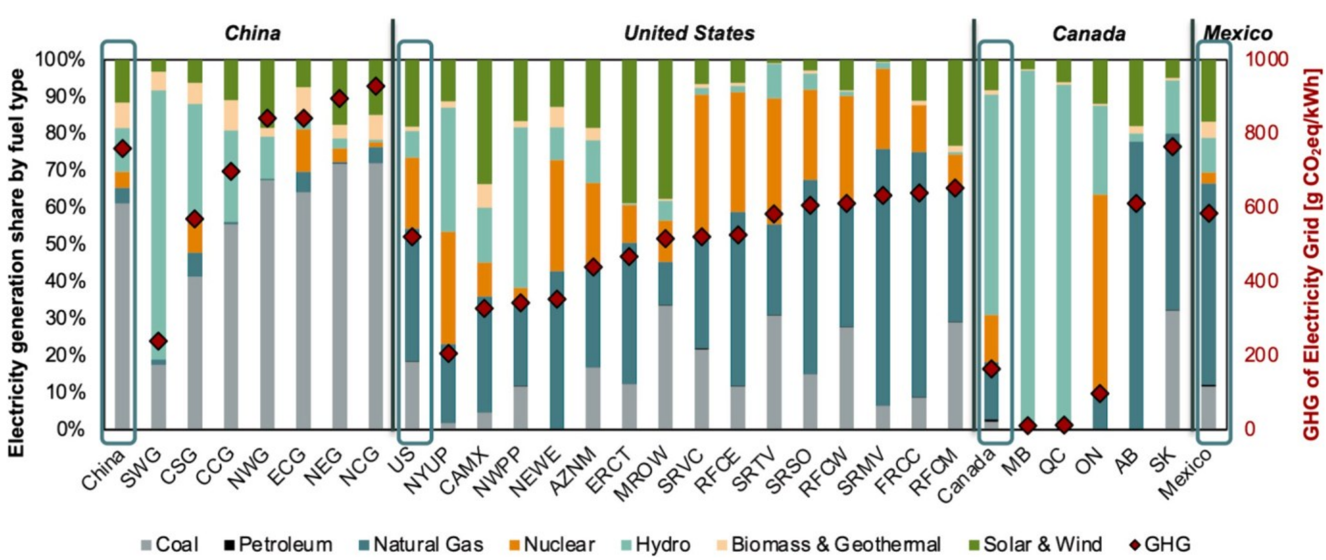

Fig. 3. Electricity generation mixes for China and North America by national average (outlined in boxes) and region and associated carbon footprint for 2024. Abbreviations are used for China's electricity subregions and Canadian provinces. China subregions: Southwest China Grid (SWG), China Southern Power Grid (CSG), Central China Grid (CCG), Northwest China Grid (NWG), East China Grid (ECG), Northeast China Grid (NEG), and North China Grid (NCG). Canadian provinces: Manitoba (MB), Quebec (QC), Ontario (ON), Alberta (AB), and Saskatchewan (SK).

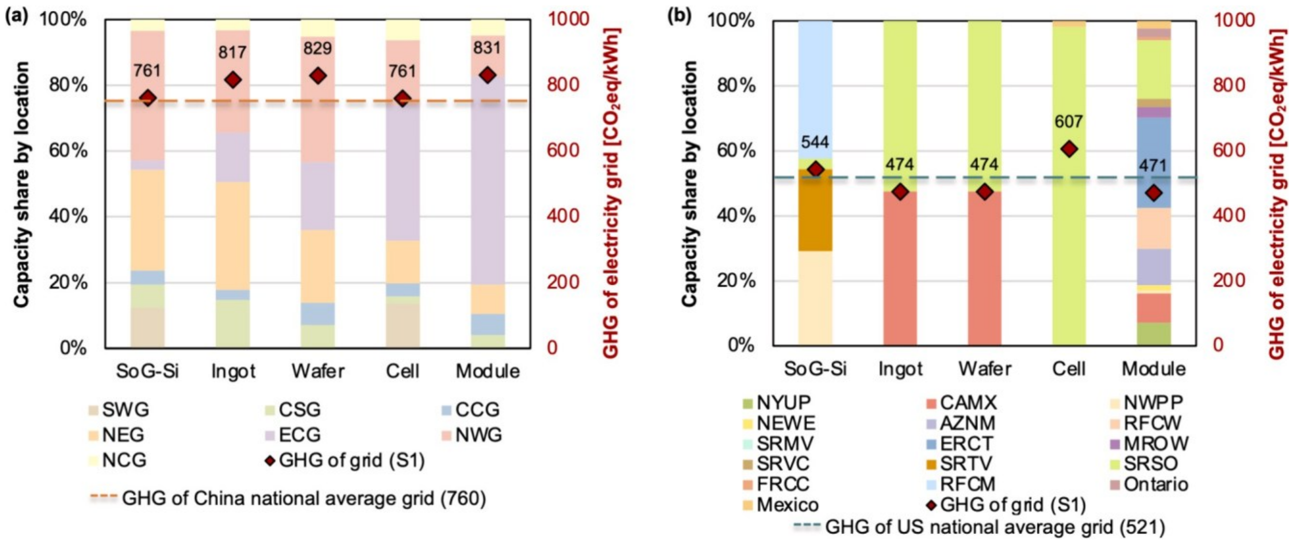

Fig. 4. Manufacturing capacity by region and GHG of weighted average electricity for each stage considered in Scenario 1 in (a) China and (b) North America for 2024. Abbreviations are used for China electricity subregions: Southwest China Grid (SWG), China Southern Power Grid (CSG), Central China Grid (CCG), Northwest China Grid (NWG), East China Grid (ECG), Northeast China Grid (NEG), and North China Grid (NCG).

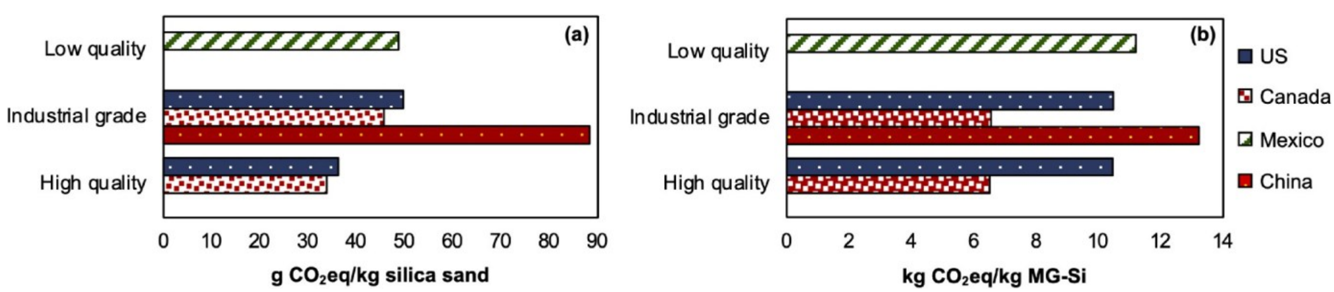

Fig. 5. a) GWP of silica sand extracted from high-quality, industrial-grade, and low-quality quartz deposits in North America and China in 2024; b) GWP of MG-Si production in North America and China in 2024 based on the national average grid.

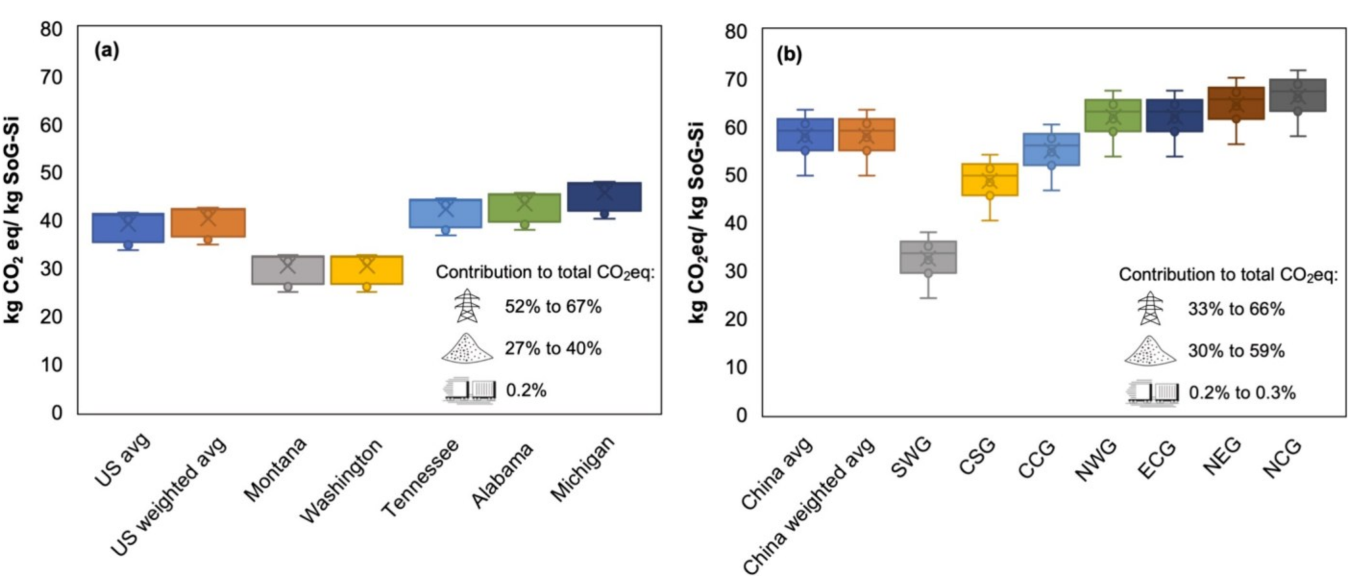

Fig. 6. Variation of GWP of SoG-Si production in a) the US and b) China, considering different MG-Si production locations. Abbreviations are used for subregions of China: Southwest China Grid (SWG), China Southern Power Grid (CSG), Central China Grid (CCG), Northwest China Grid (NWG), East China Grid (ECG), Northeast China Grid (NEG), and North China Grid (NCG).

carries a lower regional impact than Canada's average, attributable to higher shares of hydro and nuclear power generation, respectively (Fig. S6b). In contrast, in the US, MG-Si production across all locations yields a higher regional carbon footprint than the country's average. Similarly, in China, most regions exhibit higher carbon emissions than the national average production, except for the central south and southwest regions.

Since Canada and Mexico have no SoG-Si production (Fig. 2b), our assessment focuses on evaluating the GWP of SoG-Si production in the US and China. The present study delves into the regional impacts by examining the US production in subregions, including RFCM (Michigan), SRTV (Tennessee), SRSO (Alabama), and NWPP (Washington and Montana). In China, all subregions where SoG-Si production occurs are considered (Fig. 2a). An average MG-Si is accounted for SoG-Si production in the US or China, based on the country's average grid and average road transportation distances (see Table S4). The resulting GWP for SoG-Si stands at 41.23 kg CO_2eq/kg in the US (Fig. 6a) and 60.98 kg CO_2eq/kg in China (Fig. 6b), based on national average electricity. Michigan has the highest regional carbon impact due to a substantial reliance on fossil power sources, followed by Alabama, Tennessee, and Washington or Montana. In China, the highest and lowest GWP for SoG-Si production is observed for the north (NCG) region (69.24 kg CO_2eq/kg) and southwest (SWG) region (35.48 kg CO_2eq/kg), respectively.

Additionally, Fig. 6a and b illustrate the range of regional carbon footprints for SoG-Si production derived from various MG-Si sources (refer to Figs. S6 and S7). In the US, on average, the GWP of SoG-Si production can be reduced by 19 % by using MG-Si from Quebec. By comparison, in China, the carbon footprint of the average solar grade can be lowered by 11 % using MG-Si from the SWG region. However, in the SWG region, the GWP of the solar grade production can be reduced by 128 % compared to the national average using the regional grid and local MG-Si (24.18 kg CO_2eq/kg SoG-Si). These findings underline the importance of considering regional environmental impact when sourcing upstream materials for silicon solar PV manufacturing.

Acknowledging the regional disparities in electricity supply among SoG-Si production sites, manufacturers in areas with high carbon intensity grids face the imperative of integrating additional renewable energy sources to mitigate their carbon footprint. The pie charts in Fig. 7 illustrate the proportions of extra renewables versus grid electricity in the overall electricity consumption for SoG-Si production. For SoG-Si production in Tennessee, Alabama, and Michigan, 43–49 % of the total electricity consumption must be sourced from extra renewable energy to match the carbon footprint in cleaner grid regions, such as Washington or Montana (Fig. 7a). In China, the southwest region benefits from abundant hydropower sources to generate the cleanest electricity in the country. However, in the south, northwest, and northeast regions, a significant 60 %–75 % infusion of extra renewables is essential to competitively align with the lower carbon footprint in the southwest (Fig. 7b).

3.2.3. GWP and CED comparison for PV module production in China and North America

As the demand for PV technology continues to rise in the US, understanding the pros and cons of the China- and North America-made modules regarding environmental perspective is essential for proper decision-making. Thus, this section compares the GWP and CED associated with manufacturing PERC modules in monofacial (G-BS) or bifacial (G-G) designs in China and North America. A reference case and three different scenarios (as described in Table 3) are considered for this comprehensive comparison. The manufacturing locations considered for each scenario are detailed in Table 5. In Scenario 2, the integrated supply chains of representative manufacturers, Longi and Qcells, are considered for China and North America, respectively. The locations of each stage are derived from literature (see Sections S5 and S6). In Scenario 3, the region with the cleanest grid for each stage is considered based on the assessment of regional electricity mixes (see Fig. 3).

As shown in Fig. 8a and b, the carbon footprint of China's PERC modules in monofacial and bifacial designs as per the national average grid (China-Ref) is 517 and 412 kg CO_2eq/kWp, respectively. In comparison, the North American counterparts (NA-Ref) exhibit a 22.0–22.2 % lower GWP than China, which is attributed to lower emissions from electricity consumption. When considering the regional manufacturing capacity for each stage (S1), a slight increase of 1.5 % in GWP is observed in China compared to the "Reference" scenario. This difference arises because most of China's solar manufacturing facilities are in regions with higher carbon intensity grids than the national average (Fig. 4a). The higher emissions in S2 compared to the "Reference" suggest the potential for solar manufacturers to reduce the carbon footprint by adjusting supply chains or increasing the share of renewable sources in energy consumption. Although China-made modules have a higher carbon footprint than their respective North American counterparts, the prospect of achieving the lowest emissions (S3) in China (4.4 % than NA-Ref) suggests potential competitiveness with North America, narrowing the difference.

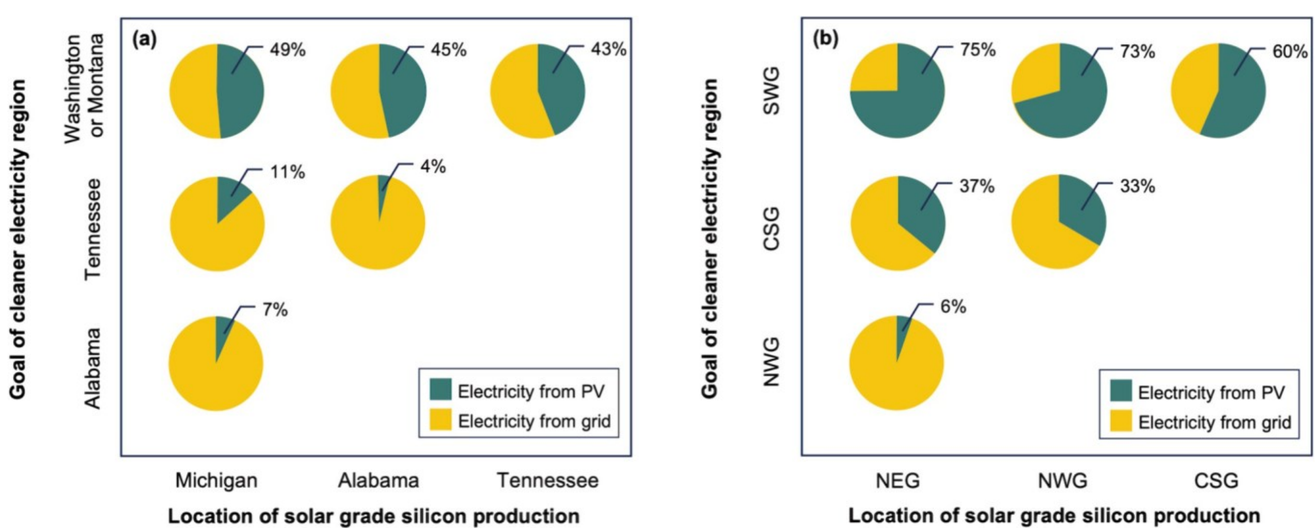

Fig. 7. Required share of renewable electricity (Electricity from PV) and local grid (Electricity from grid) to reduce the carbon footprint of SoG-Si production in different regions in (a) the US and (b) China. Abbreviations are used for subregions of China: Northeast China Grid (NEG), Southwest China Grid (SWG), China Southern Power Grid (CSG), and Northwest China Grid (NWG).

Table 5
Manufacturing locations for different scenarios.

Country	China/ North America		China	North America	China	North America
Scenarios	Reference	S1	S2	S2	S3	S3
MG-Si	Country average grid	Weighted average grid based on regional capacity	Inner Mongolia	West Virginia	Sichuan	Quebec
SoG-Si			Inner Mongolia	Washington	Sichuan	Washington
Ingot			Xi'an	Georgia	Yunnan	California
Wafer			Xi'an	Georgia	Yunnan	California
Cell			Xi'an	Georgia	Sichuan	Georgia
Module			Zhejiang	Georgia	Guangdong	Ontario

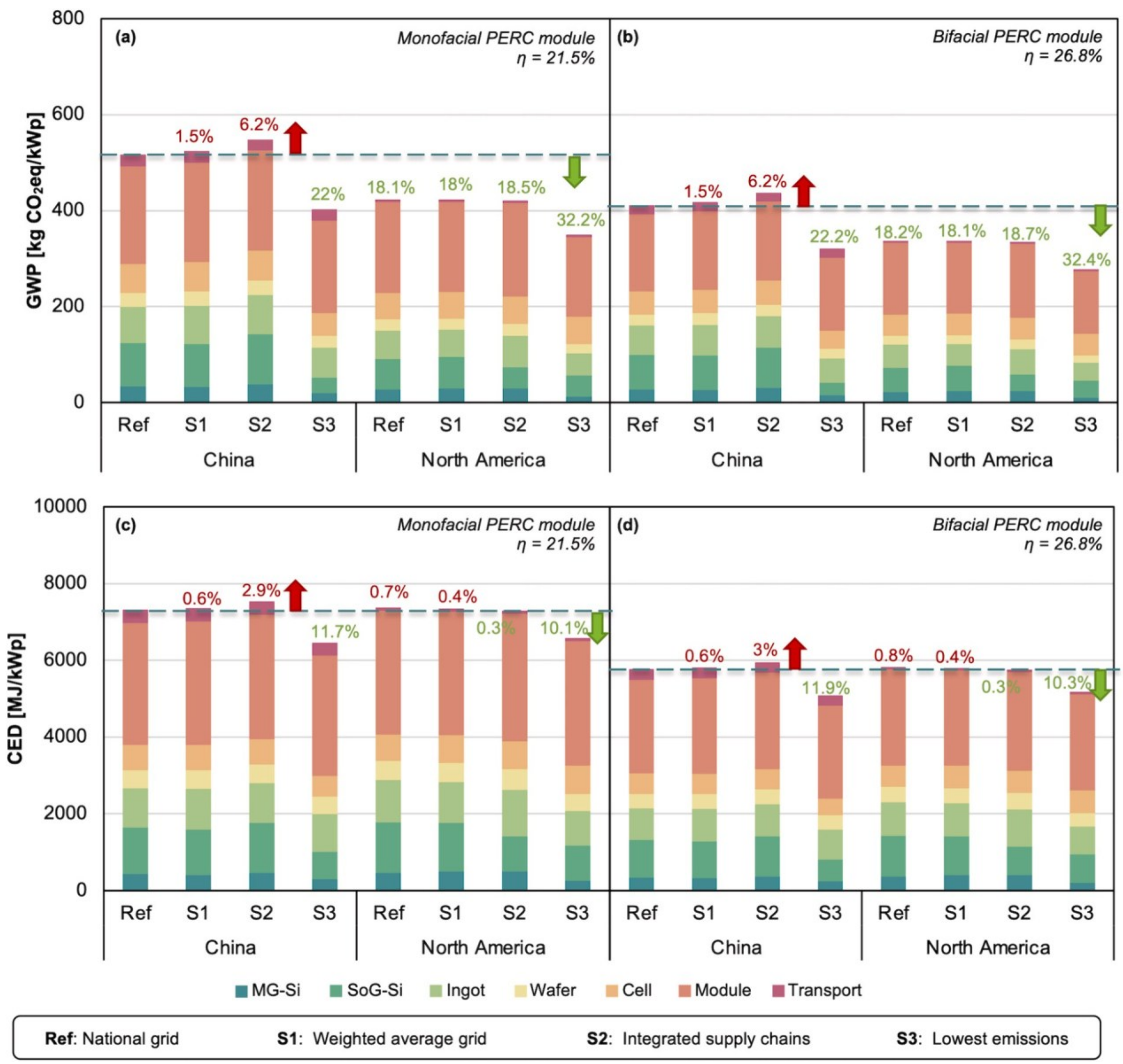

Fig. 8. The GWP (a, b) and CED (c, d) of PERC module manufacturing in China and North America for different scenarios.

Regarding the CED (Fig. 8c and d), modules manufactured in North America require 0.7–0.8 % more energy than those made in China, considering the national average grid. This is primarily due to the higher average share of nuclear energy in the US than China, demanding more energy than other fuel types. Among all scenarios, transportation makes a relatively small contribution to overall GWP and CED, constituting <6 % for China and <2 % for North America. Assuming all manufacturing capacity was located in the greenest grid regions for each component (S3) in 2024, it would save 84 and 3.6 megatonnes of CO_2eq from PV module manufacturing in China and North America, respectively, compared to the "Reference" scenario. If all modules could meet the ultra-low carbon criteria (400 CO_2eq/kWp), 86.2 and 1.1 megatonnes of CO_2eq from Chinese and North America manufacturing would be reduced.

The presented results show the GWP and CED of PV manufacturing considering announced capacity additions. Given the uncertainties regarding PV technology development, manufacturing locations, and electricity decarbonization, performing a long-term future projection analysis would be difficult. The PV industry has a rapid pace of development and evolution. The historical PV markets show that Germany and Japan led global PV production in the early 2000s (IEA, 2002; IEA, 2003). Since 2008, however, China has been the largest PV production country due to competitive costs and domestic policies supporting the PV industry (IEA, 2022b). Meanwhile, building up facilities for module assembly is relatively fast because the step is cheaper and faster to scale than others (Basore and Feldman, 2022; IREC, 2019). Thus, it is difficult to project where and how much future capacity will be located. Moreover, the transition towards cleaner energy sources varies widely across regions and is influenced by multiple factors, such as policies and socioeconomic considerations. Even though statistics regarding these forecasts are available, there are significant uncertainties. For example, in the EIA's Annual Energy Outlook 2023, the proportion of nuclear power is forecasted to remain about 10 % from 2023 to 2050. However, in March 2024, it was announced that a nuclear power station would be recommissioned to meet the clean energy goals (USDOE, 2024), so the existing forecasts fail to represent the future grids in Michigan. For China, there are no available statistics to forecast regional electricity grid mixes, so it is not possible to project the carbon footprint of future PV module production in different locations. Overall, future projections of the environmental impact of PV production are challenging and may yield unreliable results. Therefore, this work is focused on foreseeable manufacturing capacity additions based on manufacturers' announcements.

3.3. Meeting the EPEAT criteria

Whether solar manufacturers are interested in sustainability and want to improve their manufacturing practices or if they are looking to obtain certification for low-carbon solar products; solar manufacturers are actively exploring approaches to reducing carbon emissions from the supply chain. This section evaluates the potential pathways for reducing the carbon footprint of manufacturing PERC modules (G-BS design) by increasing the share of renewable, particularly solar, electricity. The electricity emission factors are adjusted based on the locations considered for the integrated supply chains (S2), where only the US locations are considered for North America, from MG-Si production to module assembly (Table 5).

As per analysis, both Chinese and US modules meet the low carbon solar criteria (630 kg CO_2eq/kWp). This is because the low carbon solar threshold is based on the production of buried contact crystalline silicon modules as per the Standard Value table approach ("Path A"), where the GWP coefficients are calculated based on the IEA PVPS for material and energy consumption and Ecoinvent v3.8 for electricity, which are outdated (Global Electronics Council, 2023). Thus, the low carbon solar criteria (630 kg CO_2eq/kWp) cannot represent the production of new module technologies and designs and their carbon footprint. To achieve ultra-low carbon solar (400 kg CO_2eq/kWp), 60 % and 15 % of the total electricity supply needs to be sourced from additional renewable sources for China and the US, respectively (Fig. 9). This translates into generating solar electricity from modules equivalent to 0.167 and 0.038 watts for each watt of module produced in China and the US, respectively. While the current EPEAT ultra-low carbon criteria impose a cap on renewable electricity purchases at 25 %, there is no restriction on behind-the-meter solar installations (Global Electronics Council, 2023). Hence, a strategic combination of PPA and on-site solar installations can be a viable approach for Chinese manufacturers aiming to meet ultra-low carbon solar criteria, mirroring the successful implementation by JinkoSolar in its Leshan and Chuxiong factories (JinkoSolar, 2022b). It is important to note that the EPEAT criteria and other certifications undergo regular reviews and revisions, allowing for potential threshold adjustments. This emphasizes the evolving nature of sustainability standards and the need for manufacturers to stay abreast of changing criteria in pursuing environmentally responsible practices.

The additional renewable energy required to meet EPEAT criteria (Fig. 9) will change depending on the manufacturing locations across the supply. In this context, we advocate for enhanced transparency from solar manufacturers about the origin of upstream materials and manufacturing locations for each stage of the manufacturing process. In particular, for large PV manufacturers with multiple facilities and suppliers, the carbon footprint for the same module model can vary. Recognizing the incentivizing role of solar carbon assessment criteria in encouraging manufacturers to reduce their carbon footprint, it would be helpful to develop guidance facilitating renewable energy integration and take it into account for a more comprehensive carbon assessment of PV.

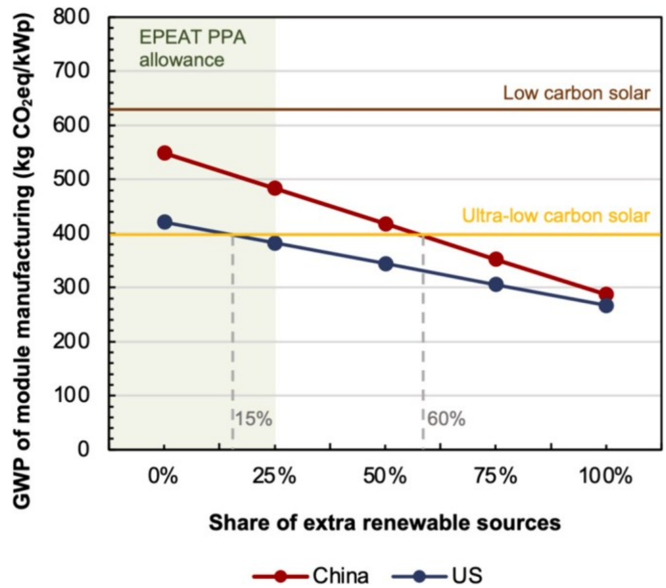

Fig. 9. Additional renewable energy for PV manufacturing to meet the EPEAT criteria (Scenario 4).

3.4. Limitations

The present work has limitations, primarily stemming from the lack of available data and the inherent assumptions embedded within the analysis framework. One limitation is the use of the electricity generation mixes of 2021 to estimate the environmental impacts associated with PV manufacturing in China in 2024. Unlike the US or Canada, there are no available statistics on future electricity mixes on a regional level for China. Moreover, the most up-to-date regional statistics on China's historical electricity generation have the reference year of 2021 (National Bureau of Statistics, 2023), which might be due to a delay in analyzing electricity production data. Considering the ambitious carbon neutrality target for China, a large amount of PV and wind have been added to the grid. On the other hand, energy demand has steadily increased in China in the last decade, but renewable capacity additions were higher than thermal (S&P Global, 2023). Therefore, our work might overestimate the carbon footprint of Chinese PV production as it underestimates ongoing grid decarbonization. Consequently, the carbon footprint difference from PV modules produced in China and North America may be less than initially suggested.

The lifetime electricity yield from PV installations, as discussed in Section 2.3, incorporates various parameters such as module lifetime, efficiency, degradation rate, performance ratio, and solar radiation. The real-world performance of PV systems presents variability, influenced by module specifications, installation angles, and local climate conditions, that is not fully investigated within this study's scope. These limitations underlie the complexity of accurately modeling the environmental benefits of PV manufacturing and the need for region-specific data to refine these assessments.

4. Conclusions

This study compares the life-cycle carbon footprint and energy demand of mono PERC modules manufactured in China and North America, considering manufacturing capacity additions and locations in 2024. Our analysis, under the "Reference" scenario, which utilizes the national average electricity grid for calculations, reveals that modules produced in North America have an 18 % lower carbon footprint than those in China, primarily due to a cleaner electricity grid in North America. In contrast, the cumulative energy demand of module production is similar because of the US's high share of nuclear power. Moreover, our findings indicate the potential for China-made modules to achieve a 4 % lower carbon footprint than the US average if production for each PV component were to occur in regions with the lowest carbon intensity grids. Both Chinese and North American modules currently meet the EPEAT low carbon solar criteria (630 kg CO_2eq/kWp). However, to meet the ultra-low carbon solar criteria (400 kg CO_2eq/kWp), a significant share of renewable energy sourcing is required - approximately 60 % for China and 15 % for the US of the total electricity supply.

The findings identify the significant impact of manufacturing locations on the overall carbon footprint of PV modules. It emphasizes that despite the concentration of PV manufacturing in carbon-intensive grid regions, opportunities exist to reduce the carbon footprint through strategic adoption of renewable energy sources, such as purchase power agreements or behind-the-meter PV systems. Our analysis estimates that achieving the EPEAT ultra-low carbon criteria necessitates the installation of 0.167 watts of PV capacity in China and 0.038 watts of PV capacity in North America for -each watt of module capacity produced, which is feasible for manufacturers to install their products on-site and achieve self-sufficiency.

Furthermore, this study introduces a novel scenario-based approach that leverages regional electricity inventory data, indicating that reliance on national averages can misrepresent the environmental impact of PV manufacturing. The study underlines the importance of using stage-specific electricity inventory data since each component may be produced in different locations. Thus, considering production locations by stage and the regional electricity supply is vital to developing the carbon assessment methodology of PV modules. Otherwise, manufacturers may take advantage of assessing carbon footprint using the country's average grid while producing products in dirty grid regions. From the data reporting perspective, this paper calls for more transparency in the solar supply chain and disclosure of information such as suppliers, facility locations, sources, and materials and energy to enable a more accurate carbon footprint assessment.

CRediT authorship contribution statement

Luyao Yuan: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Angela Farina:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Annick Anctil:** Writing – review & editing, Supervision, Software, Methodology, Funding acquisition, Data curation, Conceptualization.

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.

Acknowledgments

We thank Dr. Preeti Nain (Michigan State University) for her comments and suggestions. This work was supported by the National Science Foundation grant number NSF-2044886.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.06.014.

References

ARC Energy Research Incentives, 2023. Solar Manufacturing: The Problem with Canadian Competitiveness. https://www.arcenergyinstitute.com/solar-manufacturing-the-problem-with-canadian-competitiveness/.
Basore, P., Feldman, D., 2022. Solar Photovoltaics-supply Chain Deep Dive Assessment. USDOE Office of Policy, PO.
Canada Energy Regulator (CER), 2023. Electricity generation by region modelled in current measures. https://www.cer-rec.gc.ca/en/. (Accessed 3 February 2023).
Carbon Trust, 2020. Product Carbon Footprint Label. https://www.carbontrust.com/what-we-do/assurance-and-labelling/product-carbon-footprint-label.
Department of Science and Technology of Inner Mongolia Autonomous Region, 2023. Baotou City: scientific and technological innovation promotes the development of the clean energy industry (in Chinese). https://kjt.nmg.gov.cn/kjdt/mtjj/202311/t20231106_2406052.html?zbb=true.
Ecoinvent, 2021. Ecoinvent Database v.3.8. http://ecoinvent.org.
Ecoinvent, 2022. Ecoinvent Database v.3.9. http://ecoinvent.org.
EIA, 2022a. 2021 Annual Solar Photovoltaic Module Shipments Report. https://www.eia.gov/renewable/annual/solar_photo/pdf/pv_full_2021.pdf.
EIA, 2022b. Annual Energy Outlook. https://www.eia.gov/outlooks/aeo/.
EPA, 2022. Emissions & Generation Resource Integrated Database (eGRID). https://www.epa.gov/egrid.
EPD, EPD international, (n.d.). https://www.environdec.com/home.
European Commission, 2022. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the Regions – EU Solar Energy strategy, COM, 221 final, 2022. https://eur-lex.europa.eu/resource.html?uri=cellar:516a902d-d7a0-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF.
First Solar, 2020. First Solar Commits to Powering 100% of Global Operations with Renewable Energy by 2028. https://investor.firstsolar.com/news/news-details/2020/First-Solar-Commits-to-Powering-100-of-Global-Operations-with-Renewable-Energy-by-2028/default.aspx.
Frischknecht, R., 2022. Fact sheet: environmental life cycle assessment of electricity from PV systems (2022 update), IEA-PVPS. https://iea-pvps.org/fact-sheets/fact-sheet-environmental-life-cycle-assessment-of-electricity-from-pv-systems-2022-update/.
Frischknecht, R., Stolz, P., Krebs, L., de Wild-Scholten, M., Sinha, P., Fthenakis, V., Kim, H.C., Raugei, M., Stucki, M., 2020a. Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems, International Energy Agency, International Energy Agency (IEA) PVPS Task 12, Report T12-19:2020.
Frischknecht, R., Stolz, P., Heath, G., Raugei, M., Sinha, P., de Wild-Scholten, M., 2020b. Methodology Guidelines on Life Cycle Assessment of Photovoltaic 2020, International Energy Agency, IEA PVPS Task 12, International Energy Agency Photovoltaic Power Systems Programme. Report IEA-PVPS T12-18:2020.
Fthenakis, V., Leccisi, E., 2021. Updated sustainability status of crystalline silicon-based photovoltaic systems: life-cycle energy and environmental impact reduction trends. Prog. Photovolt. Res. Appl. 29, 1068–1077. https://doi.org/10.1002/PIP.3441.
Fu, Y., Liu, X., Yuan, Z., 2015. Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China. J. Clean. Prod. 86, 180–190. https://doi.org/10.1016/J.JCLEPRO.2014.07.057.
GEC, 2023. EPEAT registry. https://www.epeat.net/.
Gerbinet, S., Belboom, S., L´eonard, A., 2014. Life cycle analysis (LCA) of photovoltaic panels: a review. Renew. Sustain. Energy Rev. 38, 747–753. https://doi.org/10.1016/j.rser.2014.07.043.
Gibon, T., Arvesen, A., Hertwich, E.G., 2017. Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. Renew. Sustain. Energy Rev. 76, 1283–1290. https://doi.org/10.1016/j.rser.2017.03.078.
Global Electronics Council, 2023. EPEAT for solar. https://globalelectronicscouncil.org/epeat-solar-panels-inverters/.
Groom, N., 2022. Exclusive: U.S. blocks more than 1,000 solar shipments over Chinese slave labor concerns, Reuters. https://www.reuters.com/world/china/exclusive-us-blocks-more-than-1000-solar-shipments-over-chinese-slave-labor-2022-11-11/.
Hall, M., 2022. REC silicon to restart poly production at Moses Lake in 2023, Pv magazine international. https://www.pv-magazine.com/2022/06/01/rec-silicon-to-restart-poly-production-at-moses-lake-in-2023/.
Heidari, S.M., Anctil, A., 2022. Country-specific carbon footprint and cumulative energy demand of metallurgical grade silicon production for silicon photovoltaics. Resour. Conserv. Recycl. 180, 106171 https://doi.org/10.1016/j.resconrec.2022.106171.
Hemlock, 2023. HSC Markets & Technologies - Solar, Hemlock Semiconductor. https://www.hscpoly.com/markets-technologies/solar/.
IEA, 2002. Trends in Photovoltaic Applications 2001. International Energy Agency (IEA).
IEA, 2003. Trends in Photovoltaic Applications 2002. International Energy Agency (IEA).
IEA, 2022a. Will new PV Manufacturing Policies in the United States, India and the European Union Create Global PV Supply Diversification?.
IEA, 2022b. Solar PV global supply chains, International Energy Agency (IEA). https://www.iea.org/reports/solar-pv-global-supply-chains.
IEA, 2023. Net Zero Roadmap. A Global Pathway to Keep the 1.5 °C Global in Reach. 2023 Update.

IEC, 2018. IEC 61853-3, Photovoltaic (PV) Module Performance Testing and Energy Rating – Part 3: Energy Rating of PV Modules.
IREC, 2019. Q CELLS Georgia Manufacturing, Interstate Renewable Energy Council (IREC). https://www.irecusa.org/programs/solar-jobs-census/q-cells-georgia-manufacturing-plant/.
IRS, 2023. IRS provides initial guidance for the domestic content bonus credit. https://www.irs.gov/newsroom/irs-provides-initial-guidance-for-the-domestic-content-bonus-credit.
ISO, 2006. ISO 14040:2006: environmental management – life cycle assessment – principles and framework. https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en.
ISO, 2018. ISO 14067:2018: greenhouse gases – carbon footprint of products – requirements and guidelines for quantification. https://www.iso.org/standard/71206.html.
JinkoSolar, 2019. JinkoSolar joins the RE100 and EP100 green initiatives. https://ir.jinkosolar.com/news-releases/news-release-details/jinkosolar-joins-re100-and-ep100-green-initiatives.
JinkoSolar, 2022a. JinkoSolar announces its first Overseas “RE100 Factory” completely powered by renewables. https://ir.jinkosolar.com/news-releases/news-release-details/jinkosolar-announces-its-first-overseas-re100-factory-completely.
JinkoSolar, 2022b. JinkoSolar‘s second factory in China powered by 100% renewable energy. https://www.jinkosolar.com/en/site/newsdetail/1738.
Kapur, A., Graedel, T.E., 2004. Industrial ecology. In: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Elsevier, New York, pp. 373–382. https://doi.org/10.1016/B0-12-176480-X/00533-7.
Kennedy, R., 2022. US customs clears solar panels after holding them over forced labor fears, Pv magazine international. https://www.pv-magazine.com/2022/12/02/us-customs-clears-solar-panels-after-holding-them-over-forced-labor-fears/.
Krebs-Moberg, M., Pitz, M., Dorsette, T.L., Gheewala, S.H., 2021. Third generation of photovoltaic panels: a life cycle assessment. Renew. Energy 164, 556–565. https://doi.org/10.1016/J.RENENE.2020.09.054.
Leccisi, E., Raugei, M., Fthenakis, V., 2016. The energy and environmental performance of ground-mounted photovoltaic systems—a timely update. Energies 9, 622. https://doi.org/10.3390/EN9080622, 2016, Vol. 9, Page 622.
Liang, H., You, F., 2023. Reshoring silicon photovoltaics manufacturing contributes to decarbonization and climate change mitigation. Nat. Commun. 14, 1274. https://doi.org/10.1038/s41467-023-36827-z.
Liu, F., van den Bergh, J.C.J.M., 2020. Differences in CO2 emissions of solar PV production among technologies and regions: application to China, EU and USA. Energy Policy 138. https://doi.org/10.1016/J.ENPOL.2019.111234.
Longi, 2020. RE100 - LONGi. https://www.longi.com/en/sustainable-development/promise/re100/.
LTS, 2021. DATASMART LCI Package.
Ludin, N.A., Mustafa, N.I., Hanafiah, M.M., Ibrahim, M.A., Teridi, M. Asri Mat, Sepeai, S., Zaharim, A., Sopian, K., 2018. Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: a review. Renew. Sustain. Energy Rev. 96, 11–28. https://doi.org/10.1016/j.rser.2018.07.048.
Lunardi, M.M., Alvarez-Gaitan, J.P., Chang, N.L., Corkish, R., 2018. Life cycle assessment on PERC solar modules. Solar Energy Mater. Solar Cells 187, 154–159. https://doi.org/10.1016/J.SOLMAT.2018.08.004.
Luo, W., Khoo, Y.S., Kumar, A., Low, J.S.C., Li, Y., Tan, Y.S., Wang, Y., Aberle, A.G., Ramakrishna, S., 2018. A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies. Solar Energy Mater. Solar Cells 174, 157–162. https://doi.org/10.1016/J.SOLMAT.2017.08.040.
Müller, A., Friedrich, L., Reichel, C., Herceg, S., Mittag, M., Neuhaus, D.H., 2021. A comparative life cycle assessment of silicon PV modules: impact of module design, manufacturing location and inventory. Sol. Energy Mater. Sol. Cells 230, 111277. https://doi.org/10.1016/J.SOLMAT.2021.111277.
National Bureau of Statistics, 2023. China Energy Statistical Yearbook 2022.
Pandey, D., Agrawal, M., Pandey, J.S., 2011. Carbon footprint: current methods of estimation. Environ. Monit. Assess. 178, 135–160. https://doi.org/10.1007/s10661-010-1678-y.
Polverini, D., Espinosa, N., Eynard, U., Leccisi, E., Ardente, F., Mathieux, F., 2023. Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign directive. Sol. Energy 257, 1–9. https://doi.org/10.1016/j.solener.2023.04.001.
PR´e Sustainability, 2021. SimaPro Analyst.
Rayner, T., 2022. Certify and verify for sustainability, Pv magazine International. https://www.pv-magazine.com/magazine-archive/certify-and-verify-for-sustainability/.
RE100, 2023. Climate group RE100. https://www.there100.org/.
REC, 2023. Silicon Production Facilities, REC Silicon. https://recsilicon.com/about-us/silicon-production-facilities/.
S&P Global, 2023. CHINA DATA: 2022 Power Demand Growth Eases to 3.6% in 2022 From 10.3% a Year Earlier.
Secretariat of energy (SENER), 2018. Programa de Desarrollo del Sistema Electrico Nacional. Prodesen 2018-2032. https://base.energia.gob.mx/prodesen/PRODESEN2018/PRODESEN18.pdf.
Securities Times, 2022. Photovoltaic manufacturing industry chain targets Inner Mongolia, with over 100 billion investment pouring in (in Chinese). https://baijiahao.baidu.com/s?id=1744618884443299088&wfr=spider&for=pc.
SEIA, 2023a. Texas Solar. https://www.seia.org/state-solar-policy/texas-solar.
SEIA, 2023b. Georgia Solar. https://www.seia.org/state-solar-policy/georgia-solar.
SEIA, 2023c. Arizona Solar. https://www.seia.org/state-solar-policy/arizona-solar.
SEIA, 2023d. Ohio Solar. https://www.seia.org/state-solar-policy/ohio-solar.
SEIA, 2023e. New York Solar. https://www.seia.org/state-solar-policy/new-york-solar.
Skujins, A., 2023. EU solar lobby urges ban on forced labor in solar products, Pv magazine international. https://www.pv-magazine.com/2023/10/26/eu-solar-lobby-urges-ban-on-forced-labor-in-solar-products/.
Speaks, S., 2023. Petition from fort mill neighbors shows growing opposition to solar panel plant, Queen City News. https://www.qcnews.com/news/u-s/york-county/petition-from-fort-mill-neighbors-show-growing-opposition-to-solar-panel-plant/.
Sud, R., Patnaik, S., 2022. How does permitting for clean energy infrastructure work?, Brookings. https://www.brookings.edu/articles/how-does-permitting-for-clean-energy-infrastructure-work/.
Sungrow, 2020. Sungrow joins RE100 affirming its commitment to source 100% renewable electricity by 2028. https://en.sungrowpower.com/newsDetail/1802/sungrow-joins-re100-affirming-its-commitment-to-source-100-renewable-electricity-by-2028.
Susskind, L., Chun, J., Gant, A., Hodgkins, C., Cohen, J., Lohmar, S., 2022. Sources of opposition to renewable energy projects in the United States. Energy Policy 165, 112922. https://doi.org/10.1016/j.enpol.2022.112922.
The State Council, 2023. PRC, China’s Inner Mongolia to double installed new energy capacity by 2025. https://english.www.gov.cn/news/202311/20/content_WS655b45cac6d0868f4e8e16b5.html.
Ultra Low-Carbon Solar Alliance, 2021a. Reducing the Carbon Footprint of Solar: The French Model. https://ultralowcarbonsolar.org/blog/reducing-carbon-footprint-of-solar/.
Ultra Low-Carbon Solar Alliance, 2021b. South Korea Is Implementing Carbon Footprint Assessment Regulations for the PV Market. https://ultralowcarbonsolar.org/blog/south-korea-implementing-carbon-footprint-assessment-regulations/.
Ultra Low-Carbon Solar Alliance, 2023a. The Ultra Low-carbon Solar Era is Here. https://ultralowcarbonsolar.org/ultra-low-carbon-solar/.
Ultra Low-Carbon Solar Alliance, 2023b. How Much Solar Manufacturing Exists Globally Ex- China? It’’s More Than You Think. https://ultralowcarbonsolar.org/global-solar-manufacturing/.
United States Executive Office of the President, 2021. The Long-term Strategy of the United States: Pathways to Net-zero Greenhouse Gas Emissions by 2050.
US CBP, 2021. Uyghur Forced Labor Prevention Act. https://www.cbp.gov/trade/forced-labor/UFLPA.
USDOE, 2022. Federal Tax Credits for Solar Manufacturers. https://www.energy.gov/eere/solar/federal-tax-credits-solar-manufacturers.
USDOE, 2023a. On the Path to 100% Clean Electricity.
USDOE, 2023b. Supply Chains Progress Report.
USDOE, 2024. LPO announces conditional commitment to holtec palisades to finance the restoration and resumption of service of 800-MW nuclear generating station, Energy. Gov. https://www.energy.gov/lpo/articles/lpo-announces-conditional-commitment-holtec-palisades-finance-restoration-and.
VDMA, 2022. International Technology Roadmap for Photovoltaic (ITRPV) 2021 Results. International Technology Roadmap for Photovoltaic.
VDMA, 2023. International Technology Roadmap for Photovoltaic (ITRPV) 14th Edition, Key Findings & Report Presentation. International Technology Roadmap for Photovoltaic.
Wacker, 2023. WACKER at a Glance - Production Sites, Wacker Polysilicon North America, LLC. https://www.wacker.com/cms/en-us/about-wacker/wacker-at-a-glance/production-sites/charleston.html.
World Bank, 2024. Global Solar Atlas. https://globalsolaratlas.info/map.
Xia, Z., Li, Y., Chen, R., Sengupta, D., Guo, X., Xiong, B., Niu, Y., 2022. Mapping the rapid development of photovoltaic power stations in northwestern China using remote sensing. Energy Rep. 8, 4117–4127. https://doi.org/10.1016/j.egyr.2022.03.039.
Yang, D., Liu, J., Yang, J., Ding, N., 2015. Life-cycle assessment of China’s multi-crystalline silicon photovoltaic modules considering international trade. J. Clean. Prod. 94, 35–45. https://doi.org/10.1016/J.JCLEPRO.2015.02.003.
Yue, D., You, F., Darling, S.B., 2014. Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: life cycle energy and environmental comparative analysis. Solar Energy 105, 669–678. https://doi.org/10.1016/J.SOLENER.2014.04.008.