IRENA
International Renewable Energy Agency

Solar PV supply chains

Technical and ESG standards for market integration

A contribution to:

TRANSFORMING SOLAR Supply Chains
AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

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ISBN: 978-92-9260-629-9

Citation: IRENA (2024), *Solar PV supply chains: Technical and ESG standards for market integration*, International Renewable Energy Agency, Abu Dhabi.

About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation; a centre of excellence; a repository of policy, technology, resource, and financial knowledge; and a driver of action on the ground to advance the transformation of the global energy system. A global intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy and geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security, and low-carbon economic growth and prosperity. www.irena.org

Acknowledgements

This report was authored by Jaidev Dhavle (IRENA) and George Kelly (American Renewable Energy Standards and Certification Association) under the guidance of Roland Roesch (Director, IRENA Innovation and Technology Centre) and Francisco Boshell.

It also benefited from contributions and inputs from IRENA colleagues Adrian Gonzalez, Deborah Ayres, Bohan Liu, Abdullah Fahad and Paul Komor.

Valuable external review, inputs and comments were provided by Cora Dickson (US Department of Commerce), Anna Mazzoleni (Australia DCCEEW), Markus Beck (US Department of Energy), Tamiksha Singh (International Solar Alliance), Michael Parr (Ultra Low Carbon Solar Alliance), Abeer Ali Khan (First Solar), Kelly Weger (Qcells), Alexia Ruvetto (Solar Stewardship Initiative), Daniela Blazejova (Solar Power Europe), Raffaele Rossi (Solar Power Europe), Jan Clyncke (PV Cycle), John Heckman (JR Heckman LLC), Mehmet Ender (RCT Solutions), Shubhang Parekh (National Solar Energy Federation of India), Muskaan Sethi (National Solar Energy Federation of India), Vanshika Gazmer (National Solar Energy Federation of India), Huiming Zhang (China Electric Power Research Institute), Bin Zheng (China Electric Power Research Institute), Hongtao Li (China Electric Power Research Institute), Xiaodi Qin (China Electric Power Research Institute), Chao Zhao (China Electric Power Research Institute).

Publications support was provided by Francis Field and Stephanie Clarke. The report was edited by Stefanie Durbin, with design provided by Strategic Agenda.

IRENA is grateful for the generous support provided by Germany's Federal Ministry for Economic Affairs and Climate Action to prepare this publication. This report is a contribution to the Clean Energy Ministerial Transforming Solar Supply Chain Initiative.

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Table of contents

Figures

Tables

Boxes

Abbreviations

AS/NZS	Australia/New Zealand standards
BIPM	International Bureau of Weights and Measures
BIPV	building-integrated photovoltaics
BoS	balance of system
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
COP28	The 28th United Nations Climate Change Conference
CPIA	China Photovoltaic Industry Association
CSR	corporate social responsibility
CSRD	Corporate Sustainability Reporting Directive (EU)
DC	direct current
DIN	Deutsche Industrie Norm
DOE	Department of Energy (US)
EL	electroluminescence imaging
EN	European Norm
EPD	Environmental Product Declaration
EPEAT	Electronic Product Environmental Assessment Tool
ESG	environmental, social and governance
EU	European Union
EUR	euro
G20	Group of 20
GB	Chinese Guobiao
GSC	Global Solar Council
GW	gigawatt
GWO	Global Wind Organisation
IE	independent engineer
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IECEE	IEC System for Conformity Assessment Schemes for Electrotechnical Equipment and Components
IIJA	Infrastructure Investment and Jobs Act (US)
ILO	International Labour Organization
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act (US)
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
JIS	Japanese Industrial Standards
kW	kilowatt

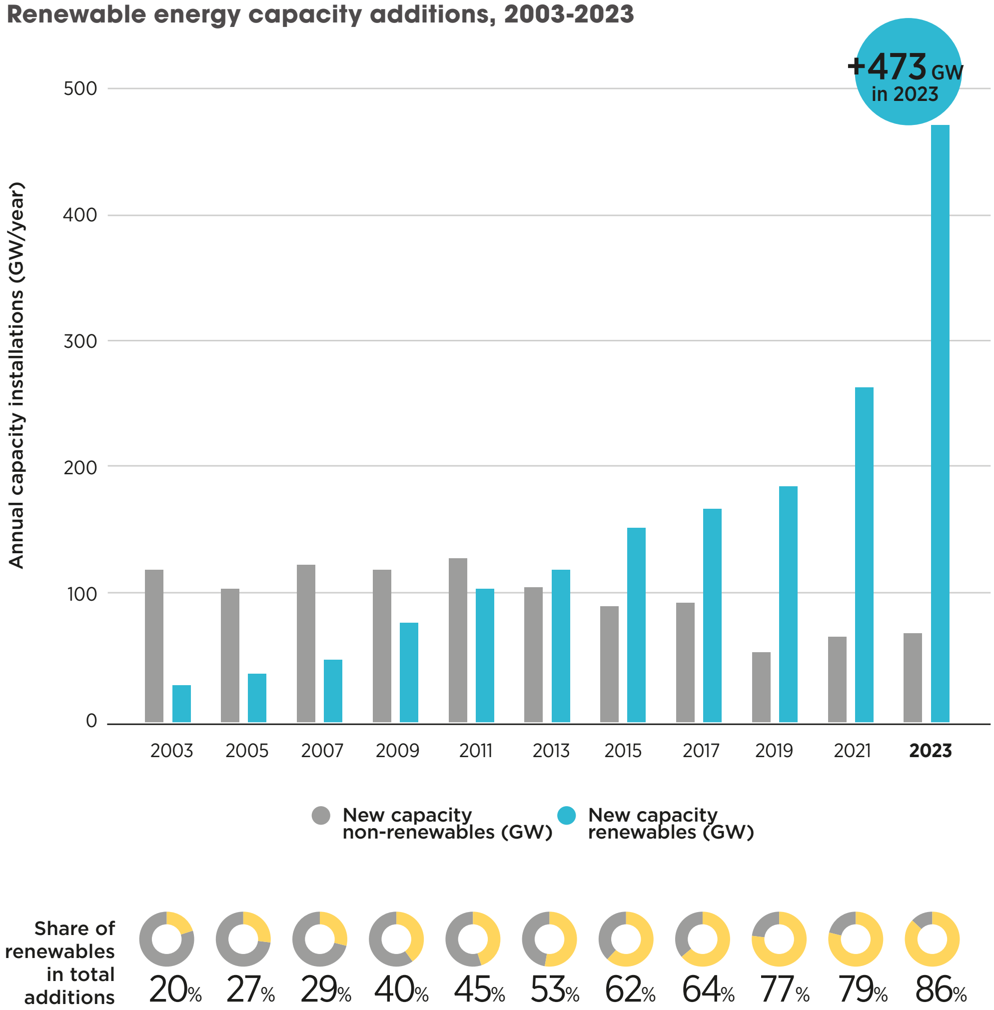
kWh	kilowatt hour
kWp	kilowatt peak
LCA	life cycle assessment
LCOE	levelised cost of electricity
M-SIPS	Modified Special Incentive Package Scheme (India)
MGS	metallurgical grade silicon
MW	megawatt
NC	national committee
NDC	Nationally Determined Contribution
NGO	non-governmental organisation
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
NZIA	Net Zero Industry Act (EU)
OPEX	operational expenditure
PCR	product category rule
PLI	Production Linked Incentive (India)
PPA	power purchase agreement
PRI	UN Principles for Responsible Investment
PSR	product-specific rule
PTB	German Metrology Institute
PV	photovoltaic
PVPS	IEA Photovoltaic Power Systems Programme
PVQAT	International PV Quality Assurance Task Force
QI	quality infrastructure
REA	renewable attribute
SC	subcommittee
SDO	standards development organisation
SEC	Securities and Exchange Commission (US)
SEMI	Semiconductor Equipment Manufacturers' Institute
SPIC	State Power Investment Corporation
SSI	Solar Stewardship Initiative
TC	technical committee
TW	terawatt
TWh	terawatt hour
UFLPA	Uyghur Forced Labor Prevention Act (US)
UL	Underwriters' Laboratories
UN	United Nations
US	United States
USD	US dollar
VCF	verified carbon footprint
WEEE	Waste from Electrical and Electronic Equipment
WG	working group
WTO	World Trade Organization

OVERVIEW: Global solar PV developments

This report is a contribution towards the Clean Energy Ministerial Transforming Solar Supply Chains (TSSC) workstream. The TSSC was launched in September 2022 at the Clean Energy Ministerial in Pittsburgh, to foster the adoption of policies that transform the global solar supply chain to be more diverse, transparent, and environmentally and socially responsible. The workstream is led by the governments of the United States and Australia and coordinated by the International Solar Alliance. Other members of the Transforming Solar Supply Chains initiative include Germany, India, UAE, and Brazil.

At the 28th United Nations (UN) Climate Change Conference (COP28) held in the United Arab Emirates, the global energy community formally declared its intent to triple renewable energy capacity and double the energy efficiency improvement rate by 2030 in recognition of the fact that the energy transition remains off track (IRENA, 2023a, 2024a). The International Renewable Energy Agency's (IRENA's) latest analysis found that the acceleration of renewable technology and adoption of energy efficiency measures can lead to a 43% reduction in global greenhouse gas emission by 2030. This finding conforms with the analysis of the Intergovernmental Panel on Climate Change (IPCC) (IRENA, 2024a). To ensure sustained success, it is crucial that new renewable energy deployment is coupled with systematic innovation that goes beyond the technological dimension alone.

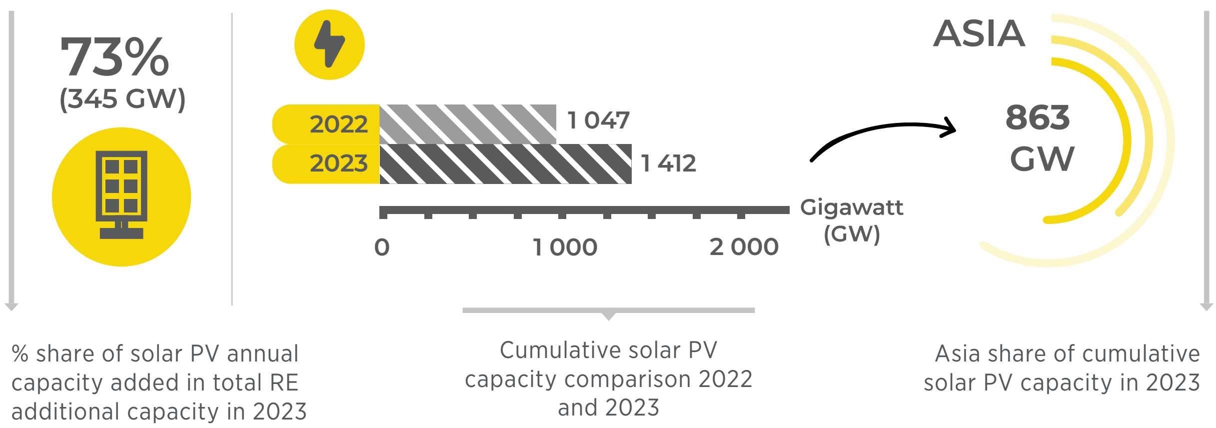
Figure 1 **Renewable energy capacity additions, 2003-2023**



Source: (IRENA, 2024a).

IRENA's latest statistics show that 2023 was a record year for renewable energy capacity installation, with 473 gigawatts (GW) added (growing from 295 GW added in 2022; see Figure 1) (IRENA, 2023a, 2024a). A significant percentage of this new capacity is concentrated in China, the European Union (EU) and the United States (US), accounting for 83% of the new capacity installed.

Within this new additional capacity, solar energy by far is the greatest contributor, accounting for 73% (345 GW), demonstrating the maturity of this technology. As of 2023, the global cumulative capacity for solar PV reached 1 412 GW (an increase from 1 047 GW in 2022) with Asia accounting for 863 GW (IRENA, 2024a, 2024b). Despite recent geopolitical and supply chain challenges to the energy transition, there has been an increased uptake of distributed solar PV residential and commercial systems in countries such as Australia, France, Germany, India, the United States and the United Kingdom (IRENA, 2024a).



CAPACITY FACTORS

IRENA has found that capacity factors for new utility-scale solar PV reached 16.2% in 2023 (an increase from 13.8% in 2010). This has been ascribed to a combination of developments including better inverter load ratios, higher average market irradiance and increased utilisation of bifacial technologies that improve the latitude profile for solar PV modules (IRENA, 2024c).

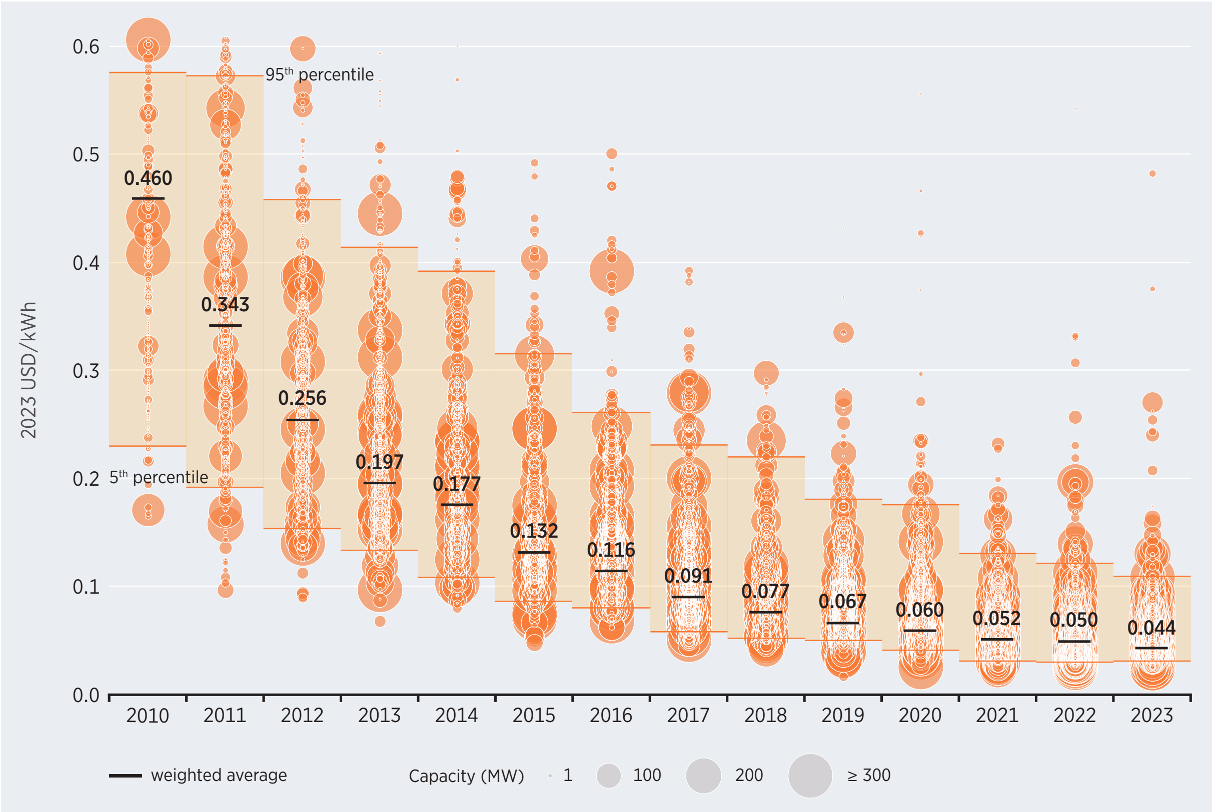
COMPETITIVENESS

IRENA's latest competitiveness analysis continues to confirm that solar PV remains the most accessible technology for countries to accelerate their energy transition efforts. With regard to the global levelised cost of electricity (LCOE) (weighted average) for utility-scale PV plants, there was an 89% decline between 2010 and 2023, from USD 0.460 (US dollar)/kWh (kilowatt hour) to USD 0.044/kWh (IRENA, 2024c). This represents a 12% year-on-year decline from 2022 (for reference, the annual decline between 2021 and 2022 was 3%) (IRENA, 2024c). See Figure 2.

THE RANGE OF LCOE COSTS

In 2023, the LCOE range also declined. For the 5th and 95th percentile of projects, the costs ranged between USD 0.031/kWh to USD 0.110/kWh. This represented 87% and 81% declines on the 5th and 95th percentile values, respectively, since 2010 (IRENA, 2024c). The LCOE range in 2023 (the gap between the 5th and the 95th percentile values) reached its lowest value since 2010 (a decline of 77%) (IRENA, 2024c).

Figure 2 **Utility-scale solar PV LCOE between 2010 and 2023**



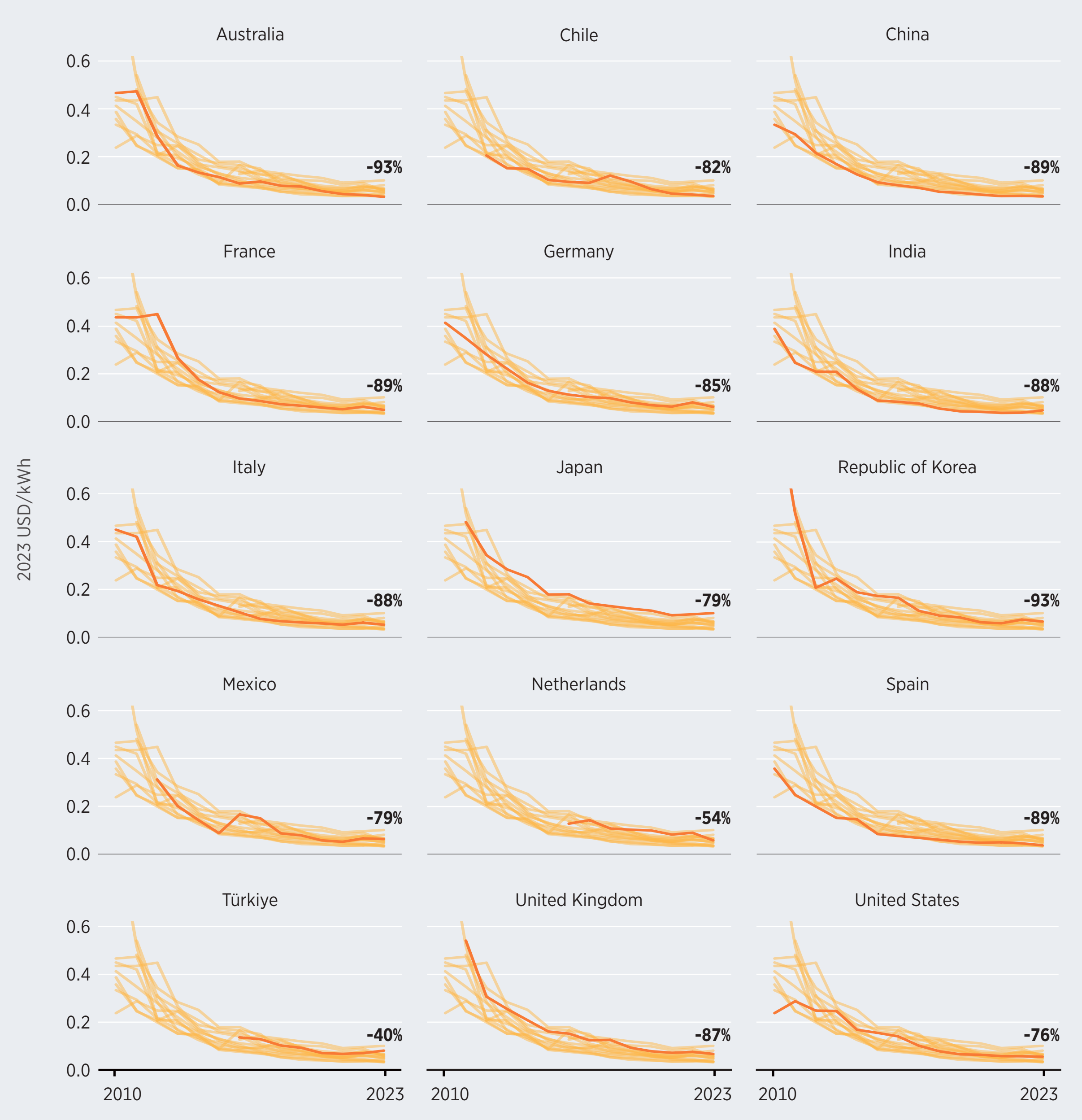
Note: MW = megawatt.
Source: (IRENA, 2024c).

The increasing competitiveness of utility-scale solar PV in select markets (where historical data are available since 2010) is shown in Figure 3. The data show that the markets where this trend is particularly strong are in Australia and the Republic of Korea (where the LCOE for both decreased by 93%) as well as in the United States (where the LCOE decreased by 76%). The decrease in the LCOE can be attributed to technological developments across the whole solar PV value chain: the availability of large polysilicon factories, improved ingot growth methods and the emergence of newer cell architectures, among other factors (IRENA, 2024c).

As shown in Figure 3, the lowest weighted-average LCOEs for the utility-scale sector in 2023 were observed in Australia and China, where LCOEs reached USD 0.034/kWh and USD 0.036/kWh, respectively. Australia's weighted-average LCOE for 2023 was 22% lower than the global weighted average for that year, highlighting improved competitiveness (IRENA, 2024c).

From an installation cost perspective, the global capacity weighted average of projects commissioned in 2023 was USD 758/kilowatt (kW), which is 86% lower than in 2010. A large proportion of the installed costs in today's solar PV market can be ascribed to balance of system (BoS) (excluding inverters), which accounts for 62% of total installed costs (IRENA, 2024c).

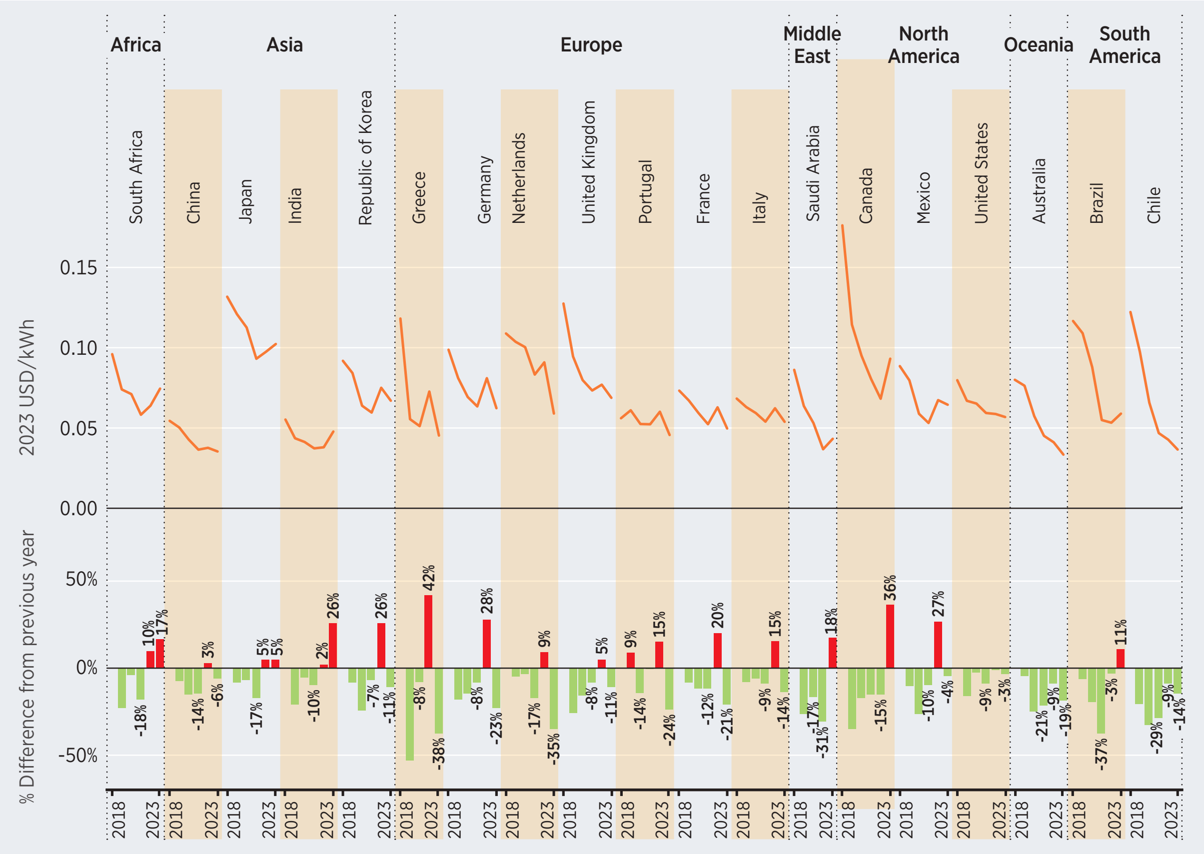
Figure 3 **Utility-scale solar PV weighted-average LCOE in selected countries (2010-2023)**



Source: (IRENA, 2024c).

Figure 4 provides the weighted-average LCOE trend for the top utility-scale markets between 2018 and 2023. Costs declined in 14 markets.

Figure 4 **Installed costs comparison in 19 solar PV markets between 2018 and 2023**



Source: (IRENA, 2024c).

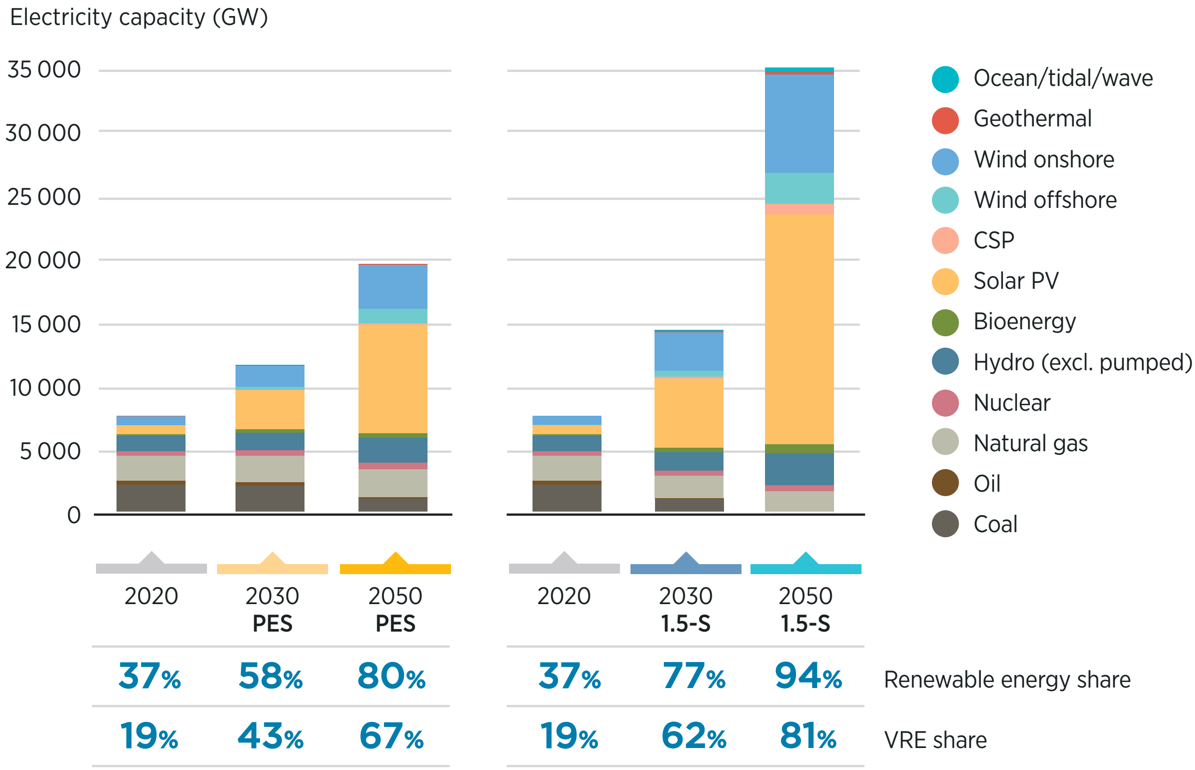
Figure 4 shows that major LCOE reductions occurred in the top markets in Europe and Oceania. All seven European markets saw utility-scale solar PV electricality costs decrease between 11% (United Kingdom) and 38% (Greece) in 2023. Australia had the most competitive LCOE, and costs declined 19% (IRENA, 2024c).

While there are positive trends in renewable technology deployment as well as the solar PV industry, within IRENA's 1.5°C Scenario it is envisioned that electricity consumption in a variety of end-use sectors will reach 87 000 terawatt hours (TWh) in 2050 – with a 2020 baseline of approximately 26 000 TWh (IRENA, 2023a). To be compliant with IRENA's 1.5°C Scenario, the Group of 20 (G20) will need to expand its renewable power generation capacity to 9.4 terawatts (TW) by 2030 (it was less than 3 TW in 2022). Furthermore, their Nationally Determined Contribution (NDC) commitments are less than half of what is required to fulfil the COP28 pledge (IRENA, 2024a).

Looking to the future, to be compliant with a 1.5°C Scenario, IRENA projects that renewable capacity additions will need to reach approximately 1 044 GW/year between 2024 and 2030. Solar PV additions will need to account for 578 GW/year of these additions, a metric that is on track, according to IRENA (IRENA, 2024a).

Variable renewables, *i.e.* energy sources that have an intermittent profile, are expected to play a significant role in shaping electricity systems and markets. Solar PV will continue to be a major contributor to renewable technology deployment. This growth is envisioned due to factors such as technology cost reductions, advancements in energy storage and continued efforts towards implementing cohesive policy frameworks for renewable development. In the 1.5°C Scenario, installed solar PV capacity would exceed 5 400 GW by 2030 and 18 200 GW by 2050 (see Figure 5).

Figure 5 **Global installed capacity by energy source: 1.5°C Scenario in 2020, 2030 and 2050**



Source: (IRENA, 2023a).

According to Wood Mackenzie's Global solar module manufacturer ranking 2024, eight of the top ten manufacturing firms are in China, and they have over ten years of proven track record in this space. Wood Mackenzie also notes that these companies have strong vertical integration and significant cell capacity to support over 50% of their module production. Some of these manufacturers can also produce wafer or even cater to complete supply chain development, from polysilicon to module.

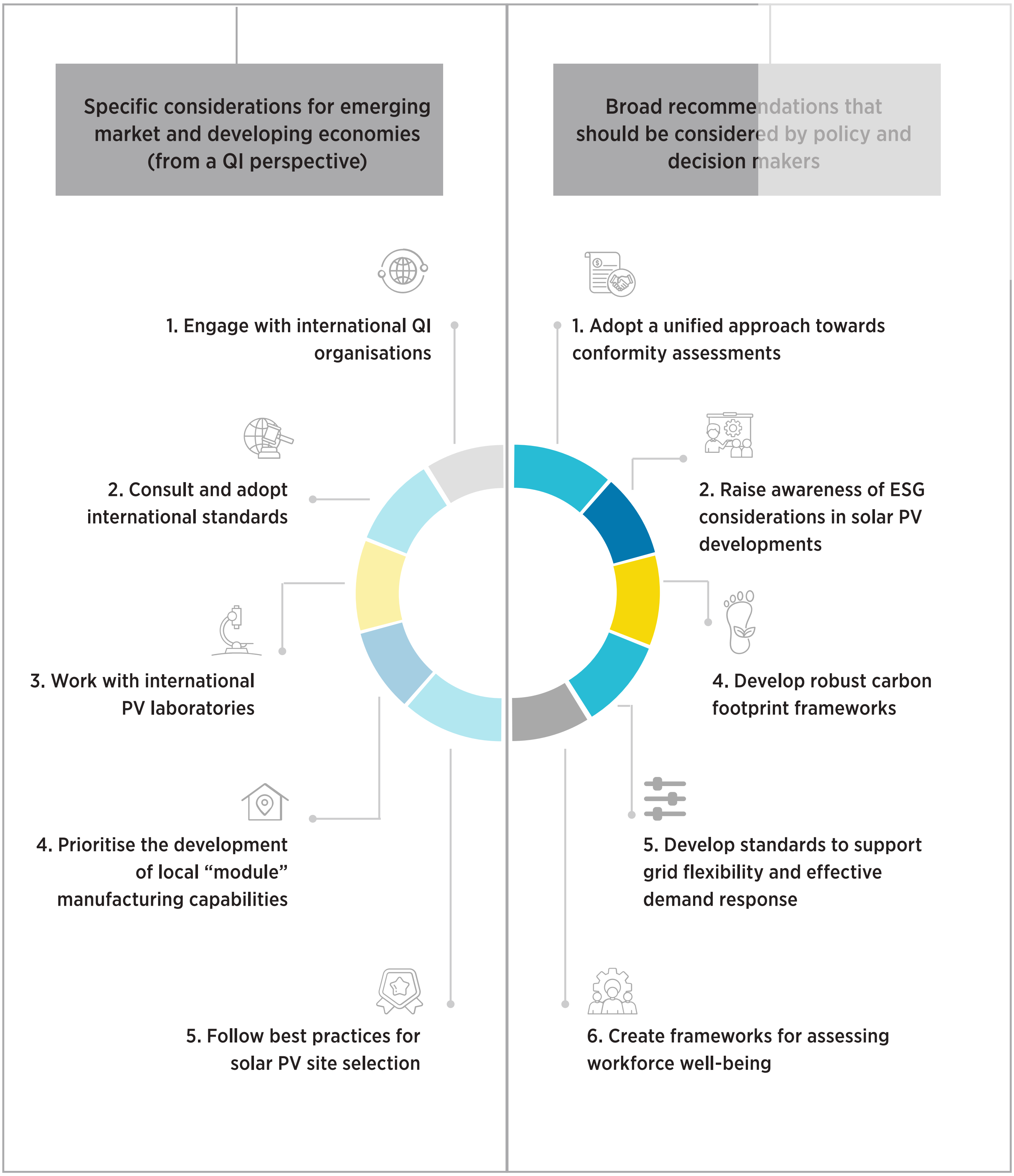
TOPCon is the primary technology and is used by all the top ten manufacturers (with highest efficiency of 23%). The largest manufacturing shipments came from the following firms: Jinko (78.5 GW), LONGi (66.4 GW), Trina (65.2 GW) and JA (53.1 GW), followed by Tongwei (31.7 GW), Canadian Solar (30.7 GW) and Astronergy (28 GW) (Wood Mackenzie, 2024a).

Given the increased and prominent role solar PV will play in achieving the energy transition, it is imperative that solar supply chains are transformed to ensure they are sustainable – by ensuring compliance with relevant international standards & certification schemes; resilient – to have strong buffers against potential external shocks as well as flexibility; and broadly distributed – to ensure greater participation of economies in different segments of the solar PV value chain. A key avenue to achieve this goal is to improve the availability of quality infrastructure[1] (QI) services for this industry, specifically environmental, social and governance (ESG) principles and standards.

The purpose of this report is therefore to identify any gaps in the existing QI provisions and make recommendations for how these can be overcome. In particular, the focus is on the **necessity of complementary ESG standards in addition to the existing QI** to make solar PV supply chains sustainable as demand for this technology grows.

[1] Quality infrastructure (QI) can be defined as the total institutional network (public and private) and the legal framework that regulates, formulates, edits and implements standards and provides evidence of its fulfilment (*i.e.* a relevant mixture of measurements, accreditation, tests, certification and inspections) (IRENA, 2015).

Figure 6 **Key recommended actions to promote ESG development in the solar PV supply chain**



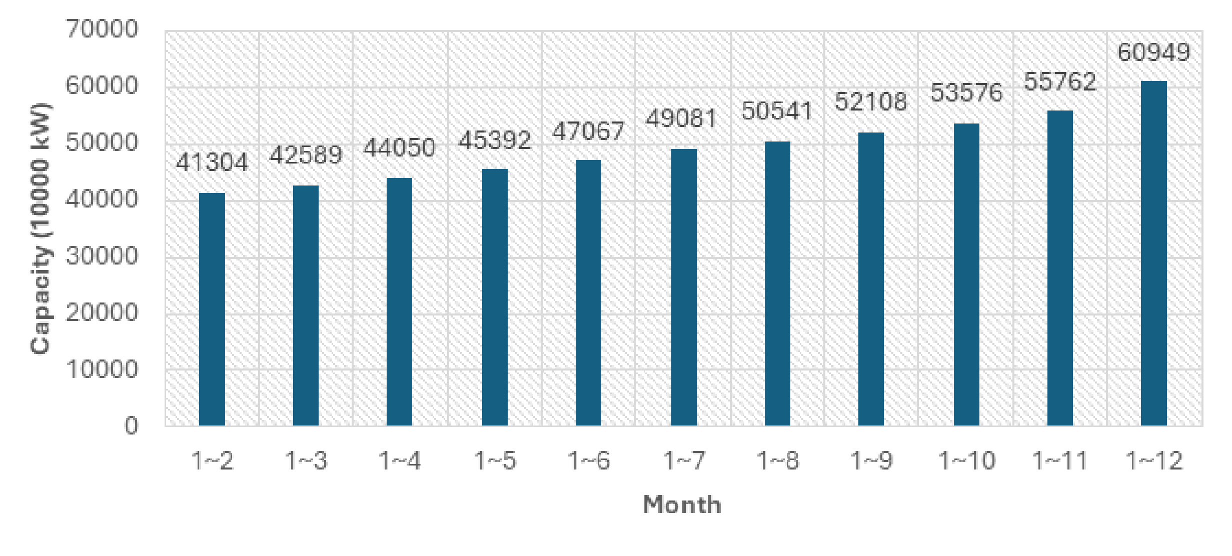
SOLAR PV DEVELOPMENTS IN KEY MARKETS

China, Europe, India and the United States are some of the key players driving the development of global solar PV. This chapter presents key data and facts about the solar PV market and manufacturing trends within these economies. There are other economies (Cambodia, Vietnam, Thailand, Philippines and Saudi Arabia among others) which are also increasing their engagement in the global solar PV development. However, these four markets have a major influence on future trends, hence a focus has been placed on them.

CHINA

China drives the global solar PV industry and is the world's largest PV market. According to the National Energy Administration, at the end of December 2023, China's cumulative installed solar power capacity reached 610 GW_{AC} (GW-alternating current). Newly installed capacity in 2023 reached 217 GW_{AC} (a 148% year-on-year increase; see figures 7 and 8) (National Energy Administration, 2024; Solar Power Europe, 2024). In December 2023 alone, 53 GW_{AC} was added, which exceeded the total new capacity added in the previous three months (National Energy Administration, 2024). Solar Power Europe estimates that the GW-direct current (DC) annual installation for solar PV reached 253.1 GW_{DC} in 2023.

Figure 7 **China's solar PV cumulative installations in 2023**

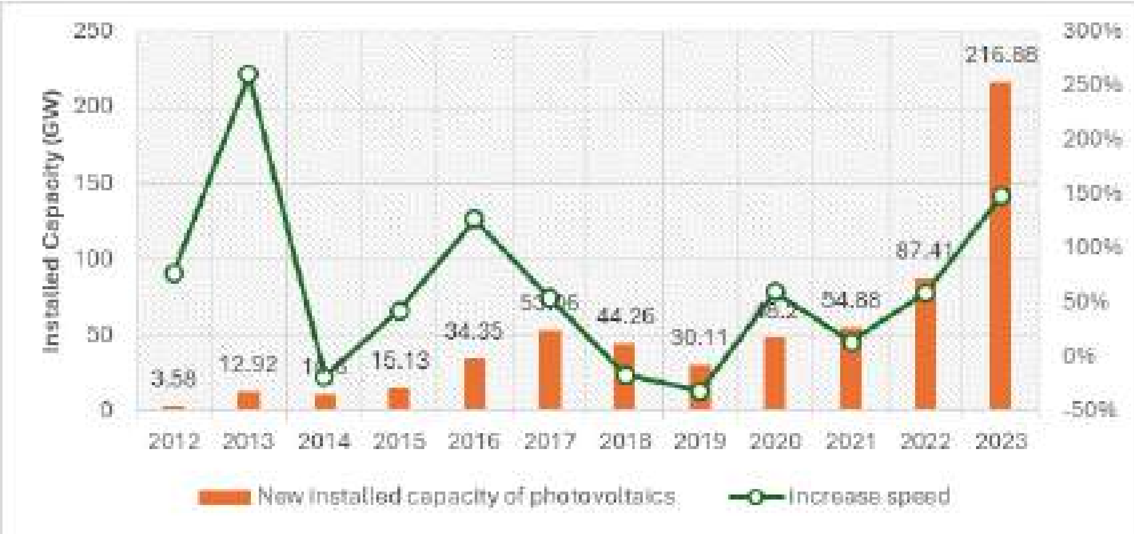


Source: (National Energy Administration, 2024).

China's PV industry has made remarkable progress in technological innovation, scale expansion and cost reduction. Not only is solar PV widely used in large-scale, centralised power stations, but the development of distributed PV in the fields of households, industry and commerce has become increasingly active.

In 2023, new installations of centralised solar PV projects exceeded 120 GW (accounting for over 55% of total installations), and distributed solar PV accounted for approximately 100 GW (representing around 45% of annual deployed capacity) (Solar Power Europe, 2024). Figure 8 shows the mix of centralised and distributed systems with each Chinese province, with Hebei, Shandong, Jiangsu, Zhejiang and Henan being leaders.

Figure 8 **China's annual newly installed capacity**



Source: (National Energy Administration, 2024).

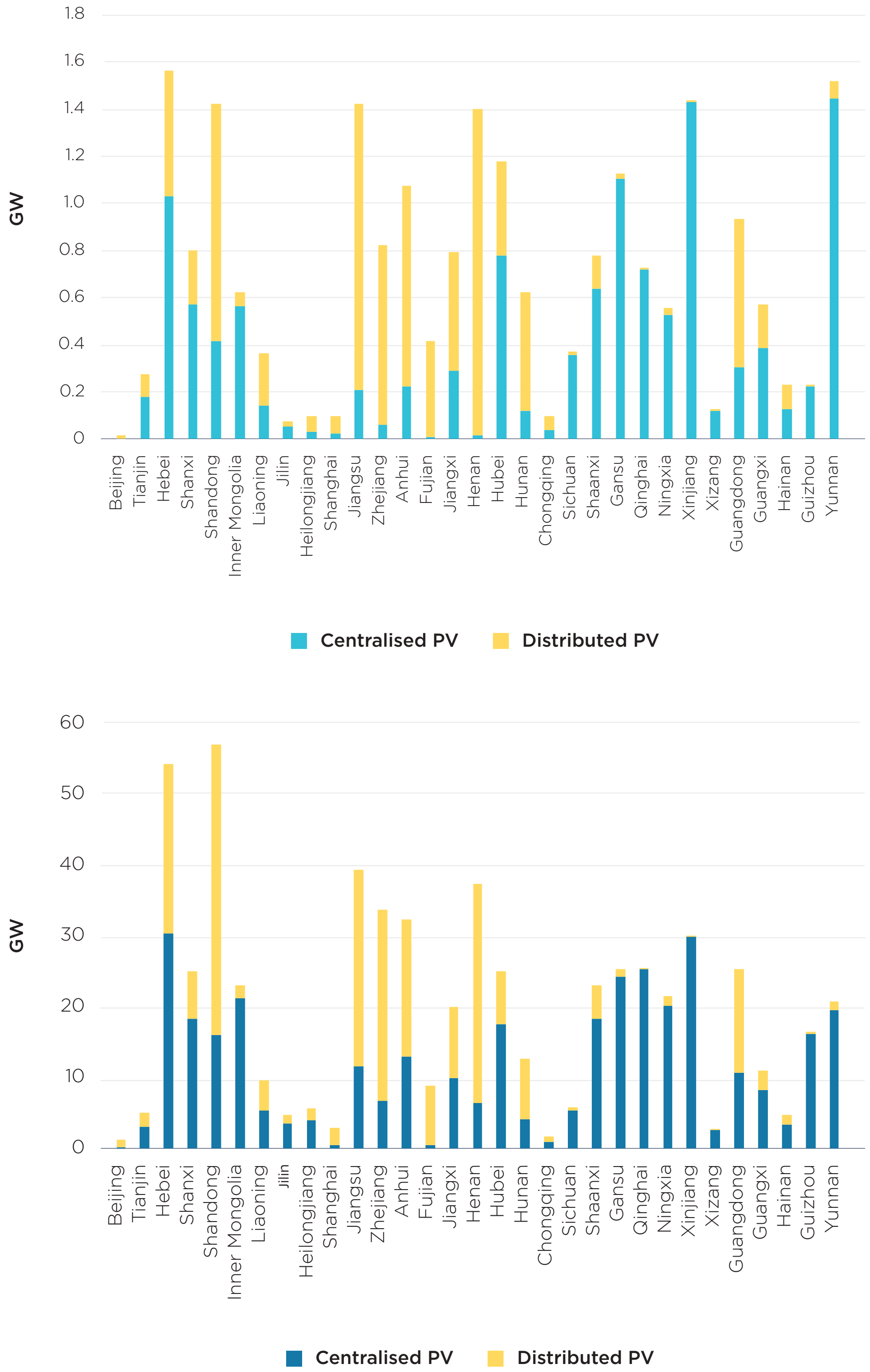
Simultaneously, the Chinese government continues to actively promote renewable energy, which provides solid policy support for the development of its national PV industry. The main market mechanisms China uses to boost solar PV uptake in the country are green electricity trading and green electricity certificates[2] (Solar Power Europe, 2024). Another important policy tool leveraged by the government is legislation regarding a guaranteed purchase mechanism of renewable electricity, which mandates grid operators to purchase electricity from renewable energy projects within their electricity grid network (Solar Power Europe, 2024).

Looking at the sector from a manufacturing perspective, in 2023 USD 80 billion was invested globally in solar PV manufacturing. Of this, 90% was invested in China (Solar Power Europe, 2024). China invested USD 77 billion in solar PV manufacturing in 2023, representing a twofold increase compared to 2022, and manufacturing costs were 30-65% cheaper compared to the United States and Europe (IEA, 2024). According to Wood Mackenzie, China's module capacity reached 1 TW/year in 2023, accounting for 80% of total global module manufacturing capacity (Crooks, 2024). To further illustrate this advantage, according to the China Silicon Industry Association, the country had a surplus of polysilicon production sufficient to produce 85 GW_{DC} of modules in March 2024 and contributing to an annual capacity exceeding 1 TW_{DC}/year (NREL, 2024). China also accounts for 95% of global wafer manufacturing capacity investments and 96% of global polysilicon manufacturing capacity investments (IEA, 2024).

In the future, with the further improvement of technology and the continuous expansion of the market, positive manufacturing trends will be seen in the United States and India. China's PV market is also expected to maintain a continuous growth trend and will sustain a 80% global market share (IEA, 2024).

[2] Key legislation examples include "Notice on Matters Relating to the Participation in Green Electricity Trading of Green Electricity Projects Enjoying Subsidies from the Central Government" and "Full Coverage of Renewable Energy Green Electricity Certificates".
[3] Key examples include "Measures for the Administration of the Full-Amount Guaranteed Purchase of Renewable Energy Electricity Generation"; "the Action Plan for Clean Energy Consumption"; and "the Notice on the Establishment of a Sound Guarantee Mechanism for the Consumption of Renewable Energy Electricity".

Figure 9 **Annual and cumulative installations by Chinese province in 2023**

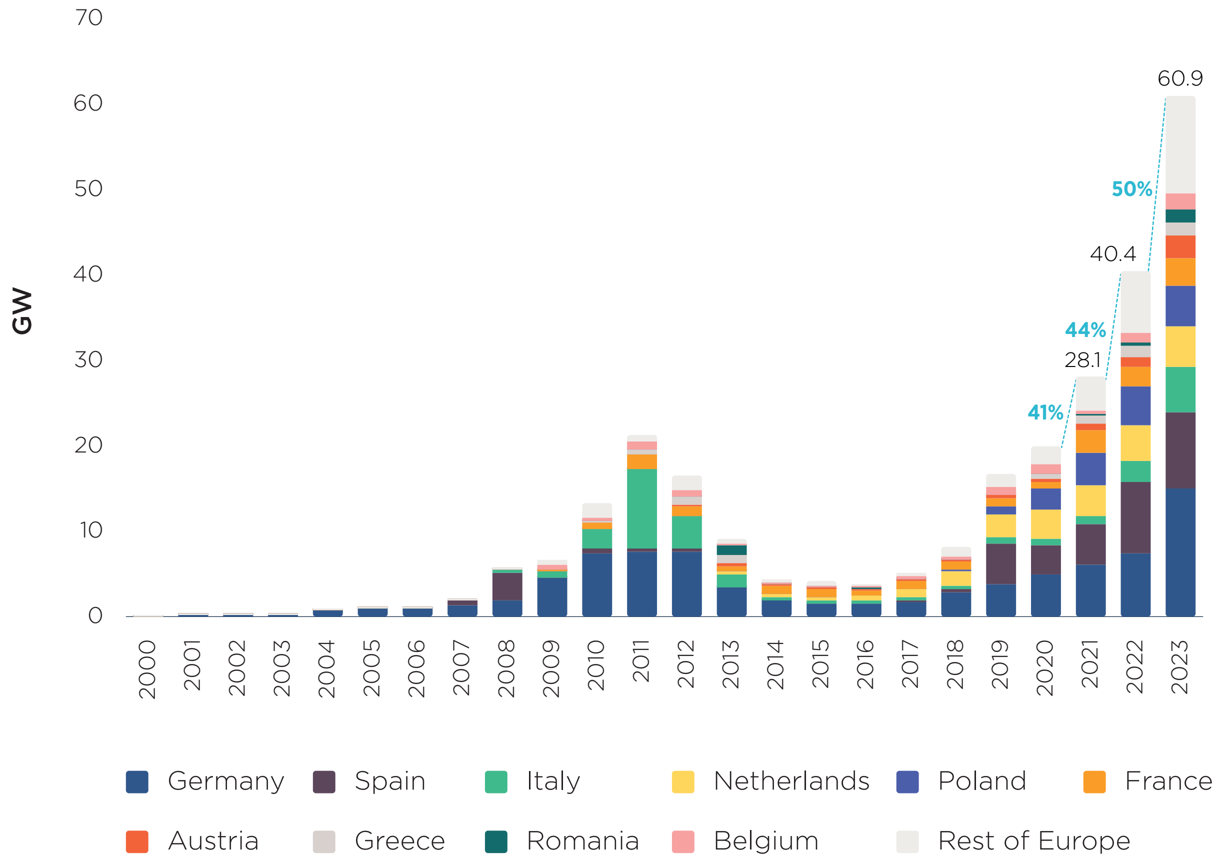


Source: (Solar Power Europe, 2024).

EUROPE

According to Solar Power Europe's recent *Global market outlook*, in 2023 approximately 61 GW of new capacity was added (an increase from 40.4 GW in 2022), thereby bringing the cumulative installed capacity to 264 GW. An annual growth projection of 40 GW^{DC} for the next five years is expected (Solar Power Europe, 2024). This positive development can be ascribed to increased political support for accelerating the deployment of clean energy technologies, innovations in permitting and administrative protocols, and the continuation of high energy prices in the region due to ongoing geopolitical situations. Germany (15 GW of installed capacity in 2023), Spain (8.9 GW in 2023) and Italy (5.2 GW in 2023) are leading market development in the region (EC JRC, 2023; Solar Power Europe, 2024) (see Figure 10 for breakdown).

Figure 10 **EU 27 annual solar capacity installations 2000-2023**



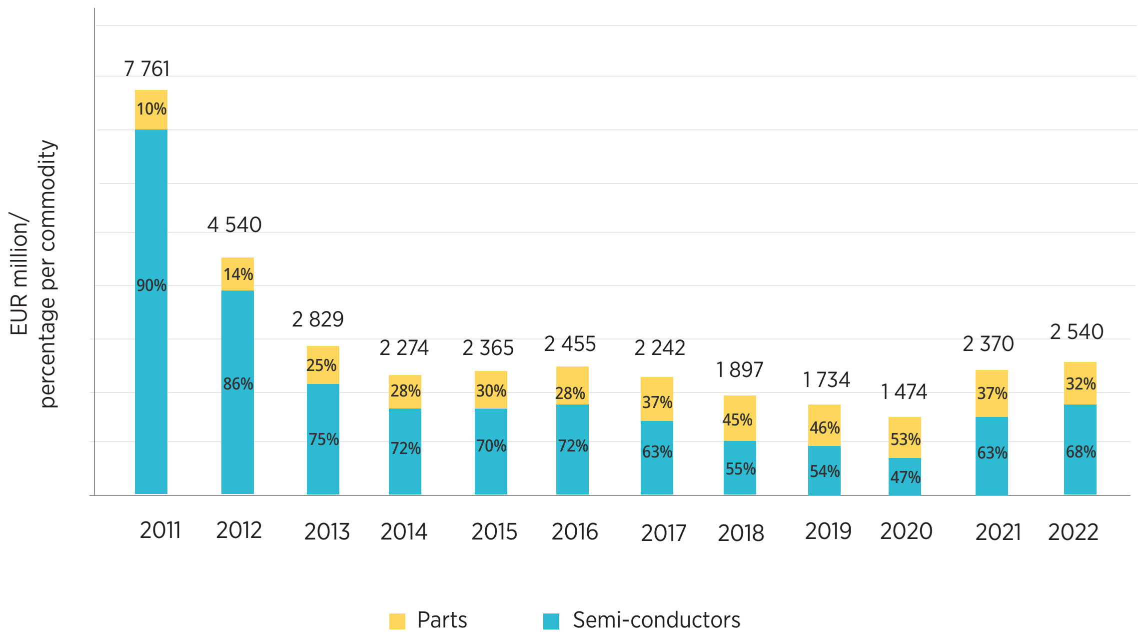
Source: (Solar Power Europe, 2024).

From a manufacturing perspective, recent research by the European Commission's Joint Research Centre notes that its position in the upstream and downstream value chains are different. With regard to equipment and inverter manufacturing, the European Union makes a significant contribution to this value chain segment, accounting for 28% of the global shipments with an export growth of 82% in 2022 (EC JRC, 2023).

The European Union cannot compete with China in terms of manufacturing capacity of crucial components such as polysilicon, wafers, cells and modules due to China's cost-effectiveness in large-scale equipment manufacturing and labour vectors (EC JRC, 2023).

Over the last ten years, the European Union's product value for the solar PV industry has shrunk by 10%, with an average value of EUR 2.2 (euro) billion (in 2022 the valuation was EUR 2.5 billion). Semiconductors were its largest share (EC JRC, 2023) (see Figure 10).

Figure 11 **EU production value per commodity for the period 2011-2022**



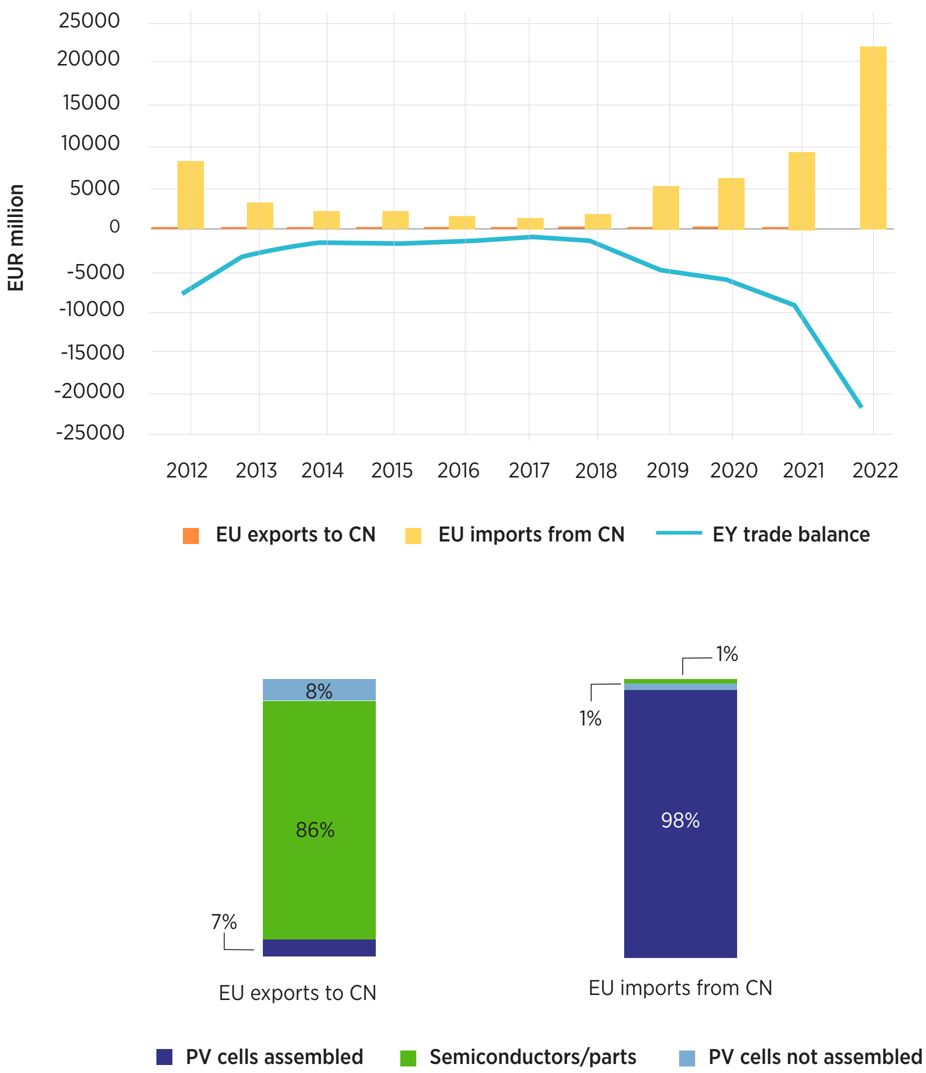
Source: (EC JRC, 2023).

Companies such as Wacker Chemie, MEMC Merano SMA and Power Electronics were leaders in manufacturing until the mid-2010s. However, since then entities in China (for example, Huawei, Tongwei Solar, Jinko Solar, Trina Solar, LONGI Green Energy Technology, etc.) and the United States (for example, First Solar, SunPower Corporation and eSolar Inc.) have become the largest contributors towards PV component manufacturing (EC JRC, 2023).

From a trade position, the JRC has found that the European Union (especially Germany, the Netherlands and Spain) still relies heavily on China to meet its solar PV supply and demand requirements. Imports reached EUR 22 billion in 2022, and the main imported products were assembled PV cells (EC JRC, 2023) (see Figure 11). EU PV exports (primarily assembled PV modules) had a valuation of EUR 0.8 billion in 2022 and mainly targeted the United Kingdom and Switzerland.

In June 2024, the European Union adopted the Net Zero Industry Act (NZIA), which mandates that clean energy manufacturing capabilities should cover 40% of the region's annual deployment by 2030. With regard to solar PV, the NZIA has set a goal of achieving 30 GW of operational manufacturing capacity throughout the value chain. The conduits that are being leveraged within this act to achieve this goal include streamlining permitting protocols as well as including corporate social responsibility (CSR) parameters (such as resilience, cybersecurity and responsible business conduct) to make public solar PV auctions successful (Wood Mackenzie, 2024b).

Figure 12 **EU solar PV trade dynamics with China 2012-2022**



Source: (EC JRC, 2023).

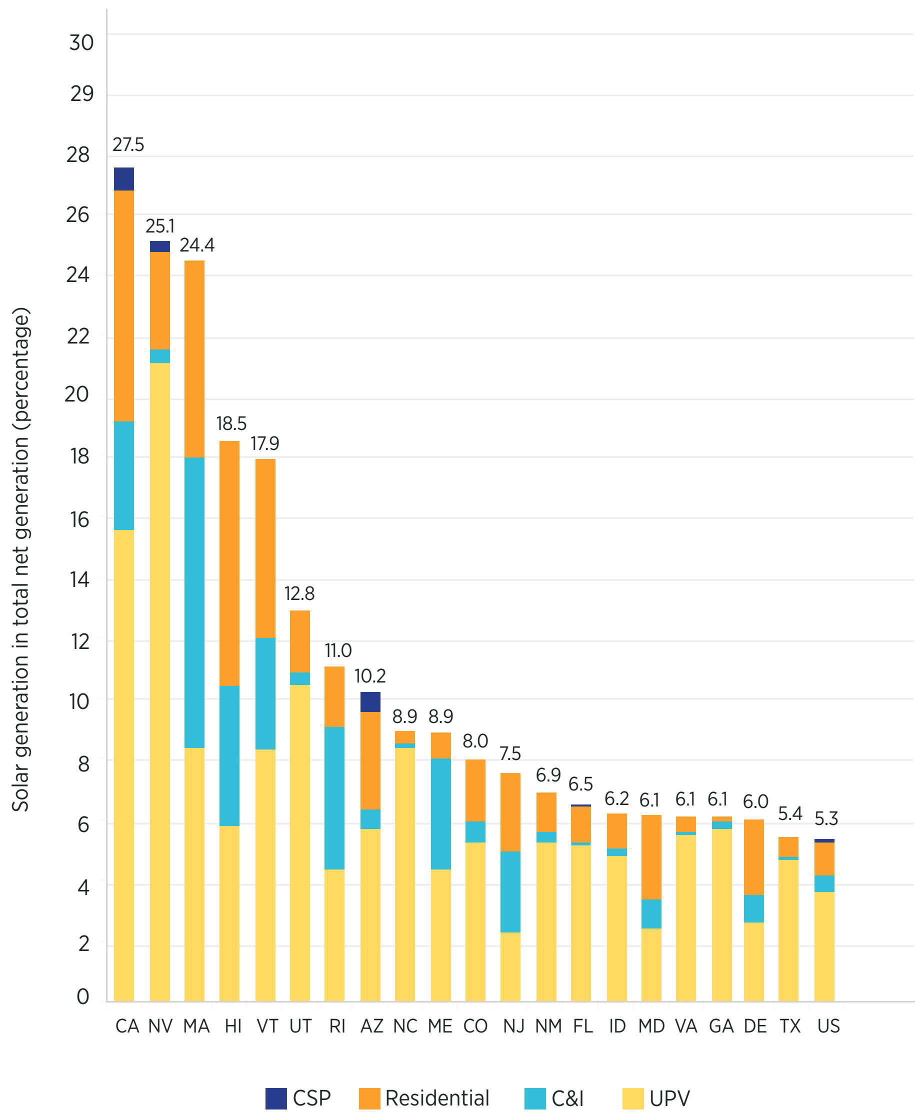
Looking to the future, according to Solar Power Europe, installed capacity additions in Europe are expected to reach 77 GW in 2024. However, Europe's market share will contract to 14% due to China's continued dominance of the global PV market (Solar Power Europe, 2024). Some of the key enablers that will continue to support the regional solar industry are the Green Deal and REPowerEU initiatives, which are aiming to accelerate regional carbon neutrality efforts by 2050. Ongoing geopolitical developments are also compelling the region to improve its energy security by increasing the deployment of renewable energy solutions while simultaneously reducing its dependence on gas.

Solar Power Europe projects that within the EU 27, 19 out of 27 markets are projected to install more solar capacity than 2023. Germany is expected to maintain its dominance and reach 16.1 GW by 2024, with Spain and Italy following suit. However, the Spanish market is projected to shrink by 12% and the Italian market to increase by 13% in 2024 (Solar Power Europe, 2024).

UNITED STATES

IRENA's latest renewable energy statistics report found that in 2023, the cumulative capacity for solar PV reached 137 GW (IRENA, 2024d). According to the US Department of Energy (DOE) Q2 2024 update, in 2023 solar PV accounted for approximately 54% of new electricity generation capacity – an increase from 6% in 2010 (NREL, 2024). Twenty-two states generated more than 5% of their electricity from solar PV, with California, Nevada, Massachusetts, Hawaii and Vermont being the top five (NREL, 2024) (see Figure 13).

Figure 13 **Solar generation as percentage of total generation in states**



Notes: AZ = Arizona; CA = California; CO = Colorado; CSP = concentrating solar power; C&I = commercial and industrial; DE = Delware; FL = Florida; GA = Georgia; HI = Hawaii; ID = Indiana; MA = Massachusetts; MD = Maryland; ME = Maine; NC = North Carolina; NJ = New Jersey; NM = New Mexico; NV = Nevada; RI = Rhode Island; TX = Texas; US = United States; UPV = utility-scale photovoltaics; UT = Utah; VA = Virginia; VT = Vermont.

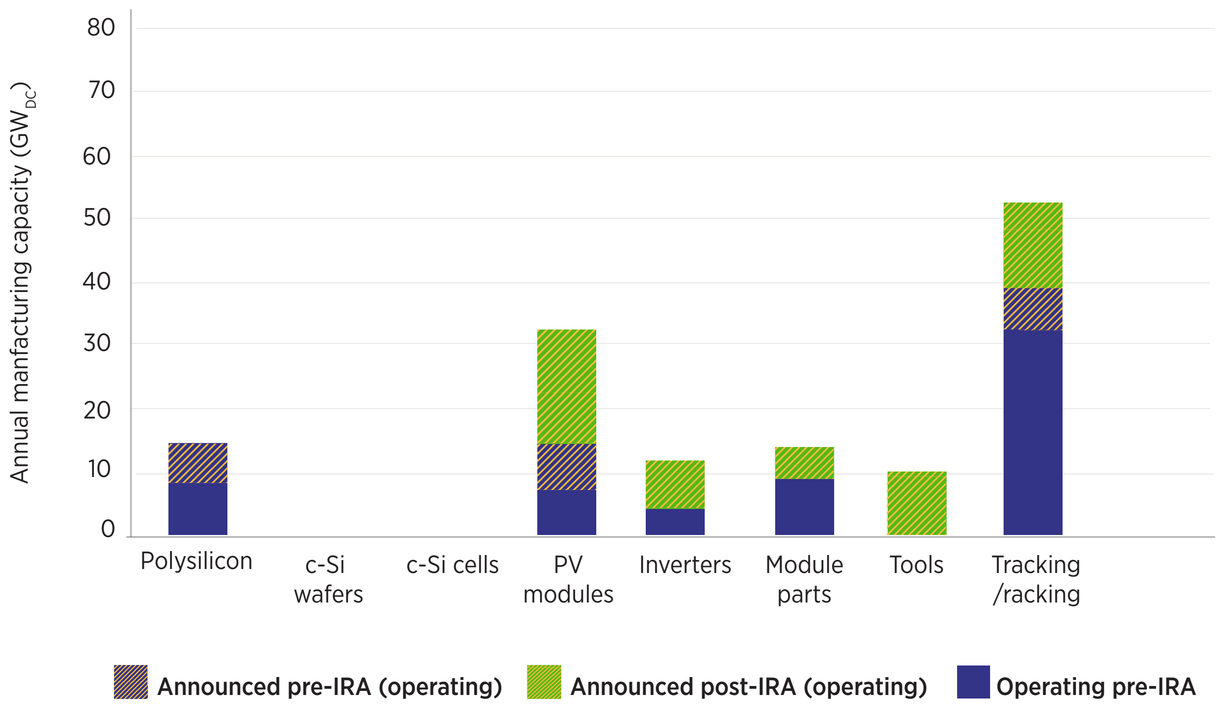
Source: (DOE, 2024).

According to a recent Deloitte analysis, the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA) have positively impacted local solar developments in the country. USD 52 billion has been invested in utility-scale solar projects in 38 states (Deloitte, 2023). The same analysis notes that IRA tax credits have created a strong incentive to accelerate manufacturing capabilities in the United States, with several companies announcing investments of USD 9.6 billion in 38 solar projects (Deloitte, 2023).

In 2023, global PV shipments reached 564 GW (a 100% increase from 2022). Of these shipments, the United States produced 7.2 GW of PV modules (with efficiencies between 18% and 20%); however, its manufacturing share within these global shipments declined from 13% to 0.9% (NREL, 2024; VDMA, 2024).

The IRA's passage has resulted in the addition of more than 70 GW of announced manufacturing capacity across the solar supply chain. This includes 25 GW of new module capacity (NREL, 2024). A breakdown of the distribution of this 70 GW of capacity across the supply chain is shown in Figure 14.

Figure 14 **Pre- and post-IRA manufacturing capacity by supply chain segment – United States**



Note: c-Si = crystalline silicon.
Source: (NREL, 2024).

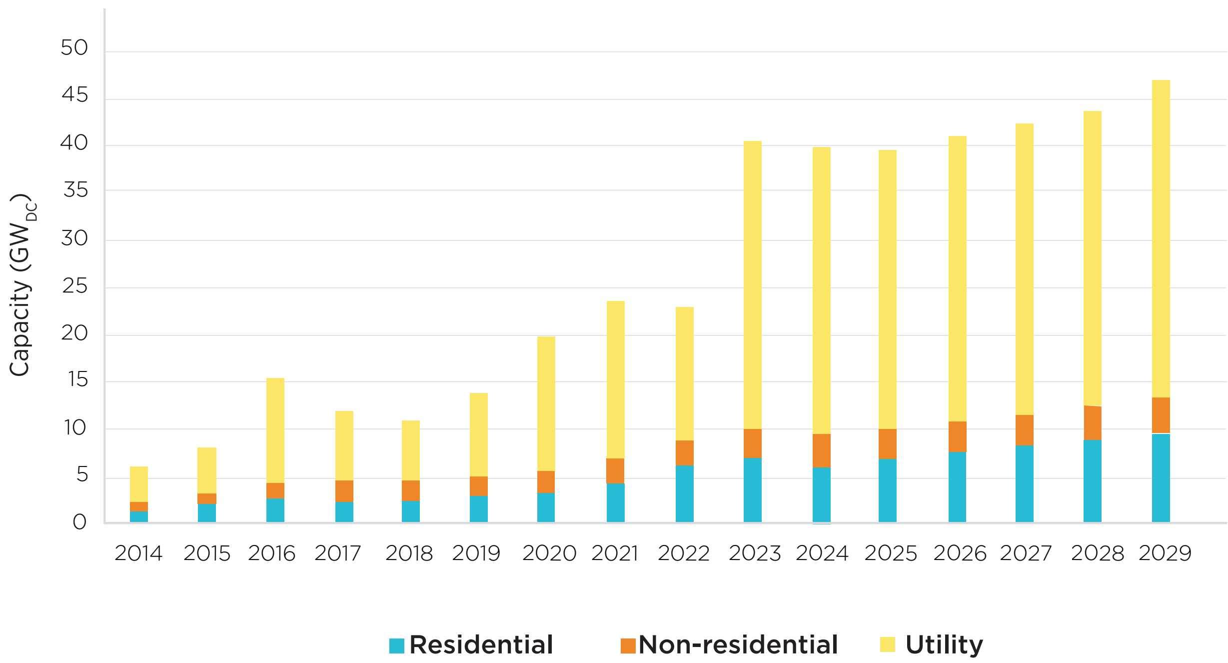
Due to geopolitical competition, the United States has recently begun to import a significant number of solar PV components from South East Asia. These components include crystalline silicon modules, crystalline silicon cells, backsheets, module frames and manufacturing equipment (Wood Mackenzie, 2024c).

In 2023, 55.6 GW_{DC} of modules (a 87% increase year on year) and 3.7 GW_{DC} of cells (46% increase year on year) were imported from Cambodia, India, Indonesia and Thailand (NREL, 2024; Wood Mackenzie, 2024c). This trend is likely to continue and could result in the United States hitting its cell import quota of 12.5 GW_{DC} by September 2024 (updated and revised from 5 GW_{DC}). Manufacturers would then pay a tariff on imported cells (NREL, 2024; Wood Mackenzie, 2024c).

The latest data from Wood Mackenzie shows that in Q1 2024, the United States imported 89 GW of modules. Of these, 72 GW were imported from Cambodia, Malaysia, Thailand and Viet Nam between June 2022 and March 2024 (resulting in an estimated surplus of 35 GW) (Wood Mackenzie, 2024c). Wood Mackenzie estimated that as of Q1 2024, more than 73 GW of operational cell capacity cumulatively was found in India, Indonesia, Republic of Korea, Lao People's Democratic Republic, Philippines, Singapore and Türkiye. However, the United States has not fully explored this capacity because some of these countries fall outside the US's Tier 1 category (Wood Mackenzie, 2024c). In summary, the current US solar PV supply chain landscape comprises module imports from South East Asia, cell imports from the Republic of Korea and the exploration of options to import modules from India and Türkiye.

In 2024, the United States increased its tariff rate on solar cells and modules to 50%. This increase has not impacted the national market because the import share of these elements from China are very low, but it would have been a different case had these tariffs also applied to wafers and glass (Wood Mackenzie, 2024c).

Figure 15 **US solar PV installation projections, 2024-2029**



Source: (SEIA, 2024).

From a policy perspective, a decision remains to be made on anti-dumping and countervailing duties (AD-CVD). In addition, a decision is expected by Q1 2025 on the imposition of broad import tariffs to be introduced for solar PV components, regardless of origin. Such tariffs would increase the competitiveness of modules manufactured in the United States if AD-CVD is affirmative.

In terms of durability, PV modules are now expected to have good operational reliability for between 20 and 30 years, which is a very positive development (NREL, 2024; Peters et al., 2021; Wiser et al., 2020).

Looking towards 2030, since the passage of the IRA, greater than 300 GW of new solar manufacturing capacity has been announced. This translates to the potential creation of 29 000 new jobs as well as USD 15 billion in investment (NREL, 2024).

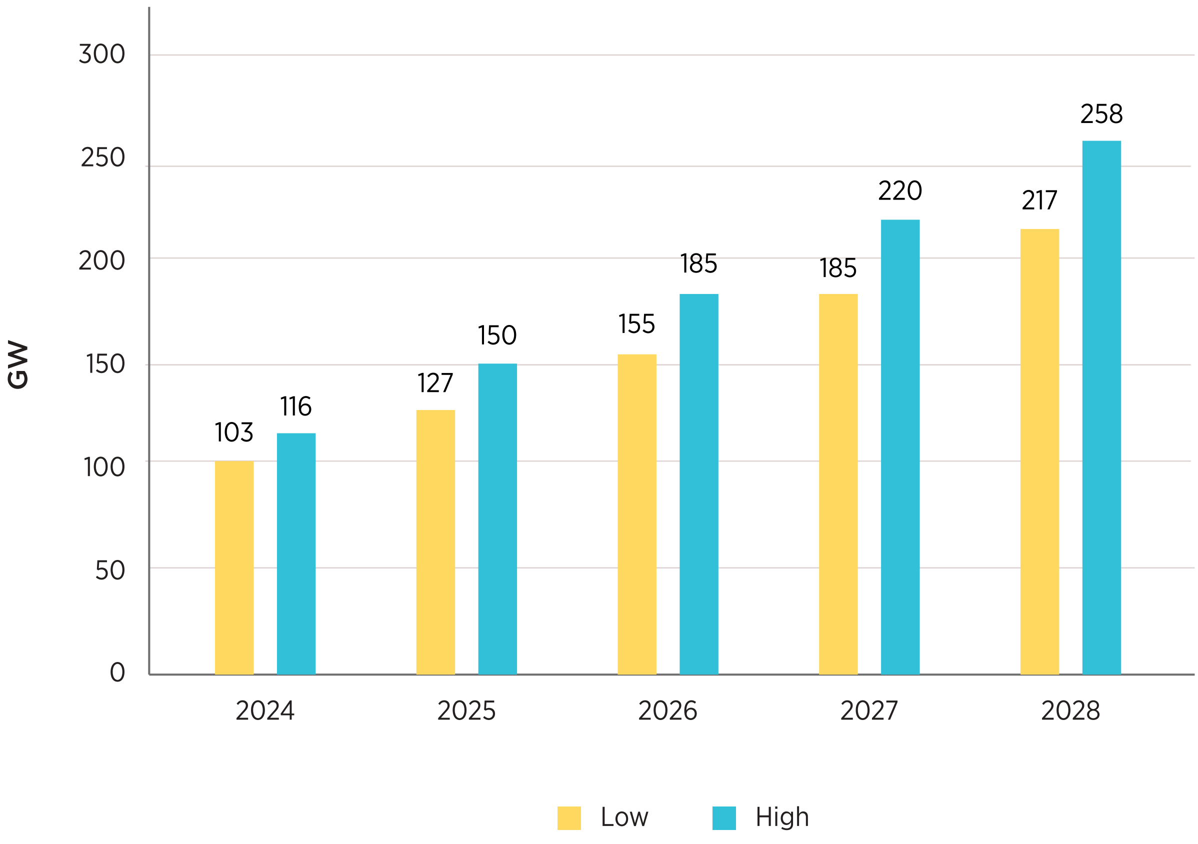
The Solar Energy Industry Association projects that for the next five years the US annual solar capacity addition will be 40 GW_{DC}. The association notes that 2024 and 2025 will have flat growth curves due to a slowdown in utility-scale solar (SEIA, 2024). Other factors that will influence solar growth development in the United States include workforce uncertainties, constraints on high-voltage equipment and volatile trade policies (SEIA, 2024). SEIA expects that between 2026 and 2029, annual growth will average in the single digits, and the largest contributors will come from residential and commercial solar projects (SEIA, 2024) (see Figure 15).

INDIA

Between April 2023 and March 2024, India installed approximately 15.5 GW of solar PV capacity. The cumulative capacity rose to 81.8 GW, of which 64.4 GW is from utility-scale installations (Solar Power Europe, 2024). Solar PV is expected to continue to play an increasing role in India's energy transition activities, with 30 GW expected to be added between 2024 and 2025 (NSEFI and Solar Power Europe, 2023; Solar Power Europe, 2024).

Figure 16 shows a forecast of India's expected solar PV installed capacity outlook to 2028.

Figure 16 **India's solar capacity outlook, 2024-2028**

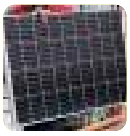


Source: (Solar Power Europe, 2024).

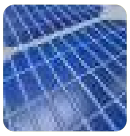
From a market development perspective, some of the key challenges that India needs to tackle as its solar PV industry grows are the availability of appropriate transmission infrastructure, access to land for utility-scale projects, and access to critical minerals and bill of materials (NSEFI and Solar Power Europe, 2023; Solar Power Europe, 2024).

India is also placing a growing premium on enhancing its manufacturing capacity by orienting itself from a module-based system to one that is vertically integrated.

According to Solar Power Europe, manufacturing capacity reached 44 GW in 2023, which is a 100% annual growth (Solar Power Europe, 2024). The National Solar Energy Federation of India notes the following solar PV manufacturing trends:



Modules:
India has the largest manufacturing capacity in the region after China. Approximately 23 companies have communicated plans to establish GW-scale module manufacturing capabilities, with a target of reaching 125 GW by 2027 (NSEFI and Solar Power Europe, 2023; Solar Power Europe, 2024).



Cells:
As of March 2023, cell manufacturing capacity reached 6.6 GW. This capacity is expected to grow fourfold by 2024 (reaching 28 GW) and over sevenfold by 2027 (reaching 80 GW) (NSEFI and Solar Power Europe, 2023; Solar Power Europe, 2024).

Ingots and wafers:
India is not currently actively manufacturing ingots and wafers. However, there are plans to start by 2025 and a target of reaching 60 GW by 2027 with support from the Production Linked Incentive (PLI) Scheme (NSEFI and Solar Power Europe, 2023; Solar Power Europe, 2024).

Figure 17 provides a forecast of India's expected manufacturing capacity outlook to 2028.

Some of the key incentives that India is leveraging to continue the growth of its manufacturing capacities include but not limited to:

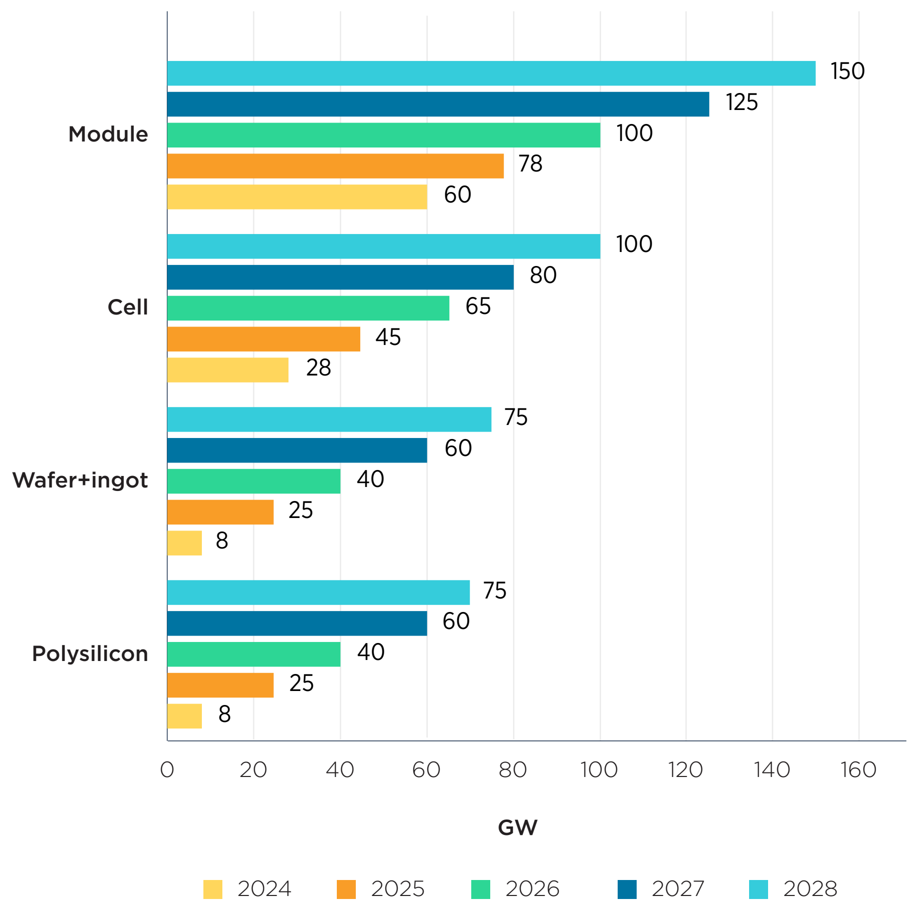
PLI Scheme: This is a scheme that was launched by the government in 2020 to boost manufacturing capacities in India. The first tranche of the scheme had a budget of EUR 500 million to build 10 GW of manufacturing capacity. After competitive bidding, this tranche was awarded to Reliance New Energy, Shirdi Sai Electricals and Adani towards the development of polysilicon-ingot-wafer-cell-module manufacturing capabilities. Building on this momentum, in 2022 the government launched a second tranche within this scheme with a valuation of EUR 1.8 billion, which is currently under implementation (NSEFI and Solar Power Europe, 2023).

Approved List of Models and Manufacturers (ALMM): To facilitate the development of a reliable solar PV market with "quality" manufacturers as well as to protect consumer/energy security interests, the Indian government issued this order, which provides a list of models and manufacturers that conform with the requirements of the Bureau of Indian Standards. The implementation of the ALMM order has been delayed due to a lack of availability of high-wattage modules, which are required for the multitude of pipeline utility-scale solar projects (NSEFI and Solar Power Europe, 2023).

Modified Special Incentive Package Scheme (M-SIPS): In an effort to accelerate large-scale manufacturing in India, in 2012 the government announced this ongoing scheme. M-SIPS aims to provide a 20-25% subsidy for capital expenditure investment for electronics manufacturing, which inter alia also constitutes solar PV (NSEFI and Solar Power Europe, 2023).

Basic customs duty: To facilitate the growth of domestic manufacturing capabilities, the government has set import duties at between 25% and 40% on modules and cells in an effort to disincentivise their import from external competitors (NSEFI and Solar Power Europe, 2023).

Figure 17 **India's solar manufacturing outlook, 2024-2028**



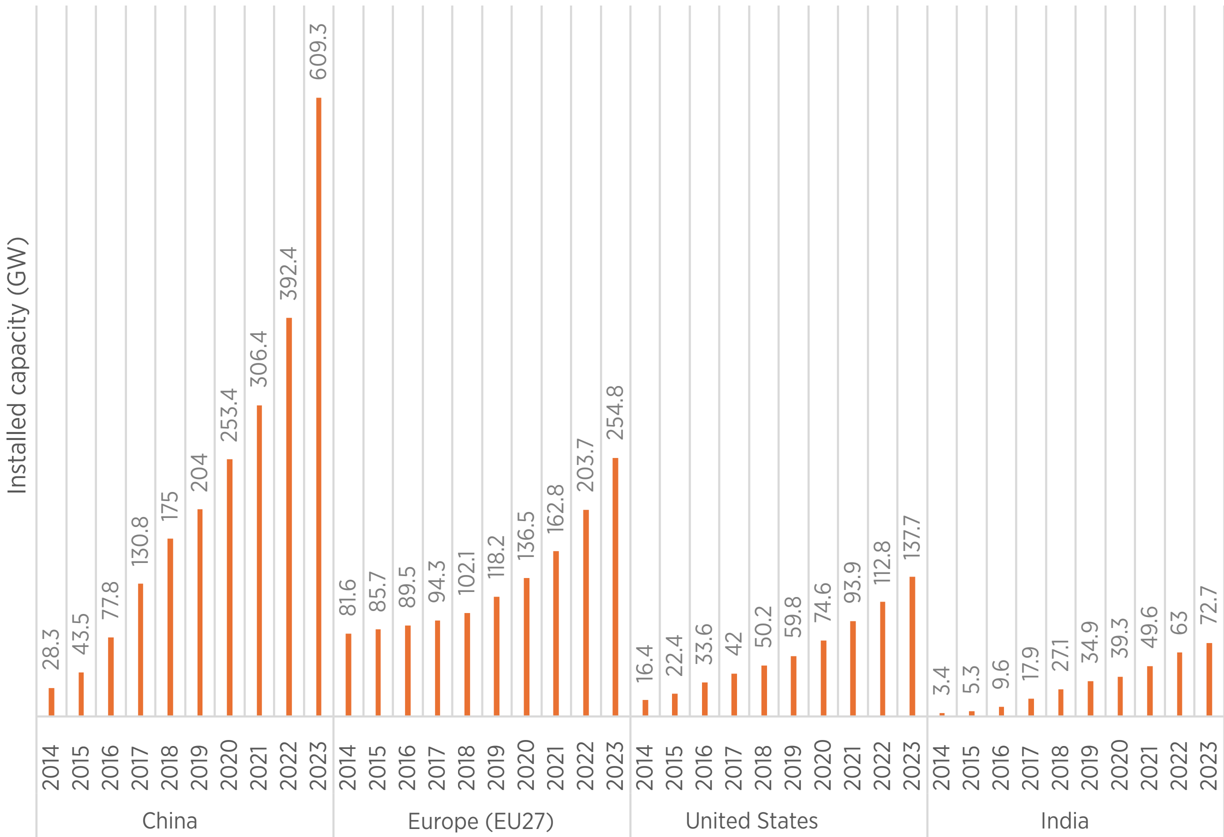
Source: (Solar Power Europe, 2024).

KEY MARKET TRENDS

Figures 18 to 20 provide a graphical summation of the cumulative installed capacity, annual installed capacity additions and module manufacturing year-end capacity in the four markets discussed in this chapter.

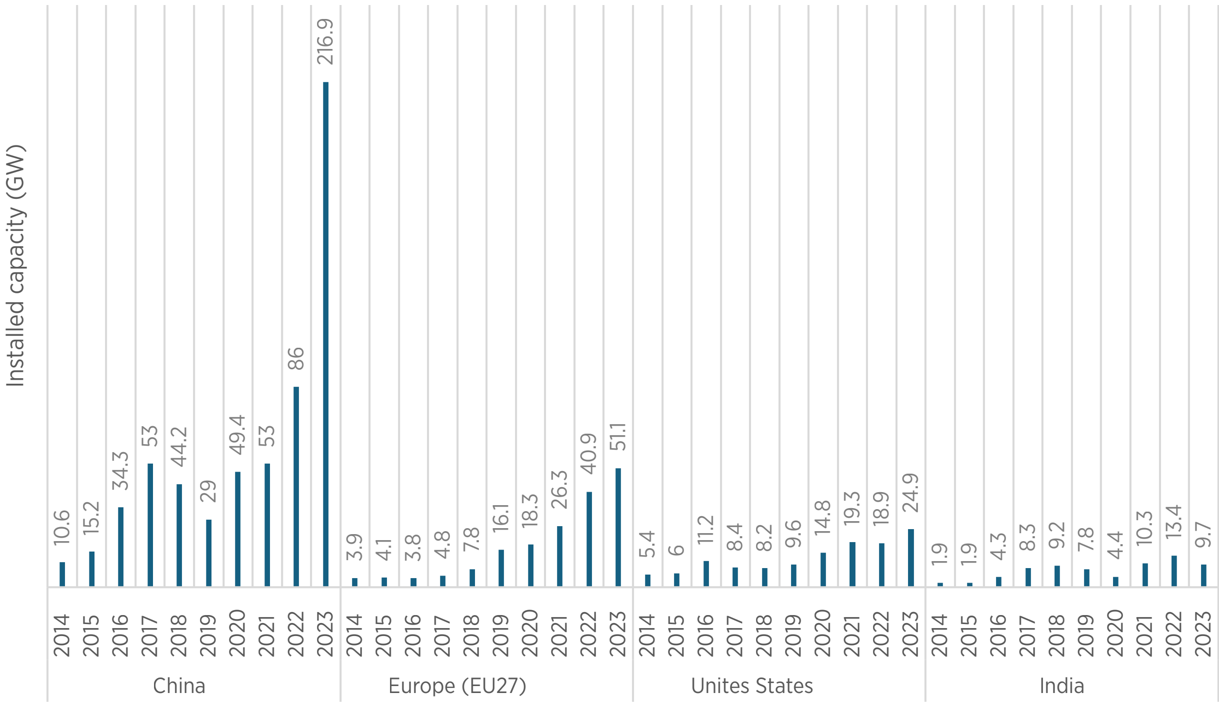
The trends presented in these figures show that China leads solar PV development globally. In other key markets, such as the United States and India, manufacturing capacity in the last three years has grown by threefold and fourfold, respectively, despite the gap with China. This indicates the growth and budding diversification of solar PV manufacturing capacity in markets beyond China.

Figure 18 **Solar PV cumulative capacity in select markets, 2014-2023**



Based on: (IRENA, 2023b, 2024d).

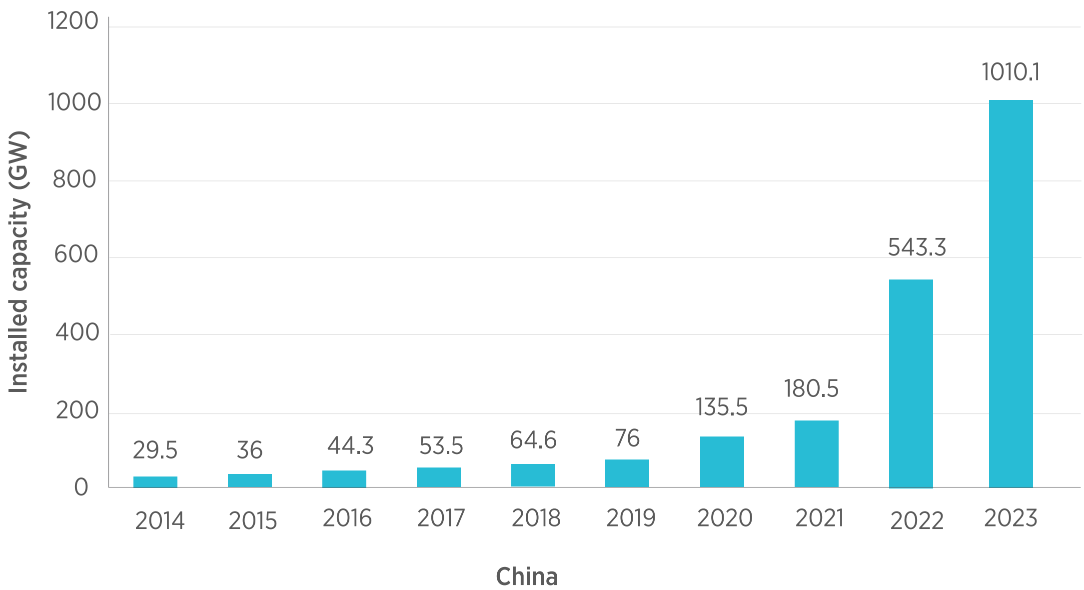
Figure 19 **Solar PV annual capacity additions in select markets, 2014-2023**



Based on: (IRENA, 2023b, 2024d).

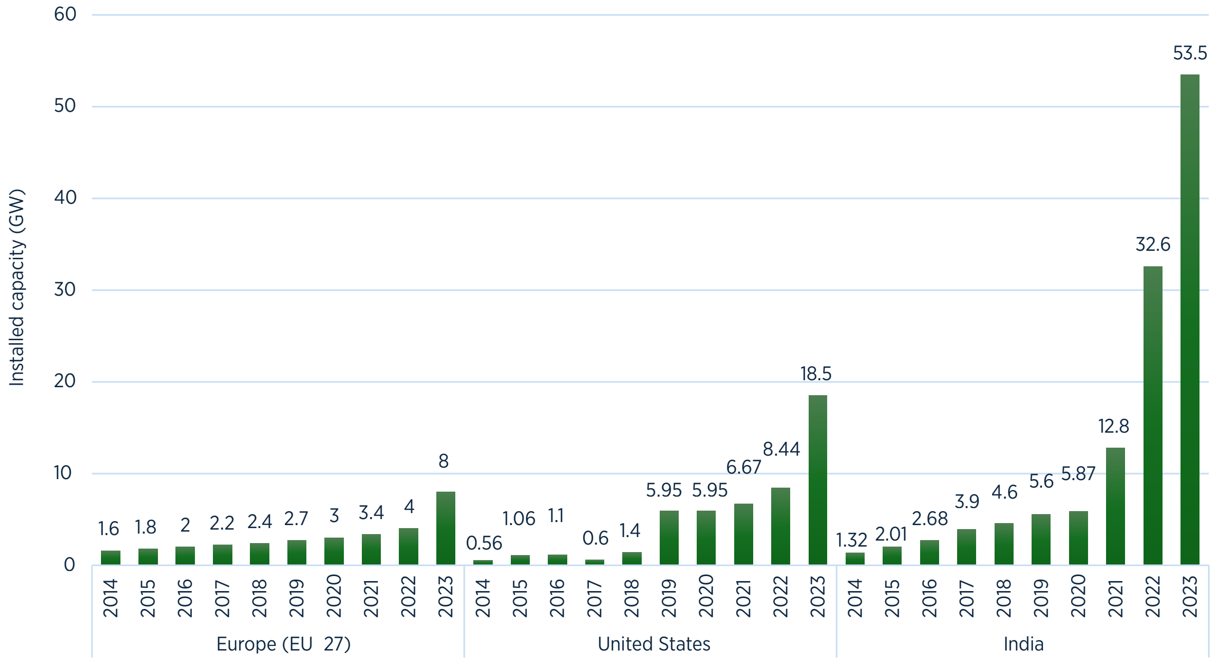
Figures 20a-b **Solar PV module year-end capacity in key markets, 2014-2023**

20a **Cumulative year-end module manufacturing capacity China**



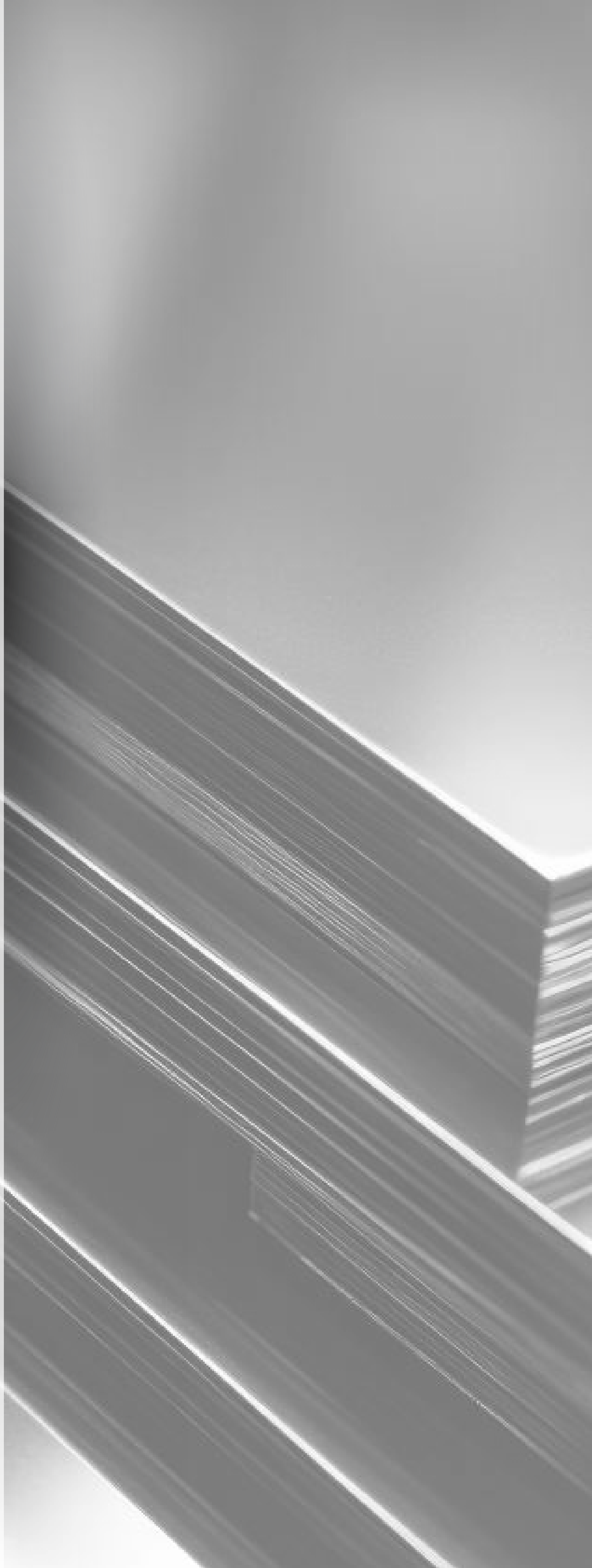
Source: Wood Mackenzie (2024d).

20b **Cumulative year end module manufacturing capacity EU 27 / United States / India**



Source: Wood Mackenzie (2024d).

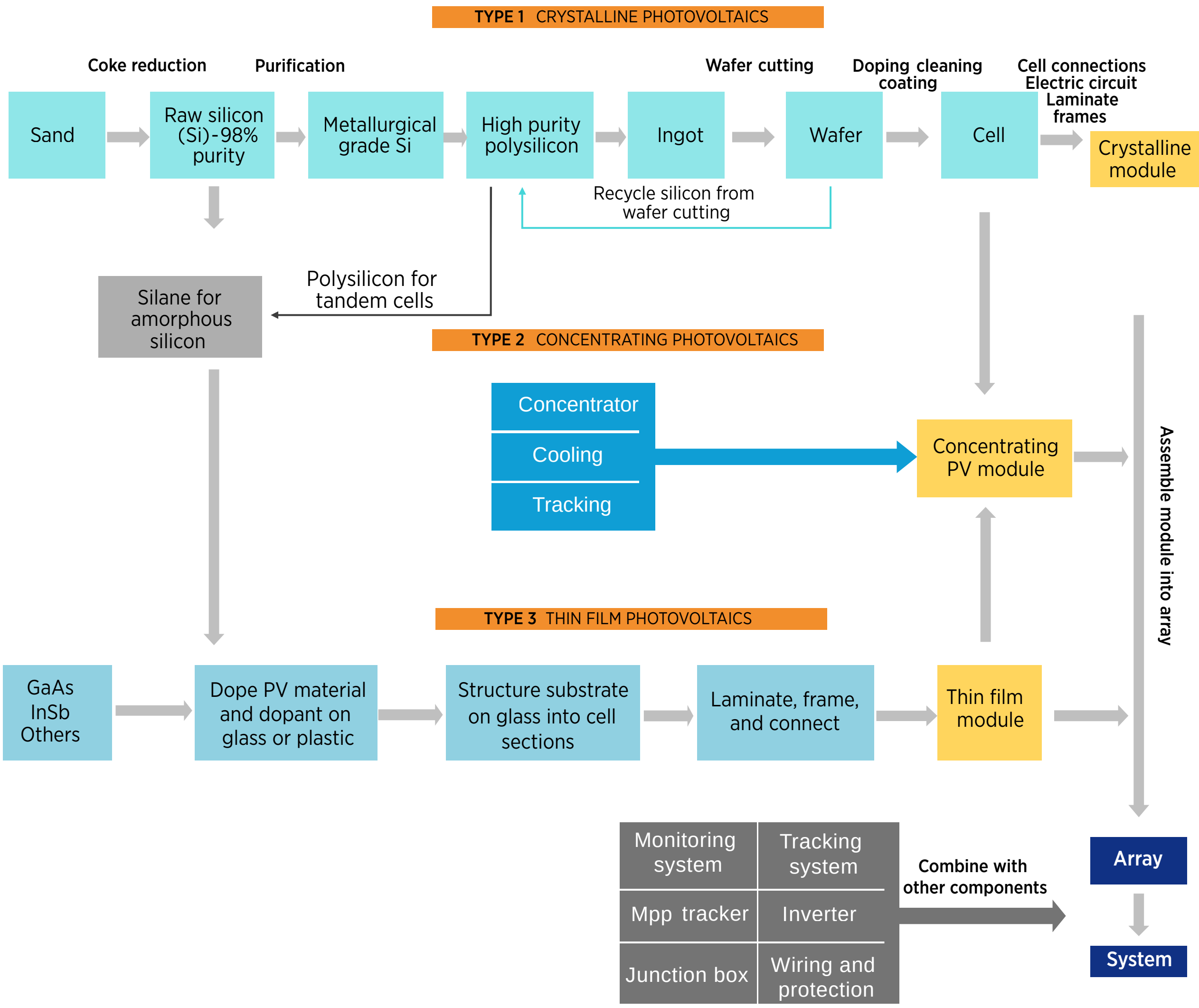
THE PV MODULE VALUE CHAIN



The PV module value chain consists of several levels. Raw materials is the first level. There are two major categories of PV module technology: 1) wafer-based (commonly called "crystalline") and 2) monolithically-integrated (known as "thin film"). The major difference is that the latter type of modules have semiconductor layers applied directly on the glass, rather than as separate components (PV cells on wafers). The rest of the basic components (glass, encapsulant, frame, junction box, cables) are similar for both technologies. The discussion below focuses on wafer-based technology, which comprises a vast majority (98%) of the global PV market (ETIP PV, 2023).

Figure 21 **The PV module value chain**

The photovoltaics value chain tracks all processes required to build a PV system.



Notes: For the production of crystalline silicon modules the process starts with sand being reduced into raw silicon. This is followed by purification, wafer cutting, doping, cleaning and coating. The cells are connected and laminated to form a module, which in turn can be assembled into an array and when combined with electrical components becomes a system. For thin-films, the value chain is shorter as modules are produced in a single step where the PV material (raw silicon, other compounds/chemicals) are deposited on glass or plastic. In concentrating photovoltaics, either crystalline silicon cells or thin-film substrates need to be combined with optical systems for concentration, cooling sink and in-built tracker before it can be assembled into an array.

Based on (Green Rhino Energy (n.d.).

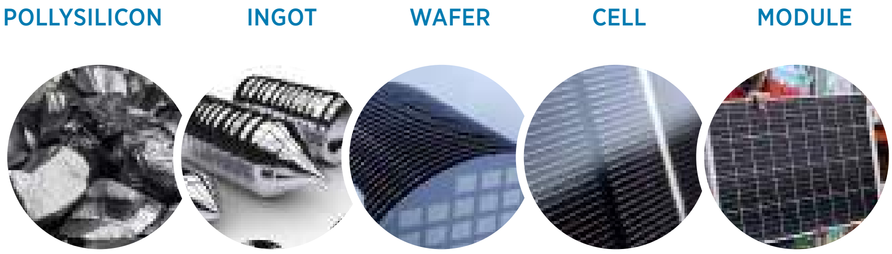


Figure 21 is a schematic representation of the PV module value chain. Silica is mined and reduced to metallurgical grade silicon (MGS) and refined into polysilicon. The polysilicon is melted along with a carefully controlled quantity of additives (*e.g.* gallium, phosphorus, antimony) to provide the desired semiconductor properties. The melted material is then formed into ingots (either monocrystalline or polycrystalline). The ingots are transformed into bricks, which are then are sliced into wafers. The wafers are made into solar cells. The cells are integrated into a module by interconnecting ribbons or wires into the desired electrical configuration, and then laminating the matrix to glass using a polymeric encapsulant. Most of the modules today are made with two sheets of glass (front and back), but some are still made with the legacy design of a single sheet of glass on the front and a polymeric back sheet. Finally, the modules are finished by attaching a junction box for the electrical output cables and are usually framed with aluminium extrusions for mechanical attachment in the final installation.

As solar PV and other renewables continue to gain more traction in the energy transition space, security and sustainability of the supply chain and its ability to promote just and fair growth. This entails businesses operating in compliance with best governance practices as well as ensuring respect to labour rights which produces equal opportunities and prospect for employees and end-users (IRENA and ILO, 2023).

Keep this in mind, some broad considerations, which are discussed later, that (IEA, 2022; IRENA, 2024e; IRENA *et al.,* 2023) have made suggestions for governments to promote domestic solar PV manufacturing that include but are not limited to:

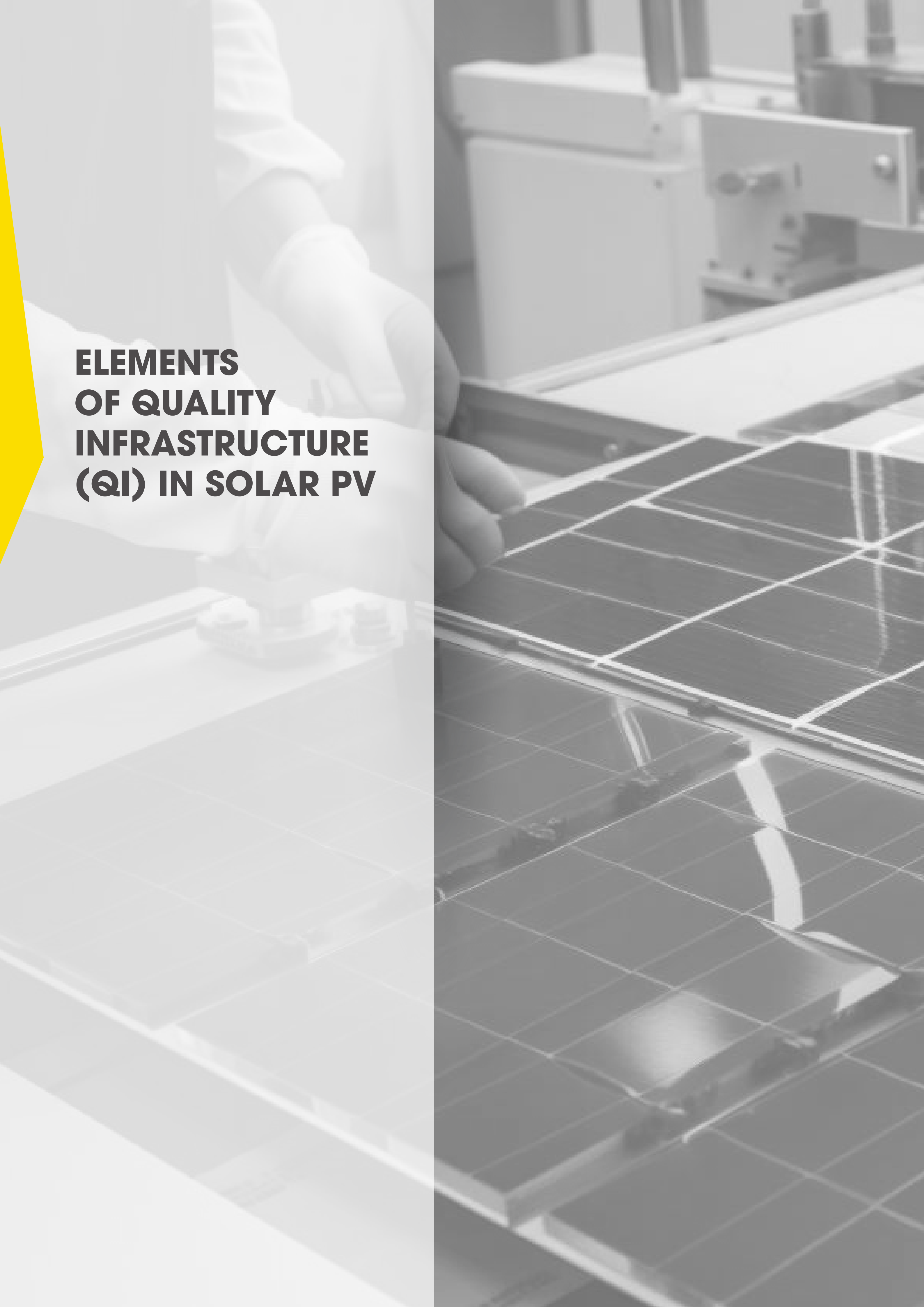
- Establish stable policy frameworks and remove barriers to deployment of solar PV technologies.

- Develop a resilient (i.e. have buffer to externalities) and efficient supply chain network that facilitates the rapid, timely and cost-effective delivery of PV modules worldwide – which can be achieved by supply chain diversification.

- Place a priority on enhancing the security and resilience of the solar PV supply chain by improving the understanding of risks while also maintaining a commitment to fair trade practices – such as complying with international framework such as WTO policies.

- Improve the environmental, social and financial sustainability of the PV industry by ensuring compliance with international quality and certification standards, ensuring labour rights are respected, and developing robust project documents and/or auctions.

ELEMENTS OF QUALITY INFRASTRUCTURE (QI) IN SOLAR PV



Standards comprise the primary element underpinning quality infrastructure (QI). In the PV industry, there are multiple international standards development organisations (SDOs) that publish standards and technical specifications. Some of the international SDOs active in energy include, but are not limited to, the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC). Many regional SDOs also publish standards to comply with local codes and regulations. Examples include European Norm (EN), Chinese Guobiao (GB), Japanese Industrial Standards (JIS), Deutsche Industrie Norm (DIN) and Australia/New Zealand standards (AS/NZS). Perspectives on essential standards along with emerging environmental, social and governance (ESG) activities are discussed later in the report.

In interviewing experts for this publication, it was noted that a perception exists among solar PV manufacturers that conformance with standards will increase operational costs due to the expense and time involved in required testing and certification. However, these experts also expressed the perception that many Tier 1 suppliers have recognised the importance of standards in bringing down operational costs by allowing for more predictability as well as providing customers with access to robust PV technology (ICTSD, 2017).

As mentioned in the overview, the solar PV industry continues to grow. With this, many stakeholders (such as bankers, investors and insurers) are looking towards robust standardisation as well as certification as avenues to mitigate business and investment risks. Given this interest, these stakeholders are contributing to standards development by providing inputs on which gaps need to be addressed to promote cost-effectiveness as well as sustainability. For the PV market to be robust and inclusive, it is essential that commonalities are established to encourage international adoption of PV technologies (ICTSD, 2017). There is also a growing interest in factoring in sustainability requirements when purchasing modules, further emphasising the necessity of compliance to appropriate standards and certification schemes.

The second element of QI is **metrology**, which is defined by the International Bureau of Weights and Measures (BIPM) as "the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology." BIPM is the body that sets the framework for understanding and measuring units, an aspect that is essential in the PV industry given its deep technological underpinnings. There are general standards that cover this topic, such as ISO 10012 (which ensures measurement processes and equipment are up to par) and ISO 17025 (which ensures that a particular laboratory meets global standards of excellence). In PV, the primary standards for metrology are contained in the IEC 60904 series, which covers measurement of PV cells and modules. Semiconductor Equipment and Materials International (SEMI) has also published many metrology standards that cover the electrical properties of PV cells, wafers and ingots.

The third important element of QI is product **testing**. The primary test standards employed throughout the industry are published by technical committee (TC) 82 and are essentially a default requirement for market participation. The IEC 61215 series sets requirements for module design qualification and the IEC 61730 series defines essential safety requirements. IEC Technical Specification 62915 provides retesting guidelines for extending qualifications when there is a change in materials or process. IEC 62446-4 specifies the guidelines for outdoor electroluminescence imaging (EL) of PV modules to facilitate the detection of latent defects of PV modules, which is being jointly drafted by TC 82 and the State Power Investment Corporation limited (SPIC). In addition to these basic tests, there are several private schemes that are intended to demonstrate increased reliability. This is usually accomplished by extending the length of the IEC tests or applying them in a different sequence.

The fourth element of QI is **certification**. This is the action or process of providing an official document attesting to fulfilment of a given standard. The most common PV module certifications are provided through the IEC System for Conformity Assessment[5] Schemes for Electrotechnical Equipment and Components (IECEE). There are two different levels of certification offered by IECEE. The “CB scheme” is essentially a default market requirement, based only on an initial test to “qualify” the module design. The “FCS scheme” includes annual factory surveillance, but it is rarely used mainly because of the additional cost for manufacturers.

Moreover, many certificates are provided through private third-party schemes that claim to be “based on the requirements” of the IEC standards but do not actually provide the necessary level of transparency for the market. This is where the QI element of **accreditation** becomes imperative. The IEC bases its system on peer assessment, meaning that each certifying body or testing laboratory is regularly audited by one of its competitors. This ensures that all are following the same rules and best practices as defined by a consensus process. Private schemes may have national accreditation, but this does not provide the same level of assurance as peer assessment.

The final QI element is **supporting research**, which is extensive in the PV industry. In addition to academic and corporate research, there are several international organisations devoted to PV. Examples include the IEA Photovoltaic Power Systems Programme (PVPS) and the International PV Quality Assurance Task Force (PVQAT).

[5] Conformity assessment refers to any activity that determines whether a product, system, service and sometimes people fulfill the requirements and characteristics described in a standard or specification. Such requirements can include performance, safety, efficiency, effectiveness, reliability, durability, or environmental impacts such as pollution or noise, for example. Verification is generally done through testing or/and inspection. This may or may not include on-going verification. (IEC, 2024a).

STANDARDS

Many important SDOs operate in the PV industry. Four SDOs specifically address different aspects of standardisation and have had the most impact on the PV module value chain. These SDOs are listed in Table 1 and are discussed in more detail in this chapter.

Compilation of PV standards – Annexed to this report is an Excel data base that includes the most relevant standards developed by the organisations listed in Table 1. Each standard has been correlated to the value chain segment to which it applies (namely PV systems, modules, cells wafers or raw materials) as well as the QI category into which it fits (product specifications, metrology, testing or supporting research). There are many existing standards that can strengthen the quality of solar PV value chains if adopted by stakeholders. In some cases, new standards are being developed, which is a time-consuming process.

Table 1 **Key SDOs for the PV module value chain**

Standards development organization (SDO)	Membership	Focus of activities
International Electrotechnical Commission	IEC national committees	Performance and safety of products, systems, and services
Semiconductor Equipment Manufacturers' Institute	SEMI member companies	Primarily manufacturing-related (materials and equipment)
Underwriters' Laboratories	UL invited experts	Product safety
ASTM international (formerly American Society for Testing and Materials)	ASTM individual experts	Measurement principles and specialty tests

Historically, many organisations based in the United States were the first movers in the PV industry and thereby have also had influence in the PV standards development, many of which have become internationally applicable through the IEC. The international standards development done by the organisations in Table 1 follow defined and accepted practices:

- IEC and ASTM ensure that their standards development conform with the WTO's principles of transparency, openness, impartiality, consensus, effectiveness and relevance. SEMI and UL do not make explicit reference to WTO principles; however, they are cognisant that their work has implications for international trade and mutual acceptance (ICTSD, 2017).

- The main difference arises in the constitution of their membership, committee structure and voting processes. In the IEC, committees are usually composed of experts appointed by national committees from member/affiliate countries. In SEMI, experts from private companies inform their standards development. ASTM allows individuals to be members; however, it only allows a single vote per organisation (in case there are multiple individuals from a single entity). UL relies on committees composed of subject matter experts to contribute to its standards development (ICTSD, 2017).

The National Science Foundation (NSF) is an SDO that developed the NSF 457 standard to underline the importance of environmental, social and governance (ESG) elements of the Electronic Product Environmental Assessment Tool (EPEAT) standard for PV, which is discussed later in this report (NSF, 2019).

It is however important to note that trade-offs can happen when considering the balance between technical expertise and process efficiency. The IEC has many working groups on different technical areas (cells, modules, systems, BoS). This is attractive to many experts but meeting logistics can be complicated per indications by experts interviewed for this study. However, organisations like SEMI have regional committees (Japan, China, United States, European Union) that have the inverse of IEC's characteristics, and there is a higher probability of duplication given many committees are working on the same topic.

Duplication of standards in the same area should be avoided in the best interests of industry because this leads to complexity and costs. SDOs are aware of this issue and are continuously striving to ensure their efforts are complementary. While many experts engage with different organisations to facilitate distinction in standards, duplication cannot be completely negated because SDOs aim to generate revenue from publications (ICTSD, 2017).

INTERNATIONAL ELECTROTECHNICAL COMMISSION

The **International Electrotechnical Commission (IEC)** develops standards covering PV modules, PV cells, module components and PV systems (the PV system standards are outside the scope of this report). IEC is responsible for preparing and publishing international standards for all electrical, electronic and related technologies. As an international organisation, IEC promotes co-operation on standards development and ensures tools and systems are available to promote the required verification of and conformity to these standards. IEC standards are often used in national standard development and are cited in the preparation of international tenders and contracts.

The IEC represents 174 countries in its standards development process, including 90 member and 84 affiliate countries. The approval of standards is done on the basis of one vote per country via the representative of national committees (NCs) (IEC, 2024b). There are 228 TCs and subcommittees (SCs) that lead standard development, and the scope and work programme is approved by participating NCs (IEC, 2024c). To start a new standard development project within a TC or SC, there is requirement to have at least five participating countries, with each nominating one expert. The TCs and SCs operate using Organisation for Standardisation/IEC directives.

IEC TC 82 covers solar PV energy systems. The scope of TC 82 is stated as:

> To prepare international standards for systems of photovoltaic conversion of solar energy into electrical energy and for all the elements in the entire photovoltaic energy system. In this context, the 'photovoltaic energy system' includes the entire field from light input to a photovoltaic cell to and includes the interface with the electrical system(s) to which energy is supplied. (IEC, 2024d).

TC 82 was established in 1981 and has 46 participating (*i.e.* voting) members and 9 observing members. There are nine dedicated working groups within TC 82, and over 650 individual experts participate in PV standards development (ICTSD, 2017) (see Table 2).

Table 2 **Working groups under IEC TC82 and their areas of work**

Code	Area of work
WG 1	Glossary
WG 2	Modules, non-concentrating
WG 3	Systems
WG 6	Balance-of-system components
WG 7	Concentrator modules
WG 8	PV cells
WG 9	BOS Components – Support Structures
JWG 1	Renewable energy off grid systems
JWG 11	Building-Integrated Photovoltaics (BIPV)
PT 600	Vehicle Integrated Photovoltaic Systems

TC 82 has published more than 200 standards. This TC has one of the largest work programmes within IEC, with 67 ongoing standard development projects (32 new and 35 revisions). Working Group 2 on modules is the most active. It focuses on the following areas: measurement principles, qualification and safety tests, energy rating, specialised stress tests, and module components and materials. A list of IEC PV standards can be found in the Annex (not all working groups were considered relevant for the purposes of this report).

Semiconductor Equipment and Materials International

Semiconductor Equipment and Materials International (SEMI) has global representation from the semiconductor, PV, and flat panel display industries. Leveraging its unique capacities, SEMI is developing standards for PV cells and wafers, as well as materials, chemicals and equipment used in the solar cell manufacturing process. SEMI's regional task forces aim to develop standards targeting specific issues that stakeholders (primarily manufacturers) experience. As mentioned previously, these task forces are composed of industry/technical experts, and they are heavily involved in the drafting process of standards with the objective of reaching a consensus version. Once such an iteration is reached, the standard is shared with a broader network comprising regional and international TCs for further review and comments. A global ballot is then organised to ensure global consensus of the standard, which culminates in its application and adoption by the industry. A list of PV-specific SEMI standards is presented in the annex.

Underwriters Laboratories

Underwriters Laboratories Inc. (UL) is responsible for the development of over 1 000 safety standards, which also cover PV-related products (ICTSD, 2017). To receive an electric permit in the United States and Canada, a certification of compliance with relevant UL standards by a nationally recognised testing body is required. UL also leads efforts to facilitate the adoption of international standards in the United States, which is a process that can have some national deviation. In its standards development protocol, UL technical panels offer online access to review their draft standards as well as allow for volunteers in their panel meetings. A list of PV-specific UL standards is included in the annex.

ASTM International

The **ASTM International** has a dedicated committee (E44), Solar, Geothermal and Other Alternative Energy Sources, established in 1978 to oversee standard development in these areas (through nine TCs). Membership of this committee is open to stakeholders (categorised as producer, users and general priorities) with relevant expertise. The committee composition is balanced by ensuring equitable voting interests among stakeholders.

The scope of E44 is stated as:

> The promotion of knowledge, stimulation of research and the development of standard test methods, specifications, guides, practices and terminology concerned with the technology for conversion of solar and geothermal renewable energy to directly usable energy forms and the application of such technology for the public benefit. The areas of interest shall encompass standards relating to methods and applications of solar and geothermal energy conversion. These methods and applications shall include the following: heating of domestic hot water; active and passive space heating and cooling; process heating; thermal conversion power generation; photovoltaic generation of electricity; and advanced energy conversion, including wind energy. Consideration shall be given to applicable materials components, subsystems, and systems in each of these methods and applications. (ASTM, 2024)

Standards development in ASTM (across the 130 TCs) is driven by input from members. These are usually industry experts and business professionals. Most of the standards developed are focused on test methods, specifications, guides and practices that have high technical accuracy and clarity.

Most of the E44 standards fall into the categories of metrology and testing of PV modules, although recently several important standards have been published in the areas of system performance (E2848 and E2939) and installation (E2766 and E3010). A list of selected E44 publications is presented in the annex. With regard to ESG, ASTM Committee F49 is working on a traceability standard leveraging blockchain technology (ASTM D8558-24)[6] that covers MGS and polysilicon within the solar PV supply chain.

Recent solar PV standard development

As previously discussed, the primary standards for PV module testing are focused on design qualification and safety. The IEC 61215 series (design requirements) and IEC 61730 series (safety requirements) include environmental exposures such as thermal cycling, damp heat and humidity/freeze cycles. They also feature mechanical tests for static and dynamic loading as well as hail resistance. Finally, there are tests for electrical fault conditions such as reverse current overload and hot spot resistance. The IEC TS 62915 retesting guidelines define which of these tests must be repeated for any given change in the materials or processes used for manufacturing.

TC 82 has also published several test sequences for specific purposes. These include IEC TS 63126 for operation at high temperatures, IEC TS 63397 for increased hail resistance, IEC 61701 for salt mist corrosion and IEC 61726 for ammonia corrosion. These special tests are sometimes required by owners or investors but are not performed on a routine basis. More information about this topic can be found in the forthcoming IRENA report *Quality infrastructure for renewables facing extreme weather conditions*.

The IEC TS 63209 series defines requirements for extended-stress testing of modules and polymeric components (e.g. backsheets and encapsulants). Published in 2021, the intent of this technical specification was for manufacturers to avoid the cost of multiple private test schemes required by individual customers. Experience to date has shown that manufacturers do these tests, but most developers and companies offering engineering, procurement and construction (EPC) do not ask for them (unless required by investors on specific projects). Similarly, TC 82 developed IEC 62941 to specify requirements for the quality management systems of PV module manufacturers. Based on the elements of ISO 9001, this standard includes PV-specific requirements for key processes such as interconnection, lamination and flash testing. It was intended to relieve manufacturers of the need for dedicated lot inspections required by many customers, but it has not been widely accepted by the industry.

More recently, TC 82's activities have focused on module materials and components, particularly those made from polymers. The IEC 62788 series includes requirements for backsheets, encapsulants and adhesives. IEC 62790 covers the safety of junction boxes and IEC 62930 specifies electric cables for PV systems. IEC 62852 is the safety standard for PV connectors, which was required because higher system voltages caused more issues with failed connectors. Due to the industry's growth, it has become more difficult to comply with the IEC standard (and national regulations) due to product availability. IEC and other SDOs are working to develop a connector intermateability standard to address this problem. The IEC 61853 series on energy yield and IEC 62938 on asymmetric snow loads are other standards that are deemed useful for solar PV.

[5] More information on the standard can be found here: [www.astm.org/d8558-24.html.](www.astm.org/d8558-24.html)

Other module components have fewer applicable standards. ASTM and ISO publish generic standards for glass, and TC 82 has published a few standards for measurement of transmission and reflection of coated glass. IEC has also published a few standards for cells and wafers, but most of the applicable standards come from SEMI. Likewise, SEMI has taken the lead in standardising specifications and measurement methods for ingots and polysilicon raw materials, as well as for processing equipment.

Box 1 provides a short description of recent standard developments undertaken by the China Photovoltaic Industry Association (CPIA).

Box 1

Brief overview of the China Photovoltaic Industry Association

The CPIA is a national, industrial and non-profit social organisation approved by the Ministry of Civil Affairs of the People's Republic of China and established by the Ministry of Industry and Information Technology of the People's Republic of China as the business supervisory unit.

The CPIA aims to safeguard the legitimate rights and interests of its members and the overall interests of the PV industry, strengthen industry self-discipline, ensure fair competition in the industry, improve the construction of the standard system, create a good development environment, promote technical exchanges and co-operation, and enhance the industry's independent innovation ability. As of March 2024, the association had more than 830 members, and the business scale of the association's member units covers most manufacturers providing raw and auxiliary materials and components of PV.

Some of the key services offered by the CPIA are as follows:

- **GBT 51368-2019 Technical Standard for the Application of Building Photovoltaic Systems:** This standard provides technical guidelines for the application of building PV systems, including system design, installation and acceptance. It is suitable for all types of buildings and helps to promote the widespread application of PV technology in the construction sector. The release of this standard not only reflects the consensus of industry, but it also makes a positive contribution to promoting the use of renewable energy and reducing carbon emissions (Ministry of Housing and Urban Rural Development, 2019).

- **GB 50797-2012 Code for Design of Photovoltaic Power Stations:** The standard emphasises the standardisation of PV power station design, which covers key elements such as site selection, equipment selection and layout, providing a solid guarantee for the safe and stable operation of PV power stations. The introduction of this standard is of great significance for promoting the development of renewable energy, optimising the energy structure and responding to climate change. Simultaneously, it also provides strong support for the sustainable development of social economy by optimising the national PV employment structure, which has led to the creation of many new jobs, especially in rural areas. This standard has also catalysed energy efficiency efforts by reducing energy consumption costs as well as facilitating the reliability of energy supply. This standard has also facilitated the reduction of greenhouse gas emissions originating from PV systems (Shanghai Electric Power Design Institute Co., Ltd., 2012).

- **China Photovoltaic Industry Association (TCPIA 0002) standard:** This standard provides a solid technical support to catalyse development in the PV industry by fostering linkages between product research and development, production process, performance evaluation, and marketing, among other variables.

  - On product development, this standard indicates the direction of innovation and technical requirements.
  - On production process, it standardizes the operation process and quality control points.
  - On performance evaluation, it establishes the scientific and rigorous test method and index system.

The CPIA also guides enterprises to pay attention to ESG responsibilities, promotes the sustainable development of enterprises, and enhances the social image and market competitiveness of enterprises.

ESG STANDARDS

Within the scope of the energy transition, there is a growing trend for entities across different industries to demonstrate that their operations, products and services are sustainable. To ascertain this parameter, stakeholders such as investors and policy makers are increasing requirements for firms to report on their financial and non-financial ESG information before any investments and/or business decision can proceed (Chen *et al.,* 2023; Henisz *et al.*, 2019; Radzi *et al.*, 2023; Şeker and Şengür, 2021; Xu and Zhu, 2024).

The prevalence of ESG performance assessment among firms allows for an independent third-party evaluation system that combines environmental protection, social responsibility and corporate governance, as well as synchronises the economic and social benefits of enterprises (Xu *et al.,* 2024). The key characteristics that underpin the three pillars of ESG are:

- **Environmental:** Key considerations that underpin this element include mitigation of climate change impacts, carbon and greenhouse gas reductions, waste management, energy efficiency, and biodiversity conservation (Henisz *et al.*, 2019; Radzi *et al.*, 2023). This is the element that most firms tend to focus on with regard to the energy transition.

- **Social:** This pillar focuses on how firms engage with their own workforce as well as clients and stakeholders. Customer satisfaction, data privacy/security, gender diversity, employee benefits and safety, and human/labour rights are all parameters that are associated with this component (Henisz *et al.,* 2019; Radzi *et al.*, 2023).

- **Governance:** This refers to companies' implementation of guidelines, their business practices and the operational protocols they use to ensure activities are compliant with international and national laws while simultaneously ensuring the demand requirements of external stakeholders/clients are met (Henisz *et al.,* 2019; Radzi *et al.*, 2023).

Figure 22 provides a graphical representation on the key parameters of ESG principles.

Figure 22 **The three pillars of ESG**

ENVIRONMENTAL	SOCIAL	GOVERNANCE
Energy usage and efficiency	Fair pay and living wages	Corporate governance
Climate change strategy	Equal employment opportunity	Risk management
Waste reduction	Employee benefits	Compliance
Biodiversity loss	Workplace health and safety	Ethical business practices
Green house gas emissions	Community engagement	Avoiding conflicts of interest
Carbon footprint reduction	Responsible supply chain	Accounting integrity and
	Partnership	Transparency
	Adhering to labour laws	

Source: (Mathis and Stedman, n.d.).

The concept of ESG originated between 2004 and 2006, when the United Nations proposed a legal framework for investment decisions that considered ESG variables (Chen et al., 2023; PRI, 2021). The UN Principles for Responsible Investment (PRI), established in 2006, facilitates the integration of ESG factors in investment decisions among its 5 000 participating financial institutions (PRI, 2021). Table 3 outlines the six ESG investing principles used by PRI today.

Table 3 **The UN Principles for Responsible Investment**

Principle 1: We will incorporate ESG issues into investment analysis and decision-making processes.
Principle 2: We will be active owners and incorporate ESG issues into our ownership policies and practices.
Principle 3: We will seek appropriate disclosure on ESG issues by the entities in which we invest.
Principle 4: We will promote acceptance and implementation of the Principles within the investment industry.
Principle 5: We will work together to enhance our effectiveness in implementing the Principles.
Principle 6: We will each report on our activities and progress towards implementing the Principles.

Source: (PRI, 2021).

Some of the benefits that are offered when companies and firms start to factor ESG considerations in their business operations include but are not limited to:

- **Top line growth:** Allows for strengthening of existing market base as well as access to new markets. This is facilitated through building trust with key stakeholders (such as investors and regulators) who can provide access to licenses and permits that can accelerate their growth (Henisz *et al.,* 2019; Radzi *et al.*, 2023).

- **Cost reductions:** Accelerating resource efficiency (energy and raw materials) creates opportunities to reduce operational costs while simultaneously promoting financial profits (Henisz *et al.,* 2019; Radzi *et al.*, 2023). General research by McKinsey has found that ESG can positively influence operating profits by as much as 60% (Henisz *et al.*, 2019).

- **Easing regulatory pressures:** Compliance with best practices associated with social and governance allows firms to reduce the chance of state interventions in their daily operations, while simultaneously allowing for strategic freedom in their operational planning activities (Henisz *et al.,* 2019; Radzi *et al.,* 2023; Xu *et al.*, 2024).

- **Increased employee productivity:** Prioritising workforce well-being and safety can increase productivity (by motivating employees to give back to the firm) as well as support the retention of qualified personnel. A sense of "purpose" is the main catalyst spurring this benefit (Henisz *et al.,* 2019; Radzi *et al.*, 2023).

- **Optimisation of investments:** Robust demonstration that business operations are compliant with best ESG practices (at all levels) can boost confidence among investors. This in turn can lead to long-term financial support and adoption of sustainable development opportunities (Chen *et al.,* 2023; Henisz *et al.*, 2019; Radzi *et al.*, 2023; Şeker *et al.*, 2021; Xu *et al.*, 2024).

ESG also has close analogues to business sustainability and CSR. However, each of these concepts are distinct. The former aims to position a company for success via the implementation of responsible management and strategies. The latter is a self-regulating approach to create societal benefits through actions. ESG represents a formal framework to develop quantifiable goals that can be reported as well as processes to track and manage progress towards their attainment.

Acceptance of ESG standardisation and compliance requirements has not gained much momentum in the PV industry and is still nascent. Some examples where countries/regions are mandating stronger compliance to ESG requirements include (but are not limited to):

- The European Union in 2023 commenced the enforcement of its Corporate Sustainability Reporting Directive (CSRD), which provides updated guidance on the rules concerning the social and environmental information that companies (across different sectors and industry) must report. The main objective of this legislation is to provide investors/stakeholders with information they require on how people and the environment are impacted by the operational activities of firms in which they would invest financially and/or identify opportunities arising from climate change and other sustainability issues (EU Commission, 2024a). Companies that are subject to the CSRD are obliged to report on their ESG compliance according to European Sustainability Reporting Standards.

- Closely tied to the EU CSRD, the Waste from Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU applies the principle of extended producer responsibility. This principle requires manufacturers to ensure their operational responsibilities also cover management of the post-consumer stage to ensure national/EU recycling and/or recovery targets are met (EU Commission, 2024b; EUROPEN, 2015). Solar PV panels, inverters and charging stations are covered under this legislation.

- The US Securities and Exchange Commission (SEC) in 2024 issued a ruling mandating that public registrants provide climate disclosure in their registration statements, IPOs and annual reports for the fiscal year ending in 2025 (United States Securities and Exchange Commission, 2024). Reporting on greenhouse gas emissions (scopes 1 and 2), the tangible impact of climate risks on business model and strategy, and a declaration of climate target goals are some of the key provisions included in the SEC rulings in an effort to introduce broad ESG compliance into the US economy (Deloitte, 2024; United States Securities and Exchange Commission, 2024).

- The US Federal Regulation Acquisition FAR 23.108 includes requirements for PV modules and inverters, recognising the EPEAT ecolabel to meet government sustainability goals through federal procurement of solar energy in construction and power purchase agreements (PPAs) via EPEATregistered PV modules and inverters (United States Government, 2024). While the US federal government is not yet a significant purchaser of PV modules and inverters, it procures a significant amount of PV-generated electricity via PPAs.

- In August 2024, Australia has also passed an amendment to its Treasury Law which requires large and medium-sized firms, starting in 2025, to disclose climate related risks and opportunities – in tandem with GHG emission reporting. Australia is also planning to establish a Net Zero Economy Authority that will provide support to workers in the energy sector with access to skills development opportunities as well as guiding new investors towards net zero transformation avenues (Segal, 2024).

- As the host country for COP 28 in 2023, the UAE announced USD 30 billion pledge to support the development of clean energy projects globally (Dimapilis, 2024). During the UAE's recent COP presidency, the Abu Dhabi Global Market implemented its own sustainable finance regulatory framework which provides guidance and regulations on ESG disclosures by companies which engage in this market (ADGM, 2023; Dimapilis, 2024).

- The United States passed the Uyghur Forced Labor Prevention Act (UFLPA) in 2021, which prohibits imports from countries that cannot demonstrate their compliance with international safe and secure workforce well-being standards and practices (Casey, 2024; United States Congress, 2021; US Customs and Border Protection, 2024). This provides another avenue to stimulate the implementation of the IRA, the United States' signature law to strengthen domestic supply chains while simultaneously reducing the environmental impact of its economic development.

- The European Commission is proposing a Forced Labour Ban Regulation to effectively ban products made with forced labour from being commercialised and/or imported into the EU single market. The regulation has recently gained approval from the EU Parliament (EU Commission, 2024c).

Box 2 describes how a Chinese firm (JA Solar) considers ESG as part of its operational activities.

Box 2

Brief overview of JA Solar's ESG efforts

JA Solar is a Chinese firm that is an industry leader in the production of polysilicon, an essential component in the development of solar PV modules. JA Solar has various industrial complexes in which it thermally processes mined silicon to yield MGS.

At its Mengte Polysilicon plant in Inner Mongolia, JA Solar uses a refined chemical process to convert MGS into trichlorosilane, which when cooled and purified forms polysilicon. The polysilicon is then processed into wafers and eventually cells, which are the basic building blocks of modules.

JA Solar recognises the importance of ESG to ensure the sustainability of its business. Some of its efforts to achieve this goal include:

- Having stringent quality systems to ensure it can trace the origin of all materials and components that pass through its facilities. JA Solar has an integrated traceability system that tracks incoming materials from ingot to wafer, cell and module that ensures knowledge of the supply chain's provenance.
- Exploring new ways to reduce energy consumption and abate emissions from its facilities to meet national targets while also reducing operational expenditure (OPEX). Increasing investments in renewable energy to meet demand/supply requirements is a priority.
- Aiming to ensure materials are sourced exclusively from the Inner Mongolia region to optimise logistics costs and guarantees the required quality standards for N-type grade silicon.
- Ensuring a sustainable governance model by complying with national laws such as the Company Law of the People's Republic of China and the Securities Law of the People's Republic of China, among other national frameworks.
- Ensuring the safety and well-being of its workforce. An example of this commitment is the compliance of all of company assets to ISO 45001 in 2023, which is the international standard that specifies requirements for an occupational health and safety management system.

A complete overview of JA Solar's ESG efforts can be found in the box sources referenced below.

Source: (JA Solar, 2024; Mounsey, 2024).

The global solar PV industry is starting to recognise the importance of having robust ESG standards and initiatives to ensure the industry's long-term sustainability in light of the continuous and increasing prominence of solar PV in catalysing the energy transition. Some of the key ESG services currently available in this industry are briefly presented in the section below.

3.1 INTERNATIONAL ESG STANDARDS

ISO 14001

ISO 14001 (Environmental management systems) "provides requirements with guidance for use that relate to environmental management systems. Other standards in the ISO 14000 series focus on specific approaches such as audits, communications, labelling and life cycle analysis, as well as environmental challenges such as climate change" (ISO, 2021a). Within the ISO 14000 series, a notable standard is ISO 14067 (Carbon footprint of products), which provides guidance and requirements on the carbon footprint reporting for a product while following life cycle assessments (LCAs) as specified in ISO 14040 and ISO 14044 (ISO, 2021a).

ISO 26000

ISO 26000 (Guidance on social responsibility) is a guidance document rather than one that provides requirements, thereby differing from convention. Hence, this standard cannot be used for certification purposes (ISO, 2021b). It aims to provide a definition of social responsibility and can be used by businesses/organisations to create social impact. The development of this standard involved extensive stakeholder consultation with representatives from governments, non-governmental organisations (NGOs), industry, consumer bodies and labour organisations. It was launched in 2010 after reaching international consensus (ISO, 2021b).

ISO 37000

ISO 37000 (Governance of organisations) is another guidance document that focuses on the governance of organisations, irrespective of type, size, location, structure or purpose. It aims to highlight key governance practices that can inform governing bodies and groups to fulfil their responsibilities and meet their purpose in line with their values. This standard is also relevant for stakeholders that are impacted by the organisation and/or its governance. The benefit of this standard if used by an organisation is the opportunity to understand its stakeholders better as well as to leverage effective creativity, cultural and performance practices to fulfil this mission objective. This standard stresses the importance of governing bodies holding their management accountable. It also stresses that such bodies should ensure that organisational norms and practices are in alignment with their purpose and values (ISO, 2021c).

IEC 63366

IEC 63366, which is under development in TC 111 (Environmental standardisation), is intended to provide common rules for the LCA of electrical and electronic products. It will be used as a template for product committees (like TC 82) to develop their own LCA standards with product-specific rules (PSRs)/product category rules (PCRs). TC 111 is asking for IEC 63366 to be published as a horizontal publication, which means two things:

- For LCA practitioners, this horizontal standard shall be applied when there is no PSR standard; LCA practitioners could use the applicable requirements and adapt requirements according to the specific product or product group/product family applied (IEC, 2023).

- For product committees, this horizontal standard shall be used as a starting point for developing their PSR standard. If a PSR standard is available, it will take precedence over this horizontal PCR standard (IEC, 2023).

IFC Performance Standards

The International Finance Corporation (IFC) has a Sustainability Framework that constitutes of a Sustainability Policy, Performance Standards, and Access to Information Policy (IFC, 2024a). Effective since 2012, there are eight performance standards focusing on the following areas: *risk management, labour, resource efficiency, community, land resettlement, biodiversity, indigenous people, cultural heritage* (IFC, 2024b). These provide core guidance to IFC clients on identification and mitigation of risks as well as robust protocols to disclose stakeholder engagement and obligations for their project level activities. These performance standards are particularly used to govern investments in EMDEs and largely followed by OECD investors.

3.2 PRIVATE ESG STANDARDS AND SERVICES

Several private sector initiatives address ESG issues. Numerous corporate and NGO efforts running in parallel with the development of international standards are taking aim at developing services and standard to track and monitor the impact across the entire product lifecycle (from the extraction of resources and manufacturing through assembly, use and end-of-life).

EPEAT

The Global Electronics Council has established the Electronic Product Environmental Assessment Tool (EPEAT) Ecolabel for the electronics sector. Computers, imaging equipment, televisions and servers, as well as PV modules and inverters, can qualify for this label. Used by private and public buyers globally since 2006, the EPEAT Ecolabel relies on transparent, multi-attribute, life-cycle based ESG criteria developed by industry stakeholders (ANSI/NSF/UL). It is intended to encourage sustainability and independent third-party verification to provide confidence to stakeholders and drive low-carbon PV manufacturing across the supply chain (Global Electronics Council, 2024). The EPEAT criteria can be found in Table 4.

Table 4 **EPEAT Ecolabel criteria**

Climate change mitigation	Sustainable use of resources	Reduction of chemicals of concern	Corporate ESG performance
• Manufacturing energy efficiency • GHG emissions in manufacturing • LCA and disclosure of cumulative energy demand and global warming potential • Carbon footprint	• Recycled content • Design for recycling • Product take back and responsible recycling • Disclosure of recovery and recycling achievement • Material recovery targets • Efficient water uses in manufacturing	• Restricted substances in product – RoHS[7], REACH[8], halogenated substance • Substance inventory and disclosure • Alternatives assessment	• Social performance and audits • Worker and health safety • Environmental management system • Responsible material sourcing • Hot spot identification and leadership compared to industry

Source: (Parr, 2024).

To ensure the high technical and sustainable quality of products, many purchasing entities are starting to require or prefer the presence of the EPEAT Ecolabel. For example, in the United States EPEAT is currently the only approved ecolabel for PV modules and PPAs in the US Environmental Protection Agency's Recommendations of Specifications, Standards and Ecolabels for Federal Purchasing (Global Electronics Council, 2024).

To facilitate uptake of this ecolabel, EPEAT is aiming to replicate globally the successes of the French governmental PV tender model, which has an integrated binding CO_2 criterion as well as established non-financial criteria[9] (PV Thin, 2023).

The main feature of the standard is to determine a verified carbon footprint (VCF)[10] based on designated third-party audit that is confirmed annually to safeguard label credibility and improve its comparability to other initiatives. Extensive records and documentation are required for the audits, but PCRs are still not standardised. EN 15804 is an early attempt to define PCRs for PV, including the production of cells, wafers, ingot blocks, solar grade silicon, solar substrates, solar superstrates and other solar grade semiconductor materials.

7 Restriction of Hazardous Substances Directive.
8 Registration, Evaluation, Authorisation and Restriction of Chemicals.
9 Based on exchanges with technical editor for the Authoring Committee of the EPEAT PV Ultra Low Carbon Solar method.
10 To determine the carbon footprint, EPEAT has developed an ultra-low carbon solar method that establishes a carbon footprint threshold below which a module must demonstrate to achieve the EPEAT registration.

Some European countries have adopted national versions of the EN standard used in the building and construction industry for PV modules (Global Electronics Council, 2024). In 2024, the VCF approach was updated with the intent to add rigor and consistency to the LCA results to prevent companies from manipulating data to achieve an artificially low embodied carbon emission profile.[11]

NSF International

NSF International, is an independent NGO that oversees the NSF/ANSI 457 Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters. This standard aims to improve the performance profile of PV modules and inverters by using established scientific principles, materials and standards. It also provides a framework as well as a set of performance criteria that PV module/inverter manufacturers should consider during the design and production of these components. From a customer perspective, this standard provides a consensus definition on sustainability and performance metrics for these components. NSF/ANSI 457 can be used with other relevant standards to support the identification of sustainable products as well as provide market access to manufacturers that conform to the standard (Kelechava, 2020; NSF, 2019).

Solar Stewardship Initiative

The Solar Stewardship Initiative (SSI) was established by SolarPower Europe and Solar Energy UK in October 2022. The SSI is in the process of becoming a fully fledged multi-stakeholder initiative by 2025. SSI endeavours to work with all stakeholders across the solar PV sector, namely manufacturers, developers, installers and purchasers, with the objective of fostering ESG principles (responsible sourcing and production in tandem with stewardship of materials) across the supply chain. SSI also strives to ensure a just and inclusive energy transition as well as the respect of human rights to enhance end-to-end transparency, sustainability and ESG performance across the solar supply chain. Businesses actively involved in the solar value chain can apply to join the SSI and have their production sites certified against the SSI Standards (Solar Stewardship Initiative, n.d.a).

The SSI provides independent third-party assurance of production sites in the global solar value chain. The SSI ESG Standard, published in December 2023, covers ESG requirements for production sites engaged in the silicon supply chain, from raw materials to modules. The covered requirements are outlined in Table 5. The SSI Traceability Standard, to be published in December 2024, is set to take the SSI assurance scheme further. With the combination of the SSI ESG Standard and the SSI Supply Chain Traceability Standard, the SSI will be able to certify exactly how each link of the supply chain is connected, creating the so-called chain of custody (Solar Stewardship Initiative, n.d.a).

[11] Based on exchanges with technical editor for the Authoring Committee of the EPEAT PV Ultra Low Carbon Solar method.

Table 5 **Topics covered by the Solar Stewardship Initiative**

Governance and business ethics	Environment	Human and labour rights
1. Business integrity 2. Policy and management 3. Stakeholders and communities 4. Transparency 5. Responsible sourcing	6. Greenhouse gas emission management 7. Water management 8. Waste management 9. Pollution management 10. Biodiversity management 11. Circularity	12. Human rights 13. Labour rights 14. Occupational health and safety

Source: (Solar Stewardship Initiative, n.d.b).

The SSI standards are designed for use by SSI independent approved assessors to verify manufacturing sites. Assessors visit a site and follow a rigorous methodology of verification, including unsupervised worker interviews, site walkthroughs and documentation reviews. Only sites that allow such a methodology can be assessed. SSI manufacturing members are required to achieve SSI certification against applicable requirements for at least two of the member's sites within one year of joining the SSI and expected to increase the number of sites every year (Solar Stewardship Initiative, n.d.a).

Social Accountability

Social Accountability 8000 (SA 8000) was launched in 2014 with the intent of providing an auditable way to assess the elements presented in Table 6 (Social Accountability International, 2024). This voluntary standard also has a certification scheme to ensure organisation compliance with international and national human and labour rights based on the UN Declaration of Human Rights and International Labour Organization (ILO) recommendations, among other best practices (Social Accountability International, 2024). This standard is meant to empower and protect all personnel working in and/or associated with an organisation, irrespective of size, geographic location or industry sector. This standard also has a management system to support organisations' sustained compliance with SA 8000 as well as to promote continuous improvement, known as social performance (Social Accountability International, 2014).

Table 6 **Topics covered by the Social Accountability 8000 standard**

Governance and business ethics	Environment
1. Child labour 2. Forced or compulsory labour 3. Health and safety 4. Freedom of association and right to collective bargaining	5. Discrimination 6. Disciplinary practices 7. Working hours 8. Remuneration 9. Management system

Solar Training Standards Initiative

The **Solar Training Standards Initiative** is a new partnership between the Global Solar Council (GSC) and Global Wind Organisation (GWO) to introduce training standards for the global solar PV technician workforce. The main rationale behind this initiative is to facilitate reduced transaction costs, promote safety assurances and drive improved productivity in the solar PV industry. GSC will be leading the training development and GWO will engage with industry to develop the related standards that will promote the safety and growth of the global solar workforce. The initial outputs will focus on common work processes and how to address the hazards and risks that utility-scale solar PV technicians experience. The training on these standards will also ensure relevant skills and knowledge are imparted to trainees in alignment with job definitions provided by organisations such as American Clean Power Guidelines for Entry Level Solar Technician Training (Global Solar Council, 2024a).

The key objectives that this initiatives aims to achieve in the long term are: 1) promoting safety and protection to solar PV workers (in large companies or small and medium-sized enterprises) through certified training; 2) reducing damage of equipment and OPEX; 3) accelerating efforts towards creating a workforce ready to meet global climate priorities; 4) providing a reliable workforce standard that can be used by emerging economies; and 5) facilitating transferable skill development opportunities (Global Solar Council, 2024b).

Responsible Business Alliance – Validated Assessment Programme

The Responsible Business Alliance's Validated Assessment Programme is used by several industries to ensure compliance with the alliance's code of conduct. This auditing framework is a set of social, environmental and ethical industry standards that are based on the Universal Declaration of Human Rights, ILO Standards, OECD Guidelines for Multinational Enterprises and ISO standards, among others. While the code of conduct is primarily designed with the electronics industry as a focus, the principles can be applied to other industries (Responsible Business Alliance, 2024a).

The audit serves as a comprehensive risk assessment platform that includes a self-assessment questionnaire and involves third-party onsite social audits conducted by vetted auditors to reduce auditing burdens on manufacturers. The audit process also incorporates corrective action plans and remediation strategies, ensuring continuous improvement (Responsible Business Alliance, 2024b).

Environmental Product Declarations

Environmental Product Declarations (EPDs) provide another avenue to declare the environmental performance of products. These declarations allow for quantitative comparison of environmental performance between products that fulfil the same function. The international standard that provides guidance on this ISO14025:2006(en), Environmental labels and declarations — Type III environmental declarations — Principles and procedures (ISO, 2006). EPDs are commonly used in the building and construction sector for material selection, and their applications are now being explored for use in other sectors. However, it must be noted that not all EPDs are comparable due to varying methodology. For the solar PV industry, the PCR register by the Norwegian EPD system (which has also been adapted by the International EPD System) is a reference example that can be followed and has a methodology similar to that followed by EPEAT.

GAPS TO BE ADDRESSED

While there is significant QI in the PV industry, and most PV projects seem to be built to an acceptable quality level, an increasing number of stakeholders engaged in the PV market report a noticeable decline in quality. An analysis undertaken by the German Metrology Institute (PTB) noted that the reputation of solar PV has been impacted negatively when QI considerations have not been sufficiently addressed, especially in emerging economies. PTB's study found that key problems impacting operations of solar PV plants include but are not limited to: installation faults (accounting for over 50% of serious defects globally), low capacities for quality control of products (locally manufactured and imported) and appropriate site selection based on robust solar irradiation data profiles (Clean Energy Associates, 2024; PTB, 2021). These challenges impact the bankability of projects because investors are faced with the aftermath of underperforming assets.

The PV sector faces some existing challenges related to conformity assessment (and therefore reduced quality and reliability). **The market for conformity assessment is very diversified** wherein independent engineers (IEs; this includes owner engineers, lender engineers, etc.) continue to dominate the market. In addition to IEs, virtually all certification bodies (including IEC participants) are operating outside of the IEC/international system by offering conformity assessment to individual in-house standards.

Therefore, while there seems to be an increasing call for standardised conformity assessment from customers, **the effectiveness of certification is not adequate to avoid performance and safety issues.** At the same time, IE reports and technical consulting – each one proposing different scopes and references – continue to hold a strong position in the market. In some cases, banks and other relevant stakeholders have identified a connection between inferior IE reports and quality issues in the field (PTB, 2021).

The key challenge continues to be that of **convincing market participants of the value of compliance with international standards, and inspection and certification to those standards**. Several countries continue to mandate certification to outdated editions of IEC standards (IRENA, 2017; PTB, 2021). This undermines the goal of international commerce based on common certifications.

A grid-related gap in QI for PV that is becoming increasingly relevant is the **lack of standards for grid-forming converters**. Grid-forming converters are a stability necessity highlighted by system operators to prevent stability issues in transitioning from conventional synchronous generators to inverter-based resources. Some regulators are starting to require grid-forming capabilities for granting grid access to PV projects, among others, which are essential for the power system to cope with high shares of variable renewable energy. However, there are practically no standards on this regard, and the mentioned regulations are generally not exhaustive on the design parameters, which can jeopardise further deployment of PV in areas where they already represent a high share of the real-time electricity mix. Regulatory efforts should therefore be encompassed with prompt development of standards to facilitate industry adoption of this technology. Policy makers must support and promote the development of grid-forming converter standards, and this should be a priority action undertaken by international SDOs. If this is not investigated, there is a risk that it will impact global solar PV supply chain development while also leading to a gridlock effect for PV.

Another important gap is the **challenge of enforcing robust traceability across the whole supply chain**, as some suppliers may use substitute materials in modules. Although retesting is required to comply with IEC guidelines (IEC TS 62915), during expert interviews for this publication, some of them noted that manufacturers potentially "shop around" for certification bodies that will grant an extension (approval of a substitute material) for minimal cost and effort. These experts also noted that there are several examples where a single PV model number is allowed to have thousands of different material combinations in the bill of materials. In many cases, such substitutions are certified based on testing only one or two modules. As noted above, the proliferation of private schemes also constitutes a gap. There is currently no incentive to agree on a default market requirement for module performance beyond the basic IEC qualification standards. IEC TS 63209-1 was intended to simplify and streamline extended testing, but it has not yet been widely adopted.

From a macro perspective, the global solar industry is becoming increasingly data driven, with information exchanges occurring between different stakeholders in the value chain. Currently, **different markets are following their own protocols with regard to how data exchanges should occur, resulting in fragmentation and a lower ability to cater to demand responses**. There is also a need for accelerated efforts to expand existing and/or develop new standards and certification to cover Type A assets as well as distributed energy resources (such as inverters) (Solar Power Europe, 2023).

Appropriate site selection during the design phase of PV projects is another gap that is particularly prevalent in emerging markets and developing economies. Data on solar irradiance are necessary for planning; however, in many locations this is not available with a high degree of reliability (IRENA, 2017; PTB, 2021). Furthermore, data on other parameters – such as wind speed, precipitation, air humidity and salinity, dust emission, groundwater levels, and composition of the mounting ground – are neglected, which impacts the performance of PV systems (IRENA, 2017; PTB, 2021). Considerations of appropriate land and water utilisation need to be strengthened when developing solar PV projects to avoid the possibility of human rights infringements (IRENA, 2017; PTB, 2021).

Regarding the emerging ESG requirements, the PV industry must address several gaps in the methodology. Over the past several years, there has been considerable resistance to proposed regulations and private schemes. This resistance is primarily a reaction to the perceived financial and administrative burden of the proposals and a reluctance to be the first adopters among competitors (NSEFI and Solar Power Europe, 2023; Parr, 2024; PTB, 2021). Manufacturers have begun to provide sustainability declarations that many stakeholders consider to be chiefly a marketing tool and that raise concerns about the perception of greenwashing (NSEFI and Solar Power Europe, 2023; Parr, 2024). A gap that enables greenwashing is the lack of transparency and credibility of a global verification system that underpins the regulation of the data used in the LCA for materials and the electricity mix (ESIA, 2024; Global Electronics Council, 2024; IRENA, 2023c; Solar Stewardship Initiative, n.d.b).

In summary, the immediate challenges that need to be addressed with regard to QI and ESG for solar PV are:

- The fragmentation and lack of consensus needed to harmonise an international ESG standard – especially for solar PV manufacturing. Given the many technical PV standards and cost pressures, industry adoption of ESG is hampered by the absence of an internationally accepted single standard.

- The objectivity of audit criteria needs to be improved. International SDOs are making efforts to close this gap, but it is necessary for different stakeholders (government, industry associations, the private sector) to support the effort.

- A lack of clarity in VCF and other ESG criteria for upstream suppliers within the solar PV supply chain. Currently, these are usually based on manufacturer declarations. Undertaking third-party verification is not common in the industry.

- A lack of a consensus method to objectively evaluate and ascertain what constitutes forced labour. However, legislation such as the EU's Forced Labour Ban regulation and Corporate Sustainability Due Diligence Directive are examples of efforts that are being made to tackle this issue.

RECOMMENDATIONS

Broad recommendations that should be considered by policy and decision makers in addressing the solar PV gaps related to QI and ESG development, as discussed in the previous section, include:

Adopt a unified approach towards conformity assessments: A priority action is to facilitate the adoption of international conformity assessment schemes based on the latest editions of international standards. Private schemes should be harmonised to improve the consistency and reliability of results and to disincentivise "shopping around" for certificates. Likewise, a further standard for supplier qualification requirements and retesting guidelines would benefit the PV industry at large.

Raise awareness on ESG considerations in solar PV developments: Consensus needs to be developed around ESG requirements to encourage their uptake in the PV industry. Leveraging the existing international standards process, it would be useful to adopt the IEC TC 111 LCA guidance (IEC 63366) or to develop PV-specific requirements (PCR) in IEC TC 82. The established international systems for consensus of experts (*e.g.* IEC and ISO) provide the quickest and most effective path to achieve widespread acceptance in the PV marketplace. A potential contribution to implementing this recommendation would be to improve the PCRs for solar PV because LCAs or EPDs based on current PCRs are fraught with mistakes and/or misrepresentations. Some experts recommend that the Norwegian system (NPCR 079) be considered as a basis for updating solar PV PCRs with the objective of creating a centralised verification programme to ensure the accuracy of the LCAs and carbon footprints under its auspices. Exploring ways to incorporate international LCA methodologies into the existing private ESG standards/services is essential to promote harmonisation.

Develop robust carbon footprint frameworks: For the evaluation of environmental impact, upstream VCF criteria must be more clearly defined. For example, calculations based on local energy mix rather than national energy mix would provide more accurate assessments for specific manufacturing sites.[12] Purchased renewable attributes (REA), such as PPAs, are hard to trace and track outside the European Union and the United States. Given that over 50% of a PV module's carbon footprint is associated with the electricity mix used, unregulated use of site-specific electricity in manufacturing opens the potential for greenwashing (Khan *et al.*, 2024). Reliance on a national grid's electricity improves the credibility of the carbon footprint assessment while reducing the massive workload of verification of global REA certificates. One expert interviewed for this report described a case in Canada where the addition of rooftop PV was not considered to be economically justified because the calculations were based on the national energy supply, which is mainly low-cost hydropower, even though the local electricity rate is significantly higher than the cost of PV. There is also a need to provide additional and improved updates to transparent international life cycle inventories, which can provide a better basis to establish common thresholds. Furthermore, efforts should also be made to improve the consistency of the data that are used to define the kilowatt peak (kWp) of a panel being evaluated, because theoretically a manufacturer could use either the low or high end of its tested range of output.

Develop standards to support grid flexibility and effective demand response: To support the development of a robust data exchange system that underpins solar PV value chains, it is imperative that a single communication standard be established. An example of such an initiative is the IEEE 2030.5 standard in the United States, which has promoted significant harmonisation and consumer benefits. This standard can be replicated in other markets. To further promote market harmonisation, grid and transmission operators should also encourage compliance with standards on the certification for "requirement for generators" of Type A assets such as EN 50549-1 and EN 50549-2. Finally, more efforts are needed to develop new standards for the use of distributed energy resources (such as inverters and Internet of Things [IoT] products). An example of such a process is the UL 2941 being developed in the United States.

Create frameworks for assessing workforce well-being: It is also necessary to develop a common methodology to evaluate human and labour rights issues. This is a role that can be led by international human and labour rights organisations. One of the experts interviewed for this report described the difficulty of obtaining objective information from workers who are engaged in supply chain operations. In addition to forced labour evaluation, increasing efforts towards reskilling workers to contribute to the energy transition; increasing engagement with labour unions/community organzations to ensure reflection of worker rights in energy transition initiatives; actively developing robust health & safety protocols for workers are other elements that are essential within this recommendation (IRENA *et al.,* 2023).

5.1 Specific considerations for emerging market and developing economies

In addition to the broad recommendations outlined above, specific recommendations (from a QI perspective) are listed below that should be considered by emerging economies as they continue to build up their solar PV manufacturing capacities.

Engage with international QI organizations: First, developing countries should participate in the international standards development process. These countries are eligible to join organisations such as ISO and IEC as affiliate members for no cost. They must designate a national committee administrator (which is often the national standards body) and then they may nominate national experts to participate in TCs that work in solar PV (for example, IEC TC 82).

Consult and adopt international standards: Once the relationship with an international QI organisation is established, developing countries should adopt the latest edition of international standards for PV. Some organisations (such as the IEC) allow for national differences to be included as necessary, but creating special requirements for conformity to national standards is not recommended. There have been cases where countries have published national standards that were lacking in technical content or simply referred to other (international) standards. This tends to discourage manufacturers from participating in the market, because of the cost of certification to multiple standards.

[12] There is a delicate balance between the granularity of criteria (e.g. local energy mix vs. national grid) and verifiability. The more local one goes, the more difficult it is to verify; hence, this trade-off needs to be recognised.

Work with international PV laboratories: Emerging economies should ensure that their national quality assurance initiatives allow for support of local manufacturing. However, they should also enable collaboration with international suppliers where appropriate. This is because, in some cases, countries have developed bureaucratic structures and procedures that impede rather than encourage adoption of international standards. Instead, emerging countries should focus on establishing a relationship with major international PV laboratories. These organisations can help establish a national or regional laboratory for PV measurements and train local experts in measurement procedures. This will also require some investment in specialised testing equipment. The international laboratories can also provide primary reference devices (PV cells and modules), which can then be used by the national laboratory to calibrate secondary reference devices and make them available to local manufacturers. Refer to Table 7 below.

Table 7 **International PV laboratories for consideration of emerging economies**

NREL (USA)	IT (India)	PTB (Germany)	CSIRO (Australia)
ESTI (EU)	QEERI (Qatar)	F-ISE (Germany)	AIST (Japan)
SERIS (Singapore)	CENER (Spain)		

Prioritise the development of local "module" manufacturing capabilities: Finally, emerging economies should start accelerating efforts to encourage local module assembly by following best practices found in countries with strong PV manufacturing capabilities. The necessary equipment is standardised and readily available from established suppliers. The cost of starting up a module production facility is significantly lower than the investment required for PV cell or wafer manufacturing. The most important activity is to establish training programmes for assembly workers focused on developing a culture of quality. Particular attention should be given to the three key manufacturing processes of cell interconnection, lamination and power output testing (using the reference devices from certified national laboratories).

Follow best practices for solar PV site selection: According to (PTB, 2021), in undertaking PV plant design emerging economies should consider the following international standards: IEC 62548 Photovoltaic (PV) arrays – Design requirements, IEC 62124 Photovoltaic (PV) stand-alone systems – Design verification, and IEC 60364-7-712 "Electrical installations for buildings – Part 7 – Requirements for special installations or locations (Section 712: Solar photovoltaic (PV) power supply systems). Technical regulations usually inform safety requirements, and conforming to climate conditions is dependent on national context. However, as an example, IEC 61701 provides guidance on salt-mist corrosion testing of PV modules for locations near the sea. For personnel who undertake PV system verification responsibilities, it is important that they are certified by a body that is accredited according to ISO 17024.

By following these suggested recommendations, emerging economies can increase their engagement with the global PV industry and participate in the creation of a new energy supply based on renewable sources. Implementing the elements of QI and ESG is the key to producing reliable high-quality products, and it is imperative that these economies leapfrog and take these actions as early as possible.

CONCLUSION

Governments have the capacity and power to adopt policies to encourage key ESG developments. However, end users of PV also have a strong influence on what is expected in the industry. Past efforts have shown that collaboration between the public and private sectors can achieve mutually beneficial results. To conclude this report, some actionable approaches that can be taken by solar PV stakeholders to factor in QI and ESG considerations in solar supply chain developments are presented in Table 8.

Table 8 **Considerations to strengthen global solar PV supply chains**

Goal	Approaches
1. **Ensure environmental and social sustainability.**	• Accelerate efforts to decarbonise manufacturing facilities and power grids through the integration of renewable power to reduce solar PV value chain emissions, especially in countries that already produce panels. • Develop new and/or expanding existing skills development programmes to expand general workforce engagement in the solar PV sector. The solar PV industry's continued growth will create new employment opportunities for both skilled and low-skilled workers. Increasing conformance to international employment standards as well as transparency on corporate policy can improve working conditions. A successful example is Denmark's Confederation of Danish Industry which support work skill development by supporting development of knowledge-sharing platforms and providing resources to ensure businesses activities are inclusive. • Continue to advocate for strong and engaged participation in the international QI ecosystem to allow for effective knowledge exchange as well as participation in QI service development. This can also be used to guide emerging markets and developing economies on how to develop an ecosystem where general quality and ESG protocols are enforced. • Consider kWp as the functional unit to allow for granular assessment of PV module sustainability and ensure methodology to assure compliance is achieved through internationally recognised carbon footprint assessment methods. • Consider using the cradle-to-gate system boundary, with kWp as a functional base, when undertaking LCAs for solar PV modules to ensure the complete value chain is factored into the assessment. • Ensure factors such as water intensity (in arid regions), appropriate land utilisation (especially if soil is fertile) and evaluation of project impact on surrounding communities are considered in PV project site selection, especially in emerging economies. International standards and protocols addressing these factors are available.

2. **Diversify solar PV chains to catalyse resilience**	• Share expert knowledge and best practices with emerging economies to facilitate diversification. Currently, a large majority of the global solar PV manufacturing capabilities as well as raw material processing is concentrated in select markets, which leaves supply chains vulnerable to disruption. • Diversify polysilicon and ingot/wafter manufacturing along the solar PV supply chain through effective policy and knowledge transfer tools. This capital-intensive part of the value chain has the highest market share and concentration. Emerging markets and developing economies should consider establishing their module assembly/manufacturing capacities before exploring upstream segments. • Ensure the supply chain is prepared for imminent power system needs by adopting regulatory frameworks and standards for grid-forming converters. • Harness international collaboration (between public and private stakeholders) to diversify import sources and reduce supply risks. Many economies are reliant on imports from solar PV leaders to satisfy their energy supply and demand requirements. • Expand local solar PV manufacturing capabilities at a national level to reinforce supply chain resiliency. Governments need to develop and replicate best practice policy and financial incentives to achieve this goal. For example, governments could subsidise electricity rates specifically for facilities that are manufacturing polysilicon, ingots or wafers to incentivise more investments in these segments of the solar PV supply chain.
3. **Continue to develop policy frameworks that accelerate energy security.**	• Energy security mitigation approaches should consider the unique political, economic, energy profiles and risk mitigation capabilities of each country. Strategies should be based on a robust assessment of these parameters as well as identification of specific/niche vulnerabilities. • Investments in energy assets and infrastructure today must factor in energy security requirements keeping a transitional and long-term perspective in mind. Decentralised solutions such as solar PV along with increased end-use electrification are expected drive the clean energy transition forward. New infrastructure must therefore take into consideration these strategic trends. • Countries, especially emerging economies, should place an emphasis on identifying segments of the solar PV supply chain where they would envision expanding their capabilities. The identification of segments should consider their alignment with domestic development priorities, how local capabilities can be leveraged, and avenues for international co-operation and partnerships. • Data deficiencies must be addressed to promote transparency across established and emerging cross-border trade routes. The establishment of new and/or adoption of existing certification, standards and transparency mechanisms is essential to facilitate energy security as well as reliable carbon accounting.

Source: (ESIA, 2024; IEA, 2022; IRENA, 2024f; IRENA et al., 2023; PTB, 2021).

REFERENCES

ADGM (2023), "ADGM Implements its Sustainable Finance Regulatory Framework", https://www.adgm.com/media/announcements/adgm-implements-its-sustainable-finance-regulatory-framework

ASTM (2024), "Committee E44 Scope", www.astm.org/get-involved/technical-committees/committee-e44/scope-e44

Casey, J. (2024), "'A huge opportunity': Michelle Davies on ESG compliance in European solar", https://www.pv-tech.org/a-huge-opportunity-michelle-davies-on-esg-compliance-in-european-solar/

Chen, S., et al. (2023), "Environmental, social, and governance (ESG) performance and financial outcomes: Analyzing the impact of ESG on financial performance", Elsevier, vol. 345/1, https://doi.org/10.1016/j.jenvman.2023.118829

Clean Energy Associates (2024), "Solar PV module quality risks", https://info.cea3.com/hubfs/CEA%20Solar%20PV%20Module%20Quality%20Risks%20Report.pdf

Crooks, E. (2024), "China's solar growth sends module prices plummeting", *Wood Mackenzie*, https://www.woodmac.com/news/opinion/chinas-solar-growth-sends-module-prices-plummeting/

Deloitte (2023), "2024 renewable energy industry outlook", https://www2.deloitte.com/us/en/insights/industry/renewable-energy/renewable-energy-industry-outlook.html

Deloitte (2024), "A landmark decision for climate disclosure requirements", https://www2.deloitte.com/us/en/pages/audit/articles/sec-climate-disclosure-guidance.html

Dimapilis, M. (2024), "The State of ESG Reporting in the Middle East", https://www.azeusconvene.com/esg/articles/esg-reporting-in-the-middle-east

DOE (2024), *"Quarterly Solar Industry Update", Solar Energy Technologies Office*, https://www.energy.gov/eere/solar/quarterly-solar-industry-update

EC JRC (2023), *Photovoltaics in the European Union - Status report on technology development, trends, value chains and markets*, Joint Research Centre, Luxembourg, https://publications.jrc.ec.europa.eu/repository/handle/JRC135034?mode=full

ESIA (2024), Comprehensive strategies for carbon footprint assessment: Best practices for European sustainability directives for PV modules, European Solar PV Industry Alliance, Brussels, https://solaralliance.eu/wp-content/uploads/2024/08/ESIA-Recommendation-Paper-Series-VII.pdf

ETIP PV (2023), *PV Manufacturing in Europe: understanding the value chain for a successful industrial policy*, ETIP Photovoltaics, https://etip-pv.eu/publications/etip-pv-publications/download/pv-industry-white-paper-6

EU Commission (2024a), "Corporate sustainability reporting", https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en

EU Commission (2024b), "Waste from Electrical and Electronic Equipment (WEEE)", https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en

EU Commission (2024c), "Products made with forced labour to be banned from EU single market", https://www.europarl.europa.eu/news/en/press-room/20240419IPR20551/products-made-with-forced-labour-to-be-banned-from-eu-single-market

EUROPEN (2015), "Extended Producer Responsibility (EPR) for used packaging", https://www.europen-packaging.eu/wp-content/uploads/2021/04/EUROPEN-factsheet-on-EPR-for-used-packaging.pdf

Global Electronics Council (2024), "About EPEAT", *Global Electronics Council*, https://www.epeat.net/about-epeat

Global Solar Council (2024a), "GSC and training standards body GWO launch Solar Training Standards Initiative", www.globalsolarcouncil.org/news/gsc-and-training-standards-body-gwo-launch-solar-training-standards-initiative/

Global Solar Council (2024b), "The GSC had its kick-off meeting for the Solar Training Standards Initiative", LinkedIn, www.linkedin.com/feed/update/urn:li:activity:7234508494324846592/

Green Rhino Energy (n.d.), "The PV Value Chain", *Green Rhino Energy*, https://www.greenrhinoenergy.com/solar/technologies/pv_valuechain.php (accessed 25 June 2024).

Henisz, W., et al. (2019), Five ways that ESG creates value, McKinsey & Company, www.mckinsey.com/~/media/McKinsey/Business%20Functions/Strategy%20and%20Corporate%20Finance/Our%20Insights/Five%20ways%20that%20ESG%20creates%20value/Five-ways-that-ESG-creates-value.ashx

ICTSD (2017), Standards in the solar photovoltaic value chain in relation to international trade, International Centre for Trade and Sustainable Development, www.greenpolicyplatform.org/sites/default/files/downloads/resource/ICTSD_standards_in_the_solar_photovoltaic_value_chain_-_final.pdf

IEA (2022), *Solar PV Global Supply Chains*, International Energy Agency, Paris, https://www.iea.org/reports/solar-pv-global-supply-chains

IEA (2024), *Advancing Clean Technology Manufacturing*, International Energy Agency, Paris, France, https://www.iea.org/reports/advancing-clean-technology-manufacturing

IEC (2023), "Product category rules for life cycle assessment of electrical and electronic products and systems.", IEC, https://www.iec.ch/ords/f?p=103:38:611367437665866::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1314,23,104630

IEC (2024a), "What is conformity assessment", www.iec.ch/conformity-assessment/what-conformity-assessment

IEC (2024b), "National Committees", www.iec.ch/national-committees

IEC (2024c), "Technical committees and subcommittees", www.iec.ch/technical-committees-and-subcommittees#tcfacts

IEC (2024d), "TC 82 scope", www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID:1276

IFC (2024a), "ESG Policies and Standards", https://www.ifc.org/en/what-we-do/sector-expertise/sustainability/policies-and-standards

IFC (2024b), "IFC's Performance Standards on Environmental and Social Sustainability", https://www.ifc.org/en/insights-reports/2012/ifc-performance-standards

IRENA (2015), *Quality infrastructure for renewable energy technologies: Guidelines for policy makers*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2015/Dec/Quality-Infrastructure-for-Renewable-Energy-Technologies-Guidelines-for-Policy-Makers

IRENA (2017), *Boosting solar PV markets: The role of quality infrastructure*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2017/Sep/Boosting-solar-PV-markets-The-role-of-quality-infrastructure

IRENA (2023a), *World energy transitions outlook 2023: 1.5°C pathway*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023

IRENA (2023b), *Renewable energy statistics 2023*, International Renewable Energy Agency, www.irena.org/Publications/2023/Jul/Renewable-energy-statistics-2023

IRENA (2023c), *Creating a global hydrogen market: Certification to enable trade*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Jan/Creating-a-global-hydrogen-market-Certification-to-enable-trade

IRENA (2024a), *Tracking COP28 outcomes: Tripling Renewbale Power Capacity by 2030*, International Renewable Energy Agency , Abu Dhabi, www.irena.org/Publications/2024/Mar/Tracking-COP28-outcomes-Tripling-renewable-power-capacity-by-2030

IRENA (2024b), *Renewable capacity statistics 2024,* International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024

IRENA (2024c), *Renewable power generation costs in 2023,* International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023

IRENA (2024d), *Renewable energy statistics 2024,* International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024

IRENA (2024e), *Small island developing states at a crossroads: The socio-economics of transitioning to renewables*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Mar/SIDS-at-a-Crossroads-The-socio-economics-of-transitioning-to-renewables

IRENA (2024f), *Geopolitics of the energy transition: Energy security*, International Renewable Energy Agency, www.irena.org/Publications/2024/Apr/Geopolitics-of-the-energy-transition-Energy-security

IRENA and ILO (2023), *Renewable energy and jobs: Annual review 2023*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Mar/Renewable-capacity-statistics-2023

ISO (2006), "Environmental labels and declarations — Type III environmental declarations — Principles and procedures", https://www.iso.org/obp/ui/#iso:std:iso:14025:ed-1:v1:en

ISO (2021a), "Environmental management systems — Requirements with guidance for use", ISO, https://www.iso.org/standard/60857.html

ISO (2021b), "Governance of organizations — Guidance", ISO, https://www.iso.org/standard/65036.html

ISO (2021c), "Guidance on social responsibility", ISO, https://www.iso.org/standard/42546.html

JA Solar (2024), *JA Solar Sustainability and ESG Report 2023*, JA Solar, http://static.cninfo.com.cn/finalpage/2024-07-10/1220589742.PDF

Kelechava, B. (2020), "Solar PV modules – Sustainability leadership objectives", https://blog.ansi.org/2020/05/solar-pv-sustainability-leadership-ansi-457/

Khan, A. A., et al. (2024), "The European Union's Ecodesign Directive – Analysis of carbon footprint assessment methodology and implications for photovoltaic module manufacturers", vol. 8/10, https://doi.org/10.1002/solr.202301011

Mathis, S., and Stedman, C. (n.d.), "Environmental, Social and Governance (ESG)", *TechTarget*, https://www.techtarget.com/whatis/definition/environmental-social-and-governance-ESG

Ministry of Housing and Urban Rural Development (2019), "Application technical standard of building photovoltaic system", General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China.

Mounsey, A. (2024), "What do we see (even deeper) in the PV Supply Chain?", LinkedIn, https://www.linkedin.com/pulse/what-do-we-see-even-deeper-pv-supply-chain-alastair-mounsey-ignne/

National Energy Administration (2024), [Solar power generation capacity exceeded 600 million kilowatts, and the proportion of coal-fired power generation capacity fell below 40% for the first time]", https://www.nea.gov.cn/2024-02/02/c_1310763217.htm

NREL (2024), "Spring 2024 - Solar Industry Update", https://www.nrel.gov/docs/fy24osti/90042.pdf

NSEFI, and Solar Power Europe (2023), *PV Supply Chain Resilience & Sustainability: India-EU Cooperation*, National Solar Energy Federation India and Solar Power Europe, https://www.cecp-eu.in/uploads/documents/events/94/PWC_Supply_Chain_Diversification_V3_Single.pdf

NSF (2019), "Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters", National Science Foundation and American National Standard for Sustainability, Ann Arbor, Michigan, https://globalelectronicscouncil.org/wp-content/uploads/NSF-457-2019-1.pdf

Parr, M. (2024), "EPEAT standard for PV", LinkedIn, www.linkedin.com/feed/update/urn:li:activity:7234298234611941376/

Peters, I. M., et al. (2021), "The value of stability in photovoltaics", vol. 5/12, https://doi.org/10.1016/j.joule.2021.10.019

PRI (2021), *Principles for Responsible Investment*, PRI Associates, https://www.unpri.org/download?ac=10948

PTB (2021), Quality infrastructure for photovoltaic systems, Physikalisch-Technische Bundesanstalt, Braunschweig (Germany), www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_9/9.3_internationale_zusammenarbeit/publikationen/Studies/PTB_Study_QI_for_PV_EN.pdf

PV Thin (2023), "Impact mechanisms of non-financial criteria and the need for resilience criteria in German PV tender", www.pvthin.org/wp-content/uploads/2023-09-Working-Paper-NFC-Impact-Mechanisms.pdf

Radzi, S., et al. (2023), "An overview of environmental, social and governance (ESG) and company performance", European Proceedings of Social and Behavioural Sciences, https://doi.org/10.15405/epsbs.2023.11.90

Responsible Business Alliance (2024a), "Code of Conduct", https://www.responsiblebusiness.org/code-of-conduct/

Responsible Business Alliance (2024b), "Validated Assessment Program (VAP)", https://www.responsiblebusiness.org/vap/about-vap/

Segal, M. (2024), "Australia Passes Law to Begin Mandatory Climate Reporting in 2025", https://www.esgtoday.com/australia-passes-law-to-begin-mandatory-climate-reporting-in-2025/

SEIA (2024), *Solar Market Insight Report Q2 2024*, Solar Energy Industries Association, Washington DC, USA, https://www.seia.org/research-resources/solar-market-insight-report-q2-2024

Şeker, Y., and Şengür, E. D. (2021), "The impact of environmental, social, and governance (ESG) performance on financial reporting quality: International evidence", Ekonomika, vol. 100/2, https://doi.org/10.15388/Ekon.2021.100.2.9

Shanghai Electric Power Design Institute Co., Ltd. (2012), "Code for Design of Photovoltaic Power Stations", Ministry of Housing and Urban Rural Development.

Social Accountability International (2014), "Social Accountability 8000", Social Accountability International, https://sa-intl.org/wp-content/uploads/2020/02/SA8000Standard2014.pdf

Solar Power Europe (2023), "High-level standardisation forum – Green Electricity System Workstream", https://single-market-economy.ec.europa.eu/single-market/european-standards/standardisation-policy/high-level-forum-european-standardisation_en

Solar Power Europe (2024), *Global Market Outlook For Solar Power 2024 - 2028*, Solar Power Europe, Brussels, Belgium, https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2024-2028#download

Solar Stewardship Initiative (n.d.a), "Get Certified", *Solar Stewardship Initiative*, https://www.solarstewardshipinitiative.org/get-certified/

Solar Stewardship Initiative (n.d.b), "ESG Standard", *Solar Stewardship Initiative*, https://www.solarstewardshipinitiative.org/ssi-standards/esg-standard/

"Solar Supply Chain Europe" (2024), SinoVoltaics, https://sinovoltaics.com/sinovoltaics-europe-solar-energy-supply-chain-map/

"Solar Supply Chain India" (2024), SinoVoltaics, https://media-01.imu.nl/storage/sinovoltaics.com/14240/sinovoltaics_sscm_india_q1-2024.pdf

"Solar Supply Chain North America" (2024), SinoVoltaics, https://sinovoltaics.com/sinovoltaics-us-solar-market-supply-chain-map-north-america/

United States Congress (2021), "To ensure that goods made with forced labor in the Xinjiang Uyghur Autonomous Region of the People's Republic of China do not enter the United States market, and for other purposes.", H.R.6256, https://www.congress.gov/bill/117th-congress/house-bill/6256/text

United States Government (2024), "23.109-3 Products and services that are subject to EPA Recommendations of Specifications, Standards, and Ecolabels", www.acquisition.gov/far/23.108-3

United States Securities and Exchange Commission (2024), "SEC Adopts Rules to Enhance and Standardize Climate-Related Disclosures for Investors", https://www.sec.gov/newsroom/press-releases/2024-31

U.S. Customs and Border Protection (2024), "Uyghur Forced Labor Prevention Act", https://www.cbp.gov/trade/forced-labor/UFLPA

VDMA (2024), *International Technology Roadmap for Photovoltaics (ITRPV) - 2023 results*, Frankfurt am Main, Germany, https://www.vdma.org/international-technology-roadmap-photovoltaic

Wiser, R., et al. (2020), "Benchmarking Utility-Scale PV Operational Expenses and Project Lifetimes: Results from a Survey of U.S. Solar Industry Professionals", *Lawrence Berkeley National Laboratory*, https://escholarship.org/uc/item/2pd8608q

WoodMac Mackenzie (2024a), "Global solar module manufacturer ranking 2024", Edinburgh, www.woodmac.com

WoodMac Mackenzie (2024b), "Global solar PV supply chain quarterly briefing: Q2 2024", Edinburgh, www.woodmac.com

Wood Mackenzie (2024c), "Navigating turbulence in the US solar supply chain", Edinburgh, www.woodmac.com

Wood Mackenzie (2024d), "Wood Mackenzie PV Pulse - August 2024", Edinburgh, www.woodmac.com

Xu, Y., and Zhu, J. (2024), "The effect of environmental, social, and governance (ESG) performance on corporate financial performance in China: Based on the perspective of innovation and financial constraints", MDPI, vol. 16/8, https://doi.org/10.3390/su16083329

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Page 21: Energy storage systems battery container units with solar panels @Freepick

Page 26: Solar panel manufacturing @Freepick

Page 32: Engineer using laptop after installing solar panels @Freepick

Page 33: Ingot plates @Freepick

Page 33: Pollysilicon @Freepick

Page 33: Silicon wafers @Freepick

Page 33: Ingot @Freepick

Page 33: PV cell @Freepick

Page 36: PV cell manufacturing equipment @Freepick

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Page 60: A man with white helmet near solar panel @Freepick

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