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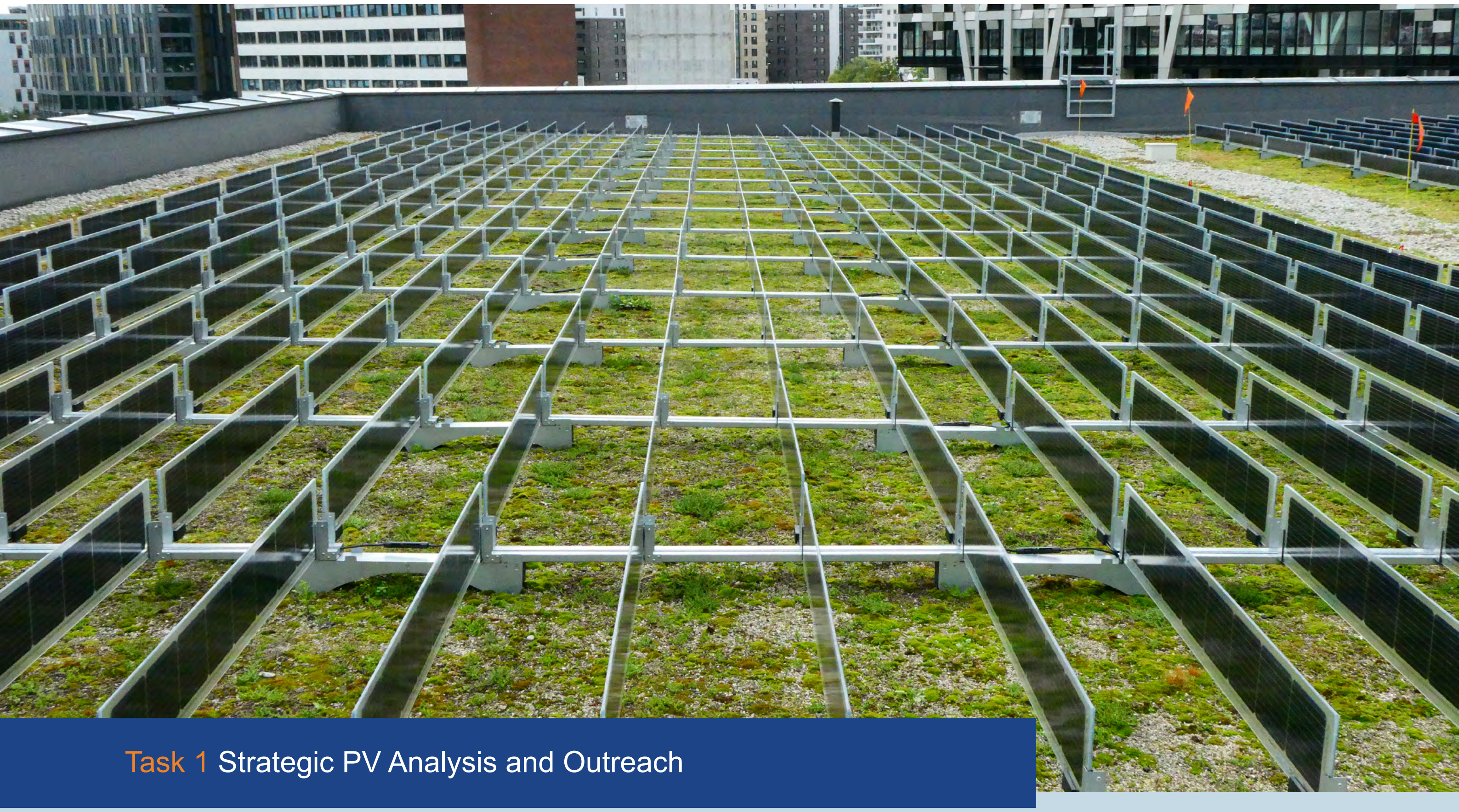
International Energy Agency
Photovoltaic Power Systems Programme



Task 1 Strategic PV Analysis and Outreach

PVPS

TRENDS IN PHOTOVOLTAIC APPLICATIONS 2024

REPORT IEA PVPS T1-43:2024

PHOTOVOLTAIC POWER SYSTEMS TECHNOLOGY COLLABORATION PROGRAMME

WHAT IS IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of thousands of experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas. This report has been prepared under Task 1, which deals with market and industry analysis, strategic research and facilitates the exchange and dissemination of information arising from the overall IEA PVPS Programme.

The IEA PVPS participating countries in 2023 are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, South Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Türkiye, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance (SEPA), the Solar Energy Industries Association, the Solar Energy Research Institute of Singapore and Enercity SA are also members.

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ISBN 978-3-907281-68-0 : Trends in Photovoltaic Applications 2024.

REPORT SCOPE AND OBJECTIVES

The Trends report's objective is to present and interpret developments in the PV power systems market and the evolving applications for these products within this market. These trends are analysed in the context of the business, policy and nontechnical environment in the reporting countries.

This report is prepared to assist those who are responsible for developing the strategies of businesses and public authorities, and to support the development of medium-term plans for electricity utilities and other providers of energy services. It also provides guidance to government officials responsible for setting energy policy and preparing national energy plans. The scope of the report is limited to PV applications with a rated power of 40 W or more. National data supplied are as accurate as possible at the time of publication. Data accuracy on production levels and system prices varies, depending on the willingness of the relevant national PV industry to provide data. This report presents the results of the 27th international survey. It provides an overview of PV power systems applications, markets and production in the reporting countries and elsewhere at the end of 2023 and analyses trends in the implementation of PV power systems between 1992 and 2023. Key data for this publication were drawn mostly from national survey reports and information summaries, which were supplied by representatives from each of the reporting countries. Information from the countries outside IEA PVPS are drawn from a variety of sources and, while every attempt is made to ensure their accuracy, the validity of some of these data cannot be assured with the same level of confidence as for IEA PVPS member countries.

ACKNOWLEDGMENT

This report has been prepared under the supervision by Task 1 participants. A special thanks to all of them.

FOREWORD

2023 was another record year for PV development and the energy transition but also a tumultuous one whose effects will have long-lasting impact on the PV industry.

Installations reached the astonishing value of 456 GW in a contrasted market: while the Chinese PV market grew significantly to absorb its own industry's overcapacities, the rest of the global PV market experienced a strong, but very much less impressive development to reach 181 GW. The year-on-year change brought the Chinese PV market well above the sum of all other markets globally, concentrating PV development at a never-seen level.

More than 1.6 TW of PV systems were operational at the beginning of the year 2024, producing more than 2 135 TWh of electricity, or 8.3% of the global electricity demand. The contribution of PV to reducing greenhouse gases emissions amounted to around 0.92 GTons of CO_2, or 2.5% of all emissions from the energy sector if we consider it now replaces baseload generation.This astonishing number confirms the status of PV as a key energy source of this century and its ability to provide affordable, decarbonized and scalable electricity suitable for all locations and system sizes.

PV is reaching maturity whilst diversifying its uses: agrivoltaics are one the key features of the year 2023, with developers of PV systems embracing the need to ensure a sustainable dual usage of land, enhancing or maintaining agriculture while adding energy production. In numerous regions, storage already improves the dispatchability of PV electricity whilst supporting stable networks and allowing increasingly high penetration rates of PV. Massive plans have been announced to either transport electricity to distant consumption sites or transform competitive PV electricity into liquid fuels. Green hydrogen and its derivatives aiming at feeding the industry with cleaner hydrogen or other chemicals could, in the coming years, open a path for starting the decarbonization of complex industrial processes.

With 7 million jobs in the solar PV sector, the contribution to the global economy has significantly accelerated in the last years, and PV contributes massively to the economy of numerous countries.

However, as 2023 has shown, the development of PV in countries with a rather stable power mix suffered from setbacks and delays. While China was accelerating its development, other countries like the USA or India increased volumes but could have achieved even higher installation levels, had various administrative, political or local issues, starting with weak grids or limited social acceptance, been resolved. Other countries couldn't match the Chinese acceleration and the PV manufacturing industry suffered huge overcapacities that resulted in a complete collapse of the price of PV components, especially modules. These low prices continue in 2024 and threaten the viability of the entire PV manufacturing industry, not only in China, but in other countries and regions where projects that were intended to create local jobs and involve populations in the development of PV have been at at risk.

This temporary imbalance between manufacturing supply and demand has put tremendous pressure on the manufacturing industry and will probably lead consolidation an possible bankruptcies. The current (mid 2024) low prices can be considered as unsustainable, however the competitiveness of PV was already guaranteed on mid 2023 prices, and prospects for a fast development in the coming years remain bright in many countries.

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Manager Task 1
IEA PVPS Programme

Daniel Mugnier
Chair
IEA PVPS Programme

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PHOTOVOLTAIC POWER SYSTEMS PROGRAMME WWW.IEA-PVPS.ORG

TOTAL BUSINESS VALUE IN PV SECTOR IN 2023

$400 BILLION USD

TOP 5 PV MARKETS IN 2023

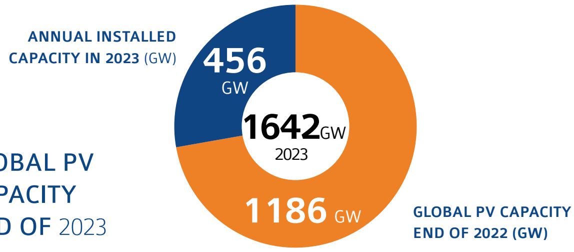
CHINA	277 GW
EU	59.8 GW
USA	33.9 GW
INDIA	13.0 GW
BRAZIL	12.4 GW

PV CONTRIBUTION TO ELECTRICITY DEMAND

8.3%

Share of PV in the global electricity demand in 2023

GLOBAL PV CAPACITY END OF 2023



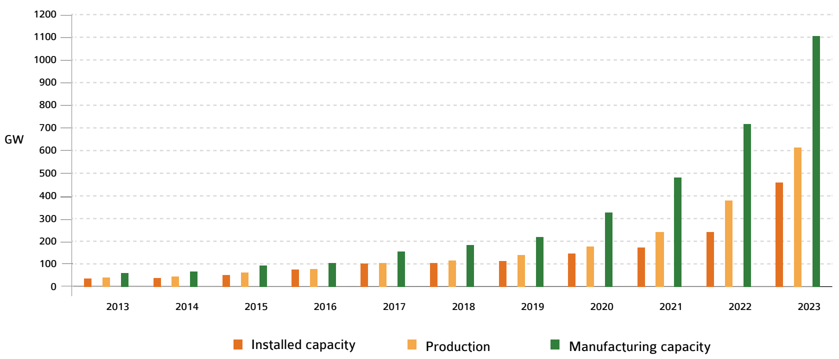
CLIMATE CHANGE IMPACTS

923

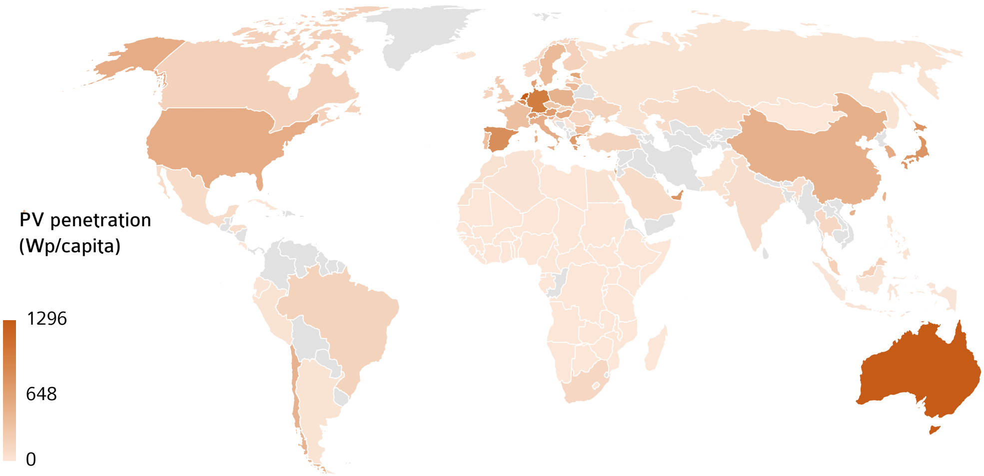
million tons of CO_2 **saved** in **2023**

* method changed from 2022; now assuming PV replaces baseload generation

YEARLY PV INSTALLATION, MODULE PV PRODUCTION AND MODULE PRODUCTION CAPACITY 2013-2023 (GW)



PV PENETRATION PER CAPITA IN 2023



54 COUNTRIES REACHED AT LEAST **1 GWp** IN 2023

PV POWER PER CAPITA

1. AUSTRALIA (1 296 Wp/CAP)
2. THE NETHERLANDS (1 288 Wp/CAP)
3. GERMANY (974 Wp/CAP)
4. BELGIUM (842 Wp/CAP)
5. SPAIN (806 Wp/CAP)

36 COUNTRIES INSTALLED AT LEAST **1 GWp** IN 2023

SOURCE IEA PVPS & OTHERS

one

INTRODUCTION TO THE CONCEPTS AND METHODOLOGY

PV TECHNOLOGY

Photovoltaic (PV) devices convert light directly into electricity and should not be confused with other solar technologies such as concentrated solar power (CSP) or solar thermal for heating and cooling. The key components of a PV power system are various types of photovoltaic cells (often called solar cells) interconnected and encapsulated to form a photovoltaic module (the commercial product), the mounting structure for the module or array, the inverter (one or multiple, essential for grid-connected systems and required for most off-grid systems) the cabling to connect the modules with each other and with the inverter(s), the storage battery and charge controller (for off-grid systems but also increasingly for grid-connected ones).

CELLS, MODULES AND SYSTEMS

Photovoltaic cells represent the smallest unit in a photovoltaic power producing device. Wafer sizes, and thus cell sizes, have progressively increased, as this is considered by industrial actors to be an easy way to improve cell and module wattage. Until recently, wafer sizes ranged from 156.75 x 156.75 square mm (named M2) up to 210 x 210 square mm (named M12). In 2023, a variety of cell sizes and shapes were present on the market, although a majority of cells were 210 mm square and 182 mm square. However, in 2023 and 2024, major manufacturers came to a consensus and agreed to standardise towards rectangular cells, either the 182R - a cell with a short side of 182mm and a long side from 188 mm up to 210 mm – or the 210R (182 mm x 210 mm) and consequently these are expected to progressively replace the 182 mm square or 210 mm square present on the market in 2023. In general, cells can be classified as wafer-based crystalline silicon (c-Si) (mono- and multi-crystalline), compound semiconductor (thin-film), or organic.

Today, c-Si technologies account for more than 98% of the overall cell production. Monocrystalline or Single crystalline PV cells, formed with wafers manufactured using a single-crystal growth method, feature commercial efficiencies between 20% and 25% (single junction). The silicon PV module market is nearly exclusively composed of these cells (approaching 100%), as they have replaced multicrystalline silicon (mc-Si) cells, also called polycrystalline. These were formed with multicrystalline wafers, manufactured by a cast solidification process. They were less efficient, with an average conversion efficiency of approximately 18% - 21% in mass production (single-junction) and although there are nearly no new modules with this technology entering the market, they are present in a large volume of already operational PV systems.

Thin-film cells are formed by depositing extremely thin layers of photovoltaic semiconductor materials onto a backing material such as glass, stainless steel or plastic. III-V compound semiconductor PV cells are formed using materials such as Gallium Arsenide (GaAs) on Germanium (Ge) substrates and have high conversion efficiencies from 25% up to 30% (not concentrated). Due to their high cost, they are typically used in space applications. Thin-film modules used to have lower conversion efficiencies than basic crystalline silicon technologies, but this has changed in recent years. They are potentially less expensive to manufacture than crystalline cells thanks to the reduced number of manufacturing steps from raw materials to modules, and to reduced energy demand.

PV TECHNOLOGY / CONTINUED

Thin-film materials commercially used are cadmium telluride (CdTe), and copperindium-(gallium)-diselenide (CIGS and CIS). Amorphous (a-Si) and micromorph silicon (μ-Si) used to have a significant market share but failed to follow both the price decline of crystalline silicon cells and the efficiency increase of other thin film technologies. The thin-film cell technology efficiency ranges between 14% (OPV)[1] , 12% (a-Si), 19.2% (CIGS and CIS), 19.9% (CdTe), 25.1% single junction GaAs and 31.2% three-junction GaAs (non-concentrated) and above 35% for some CPV modules. It should be noted that cell conversion efficiencies are generally 2.5% higher than the commercial module efficiency indicated here.

Organic thin-film PV (OPV) cells use dye or organic semiconductors as the light-harvesting active layer. Organic and inorganic hybrid materials such as perovskites are also used for photovoltaic materials. Perovskite technology has created increasing interest and research over the last few years and is currently the fastest-advancing solar technology. Despite the potentially low production costs, stable products are difficult to manufacture, nevertheless development and demonstration activities are underway. Tandem cells based on perovskites are an important focal point of current research, with either a crystalline silicon base or a thin film base and could hit the market sooner than pure perovskites products. In 2023, an experimental perovskite solar cell achieved 33.9% efficiency in silicon-based tandem and 24.9% efficiencies in CIGS or CIS-based tandems. Several Chinese manufacturers have announced shipping perovskite modules in 2022 and 2023.

Photovoltaic modules are typically rated from 350 W to 600 W, or even up to 740W in 2023 for bifacial glass modules, depending on the technology and the size – although typical sizes for residential systems in 2023 was 350 W to 435 W, with larger modules above 540 W more often reserved for centralised ground mounted systems. Specialized products for building integrated PV systems (BIPV) exist, sometimes with higher nominal power due to their larger sizes. Crystalline silicon modules consist of individual PV cells connected and encapsulated between a transparent front, usually glass, and a backing material, usually plastic or glass. Thin-film modules encapsulate PV cells formed into a single substrate, in a flexible or fixed module, with transparent plastic or glass as the front material.

A PV system consists of one or several PV modules, connected to either an electricity network (grid-connected PV) or to a series of loads (off-grid).

1 Module efficiencies are reported from the NREL Champion Module Efficiencies for small or standard modules: https://www.nrel.gov/pv/module-efficiency.html

It comprises various electric devices aimed at adapting the electricity output of the module(s) to the standards of the network/grid or the load: inverters, charge controllers or batteries.

A wide range of mounting structures have been developed — especially for BIPV — including PV facades, sloped and flat roof mountings, integrated (opaque or semi-transparent) glass-glass modules and PV tiles.

Single or two-axis tracking systems are attractive for ground-mounted systems, particularly for PV utilization in countries with a high share of direct irradiation. By using such systems, the energy yield can be increased from 15% to 35% for single axis and 25% to 50% for dual axis trackers compared with fixed systems. The precise gain depends not only on the latitude of the system, but also the orientation of single axis trackers and the eventual controls and algorithms used to manage the tracking system

PV APPLICATIONS AND MARKET SEGMENTS

When considering distributed PV systems on buildings, it is necessary to distinguish building applied photovoltaics (BAPV) and buildings integrated photovoltaics (BIPV) systems. BAPV refers to PV systems installed on an existing building as an addition to the existing envelope while BIPV implies that the PV replaces conventional building materials such as roofing elements or facades. IEA PVPS Task 15 has reviewed several definitions and versions of how to define BIPV, and compiled it into one:

"A BIPV module is a PV module and a construction product together, designed to be a component of the building. A BIPV product is the smallest (electrically and mechanically) non-divisible photovoltaic unit in a BIPV system which retains building-related functionality. If the BIPV product is dismounted, it would have to be replaced by an appropriate construction product.

A BIPV system is a photovoltaic system in which the PV modules satisfy the definition above for BIPV products. It includes the electrical components needed to connect the PV modules to external AC or DC circuits and the mechanical mounting systems needed to integrate the BIPV products into the building."

And the same definition is used in this report. Amongst BIPV solutions, PV tiles, or PV shingles, are typically small, rectangular solar panels that can be installed alongside conventional tiles or slates using a traditional racking system used for this type of building product. BIPV products can take various shapes, colours and sizes and be manufactured using various materials, although a vast majority use a glass sandwich composition. They generally replace conventional building envelope solutions, or, less often, provide elements of architectural interest.

Bifacial PV modules collect light on both sides of the panel. Depending on the reflection of the ground underneath the modules (albedo), the energy production increase is estimated to be around 15% but may reach a maximum of up to 30-35% with single axis tracking systems. Bifacial modules have a growing competitive advantage despite higher overall installation costs, and it is estimated that more than 90% of cells deployed in 2023 were bifacial, however many were assembled in monofacial modules, leaving approximately 50% of the 2023 annual PV market composed of bifacials modules. Some challenges remain in being able to accurately simulate the performance of bifacial modules.

Floating PV systems are mounted on a structure that floats on a water surface and can be associated with existing grid connections, for instance when in the vicinity of a hydro power dam. The development of floating PV on man-made water areas is a solution to land scarcity problems in high population density areas and presents other advantages including reduced evaporation rates in dry climates and improved cooling of PV modules for better efficiency in warm climates. Off-shore floating PV systems are installed in several places.

Agricultural PV combines crops and energy production on the same site. PV can either be a static tool added into pastures or crops or a dynamic tool to facilitate agricultural production. The sharing of light between these two types of production potentially allows a higher crop yield, depending on the climate and the selection of the crop variety and can even be mutually beneficial in some cases, as the water which evaporates from the crops can contribute to a reduction of the PV modules' operating temperature. When combined with grazing, the shade provided by modules can increase grass quality in some climates whilst livestock grazing reduces maintenance costs for the PV system.

PV thermal hybrid solar installations (PVT) combine a solar module with a solar thermal collector, converting sunlight into electricity and capturing the remaining waste heat from the PV module to produce hot water or feed heating systems. The water circulating in the modules can reduce the operating temperature of the modules, which benefits the global performances of the system.

Vehicle integrated PV (VIPV) designates the integration of solar cells into the shell of vehicles to reduce emissions in the mobility sector. Solar cell technological developments allow new models to meet both aesthetic expectations for car design and technical requirements, such as light weight and resistance to load. Vehicle applied PV (VAPV) relates to the use of PV modules on vehicles without integration.

Infrastructure Integrated PV (IIPV) is when PV is integrated into infrastructure such as noise barriers, dam walls, pavement, roads, etc. New applications are being demonstrated regularly.

Solar Home Systems (SHS) or pico PV systems combine the use of efficient lights (mostly LEDs) with charge controllers and batteries. With a small PV panel of only a few watts, essential services can be provided, such as lighting, phone charging and powering a radio or a small computer. Expandable versions of pico PV systems have entered the market and enabled starting with a small kit and adding extra loads later. They are mainly used for off-grid basic electrification, predominantly in developing countries.

GRID-CONNECTED PV SYSTEMS

In grid-connected PV systems, an inverter is used to convert electricity from direct current (DC) as produced by the PV array to alternating current (AC) that is then supplied to the electricity network. The typical weighted conversion efficiency is in the range of 95% to 99%. Most inverters incorporate a Maximum Power Point Tracker (MPPT), which continuously adjusts the load impedance to provide the maximum power from the PV array. One inverter can be used for the whole array or separate inverters may be used for each string of modules. PV modules with integrated inverters, usually referred to as "AC modules", can be directly connected to the electricity network (where approved by network operators). They offer better partial shading management and installation flexibility. Similarly, micro-inverters connected to up to four panels also exist, and despite their higher initial cost, they present some advantages where array sizes are small and maximal performance is to be achieved. "AC modules" could see increasing use in residential systems but also linear PV systems where savings can be made on cable costs when using AC modules. In some specific projects, DC to DC inverters are used as the electricity generated is injected to DC lines such as tram and railway networks.

Grid-connected distributed PV systems are installed to provide power to a grid-connected customer or directly to the electricity network - nearly always the distribution network but, for the largest utility scale systems, sometimes the transmission network. Such systems may be on, or integrated into, the customer's premises - often on the demand side of the electricity meter, on residential, commercial or industrial buildings, or simply in the built environment on motorway sound-barriers, etc. Size is not a determining feature – while a 1 MW PV system on a rooftop may be large by PV standards, this is not the case for other forms of distributed generation.

PV APPLICATIONS AND MARKET SEGMENTS / CONTINUED

Grid-connected centralized PV systems (also called utility scale systems) perform the functions of centralized power stations. The power supplied is not physically associated with an electricity customer, and the system is not located to specifically perform functions on the electricity network other than the supply of bulk power. These systems are typically ground-mounted and function independently of any nearby development.

Hybrid systems combine the+ advantages of PV and diesel generation in mini grids. They allow mitigating fuel price increases, deliver operating cost reductions, and offer higher service quality than traditional single-source generation systems. Increasingly, diesel generators are being reserved for worst case situations as battery storage becomes cheaper. Combining these technologies provides a reliable and cost-effective power source in remote places such as for telecom base stations. Large-scale hybrids can be used for large cities powered today by diesel generators and have been seen, for instance in central Africa, often in combination with battery storage.

OFF-GRID PV SYSTEMS

For most off-grid systems, a storage battery is required to provide energy during low-light periods. Several battery technologies for off-grid PV systems are commonly commercialised in 2023 including different types of lead-acid batteries and lithium-ion. Each type of battery has specific advantages. The lifetime of a battery varies, depending on the operating regime and conditions, but is typically between 5 and 15 years depending on the technology, usage and maintenance. For some specific applications – typically, water pumping - no storage battery is needed, and energy is consumed as it is generated.

A charge controller (or regulator) is used to maintain the battery at the highest possible state of charge and provide the user with the required quantity of electricity, while protecting the battery from deep discharge or overcharging. Some charge controllers also have integrated MPP trackers to maximize the PV electricity generated. If there is a requirement for AC electricity, a "stand-alone inverter" can supply conventional AC appliances.

Off-grid domestic systems provide electricity to households and villages that are not connected to the utility electricity network. They provide electricity for lighting, refrigeration and other low power loads, have been installed worldwide and are increasingly the most competitive technology to meet the energy demands of off-grid communities.

Off-grid non-domestic installations were the first commercial application for terrestrial PV systems. They provide power for a wide range of applications, such as telecommunications, water pumping, vaccine refrigeration and navigational aids. These are applications where small amounts of electricity have a high value, thus making PV commercially cost competitive with other small generating sources.

METHODOLOGY FOR THE MAIN PV MARKET DEVELOPMENT INDICATORS

This report counts all PV installations, both grid-connected and reported off-grid installations. By convention, the numbers reported refer to the nominal power of PV systems installed. These are expressed in W (or Wp) or Wdc. Several methodological steps are taken when compiling data.

Power capacity reported in AC is converted to DC (nominal) power when necessary to calculate the most precise installation numbers every year: Some countries report the power output of the PV inverter or even the power of the grid connection. The difference between the standard DC Power (in Wp) and the AC power can range from as little as 5 % (conversion losses) to as much as 40 % (for instance some grid regulations limit output to as little as 65 % of the peak power from the PV system, but also higher DC/AC ratios reflect the evolution of utility-scale PV systems). For some countries, this means publishing different values to official data – for example, China's National Energy Administration (NEA) publishes in AC and PVPS applies a conversion ratio from AC to DC. A range of values is often provided to account for uncertainty in AC/DC conversion ratios, in particular with regards to new utility scale capacity in China, where the minimal annual volume considers official China reporting, and the maximal annual volume considers a further 42 GW that could have been installed considering the uncertainty surrounding official conversion ratios from AC to DC of utility scale systems. For many figures, these two values have been represented with full (minimum) and additional shaded (maximum) bars. If no range is specified, compiled data refers to the higher totals for China. (Note that the IEA PVPS Snapshot published in April 2024 used the lower of these two values).

Inclusion of countries in geographical or political blocs and regions (see Annex 4): for tables and graph reporting data for major markets, data from member countries of the European Union is reported. When referencing regions, data from all countries on the European continent is aggregated. Unless specified otherwise, the term Europe includes all countries on the continent. The European Commission is a member of the IEA PVPS however this report no longer counts all EU members in IEA PVPS blocs unless specified. Chinese Taipei refers to the economic region, Türkiye is included in Europe, and Korea refers to South Korea.

Global data should be considered as indications rather than exact statistics. Data from countries outside of the IEA PVPS network have been obtained through different sources, some of them based on custom trade statistics.

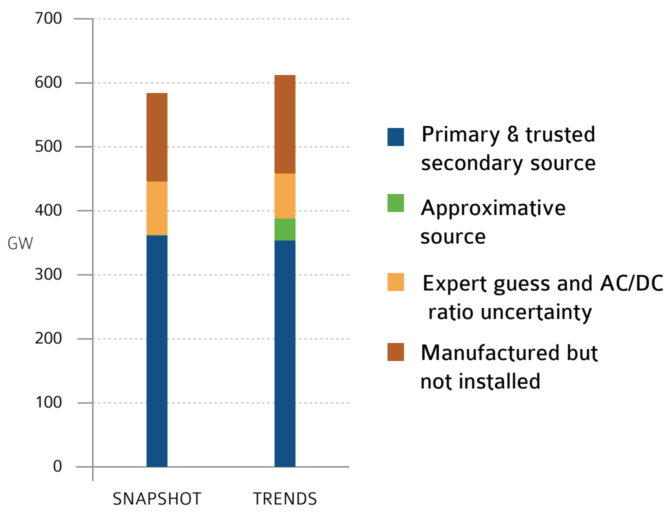
As the PV market grows constantly, reporting of PV installations is becoming more complex. IEA PVPS has decided to count all PV installations, both grid-connected and off-grid, when numbers are reported, and to estimate the remaining part on unreported installations. For countries with historically significant capacity and good reporting, a slow yet growing gap between shipped/imported capacity and installed capacity can be attributed to several factors including conversion factors from AC to DC, repowering and decommissioning. The extremely fast paced development of micro systems (plug&play systems with only a few modules), whilst not significant in overall volumes is symptomatic of the development of unreported systems reaching the market and sometimes being invisible to distribution system operators (DSO) and data collection.

METHODOLOGY FOR THE MAIN PV MARKET DEVELOPMENT INDICATORS / CONTINUED

Other market evolutions such as off-grid applications are difficult to track even in member countries, and significant growth in installations in third countries without a robust reporting system is also a likely source of underreporting. In light of this, reporting here takes into account reported and expert estimates of new commissioned capacity as well as probable unreported volumes installed in one of the above contexts. Data on estimated shipped capacity from custom sources, in inventories, has been incorporated in Figure 1.1 to improve market visibility. As can be seen, between estimations published in the Snapshot in April 2024 and those in this publication, many countries have firmed their evaluation of annual installed volumes. In particular, volumes for India and smaller countries have been revised.

With significant overcapacity in manufacturing, it should be noted that approximately 150 GW of capacity was manufactured but not commissioned; some of this volume has been installed and will be included in 2024 figures as it is commissioned; some of this volume is in inventories in Europe and, to a lesser extent, other countries, whilst the remainder is in export inventories or manufacturers inventories in China.

FIGURE 1.1: ANNUAL INSTALLED VS ANNUAL SHIPPED VOLUMES AND EVOLUTION OF DATA ESTIMATIONS



SOURCE IEA PVPS & OTHERS

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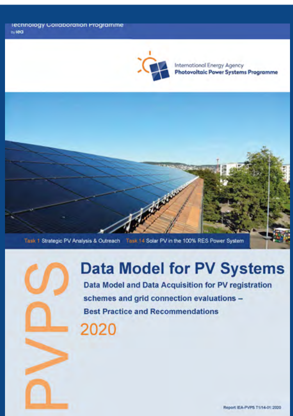
PV MARKET DEVELOPMENT TRENDS

Over 1.64 TW of PV plants have been installed globally, of which over 50% has been installed in the past three years. In 2023, more than 35 countries had a GW-scale annual market. Whilst the number of national markets with measurable contributions to global PV capacity is increasing every year, the concentration of the market in China over the past three years has decreased their relative importance.

A large majority of PV installations are grid-connected and feed electricity into either the consumer's internal electrical circuit or the electrical grid. PV installation data is reported in DC by default in this report, and this report converts any data officially reported in AC to DC to maintain coherency. When official reporting is in AC, announced capacities may be specified as MWac or MWdc in this report, if necessary, however by default, MW implies MWdc. See Chapter 1 for more information on data conversion methodology, uncertainty and in particular the impact on evaluations of China market figures. For more information on registering PV installations, download the IEA PVPS report on registering PV installation

Download the "Data Model for PV Systems" reports



THE GLOBAL INSTALLED CAPACITY

Global PV installed capacity (GW)

+38% YoY growth

At the end of 2023, the cumulative global installed capacity reached 1 642.0 GW[1] – consistent with the preliminary estimation of 1 624 GW published in the IEA-PVPS Snapshot of Global PV Markets 2023 in April of this year.

It appears that 413.8 GW represented the **minimum** capacity based on trustable sources, and 456.0 GW represented the **most probable** capacity installed during 2023. This volume is almost double that of 2022, itself well above 2021 volumes – resulting from a combination of increased action on climate imperatives, plummeting module costs and actions in China to absorb manufacturing capacity.

1. China's National Energy Administration (NEA) publishes in AC and PVPS applies a conversion ratio from AC to DC. A range of values is often provided to account for uncertainty in AC/DC conversion ratios, in particular with regards to new utility scale capacity in China, where the minimal annual volume considers official China reporting and the maximal annual volume considers a further 42 GW that could have been installed considering the uncertainty surrounding official conversion ratios from AC to DC of Utility scale systems. For many figures, these two values have been represented with full (minimum) and additional shaded (maximum) bars. If no range is specified, compiled data refers to the higher totals with Official China reporting values. Note that the IEA PVPS Snapshot published in April 2024 used the lower of these two values

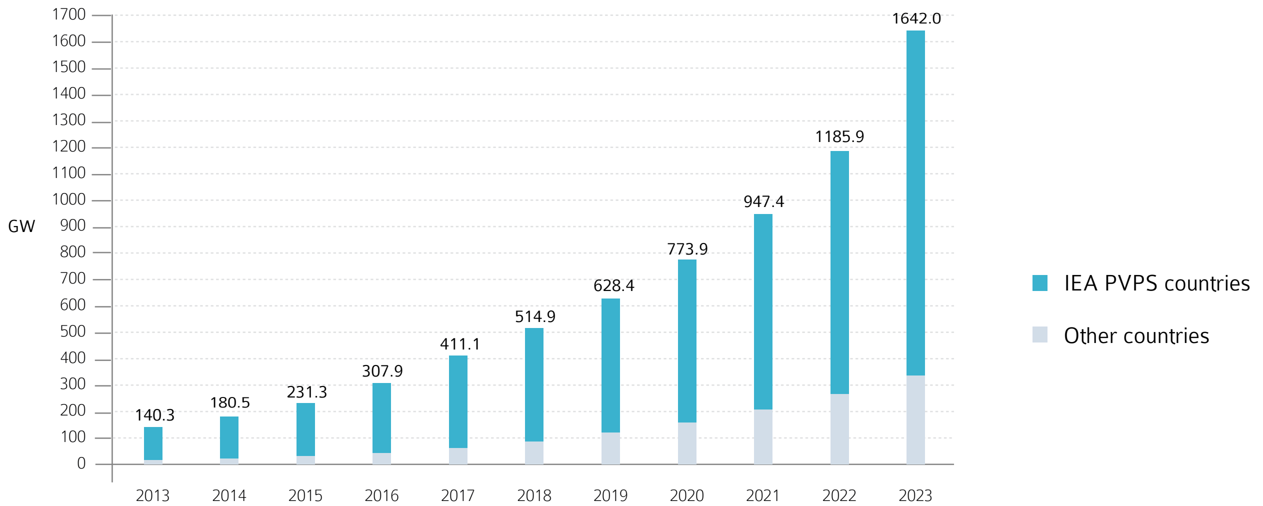
THE GLOBAL INSTALLED CAPACITY / CONTINUED

Among the trustable sources, the group of IEA PVPS[2] countries represented 1305.7 GW of the global installed capacity. The IEA PVPS participating countries in 2023 are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, South Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Türkiye, and the United States of America (USA). The European Commission is a member of the IEA PVPS and, as such, in this report its member countries are counted in IEA PVPS block.

2. For the purpose of this report, IEA PVPS countries are those that are members in their own right – or, as occasionally mentioned explicitly those that are a member in their own right or through the adhesion of the EC.

The other key markets that have been considered and which are not part of the IEA PVPS Programme represented a total cumulative capacity of 336.2 GW at the end of 2023. Amongst them, India still covered around one third of this capacity with 92.6 GW whilst Brazil (37.8 GW), Vietnam (18.6 GW) and the UK (16.0 GW) scored the three first places. These countries represented from 5% (UK) to 28% (India) of the cumulative non-IEA PVPS capacity. Other non-IEA PVPS countries to have significant cumulative volumes include MENA countries with world-record size systems coming progressively online such as the UAE (7.1 GW) and Saudi Arabia (2.9 GW), Chinese Taipei (10.4 GW) and Pakistan (4.5 GW) in Asia. In Europe, Poland (17.4 GW) and Greece (7.2 GW) are the largest cumulative markets, followed by Ukraine (6.2 GW), although here the market has stalled given the ongoing conflict. Another five non-IEA PVPS European countries have cumulative capacity over 2 GW.

FIGURE 2.1: EVOLUTION OF CUMULATIVE PV INSTALLATIONS



SOURCE IEA PVPS & OTHERS

PV PENETRATION PER CAPITA

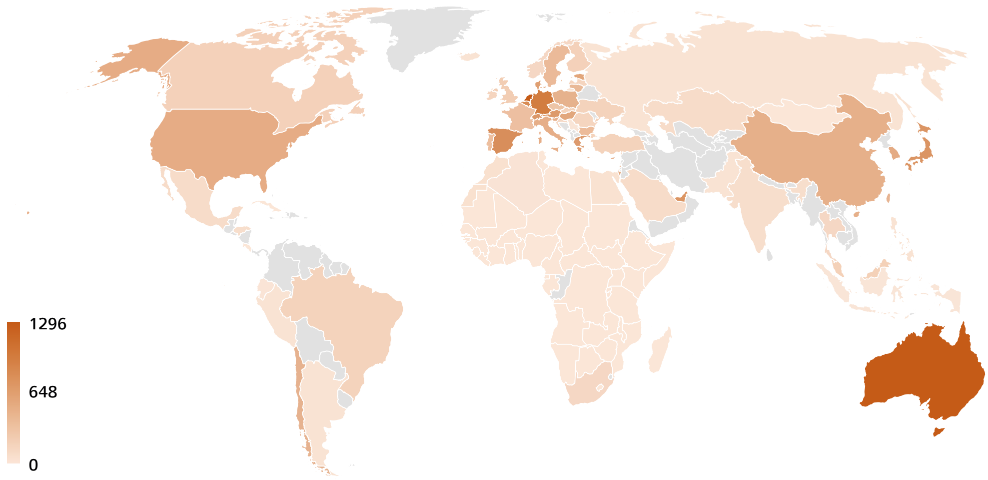
PV penetration can be measured either as a ratio of Wp per capita or kWh generated to meet a countries electricity demand – here we look at the volume of PV capacity relative to the country's population, indicating the relative efforts made by different countries.

Australia has reached and maintained its place as the highest installed PV capacity per inhabitant with 1 296 W/cap (up 11% on 2022) in IEA-PVPS and surveyed countries. The Netherlands is catching up quickly but is once again second with 1 288 W/cap (+25%). Germany (974 W/cap), Belgium (842 W/cap), Spain (806 W/cap) and Japan (734 W/cap) kept their top spots. Some big utility-scale systems commissioned in 2023 have allowed the UAE to double their rate to 751 W/cap. Another 10 countries now have more than 500 W/cap, including the USA. With the large volumes installed in China, their penetration rate jumped 50% up to 490 W/cap. Of the largest country markets, India (65 W/cap) and Brazil (175 W/cap) still lag behind.

Typical residential systems have modules with an individual power of 350 Wp to 435 Wp – and now nearly 30 countries have the equivalent of 1 to 3 modules installed per person.

Both Australia and the Netherlands have installed more than 1 250 W/cap.

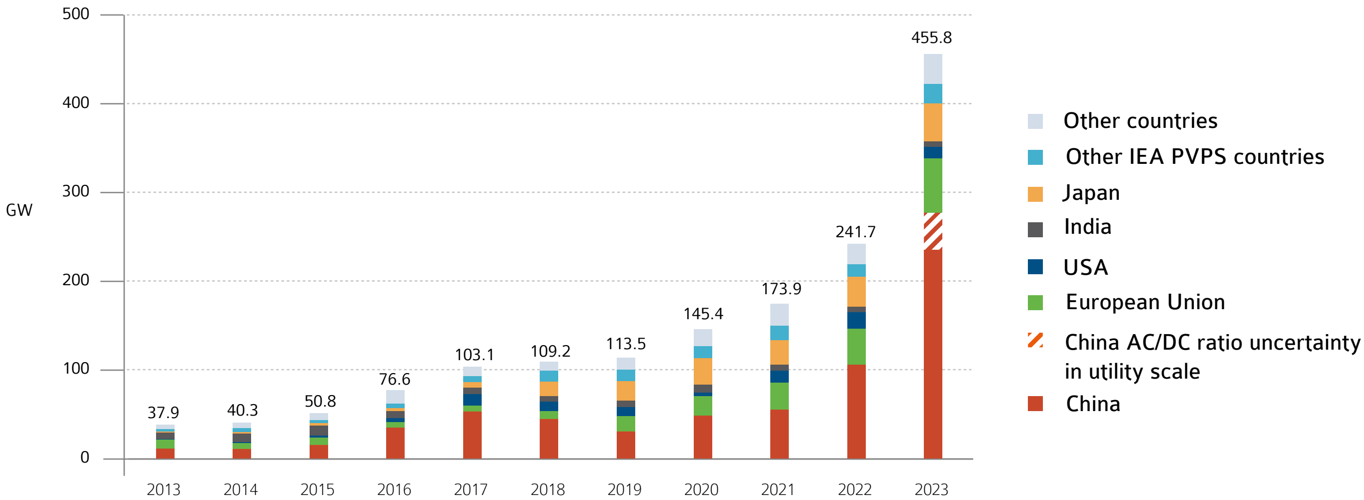
FIGURE 2.2: PV PENETRATION PER CAPITA IN 2023



SOURCE IEA PVPS & OTHERS

EVOLUTION OF PV ANNUAL INSTALLATIONS

FIGURE 2.3: EVOLUTION OF ANNUAL PV INSTALLATIONS IN MAJOR MARKETS



SOURCE IEA PVPS & OTHERS

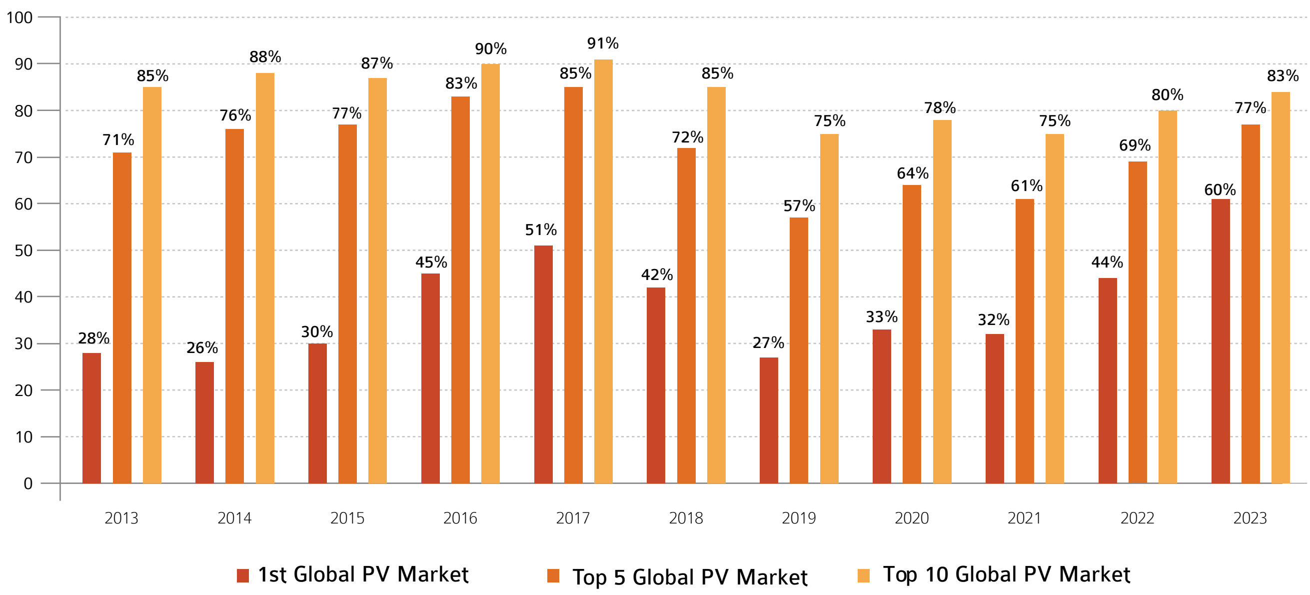
THE GLOBAL INSTALLED CAPACITY / CONTINUED

The IEA PVPS countries installed at least 385.8 GW in 2023. While they are more difficult to track with a high level of certainty, installations in non-IEA PVPS countries contributed an estimated amount of 70.2 GW. After two years of what was perceived as strong growth, 2023 beat all the records, nearly doubling 2022 annual capacity as module prices dropped. Consumer, and investor confidence in the ability of PV to provide reliable and stable electricity generation costs as a shelter from electricity market fluctuations was maintained.

Much of the growth has been achieved in China, where installed volumes jumped through the year, although they struggled to keep up with the volume of manufacturing capacity available. Between 235.0 GW and 277.2 GW was installed (converted from China's National Energy Administration's AC figures and depending on the AC/DC conversion ratio used). Whilst there is an increasingly large uncertainty around the nominal capacity installed in utility-scale plants (the inverter/module ratio is estimated based on industry practices and a few percentage points error can lead to tens of GW of difference in estimated volumes), it is clear that the Chinese market was driven by the centralised segment this year, with just 35% of new capacity in the distributed segment. The Chinese market represented more than 60% of the global installations in 2023, up from last year's 45%. This market dominance is similar to the role Germany played through the mid-late 2000's, and the long-term impacts are difficult to judge. The cumulative capacity installed in China reached at least 649.0 GW and as much as 691.2 GW.

Taken as a bloc, the **European Union** would come in second after China in terms of annual installed capacity, maintaining strong growth rates for the fifth year in a row. The combined annual new capacity was 58.2 GW, led by **Germany** that doubled its market to reach 15.0 GW, **Spain** with a steady 8.9 GW and strong contributions from **Italy** (5.3 GW), **Poland** (4.9 GW) and the **Netherlands** (4.8 GW).

FIGURE 2.4: EVOLUTION OF MARKET SHARE OF TOP COUNTRIES



SOURCE IEA PVPS & OTHERS

The USA annual market grew nearly 50% reaching 33.9 GW, after a slower 2022 (23.1 GW) and 2021 (24.8 GW). Some of the issues that hindered the 2022 market seem to have been partially resolved, including installation backlogs due to supply chain issues. The market remains a utility-scale market, with 24.3 GW or just over 70% of new capacity centralised. The decentralised market saw a robust 9.5 GW installed, solidly above 2022's 8.2 GW. By the end of 2022, the USA reached 177.3 GW of cumulative installed capacity.

After revisions to data for both Germany and India since the publication of the IEA PVPS Snapshot in April, Germany has made it back into the top 3 countries for the first time since 2011, after doubling 2022 volumes to install 15.0 GW, for a total cumulative capacity of 82.3 GW. India was in fourth place with 13.0 GW installed, up from the previous year's 18.1 GW, for a total cumulative capacity of 92.6 GW.

Whilst the market in Brazil didn't maintain the high growth rates of the previous four years, it was still a growth market with 12.4 GW, reaching 37.8 GW cumulative capacity, confirming its place as a globally important market.

With the dominance of the Chinese markWet, it is no surprise that the market share of the top countries is becoming more and more elevated - smaller markets are contributing proportionally less to global installation numbers than the major markets. China has done much to absorb the results of its manufacturing capacity growth.

Behind the top 5, Spain in 6th place, (8.9 GW for 38.90GW cumulative capacity) and Japan in 7th place (6.3 GW for 91.4 GW cumulative capacity) remained major (steady) markets. Italy made it back to the top 10 on the back of strong growth, with 5.3 GW new capacity for a cumulative capacity of 30.3 GW. Both Poland and the Netherlands had similar volumes in 2023 to 2022: Poland with 4.9 GW annual for 17.4 GW cumulative capacity and the Netherlands 4.8 GW of new installations for a total of 23.0 GW.

Together, these 10 markets cover around 84% of the 2023 annual world market, a sign that the growth of the global PV market has been driven by a limited number of countries once again. Market concentration has beWen fuelling fears for the market's stability in the past, if one of the top three or top five markets would experience a slowdown, although the past years have shown that when one market slows, another is often in growth (witness USA/India, for example). As shown in Figure 2.4, the market concentration steadily decreased in 2019 before growing again in 2020, stabilising in 2021, then growing even more in 2022 and 2023, due to the growth of the Chinese PV market. As new markets are starting to emerge, the concentration of the global PV market minus China

TABLE 2.1: EVOLUTION OF TOP 10 MARKETS

RANKING	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
1	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA
2	JAPAN	JAPAN	JAPAN	USA	INDIA	INDIA	USA	USA	USA	USA	USA
3	USA	USA	USA	JAPAN	USA	USA	INDIA	VIETNAM	INDIA	INDIA	GERMANY
4	GERMANY	UK	UK	INDIA	JAPAN	JAPAN	JAPAN	JAPAN	JAPAN	BRAZIL	INDIA
5	ITALY	GERMANY	INDIA	UK	TÜRKIYE	AUSTRALIA	VIETNAM	GERMANY	GERMANY	SPAIN	BRAZIL
6	UK	SOUTH AFRICA	GERMANY	GERMANY	GERMANY	TÜRKIYE	AUSTRALIA	AUSTRALIA	BRAZIL	GERMANY	SPAIN
7	ROMANIA	FRANCE	SOUTH KOREA	THAILAND	SOUTH KOREA	GERMANY	SPAIN	SOUTH KOREA	SPAIN	JAPAN	JAPAN
8	INDIA	SOUTH KOREA	AUSTRALIA	SOUTH KOREA	AUSTRALIA	MEXICO	GERMANY	INDIA	AUSTRALIA	POLAND	ITALY
9	GREECE	AUSTRALIA	FRANCE	AUSTRALIA	BRAZIL	SOUTH KOREA	UKRAINE	SPAIN	SOUTH KOREA	AUSTRALIA	POLAND
10	AUSTRALIA	INDIA	CANADA	TÜRKIYE	UK	NETHERLANDS	SOUTH KOREA	NETHERLANDS	POLAND	NETHERLANDS	NETHERLANDS
RANKING EU	2	3	3	4	5	4	2	2	2	2	2
MARKET LEVEL TO ACCESS THE TOP 10											
	792 MW	779 MW	675 MW	818 MW	944 MW	1 621 MW	3 130 MW	3 492 MW	3 710 MW	4 200 MW	4 788 MW

SOURCE IEA PVPS & OTHERS

THE GLOBAL INSTALLED CAPACITY / CONTINUED

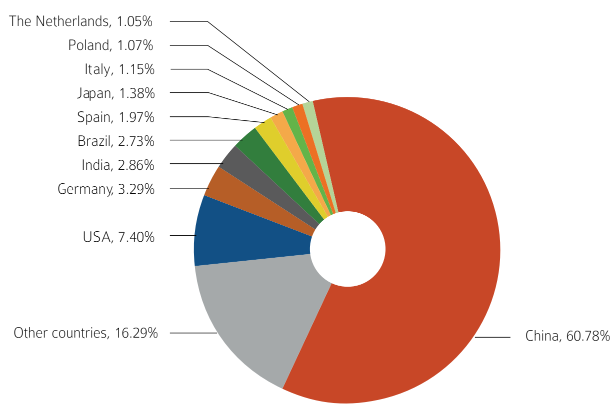
reduces, and therefore the risks. However, the size of the Chinese PV market continues to shape the evolution of the PV market as a whole. As we have seen in 2019, the global growth was limited due to the decline of the first market, which almost wiped out the global growth, while in 2022 and 2023, China's installations maximized global growth. By mid-2024, approximately 100 GW of new capacity was installed in China – whilst the quarterly volumes are higher than the same period last year, if the 2nd half year is steady this would lead to similar total volumes in 2024 as 2023.

As detailed above, the IEA PVPS choice consists in reporting DC capacities. An estimate of AC capacities would put the new installed capacities number between 305 GWac to 385 GWac in 2023. This number (in the same way as the DC number) is an approximation of the reality and represents an estimated value of the maximum power that all PV systems globally could generate instantaneously, assuming they would all produce at the same time. This number is indicative and should in no case be used for energy production calculation.

Other countries that installed several GW in 2023 and were found in the top 10 countries in the past couldn't reach the volumes required this year, but remained close: Australia, France and South Korea all installed more than 3 GW in 2023 – all three have had markets fluctuating between 3 GW and 5 GW in the past years, and whilst it appears that France may be accelerating growth, Australia and South Korea have experienced stable markets or slightly decreasing installation rates. Preliminary indications point to a stabilisation in those markets that have reached market competitiveness across most segments as in the USA or Australia, whilst those in protected markets are more closely linked to capacities planned within support mechanisms (France...).

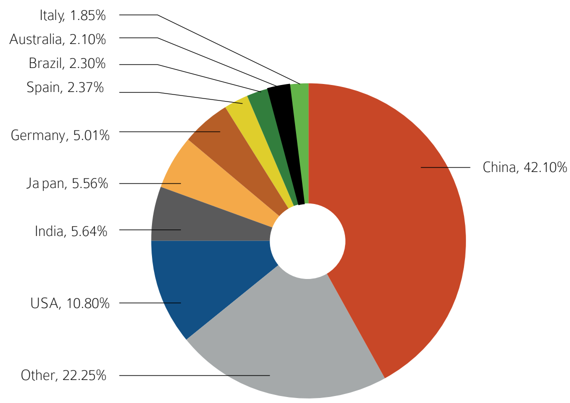
Over 30 countries had more than 1 GW newly installed in 2023, spread across all continents, with the notable arrival of several countries in the Middle East and Africa.

FIGURE 2.5: GLOBAL PV MARKET IN 2023



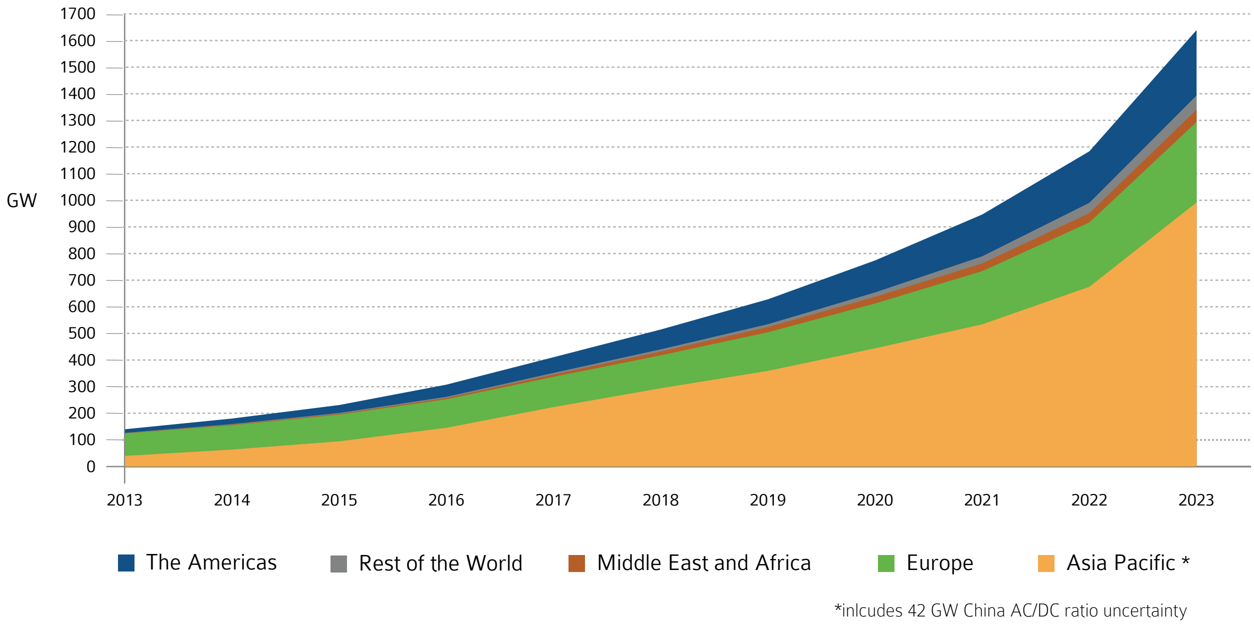
SOURCE IEA PVPS & OTHERS

FIGURE 2.6: CUMULATIVE PV CAPACITY END 2023



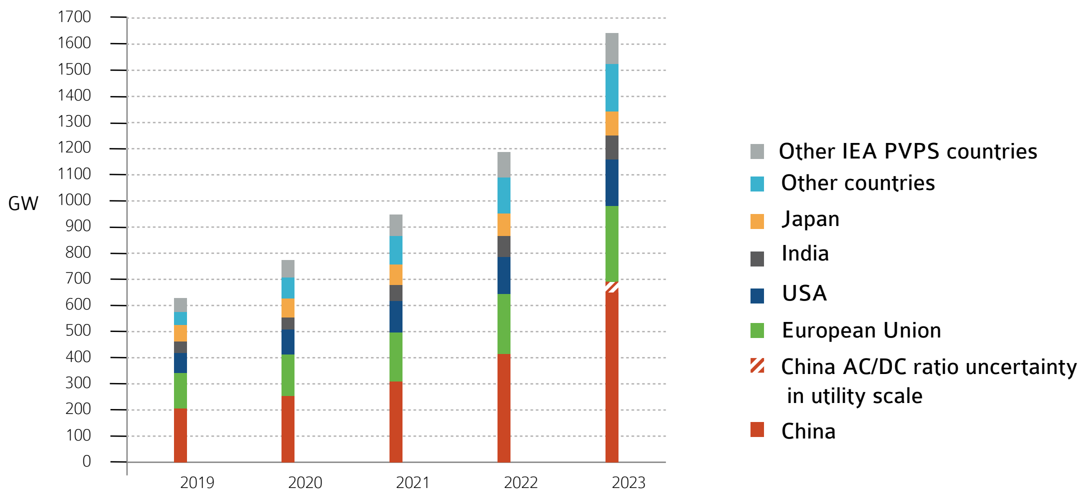
SOURCE IEA PVPS & OTHERS

FIGURE 2.7: EVOLUTION OF REGIONAL PV INSTALLATIONS



SOURCE IEA PVPS & OTHERS

FIGURE 2.8: 2018-2023 GROWTH IN MAJOR MARKETS



SOURCE IEA PVPS & OTHERS

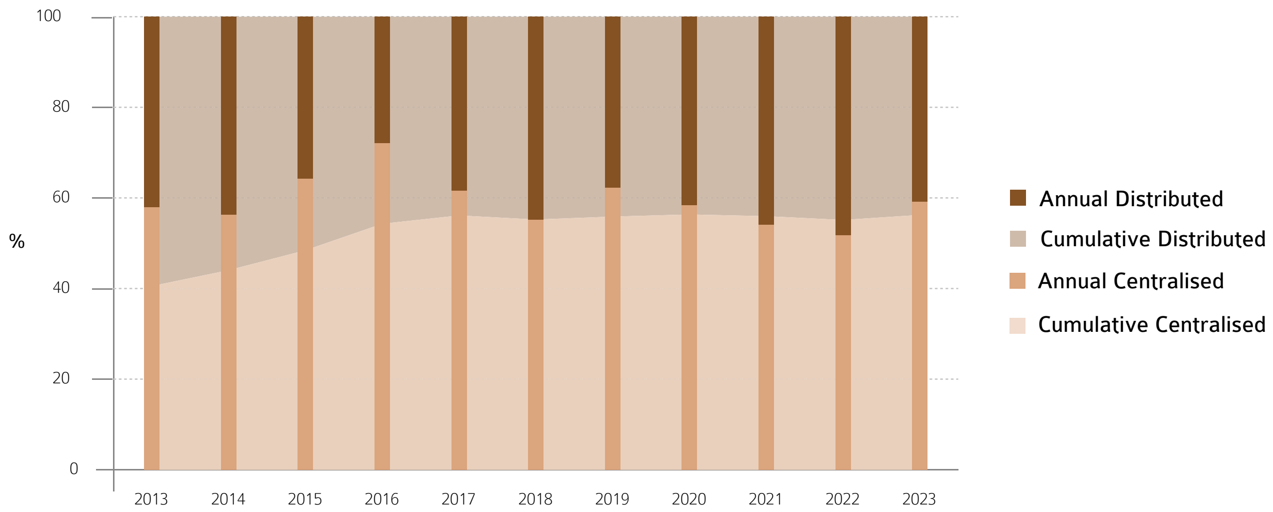
PV MARKET SEGMENTS

We consider three market segments in this report; centralised (large systems above a few MW up to utility-scale and mostly feeding electricity to the grid), distributed (anything below this connected to the grid and connected to a consumption point) and off-grid. Off-grid has been included in distributed volumes in this report's market statistics With different reporting systems from one country to another, there is no specific system size separating centralised from distributed, however, the segmentation is undertaken in most markets by governments, utilities and industry associations as the impacts are quite different, affecting grid connection, grid capacity, fiscality and taxation and the ability to properly count and evaluate capacities. Additionally, for some markets, the conversion of AC power to DC power is built on different conversion coefficients, in line with industry practices.

Overall, it is estimated that the centralised segment (59% or 267.0 GW) slightly outweighed the distributed segment (41% or 189.0 GW) in new annual capacity in 2023, with a swing towards more centralised systems – although it must be noted that the 42.2 GW of probable extra capacity in China is included in the centralised volumes. This globally balanced result is on the one hand a reflection of the mostly balanced Chinese market but belies significant differences in other major markets.

The share of utility-scale still represented around 56% of cumulative installed capacity, slightly up from last year's 55%. Off-grid and edge-of-the-grid applications are increasingly integrated into distributed installations, with little ability in most countries to track volumes.

FIGURE 2.9: ANNUAL SHARE OF CENTRALIZED AND DISTRIBUTED GRID-CONNECTED INSTALLATIONS 2013-2023



2

SOURCE IEA PVPS & OTHERS

Except for the European market that incentivized residential segments from the start, most of the major PV developments in emerging PV markets tended to come from utility-scale PV in the past. The drop in module prices and the increasing attractivity of self-consumption across the world is likely to change this, which has been demonstrated in Brazil and Vietnam, and more recently South Africa in 2023.

UTILITY-SCALE PV

Utility-scale PV plants are in general ground-mounted (or floating) installations. In some cases, they could be used for self-consumption when close to large consumption centres or industries, but generally they feed electricity directly into the grid. Utility-scale applications are thriving in both new and established PV markets. In new or maturing markets, many countries propose tendering processes to select the most competitive projects, or to guide the types of land available.

TABLE 2.2: TOP 10 COUNTRIES FOR CENTRALISED PV INSTALLED IN 2023

COUNTRY	GW
CHINA *	180.89
USA	24.34
INDIA	10.03
SPAIN	6.94
GERMANY	4.65
BRAZIL	4.1
THAILAND	3.48
JAPAN	2.97
NETHERLANDS	2.82
SOUTH KOREA	2.97

*includes 42GW AC/DC conversion uncertain volumes

SOURCE IEA PVPS & OTHERS

TABLE 2.3: TOP 10 COUNTRIES FOR CENTRALISED PV CUMULATIVE CAPACITY IN 2023

COUNTRY	GW
CHINA*	435.26
USA	117.25
INDIA	76.87
JAPAN	36.85
SPAIN	30.64
SOUTH KOREA	23.94
GERMANY	18.39
NETHERLANDS	13.57
BRAZIL	11.49
AUSTRALIA	11.36

*includes 42GW AC/DC conversion uncertain volumes

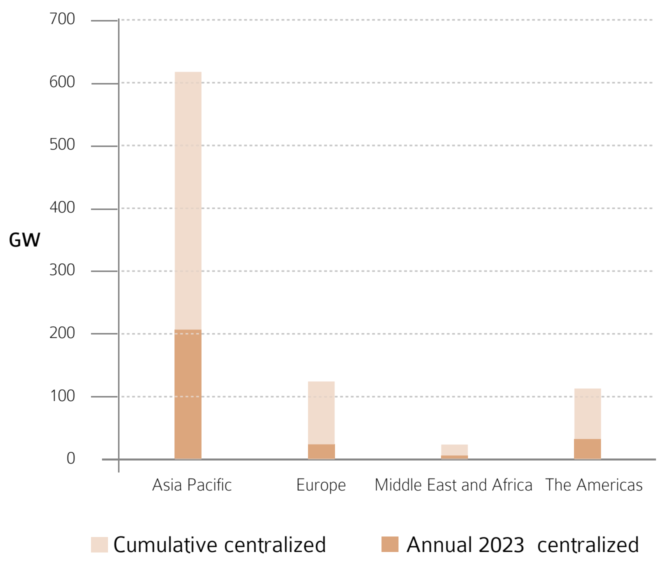
. SOURCE IEA PVPS & OTHERS

Utility-scale systems are providing a majority of new capacity in some key markets such as India, the USA, Spain and South Korea. The commissioning of very large-scale utility systems in the MENA region – Saudi Arabia and the UAE ahead of a number of other countries in 2024 and 2025 – will add new countries that are driven by centralised systems, however most national markets were not led by this segment in 2023.

Merchant PV, where PV electricity is directly sold to electricity markets and corporate PPAs, where it is directly sold to corporate consumers continues to grow in many countries. Trials conducted in the past years, especially in 2022 pulled by the high electricity markets costs, gave developers and investors' confidence in the ability to create viable projects. Whilst merchant PV is in its early phases, the impacts of negative prices and price cannibalisation are two subjects that will be closely monitored by investors over the next few years. In parallel, the limitations that are already being seen due to grid congestion, social acceptance or strict environmental impact study requirements remain important barriers. Experience has demonstrated that securing grid connection can lead project developers to tender very low bids just to secure grid connection capacity (Portugal, Spain), whilst some countries have had to specifically invest in and develop grid capacity to ensure the continued development of utility-scale systems (Australia, Austria, Brazil, France).

New utility-scale PV plants are also using trackers to maximise production and the use of bifacial PV modules is increasing relatively fast as well. Floating PV is becoming a significant segment. The addition of storage systems has also become a trend in some countries, either pushed by specific rules in tenders or by attractive conditions for grid services and wholesale markets (Australia, Germany, USA). In 2023, centralised PV amounted to 269.9 GW (59% of new capacity) globally and the total installed capacity for all of these applications amounted to 877.5 GW or 54% of the cumulative installed capacity.

FIGURE 2.10: CENTRALIZED PV INSTALLED CAPACITY PER REGION 2023



SOURCE IEA PVPS & OTHERS

PV MARKET SEGMENTS / CONTINUED

PROSUMERS, POWERING THE DISTRIBUTED PV MARKET

Prosumers are consumers producing part (or all) of their own electricity consumption – and whilst technically any generator in proximity to a consumption point will feed that consumption point, prosumer as a term is reserved for situations where this self-consumption is both based on electron flows and financial flows i.e., the consumer is on the same side of the meter as the generator. The development of prosumer markets is important as it can remove pressure on financial incentives and, in parallel, reduce demand on grid capacity.

Historically driven by simple schemes such as net-metering, prosumer segments are increasingly developed around the concept of self-consumption, where a distinction is made between the electricity consumed on site and the electricity injected into the grid on a close to real time timestep, thereby incentivizing self-consumption.

An important factor in the success of self-consumption schemes is the retail electricity price that is still being maintained artificially low in some countries – even through the high prices of 2022. Subsidies for fossil fuels are still a reality and reduce the attractiveness of solar PV installations, across all market segments including self-consumption. However, PV markets tend to grow quickly when electricity prices increase, and overall, there is a clear trend toward self-consumption of PV electricity in most of countries, often with regulations offering a value for the excess electricity, either through government mechanisms or utility schemes. This can be done with a FiT, a feed-in-premium added to the spot market price or more complex net-billing including time-of-use rates. Unfortunately, the move towards pure self-consumption schemes can create temporary market slowdowns, especially if the transition is abrupt as consumers and market players adapt their understanding (California, USA in 2023). However, if the market conditions are favourable and the market regains confidence, self-consumption can become a market driver for the distributed segment. Countries where the distributed segment is driving overall market growth include Germany, Brazil, Italy, Poland, Australia, Austria, Sweden and many smaller European countries.

TABLE 2.4: TOP 10 COUNTRIES FOR DISTRIBUTED PV INSTALLED IN 2023

COUNTRY	GW
CHINA	96.29
GERMANY	10.36
USA	9.53
BRAZIL	8.35
ITALY	4.40
POLAND	3.65
JAPAN	3.33
AUSTRALIA	3.15
INDIA	2.99
SOUTH AFRICA	2.60

. SOURCE IEA PVPS 8 OTHERS

TABLE 2.5: TOP 10 COUNTRIES FOR DISTRIBUTED PV TOTAL INSTALLED CAPACITY IN 2023

COUNTRY	GW
CHINA	255.62
GERMANY	63.92
USA	60.10
JAPAN	54.33
BRAZIL	26.33
AUSTRALIA	22.73
ITALY	21.6
INDIA	15.29
POLAND	13.40
FRANCE	12.67

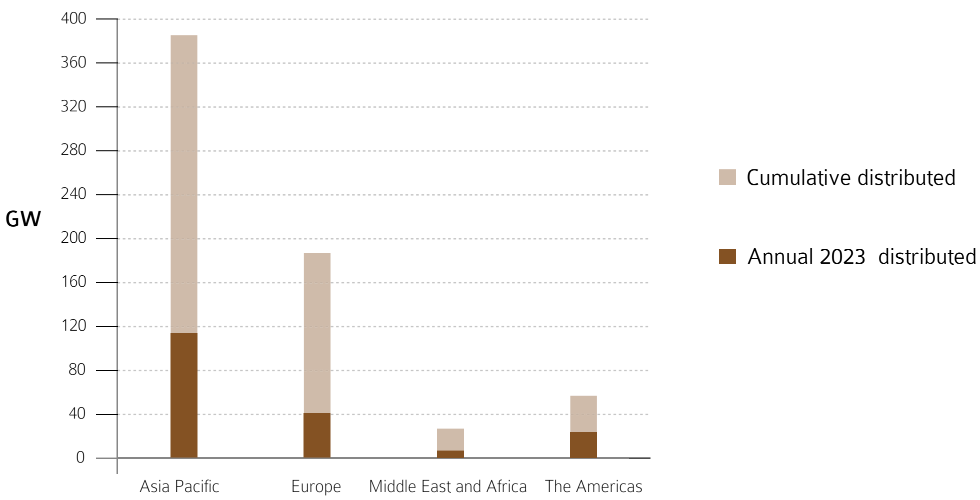
. SOURCE IEA PVPS 8 OTHERS

The distributed market has been oscillating around 16-19 GW from 2011 to 2016, until China succeeded in developing its own distributed market: it allowed the distributed PV market to grow significantly by roughly doubling over several years from 2016 to 2018. In 2023, this market grew to 189.0 GW[1], up from 177.7 GW in 2022.

An increasing number of countries, particularly in Europe, promote collective and distributed self-consumption as a new model for residential and commercial electricity customers. This model allows different consumers located in the same building or private area (collective self-consumption), or in the same geographical area using the public grid (distributed, virtual or delocalized self-consumption), to share the self-generated electricity, unlocking access to self-consumption for a wider range of consumers. If well implemented, this can allow the development of new business models for prosumers, create jobs and local added value while reducing the price of electricity for consumers and energy communities. These models of production could also reduce the impacts on the grid of PV systems by encouraging consumers to adapt their consumption to solar generation hours.

1. Including off-grid systems

FIGURE 2.11: DISTRIBUTED PV INSTALLED CAPACITY PER REGION 2023



SOURCE IEA PVPS 8 OTHERS

DUAL USAGE AND EMERGING PV MARKET SEGMENTS

The installation of photovoltaic installations on infrastructure or land used for other purpose is a response to the competition for land implied by the massive development of new PV capacities, and the resulting questions around social acceptance. The social acceptance of PV and the availability of land surfaces are key considerations for the massive deployment of new PV capacity in a certain number of countries - typically where there is existing or spreading urbanisation, sustained or regular loss of agricultural land or a strong push to preserve heritage buildings and natural landscapes for aesthetic and cultural reasons.

For ground-mounted installations, competition has arisen between other uses and electricity production, dominated by conflict for agricultural land. By proposing a combined use for both agricultural production and energy production, agrivoltaics offers an acceptable alternative. Floating solar photovoltaics is a particularly dynamic market segment in Asian regions where the tension on land use is strong, using the available surfaces on natural and artificial lakes and reservoirs. These market trends in the centralized segment are strong and underpinned by the same imperative of dual land use. The use of other infrastructure such as canopies on canals or noise barriers along highways is also becoming more common, driven by the same motivating factors of access to land without generating conflict or opposition.

On a smaller individual scale, integrating PV into and onto buildings has been a target for specialised companies for a long time – and has even been the mainstay of public policies for the distributed segment in the past in some countries (most notably France). In particular, the European Union is encouraging member states to develop ambitious targets. It can be attractive because it uses existing buildings but also can lead to a more harmonious integration in the environment, reducing social resistance.

AGRIVOLTAICS

The development of PV on agricultural land has been a reality since the beginning of utility-scale PV deployment. In some cases, crops were replaced by photovoltaics and land use shifted towards electricity production; in other cases, low intensity grazing continued around modules. Agrivoltaics, however, proposes a different approach by using land for both food and energy production at the same time. As PV penetration rates increase in many countries, competition for land can limit PV development – some countries have even regulated access to agricultural land for PV through legislation or conditions in tenders (Italy, France, South Korea).

The potential for PV on agricultural land, and how this segment can contribute to achieving renewable energy targets has been studied in different regions, and whilst government and developer interest has increased, so has reluctance or opposition from farmers and the general public. To give an example of the potential of this segment, in Japan, a mapping of all agricultural land suitable for PV concluded that just 10% could hold 440 GW of PV – whilst in 2023, Japan's cumulative capacity across all segments is "only" 91.4 GW. South Korea has set a target of 10 GW of agrivoltaics as part of its 46.5 GW 2030 PV target, to be compared with the cumulative capacity in 2023 of 27.6 GW. It has been estimated that covering just 1% of the European Union's agricultural lands could allow the installation of 410 GW – but just 15% of this was installed in 2023 (59.8 GW) whilst the top target of the RePowerEU plan is set at 750 GW in 2030.

PV on agricultural land is implemented with different configurations and designs, and sometimes specific vocabularies:

- PV systems above crops or plants; the PV system allows for growing different kinds of crops but with reduced solar insulation and could provide new services and business models – such as protection against hazards that damage crops (hail, excessive sun), water saving though reduced evaporation, and environments adapted to crops that would not have been possible in the actual or future climate conditions. This dual use requires specific technical solutions such as elevated PV plants, where either the density of the panels is reduced and adapted to the crops needs or the panels are mobile and their position (tilt) is modified to maximize PV production or crop production depending on the weather conditions. The density can be adapted by the design of the PV plant by spreading modules out or by modifying the module itself to be semi-transparent.
- Crops, grassland, pollinator habitat and grazing can be hosted between the rows of PV plants. The systems must enable the land to maintain its agricultural vocation. The shade supplied by the systems can increase grass production and reduce animal (and worker) heat stress – indeed, in some countries increased shading for animals as temperatures increase because of climate change could be an important motivator. The design of the PV plant must be adapted to the activity: adequate space between the rows to allow agricultural machinery, the right height, electrical and dust protection. Ground-mounted PV plants, some with trackers, are implemented at a utility-scale level. Vertical bifacial PV is also being tested in several plants, as the impact of the PV on the land available for the agricultural activity is very low.
- PV systems are also developed and integrated in greenhouses.

Even if the potential for PV on agricultural lands is important, other factors must be taken into consideration. Food production security and agricultural sufficiency are generally the first priority, with the agricultural sector's economic balance, environmental evaluations, social acceptance and water management also important factors. Japan was a pioneer where "solar sharing" was defined in 2003, referring to PV installations where 80% of agricultural yields are maintained - guidelines were published in 2021 and updated in 2023. France, Germany and Italy have published legal frameworks or guidelines in 2022 and 2023. Italy adopted a Decree in December 2023, dedicated to "advanced AgriPV". DIN SPEC 91434, the German Standard for agrivoltaics shapes the German framework and support scheme. Criteria are based on agricultural yield (at least 66% of the reference yield) and the agricultural use of the land must be guaranteed. "Interval" and "overhead systems" are differentiated in the definition, as are the expected outcomes. In France, agrivoltaics is defined by law - an agrivoltaic installation is considered to be an installation which directly contributes to agricultural activities: improving agronomic potential, protection against hazards, improving animal welfare and guaranteeing significant agricultural production.

System costs and profitability vary depending on the importance given to agricultural production compared to energy production. Support mechanisms and financial aid intensity can also vary accordingly. PV systems falling under the most restrictive definition of agrivoltaics typically receive higher incentives.

Generally, in the different frameworks and support mechanisms, two types of PV projects are considered:

- PV plants where some form of agricultural production is maintained. These systems are already economically viable and cost-effective. Energy production dominates but agricultural production is maintained. These projects often participate in the classic competitive tenders or negotiate PPAs.
- PV plants complying with advanced criteria where they enhance agricultural production and farmer revenue. Agricultural production profitability must dominate, and energy production is an added value. This type of plant requires being adapted to the specific crops underneath.

Agrivoltaics is still an emerging market when compared to global PV capacity. Japan has seen more than 1 800 agrivoltaic farms commissioned, but most of them are small systems. Between 2013 and 2021, less than 1 GW was installed. China has also an important installed capacity, but this segment doesn't appear to be monitored separately. Italy announced support for 1,5 billion EUR including the so-called agrisolar park in rural areas, and by mid-2023 had awarded nearly 0.5 GW of projects. Specific calls for tender have been set for agrivoltaics in numerous countries including Israel with a tender for 100 MW of agrivoltaic systems in 2022. In the USA, there is more than 10 GW of projects that are combined with grazing or pollinator/native habitats, but a much smaller volume (less than 1 GW) protecting crops or on greenhouses.

IIPV: INFRASTRUCTURE INTEGRATED PV

The massive deployment of new PV capacity is presenting new challenges such as social acceptance and the availability of land surfaces for new installations. For ground-mounted installations, competition has intensified between other uses and electricity production; particularly where tensions over land are high: intense urbanisation, need to maintain agricultural production, preservation of buildings and natural landscapes, etc.

Unused land close to transport infrastructures (along roads, highways and railways) and waterways (irrigation canals, banks, dikes, etc.) has significant potential for the installation of PV power plants and can be an opportunity for new surfaces for PV with better social acceptance, and the rapid decline in PV prices in recent years has allowed PV systems to increase their competitiveness and creates new opportunities for these innovative deployment solutions.

The European Commission's Joint Research Centre (JRC) has assessed the potential for large-scale deployment of vertical solar panels along major roads and railways in Europe. The results reveal a total potential of 403 GWp within the European Union for this type of integration alone, compared to the EU's 2030 target of 750 GWp. The study also establishes that considering only railway lines, the total annual production of PV electricity could potentially reach 250% of the current annual electricity consumption of the EU rail network. This approach offers considerable potential to power the EU's energy needs while contributing to the decarbonisation of the transport sector.

The integration of solar PV energy along transport infrastructure can make a significant contribution to the energy transition. Vertical PV walls along roads, motorways and railways, whether or not integrated with noise barriers, have historically been developed in Europe (Switzerland, Germany, Austria, the Netherlands) and are attracting growing and continuous interest with new projects coming online in the past years around the world (South Korea,

DUAL USAGE AND EMERGING PV MARKET SEGMENTS / CONTINUED

USA, the Netherlands). The electricity production generated by PV installations along roads could contribute to the decarbonisation of this sector as electric vehicles become the norm, by producing energy as close as possible to consumption.

Several pilot projects for elevated PV systems over bicycle paths and roads are announced (Germany, France), as well as experiments on dikes (Netherlands). PV shade canopies on irrigation canals, developed in India since the 2010s, are starting to be announced in regions subject to high evaporation rates (USA, Spain, even France). National railway companies and private developers are also announcing pilot projects along their networks (UK) on previously unexploited linear land.

The types of systems (ground mounted, vertical, integrated into existing infrastructure, in canopies) are numerous and present different levels of technological, industrial and commercial maturity. One of the challenges of these installations lies in the fact that the support's initial use (noise barrier, sunshade) must be preserved while allowing the production of electricity - the proper functioning of structures, systems and equipment, as well as their maintainability, should be ensured. For those installations on linear land (long and narrow) technical and regulatory questions remain to be resolved, in particular with regards to the use of often public lands for private benefits, whilst the electrical architecture and connection possibilities must be studied to achieve both technical and economic viability.

FLOATING PV: CONTINUED GROWTH

In densely populated areas, the proximity of water bodies to load centres is often an advantage. Traditional land-based PV systems face competition for land use with industrial or agricultural activities, or may not be economically viable due to the high cost of land. Japan was one of the early adopters of Floating PV (FPV), with over 200 projects. FPV is even possible in city states such as Singapore, and archipelagos such as Indonesia. The highest installed FPV capacity to date is deployed in China (expected to be over 2.7 GW for about 50 projects by the end of 2023).

By the end of 2023, the global installed capacity of FPV systems is estimated to have reached approximately 7 GW. This represents a significant growth, with the capacity expanding from 5.7 GW in 2022. Most of the growth in 2023 was in Asia-Pacific as in previous years, with large-scale projects in Indonesia (192 MW Cirata Floating Power Plant), Thailand (60 MW), India, Bangladesh (3.2 MW) and China (650 MW). In Europe in 2023, several countries, including Latvia (2.1 MW) and Albania (2 MW), inaugurated their first FPV projects, marking a significant milestone in their renewable energy initiatives. Meanwhile, France (Cintegabelle 8.7 MW) continued to expand its installations. In the rest of the world, significant FPV projects were commissioned in 2023 in Israel (31 MW), Ghana (Bui Hydro-Solar PV Hybrid 5 MW), USA (Canoe Brook Reservoir 8.9 MW) and Colombia (Aquasol 1.5 MW). Project development remained dynamic, with new contracts for increasingly larger projects signed in India after a specific tender round; additionally, aggressive development targets have been set by development companies for the creation of strong localised portfolios of FPV in India (100 MW in Assam), Philippines (100 MW), France (74.3 MW), China (2 GW) or even Zimbabwe (1 GW), whilst local governments and utilities are increasingly incorporating the development of FPV into generation and climate action roadmaps (Germany, Spain, Portugal, India). Specific tenders have been run in some countries (Malaysia, Sri Lanka, Kenya, Portugal).

Floating PV has gained an early foothold on subsidence areas of former (coal) mines and quarries filled with ground water, unsuitable for industrial or agricultural activities and generally with little bioactivities (leading to minimal environmental impacts). Installing FPV on hydropower dams has advantages (for example, streamlining grid connection when conjointly operating the solar and hydro power generation, rather than pure colocation of the FPV plant on the reservoir). Apart from the diurnal cycle (i.e., generating solar power during the day and saving water for hydropower generation at night), there is also a possible seasonal benefit in areas with dry and wet seasons. Depending on the turbines and their reaction times, it is also possible to buffer some of the short-term variability from solar (due to cloud movements) and use the reservoirs as a "giant battery". Planned PV projects on hydropower reservoirs often aim for large capacities such as in Thailand (2.7 GW), Malaysia (2.5 GW) and Zimbabwe (1 GW).

The challenges of near-shore and off-shore marine FPV projects are the more demanding environments, where tidal currents, rich marine life, wind, waves and the presence of salt water all need to be considered. The potential for near-shore areas is significant as unused space can be activated for energy harvesting close to load centres in coastal settlements and harbours. Going further off-shore aggravates the challenges and cost but still has possible applications, especially for powering oil and gas platforms or for using the existing transmission infrastructure and vast ocean spaces between the towers in off-shore wind farms (construction of a 1 GW project started in China in 2023 and pilot projects in the Netherlands and Belgium).

Most of the installations in operation use HDPE plastic floats, (Ciel & Terre, Sungrow, and BayWa r.e. together have a significant market share) but there are an increasing number of different designs, ranging from a combination of floats and metal structures (e.g.

Zimmermann) to membranes that are held in place by large plastic rings (e.g. Ocean Sun). For off-shore applications, more robust designs are being test-bedded, for example by Oceans of Energy or SolarDuck.

Going beyond floating solar, the use of near-shore pile based fixed systems to take advantage of unoccupied space is also being explored, for example with the ambitious goal of 11.25 GW in Shandong Province (China) spread across 10 plants.

The PV market is expected to achieve 20 GW of installed capacity between 2024 and 2030, with India and China contributing to more than 40% of this expansion. Different studies have evaluated regional potentials – a study conducted by researchers in the UK[1] found that covering just 10% of the surface of unprotected lakes and reservoirs within 10 km of population centres worldwide with FPV could generate 1 302 TWh of electricity annually. The study found that on average, countries could cover 16% of their annual electricity consumption with FPV, whilst five countries, including Benin and Rwanda, could cover all their electricity needs this way. Additionally, an Australian study estimates that offshore floating solar panels in favourable conditions could generate 220 000 TWh annually. The fast deployment has not been without problems, as the environmental impacts are still not properly understood, whether it be the biological impacts on water flora and fauna, or hydrological impacts, particularly on flood prone waterways. An increasing understanding may lead to revised development strategies, as seems to the case in China.

BIPV: A NICHE MARKET

Market perspectives for BIPV are positive, as past obstacles are progressively overcome and the regulatory pressure to decarbonize the energy consumption of buildings increases, particularly in Europe and China. BIPV benefits from the global PV momentum, especially in land-constrained areas where rooftop PV is developing fast. However, the inflationist environment in the USA and Europe heavily hit the construction sector, which hindered the growth of the BIPV market. In China, the real estate sector has known an unprecedented slow-down.

The lack of knowledge amongst professionals of the building construction sector also hinders BIPV growth. Although knowledge is increasing, there is also a real shortage of people combining PV- and building-related skills (across design, performance simulations, knowledge of existing products, technical constraints, ...). Much remains to be done for education and training to generalize BIPV.

Market figures are difficult to estimate. With multiple business models, different incentives, many kinds of buildings and infrastructure, BIPV covers many applications with a large variety of technical solutions – and what is counted as BIPV also changes from one country to another.

The market is split between industrial products (prefabricated tiles...) and custom-made architectural products, and the differences between custom-made elements and traditional glass-glass modules can be difficult to assess. Simplified BIPV, using conventional PV modules with dedicated mounting structures, is still leading the BIPV market. While supply has been "Western-centered" for a long time, in China many manufacturers are adding BIPV products to their catalogue, including mainstream manufacturers. Research that will benefit BIPV include emerging technologies such as perovskites (for module shape and transparency customization), and cell connections such as matrix shingling for greater freedom customisation.

Depending on the definition considered, the BIPV market ranged from 250 MW to 450 MW per year in Europe last year, indicating a moderate growth or even a stagnation. Globally, the BIPV market probably approached 3 GW, with an increasing number of projects in Asia. It is expected to keep on growing, but at a slower pace than the rest of the PV market.

OFF-GRID MARKET DEVELOPMENT

Numbers for off-grid applications are generally not tracked with the same level of accuracy as grid-connected applications, and volumes are marginal compared to the grid-connected market because the rapid deployment of grid-connected PV and the size of utility-scale -systems. Nevertheless, off-grid applications continue to develop mainly thanks to rural electrification programs essentially in Asia and Africa but also in South America, and mini-grid development in Africa.

In some countries in Asia and in Africa, off-grid systems with back-up represent an alternative to bringing the grid into remote areas or as an anticipation of grid connection. Two types of off-grid systems can be distinguished:

- Mini-grids, also termed as isolated grids, involve small-scale electricity generation with a capacity between 10 kW and 10 MW. This grid uses one or more renewable energy sources (solar, hydro, wind, biomass) to generate electricity and serves a limited number of consumers in isolation from national electricity transmission network. Back-up power can be batteries and/or diesel generators.

1. https://doi.org/10.1038/s44221-024-00251-4

DUAL USAGE AND EMERGING PV MARKET SEGMENTS /CONTINUED

- Stand-alone systems, for instance solar home systems (SHS) that are not connected to a central power distribution system and supply power for individual appliances, households or small businesses. Batteries are also used to extend the daily duration of energy use.

PV increasingly represents a competitive alternative to providing electricity in areas where traditional grids have not yet been deployed. In the same way as, mobile phones are connecting people without the traditional lines, PV is expected to leapfrog complex and costly grid infrastructure, especially to reach the "last miles".

In developing countries (Africa), mini grids are being built to electrify villages and small regions as an alternative to extending costly distribution networks. In some countries, most notably in Australia, as grid infrastructure becomes fragile in the face of extreme climate events (heat waves, fires, floods and storms), micro-grids are being built in edge-of-grid situations to reduce the cost of replacing damaged infrastructure and to provide more resilience for local populations.

Stand-alone systems tend to be specific to countries that have enough solar resources throughout the year to make a PV system viable - regions where there is demand for low energy applications (lighting, smartphone charging). The challenge of providing electricity for lighting and communication, including access to the internet, is being met by PV as one of the most reliable and promising sources of electricity in developing countries. Specific business models are developed (in Africa for instance) and large energy groups are targeting millions of people with such products. After a record 2022 year, it is estimated that 2023 volumes for this type of systems was slightly lower[2].

PV has also been deployed to power off-grid agricultural purposes such as water pumping installations.

In most developed countries in Europe, Asia or the Americas, there is little need for these systems, however, the future development of off-grid applications for remote islands and rural or underserved areas remains an important potential market.

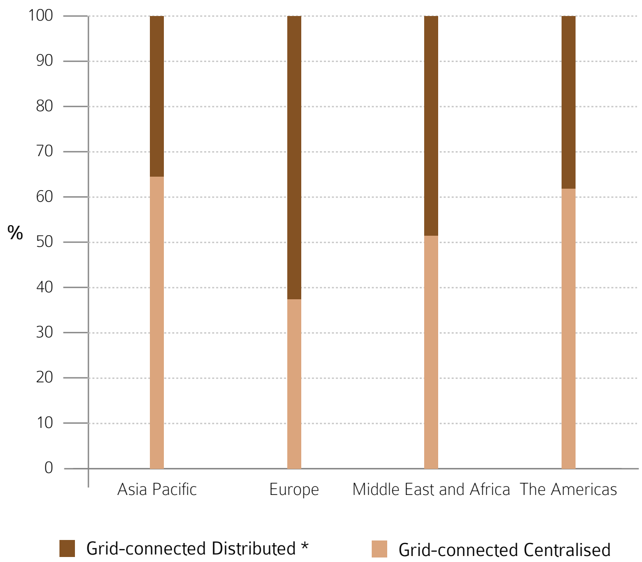
PV DEVELOPMENT PER REGION

The early years of PV development started with the introduction of incentives in Europe, particularly in Germany, and caused a major market uptake in Europe that peaked in 2008. While the global market size grew slowly in the early 2000s, from around 200 MW in 2000 to around 1 GW in 2004, significant investments in Europe pushed the market faster after this. In 2008, Spain fuelled market development while Europe as a whole accounted for more than 80% of the global market until 2010, with 8 GW in 2006, booming to 17 GW in 2010.

From 2011 onward, the share of Asia and the Americas started to grow rapidly as some European markets contracted in a post-boom "bust" phase (Spain, France) with Asia taking the lead. This evolution has had Asia's share oscillating between 50% and 75%; in 2023, it reached nearly 70%.

Detailed information about most IEA PVPS countries can be found in the yearly National Survey Reports and the Annual Report of the programme. IEA PVPS Task 1 representatives can be contacted for more information about their own individual countries.

FIGURE 2.12: ANNUAL GRID-CONNECTED CENTRALIZED AND DISTRIBUTED PV INSTALLATIONS BY REGION IN 2023



*includes off-grid

SOURCE IEA PVPS & OTHERS

2. https://www.gogla.org

THE AMERICAS

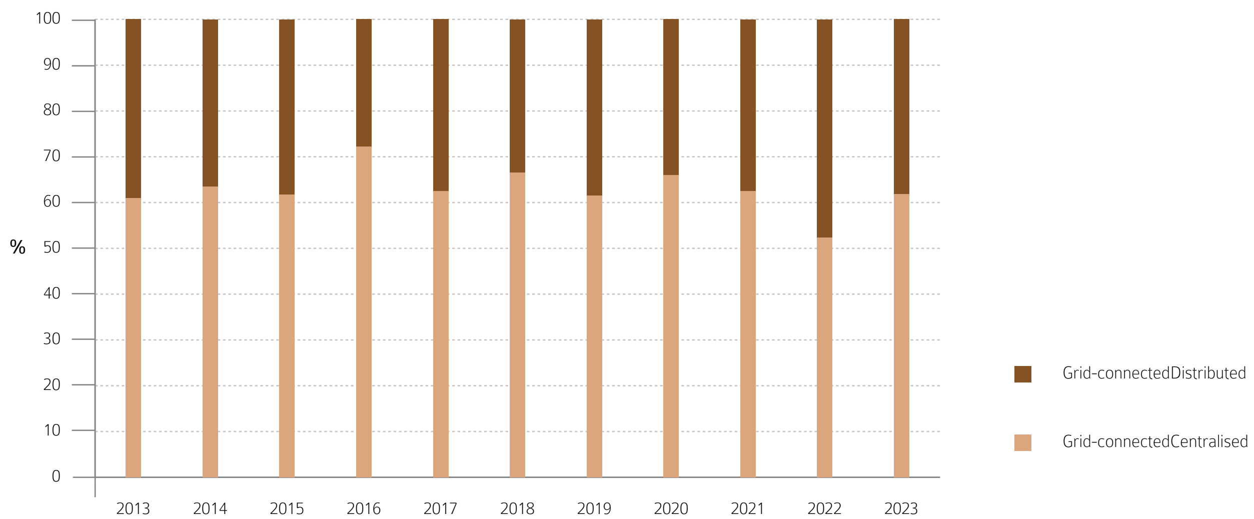
The Americas saw 52.6 GW of PV installed in 2023 for a total cumulative capacity of 248.4 GW in 2023. This represented nearly 12% of annual global capacity, down from last year's 16% as the Chinese market leapt beyond other markets capacity to follow. As in 2022, most of these capacities are installed in the USA and Brazil, but several countries have cumulative capacity over the GW level and continue to instal several hundred MW per year (Canada, Chile, Mexico).

PV is developing in the Americas in both the distributed and centralised segments; the USA is pulled by the utility-scale segment, as is the market in Canada, running both on tenders and PPAs, whilst in Brazil distributed solar is the largest segment. USA has by far the largest installed capacity, adding 33.9 GW to reach a cumulative capacity of 177.3 GW – 2023 was the biggest year for solar in the USA ever, as systems delayed by supply chain and grid queue issues in 2022 were connected. Utility solar jumped from 14.59 GW in 2022 (18.2 GW in 2021) up to 24.3 GW in 2023, whilst annual distributed solar volumes increased as well adding 9.5 GW, up from 8.2 GW in 2022. The Inflation Reduction Act of 2022 (IRA) incentives also played their part in the growth, as did evolving electricity consumption rates and renewable energy standards and pledges as well as support for solar communities. Evolving quite differently, Brazil continued to be the 2nd market in the Americas and the 5th worldwide, adding 12.4 GW of which 67% (8.3 GW) was in the distributed segment – with over 30 GW of distributed projects having requested grid connection, although it remains to be seen how much of this capacity will be effectively commissioned. Its cumulative capacity is now 37.8 GW.

Outside of the IEA PVPS countries, Mexico added 1.6 GW of new capacity in 2023, including the commissioning of the first phase (120 MW) of a 1 GW plant in Sonora. Distributed solar continued strongly with 480 MW of new capacity.

Other South American markets remain low compared to Brazil, but hundreds of MW are still coming online in most countries as smaller centralised system of a few dozen or hundred MW are planned. The PV market picked up in Argentina after a very slow 2022, nearly climbing back to 2021 volume, but was still only a few hundred MW although plans are underway for a multi GW system. In Ecuador, the government selected laureates from its 2021 competitive tenders, but downgraded its election of an initial 345 MW of projects to just 120 MW. Chile was the 2nd largest market in South America, heading towards 10 GW cumulative capacity, with more than 1.3 GW commissioned in 2023, across utility, commercial and distributed solar. In Colombia, approximately 200 MW of utility-scale PV came online in 2023, with more than 1 GW of projects beginning construction, and over 5 GW of capacity was selected in tenders and there is growing interest in distributed solar for commercial projects.

FIGURE 2.13: EVOLUTION OF PV INSTALLATIONS IN THE AMERICAS PER SEGMENT



SOURCE IEA PVPS & OTHERS

PV DEVELOPMENT PER REGION / CONTINUED

ASIA-PACIFIC

The Asia-Pacific region installed 314.4 GW in 2023 and the total installed capacity reached nearly 1 TW, with a minimum of 946.2 GW up to a probable 988.8 GW. The market remained strong across all of Asia Pacific, with a few exceptions where volumes were down compared to 2022 – for example in India, and in the utility-scale segments of Japan and Australia. The region represented 69% of global annual capacity, up from 59% in 2022, and cumulative capacity in the region has now tipped over the 60% mark.

The size of the Chinese PV market makes it a dominant player in the Asian and global PV markets, while all other markets are lagging behind. Asia is home to several IEA-PVPS GW-scale markets in 2023: China, Japan but also Australia, South Korea, with lesser volumes in Malaysia.

China installed 277.2 GWdc (converted from China's National Energy Administration AC figures using the IEA-PVPS AC/DC conversion ratio as explained in this report), reaching a cumulative capacity of 691.2 GWdc. After two years of balanced growth in the distributed and centralised segments, 2023 saw a real pull from the centralised segment (65% of new capacity). Volumes were spread unevenly across the country, with the highest concentration in the provinces running south down the coast from Beijing, although the capacity in the western province of Xinjiang is catching up to some of the coastal provinces. 2023 was declared a "pivotal year for deployment of renewables" by the National Energy Agency, with the annual target of 160 GW well and truly met.

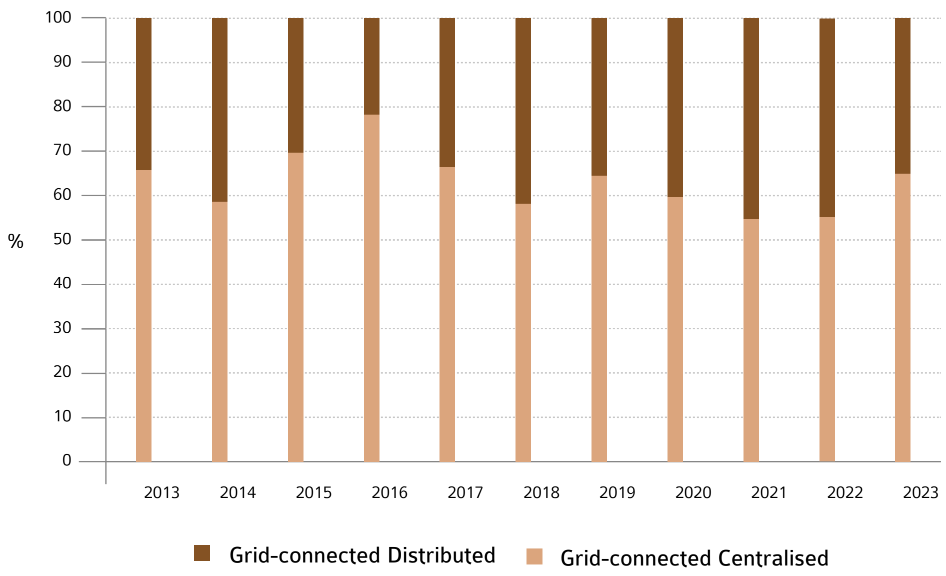
Outside of the IEA-PVPS network, the largest market in terms of installations and potential is India. Given the population of the country, its potential is on a level with China, (or more, given the need for electrification). After a slow 2020 at just 4.4 GW due to a series of administrative issues and difficulties, the market picked up in 2021 (13 GW) and 2022 (18 GW) and continued in 2023 adding 13.0 GW of grid connected PV (revised from the IEA PVPS Snapshot publication in April 2024). The annual India market share of utility-scale PV was identical in 2023 and 2022 at over 75%. Over 50 GW of tenders were called in 2023, and many of these were for solar+storage, technology neutral or hybrid systems. The distributed market rose slightly but is still far behind the deployment of utility-scale PV; off grid systems represent considerable volumes for a range of applications.

The market in Japan was down to 6.3 GW from 6.6 GW in 2022, reaching a cumulative capacity of 91.4 GW, The Japanese market is slowly contracting year on year, dropping to its lowest annual addition of new capacity since 2012. Tenders through the year were undersubscribed, and the market share of centralised systems dropped to 47% (from 56% in 2022). FiT were increased for some segments to encourage building applied systems, and the distributed market grew for the first time in several years, up 15%.

Both South Korea and Australia had stable markets; South Korea at a steady 3.3 GW (for a cumulative capacity of 27.6 GW) and Australia at 4.2 GW (for a cumulative capacity of 34.5 GW). The two markets are dissimilar though – carried by centralised systems in South Korea and the distributed segment in Australia. Australia is investing in new grid capacity to facilitate further development of utility-scale PV as it heads into what is expected to be regular 100% renewable supply over several hours before the end of 2025.

Chinese Taipei added 2.7 GW or 25% of its cumulative capacity in a single year to reach 10.4 GW, whilst Thailand's market was a standout, adding roughly 4 GW to reach 8.9 GW. Whilst the market in the Philippines remained small in 2023, the liberalised energy market has proved attractive for foreign investment and several GW are in the planning stages, including a 1 GW floating plant whilst construction commenced on a 4 GW system - 2024 should see some significant capacity additions. Malaysia added 0.7 GW for a cumulative total of 3.4 GW. In Pakistan, large volumes of modules (over 7 GW according to some sources) were imported in 2023, with approximately 1.3 GW installed – a series of tenders to equip government buildings were run, as well as a 600 MW competitive tender. Bangladesh added a 275 MW utility-scale system and gave approval for over 1.5 GW as it improved access for foreign ownership. Textile manufacturers have begun equipping premises both in Pakistan and Bangladesh to meet their client's climate targets, in what may be the beginning of a new trend in commercial and industrial systems. In Indonesia, several hundred MW were commissioned, including a 192 MW floating PV system, ahead of a planned expansion to 500 MW.

FIGURE 2.14: EVOLUTION OF PV INSTALLATIONS IN ASIA PACIFIC PER SEGMENT



SOURCE IEA PVPS & OTHERS

EUROPE

Europe led the development of PV for many years, adding a large proportion of the world's capacity through the period 2000 to 2012 to reach 70% of cumulative capacity in 2012. The steep price drops from 2009 to 2012, mostly due to the ramping up of Chinese manufacturing capacity, had significant impacts on European markets. Very fast development of PV over short periods of times ("PV booms") led to a demonstrated opposition from many stakeholders from the traditional energy sector, with different mechanisms resulting in declining markets in several countries. From 2013 to 2017, the growth of European PV installations slowed significantly whilst there was rapid growth in the rest of the world, mainly in Asia and the Americas. In addition, several countries implemented measures to decrease the cost of support mechanisms for PV installations by retroactively changing the remuneration levels or by adding taxes. This phenomenon happened mostly in Europe, where the fast development of PV took place before other regions of the world: Spain, Italy, Czech Republic, Belgium, France and others took some measures with a consequent impact on the confidence of financial backers, developers and prosumers.

The situation improved gradually in most countries and PV installations rose in Europe through the early 2020's. Since then, most European markets have grown each year – especially in the distributed segment, pulled by growing adoption of residential, commercial and industrial self-consumption sparked by the high electricity prices of 2022. Cumulative capacity across Europe reached 63.3 GW, up in absolute value from 42.4 GW in 2022, but slipping to 14% of the global market, down from 17.5%. The cumulative capacity in Europe is now 305.2 GW.

It is important to distinguish the European Union and its countries, which benefit from a common regulatory framework for part of the energy market, and other European countries which have their own energy regulations and are not part of the European Union.

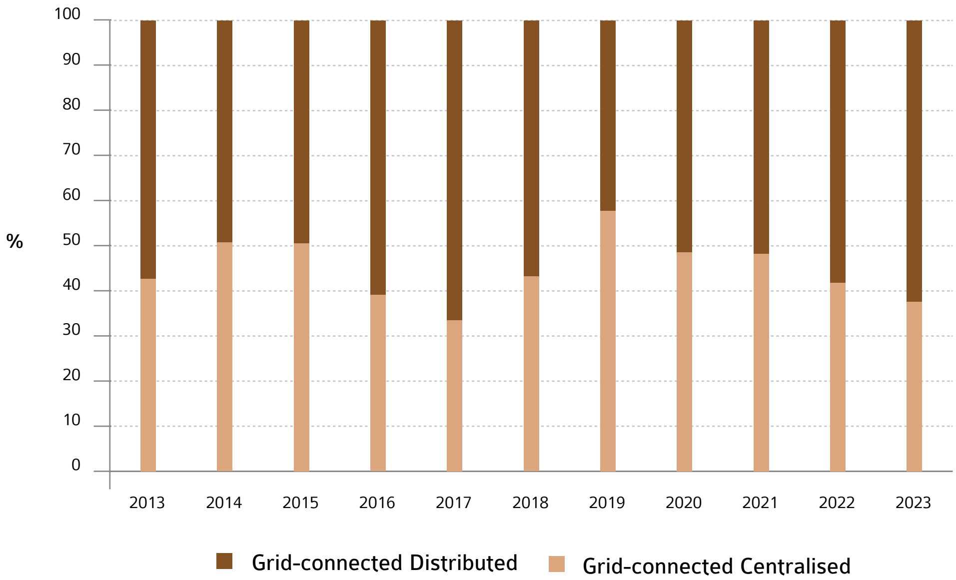
Whilst most European countries used Feed-in Tariff schemes to start developing PV, the movement to self-consumption (or variants) for distributed PV is accelerating while tenders and PPA's become the standard for utility-scale PV. These trends are not unique to Europe, but self-consumption developed faster here than in other locations, no doubt due to the high electricity consumption prices. The development of collective and delocalized self-consumption is also accelerating in EU countries where regulatory frameworks are catching up to market demands[1].

1. See the IEA PVPS Task 14 paper "Self-consumption of electricity produced with photovoltaic systems in apartment buildings - Update of the situation in various IEA PVPS countries"

PV DEVELOPMENT PER REGION / CONTINUED

BIPV has been incentivized in Europe more than in any other part of the world in the past but remains a niche market after several GW of installations. Simplified BIPV seems to develop well in some countries and is likely to increase, always as a niche market, with a slow deployment by different countries of mandatory solar of some sort in building regulations as a response to ambitious climate targets. Merchant utility-scale PV developed in Spain, Germany and France initially with more recent projects in Romania, - and could take a significant market share in a near future, along with PPA and corporate PPA's whose market shares continue to grow. In general, PV development in Europe continued to be dynamic over 2023 as China's manufacturing overcapacity is targeting the more open European market, rather than the USA and India.

FIGURE 2.15: EVOLUTION OF PV INSTALLATIONS IN EUROPE PER SEGMENT



SOURCE IEA PVPS & OTHERS

EUROPEAN UNION

At the end of 2023, the total installed PV power capacity in the European Union had reached 273.7 GW, or 90% of the capacity in Europe. As in the wider European market, residential, commercial and industrial rooftops are the most important segment, with 61% of new capacity additions (up from 57% in 2022). The market in 2023 was largely influenced by the remnants of the electricity market price spikes of late 2022 and the aggressive pricing of modules as manufacturing capacity in China increased significantly. Fourteen countries installed more than 1 GW, with Germany heading the list (15.0 GW), followed by Spain (8.9GW), Italy (5.3 GW), Poland (4.9 GW), the Netherlands (4.8 GW), France (4.0 GW) and Austria (2.6 GW). Belgium, Sweden, Hungary, Greece, Portugal, Bulgaria and Romania all installed between 1 GW and 2 GW of new capacity. Market split between centralised and distributed generation varies from country to country; the European markets with more than 0.5 GW centralised PV where utility-scale PV is a market driver are Spain, the Netherlands, Hungary and Bulgaria; on the opposite end, more than a dozen countries with over 0.5 GW of new distributed capacity were driven by the distributed market – most notably, Germany, Italy, Poland, France and Austria.

The Netherlands continued to lead in terms of installed capacity per capita in the EU with 1288 Wp. The number of EU countries that had a penetration rate above the European Union average, now 488 Wp/capita, doubled from six to twelve – with five above 700 Wp per capita: Germany (974 Wp), Belgium (842 Wp), Spain (806 Wp) and Austria (700 Wp) and an additional five above the EU average.

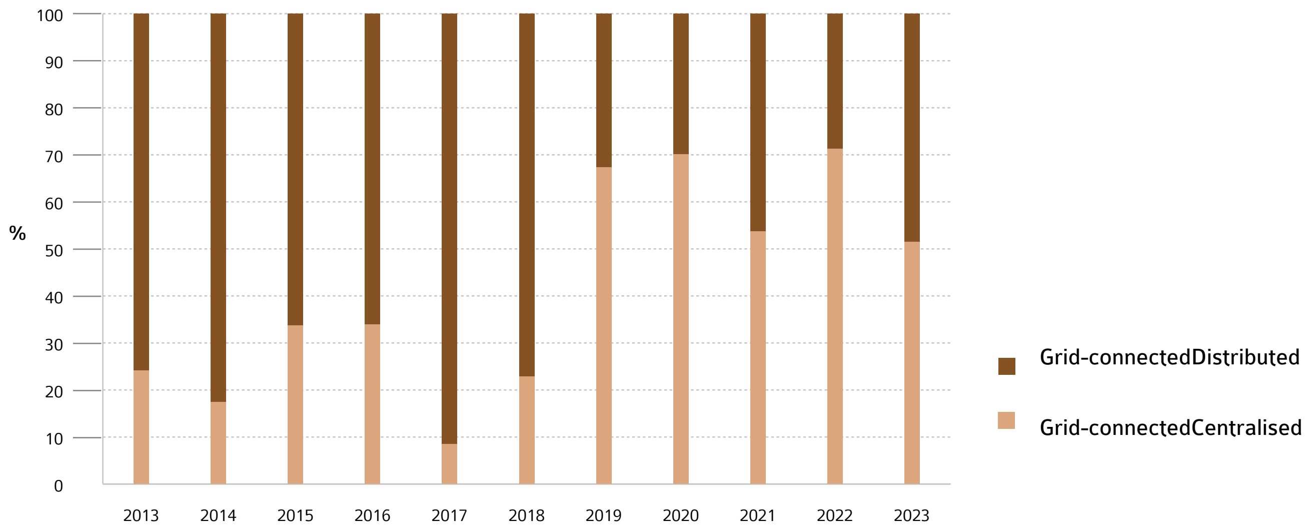
OTHER EUROPEAN COUNTRIES

Outside of the IEA-PVPS network, UK was a growth market with 1.3 GW in 2023, nearly double the 2022 value. The country had 16.0 GW of PV at the end of the year 2023 and awarded 1.9 GW of capacity in tenders last year, expected to come online through 2025 to 2028, pushing the utility segment to the front. Switzerland continued to expand with 1.6 GW installed, once again, almost all rooftop systems.

MIDDLE EAST AND AFRICA

In Middle East and Africa countries, the development of PV remains modest compared to the larger markets, especially in the African countries. However, almost all countries saw a small development of PV in the last years and some of them a significant increase. There is a clear trend in most countries to include PV in energy planning, to set national targets and to prepare the regulatory framework to accommodate PV.

FIGURE 2.16: EVOLUTION OF PV INSTALLATIONS IN AFRICA AND THE MIDDLE EAST PER SEGMENT



SOURCE IEA PVPS & OTHERS

MIDDLE EAST

With high irradiation, the Middle East is amongst one of the most competitive places for PV installations, with PPAs granted through tendering processes among the lowest in the world, building on excellent irradiation levels. In 2023, several large-scale systems came online, bringing the annual capacity up to 7.5 GW, well above last year's 5.5 GW. Three countries in the region added 1.9 GW in 2023: Saudi Arabia (for a cumulative total of just 2.9 GW), Türkiye, who reached the region's highest cumulative capacity of 14.4 GW, and the UAE (cumulative capacity of 7.1 GW). Israel maintained its market at 1.1 GW for a total of 5.7 GW, with the other regional markets trailing.

In the region, energy prices are often supported by government spending, which limited the ability of PV to compete for years, however, countries such as Iran, Qatar, Kuwait, Saudi Arabia, Bahrain, Jordan, Oman and the United Arab Emirates have or are defining targets for renewable and solar energy for the coming years. Conditions are slowly changing for distributed PV, with net-metering being proposed in some countries such as in Türkiye, Egypt, Dubai where the upper limit was lowered in 2023, Bahrain, Jordan (transitioning to net billing in 2024), and FiT or other mechanisms in Iran, Israel, Saudi Arabia, Tunisia, with plans to introduce similar schemes in Qatar, and Morocco. The UAE is facilitating the connection of distributed generation to the network to help relieve peak loads. Türkiye is looking to sustainable building mandates to promote distributed solar. Another trend in the fast-developing region is the willingness for governments to develop brand new cities or neighbourhoods, which aim at becoming showcases of renewable energies. This was the case for Masdar City (UAE) or Spark and Neom (Saudi Arabia).

PV DEVELOPMENT PER REGION / CONTINUED

For centralised PV, tenders are an integral part of the plans for PV development in the short and long term in the region, with government and state-owned organisations tendering for single site or multi-site projects as procurement exercises. Examples in 2023 include Saudi Arabia (3.7 GW in the 5th round of its NREP). Morocco called for 400 MW of solar+storage for Noor III and Tunisia called tenders for 1 GW. Projects for solar powered green ammonia or hydrogen are underway in Jordan, Egypt and the UAE (the UAE is looking to green the steel industry). In parallel, plans for a 10 GW metallurgical silicon, polysilicon, cell and module manufacturing plant in Saudi Arabia have been initiated .

AFRICA

The African market is dynamic but difficult to follow, with market reports diverging in terms of capacity, depending on their sources. On top of weak reporting standards and capabilities in many African countries, probably significant volumes of off grid micro and small-scale PV seem to be unreported to authorities. COVID impacted growth in Africa, and the shrunken market from 2019 to 2021 resulted in a break in the previous positive trend of PV development and rural electrification, as fiscal resources were diverted to food and primary necessities.

Africa is by far the smallest regional market, with just an estimated 20 GW of cumulative capacity installed, of which over 3.7 GW was installed in 2023[1]. South Africa is the largest market, with 3.0 GW of new capacity in 2023 – of which 2.6 GW was distributed - to reach a cumulative capacity of 7.5 GW. Whilst other countries have nascent commercial and industrial segments, volumes remain low – the 30 MW Gorou Banda Solar Power plant was inaugurated in Niger, Zambia saw a 33 MW plant come online with plans for over 2 GW more, and tenders for a 30 MW solar+storage plant in Eritrea and 30 MW floating PV in Kenya were launched. Financing for a 50 MW system in Sierra Leone was confirmed.

Large-scale systems remain a main contributor, but the commercial and industrial segment is slowly gaining momentum and maturity as companies seek to hedge against future rises in electricity prices by generating their own power.

Large scale systems for low-carbon hydrogen projects are underway or under discussion, primarily looking to produce ammonia for fertiliser, both strengthening Africa's food security and taking advantage of the excellent irradiation available in many African countries. Experts are confident that the production of highly competitive H2 can be reached.

1. According to the African Solar Industry Association.

The question of African power infrastructure and markets is essential since many countries have a small, centralized power demand, sometimes below 500 MW. In this respect, the question is not only to connect PV to the grid but also to reinforce the electricity grid infrastructure and interconnection with neighbouring countries.

Mini-grids are an important tool for rural electrification, and a series of projects were announced or developed in 2023 (Angola, Botswana, Ghana, Nigeria, Senegal, Somalia, for example). This segment is still very dependent on grants and subsidies while it tries to identify solutions that will lead to pure commercial bankability.

One of the main difficulties for these segments is attracting private investment (with investors wary of the risk levels and upfront cost). However, new renewable energy markets are showing greater appeal to international and local investors - and the most competitive segment for the development of solar in Africa, especially in remote areas i.e. PV plants to replace or complement existing diesel generators, is of interest to investors.

Early solar PV development was supported by government and donor-supported rural electrification with micro and small systems, but the transition to a more market-based development can now be observed. Pay-as-you-go models are used to bypass financing difficulties for residential consumers whilst different pricing formats exist to foster access to clean and reliable electricity. Off-grid PV applications, such as water pumping, are expected to play a growing role in bringing affordable power to consumers.

Support policies and facilitating regulation are more than ever necessary to accelerate uptake ahead of the expected increase in energy consumption and electricity access due to a multitude of factors including population growth and socioeconomic dynamics (increases in the energy consumption per capita for those countries with high electrification rates), decarbonisation of electricity production, electrification of industry and transport, production of green hydrogen...

Africa is already facing severe climate change consequences including water stress and reduced food production, so emerging dual usages such as agrivoltaics and floating PV are potential tools to increase food resources and protect water resources whilst producing electricity.

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PV DEVELOPMENT PER REGION / CONTINUED

TABLE 2.6: 2023 PV MARKETS STATISTICS IN DETAIL

COUNTRY	2023 ANNUAL CAPACITY (MW)			2023 CUMULATIVE CAPACITY (MW)		
	DECENTRALIZED	CENTRALIZED	TOTAL	DECENTRALIZED	CENTRALIZED	TOTAL
AUSTRALIA	3 182	972	4 153	23 165	11 356	34 522
AUSTRIA	2 295	308	2 603	5 832	563	6 395
BELGIUM	1 621	185	1 806	9 533	422	9 955
CANADA	99	724	823	2 337	5 003	7 340
CHINA	96 290	180 886	277 176	255 980	435 261	691 241
DENMARK	321	167	487	2 031	1 879	3 910
FINLAND	302	16	318	959	49	1 008
FRANCE	2 587	1 374	3 961	12 701	10 963	23 664
GERMANY	10 357	4 648	15 005	63 916	18 389	82 305
ISRAEL	830	320	1 150	3 472	2 185	5 657
ITALY	4 399	856	5 255	21 060	9 259	30 319
JAPAN	3 328	2 972	6 300	54 517	36 849	91 366
KOREA	514	2 792	3 306	3 675	23 944	27 619
MALAYSIA	266	444	710	1 289	2 100	3 390
MOROCCO	693	35	728	1 679	35	1 714
NETHERLANDS	1 964	2 824	4 788	9 463	13 574	23 037
NORWAY	299	4	303	653	4	657
PORTUGAL	775	509	1 285	1 522	2 300	3 822
SOUTH AFRICA	2 600	365	2 965	5 205	2 299	7 504
SPAIN	2 047	6 940	8 987	8 346	30 640	38 986
SWEDEN	1 611	77	1 688	3 945	270	4 215
SWITZERLAND	1 641	0	1 641	6 306	68	6 375
THAILAND	1 103	3 484	4 587	2 380	6 620	9 002
TÜRKIYE	1 027	840	1 867	11 309	3 084	14 393
USA	9 530	24 345	33 875	60 096	117 248	177 344
IEA PVPS	**149 681**	**236 086**	**385 766**	**571 372**	**734 366**	**1 305 739**
BRAZIL	8 346	4 100	12 446	26 330	11 487	37 817
INDIA	2 995	10 025	13 020	15 771	106	92 645
NON-IEA PVPS	39 346	30 890	70 244	156 529	179 941	336 218
TOTAL	189 027	266 975	456 010	727 900	914 307	1 641 956

SOURCE IEA PVPS 8 OTHERS

three

POLICY FRAMEWORK

As the cost environment of PV changed over the past two years, from the high costs yet high competitivity of mid-2022 to the plummeting module costs but lesser competitivity of late 2023, the importance of policy support even in conditions of market competitivity has become increasingly apparent.

From the late 90's onwards, the development of PV was pushed by various support mechanisms – from feed-in tariffs, direct subsidies, and tax credits to competitive calls for tender and feed-in premiums. The initial goal was generally to compensate for the lack of competitivity by reducing the gap between the cost of electricity from PV and the cost of electricity from conventional sources. More recently, the rapid reduction in PV costs has meant that competitiveness is no longer a problem in several countries and across different segments (for more detail, see Chapter 6, competitiveness of PV electricity).

Support mechanisms for centralized PV are increasingly becoming additional to market remuneration with competitive tenders operating as guarantees for a minimal remuneration after taking into account market sales, pushing the development of power purchase agreements (PPA) and market sales (merchant PV). These Contract for Difference schemes demonstrated their ability to funnel profits from high electricity market costs back to the government in 2022. When PV is so competitive that no financial incentives are required, large-scale systems are moving directly to PPAs, with a trend to diminish contract length – inevitably, many PV systems operating initially in these private contracts will end up with electricity sales on wholesale markets (merchant PV). After a series of undersubscribed tenders in 2022 due to the attractively high market electricity prices of 2022, tenders in some European countries were largely oversubscribed in 2023 as the stability of guaranteed remuneration and (easier) financing was balanced with volatile electricity market costs and higher financing costs.

In new markets, support for distributed PV often begins with net metering, before setting feed-in tariffs, and finally ends in some form of net billing where excess electricity after self-consumption is bought at a utility or government-set rate; this rate can be lower than wholesale electricity costs (to discourage excess) or benefit from feed-in tariffs at premium rates. Direct subsidies and tax credits remain present across the world, although direct subsidy policies tend to be fragile due to their high upfront costs for governments – and are increasingly reserved for stimulating specific market segments.

For residential and commercial markets, in many countries self-consumption has become the model of choice with regulations and support measures being adapted to accommodate this. Whilst in some competitive markets support mechanisms have been stopped or adapted to encourage emerging segments such as building Integrated PV or AgriPV, climate imperatives, the search for energy sovereignty, and ambitious PV development goals mean that other countries are stepping up to accelerate deployment by increasing support budgets or support levels. Many different indirect policies to encourage or facilitate PV such as mandatory solar on buildings and car parks and support mechanisms addressing permitting complexity and costs, facilitated access to electricity markets, or grid access policies for prosumers are being used across the world to accelerate PV deployment.

Where complete competitivity is not yet present, support schemes are evolving according to market maturity, and investor confidence. Therefore, targeted financial incentives might still be needed for some years to overcome costs or investment barriers in specific countries. The electricity market volatility of the past few years has demonstrated that support mechanisms need a certain level of agility, and that competitivity can be insufficient for financing long-term project viability.

Where market volumes are strong, a large part of new policies are focused on self-consumption schemes, citizen communities, and innovative forms of collective and delocalized self-consumption. Policies supporting self-consumption might be considered as non-financial incentives since they set up the regulatory environment to allow consumers to become prosumers or an energy community.

The electrification of usages is an important factor in the energy transition, and the sale of battery storage, heat pumps and EV are increasing rapidly for residential and commercial users, whilst big batteries are enabling fast transitions in areas with high penetration rates of renewable energies and increasingly saturated grids. In parallel, the development of "green" hydrogen projects powered by solar and other renewable electricity continues stronger than before as the fragility of gas supply pushes governments to accelerate support for alternatives.

Taxes and the financing of distribution and transmission grids are still animating the debate, shaping the regulatory framework and impacting the business models and the price for PV electricity.

PV MARKET DRIVERS AND SUPPORT SCHEMES

The question of market drivers is a complex one since the market is always driven by a combination of several regulations and incentives.

ACCESS TO SUPPORT MECHANISMS AND REMUNERATION MODELS.

Access to support mechanisms can be through open-access schemes (either unlimited or capped in volume or time, generally with a series of mandatory requirements relating to system size or installation type, sometimes associated with minimal installer qualifications or product certification) or through competitive tenders. Remuneration models tend to include feed-in tariffs (FiT) or premiums (FiP) – sometimes for all the electricity generated from a system, sometimes for excess generation after self-consumption (net billing), green certificates or direct subsidies in open access schemes, whilst tenders are seeing a shift away from feed-in tariffs to feed-in premiums and contracts for difference (CfD) – but also to tenders for electricity or generation capacity procurement. Power purchase agreements between generators and consumers can be modelled on any of these mechanisms.

FEED-IN TARIFFS AND PREMIUMS IN OPEN ACCES SCHEMES

Predefined feed-in tariffs remain an important tool for ensuring roll-out of PV in the distributed segment, and whilst many existing schemes continued through 2023, others were discontinued. Feed-in tariffs work on a simple principle – electricity produced by the PV system and injected into the grid is paid at a predefined price and guaranteed during a fixed period (often 10 or 20 years). FiT are paid in general by official bodies or utilities and were set-up to stimulate local PV market segments. Generally, only available for small or small to medium-sized systems, the FiT can be fixed over the contract period, or be indexed to inflation or some other indicator, and it can be made available for systems that inject the entirety of their electricity into the grid or, increasingly, only the excess after self-consumption (also called net billing). In some countries, system owners may be able to choose between total injection or the injection of excess after self-consumption and may even be allowed to migrate from one model to another. FiT have demonstrated their efficiency as drivers for the development of residential markets and remain a tool for incentivising self-consumption by managing excess generation without batteries.

Amongst the IEA PVPS member countries that had a government (national, federal or state) mandated open access FiT scheme in 2023, most cover the residential sector, (Austria, Canada, China (ended), France, Germany, Greece (new), Japan, Portugal, Switzerland, Thailand, USA), sometimes extending to the commercial and industrial segments (Austria, France, Germany, Japan). With increased competitiveness, a few countries have or are phasing out government-based FiT schemes (Australia, where utilities set net billing feed-in tariffs as part of their customer acquisition and loyalty strategies, some states have set minimum rates). With the large drop in price experienced over 2023 for modules, some countries (France, California, New York and Indiana in the USA), once again adjusted feed-in tariff levels to take into account the changing profitability of PV.

Increasingly countries are either dropping FiT (in 2023, South Korea) or reserving them for excess injections after self-consumption (net billing FiT) as grid parity is reached. Depending on the country specifics, FiT can be defined at the national level and at the regional, county or city level (Australia, Canada, China, USA etc.) with some regions opting for it and others not, or with different characteristics. FiT can also be granted by utilities themselves (Australia, USA, China (Hong Kong)), outside of the policy framework to increase customer fidelity.

Feed-in premiums (FiP) are premiums paid on top of the wholesale electricity market price. Fixed and variable premiums can be considered. Sweden and Austria are using a fixed FiP for small decentralized systems – in the case of Sweden, it is managed through tax credits per kWh generated.

Defining FiT or FiP levels that adequately incentivise PV without overcompensating can be a delicate task, particularly when costs are volatile or subject to steep declines. Entities bearing the cost of FiTs (governments or utilities) will generally seek adjustment mechanisms to ensure that market booms do not lead to cost blowouts and/or over-compensation, a lesson learned from past market booms that occurred in countries such as Spain in 2008, France in 2009, Czech Republic in 2010, Italy in 2011, Belgium in 2012, to a certain extent in China in 2015, 2016 and 2017, and to a lesser extent to other countries. These booms strained budgets and negatively affected the public perception of PV, and most of these markets took years to recover and reexperience growth.

To keep market development stable or financially viable for cost bearers, adjustment mechanisms can include periodic industry negotiations, inflation, and market growth indexation.

Many countries adopted the principle of decreasing FiT levels over time or introduced limited budgets, building on the experience of a consistently reducing price curve for PV systems. In Germany, the level of the FiT can be adapted monthly to reduce the profitability of PV investments if the market is growing faster than the target decided by the government. In Japan Fit are adjusted regularly – and in 2023 were increased for commercial-sized rooftop systems to encourage this specific segment. In France, the FiT decrease is dependent on both installation rates and economic indicators. The economic indicators and government intervention also allow for increased or decreased FiT if economic conditions (such as cost increases or booming investment) require it.

INCENTIVIZED SELF-CONSUMPTION

Self-consumption, supported by different mechanisms such as net-metering, net-billing, premiums on self-consumed electricity or investment subsidies is becoming the norm in an increasing number of countries. Various forms of support to self-consumption schemes exist, from the historically deployed "net metering" used to develop the market of small-scale PV installations on buildings that were adopted in a large number of countries, although with different definitions of what, precisely, net metering meant (the same vocabulary can imply different regulations and different remuneration models. The best example is in the USA, with the wording "net-metering" being used for different self-consumption schemes in different states).

Genuine "net-metering" which offers credits at the same rate as consumption for PV electricity injected into the grid, has previously supported market development in Belgium, Canada, Denmark, Hungary, the Netherlands, Portugal, South Korea, the USA, and even Pakistan but such policies continue being replaced by net billing, self-consumption policies encouraging real-time consumption of PV electricity (Poland, Arkansas, North Carolina, Idaho, and Hawaii in the USA in 2023 alone).

Net billing can be incentivized with a feed-in tariff (or feed-in premium added on top of the spot price) for the excess PV electricity fed into the grid. This is for example the case in France, Italy, Japan. It can also be associated with time of use rates or low rates to discourage sending excess electricity to the grid, for example encouraging investment in battery storage (Australia and California (USA)). As grids in some parts of the world become more congested, or as distributed solar outpaces consumption, curtailment policies are put in place that no longer guarantee access to the network at all times (Australia, South Korea).

Although net metering is being replaced in historical markets, countries such as Malaysia or Ecuador introduced net metering for residential PV owners recently. Several emerging PV countries have implemented net metering schemes in recent years (Chile, Jordan, UAE (Dubai), Morocco and Tunisia). While the self-consumption and net metering schemes are based on an energy compensation of electricity flows, other systems exist. Italy attributes different prices to consumed electricity and the electricity fed into the grid.

DIRECT SUBSIDIES, REBATES AND TAX BREAKS

Direct subsidies remain in place in many countries. Most of the time they cover only a part of the total installation cost. PV is characterized by limited maintenance costs, no fuel costs but high upfront investment and this has led some countries to put policies in place that reduce the upfront investment to incentivize PV. Direct subsidies were implemented in the early phase of PV development in countries such as Austria, Australia, Canada, Finland, Italy, Japan, South Korea, Lithuania, Norway, and Sweden just to mention a few.

Incentives can be granted by a wide variety of authorities or sometimes by utilities themselves. They can be unique or add up to each other. Their lifetime is generally quite short, with frequent policy changes, at least to adapt the financial parameters to current project economics and political priorities. Next to central governments, regional states or provinces can propose either the main incentive or some additional ones. Municipalities are more and more involved in renewable energy development and can offer additional advantages. In some cases, utilities are proposing specific deployment schemes to their own customers, generally in the absence of national or local incentives, but sometimes to complement them.

In most countries, this support mechanism has not demonstrated its ability to support and accelerate PV development over the long term and was progressively replaced by FiTs, although not completely phased out everywhere. However, because of the psychological attractiveness of direct upfront subsidies for the residential sector (depending on local culture they can be more attractive to end users than deferred payments through FiT), some countries have continued to use direct subsidies alone (Flanders in Belgium, South Korea, Norway, Poland, Italy, Switzerland) or in conjunction with other support mechanisms (France, for self-consumption with net billing), Australia, Austria, Germany, Greece for PV with storage. Switzerland gives bonuses on top of its direct subsidies depending on the size, inclination, and altitude of systems. South Korea continues to provide direct subsidies in different programs for

PV MARKET DRIVERS AND SUPPORT SCHEMES / CONTINUED

residential systems (since 2004) and building applied systems on commercial buildings (with priority given to BIPV systems).

Governments have also used direct subsidies to encourage very specific segments on an experimental basis - Japan joined Austria, Finland with subsidies for agricultural systems and sometimes systems on other specific land usages. The USA has a diversity of state and local subsidies for solar installation, often targeted at increasing deployment in low-income and/or historically marginalized communities (South Korea also). The landmark Inflation Reduction Act also included increases to grant programs targeting both rural deployment and deployment in indigenous communities, as well as creating several new grant programs incentivizing deployment in historically marginalized communities. Different regions in Italy have set up capital investment subsidies in 2023; one region has launched a scheme that should be self-sustaining for families in energy poverty situations that cover installation and maintenance costs, with self-consumed electricity free for the residents and excess electricity sales feeding the financing fund. Many countries have capital subsidies for local government authorities installing PV (Italy, Japan South Korea, some states in the USA, California, New York, Nevada, Illinois, etc) – often with conditions mandating the use of building integrated PV.

Tax credits have been used for a long time around the world, either on their own or associated with FiT, direct subsidies or rebates. (as early as 2005 in France, USA), and spread to a large variety of countries, ranging from Belgium and Canada to Japan and others. Tax credits can be applied to equipment costs, labour costs or, more rarely, even electricity (Sweden).

Tax credits have been introduced (or re-introduced) in the past few years including in Germany (2022), Italy (2023), Sweden (2015, 2021). Tax credits can be open to individuals (USA, Italy, Switzerland, Germany, Finland, Sweden) or commercial entities (USA, Switzerland, Germany, Sweden (limited to small systems)), and operate on a yearly or multi-year basis. Tax credits remain a popular tool that is relatively easy to adjust (for example in the USA in 2022 as part of the Inflation Reduction Act). Storage installed with, or added to existing PV can also be eligible for tax credits (USA, Austria and Sweden). Occasionally, tax incentives can be increased for low-income households (USA, UK) or limited to self-consumption systems (Spain), and for specific requirements such as local module production (Italy, USA).

Elsewhere, exemption from import duties for PV modules can also stimulate markets with little or no local manufacturing (Pakistan, Benin, Uganda, Mali, amongst others).

COMPETITIVE TENDERS

Competitive tenders are used to control the volume, budget, location and type of photovoltaic systems that could benefit from support mechanisms. Competitive tenders have been adopted in many countries around the world, with the clear aim of increasing the competitiveness of PV electricity. They can be run by state organizations or utilities looking to secure increased supply and security of supply on one hand and reduce supply costs on the other.

In Europe the Netherlands and France were early adopters of competitive tenders, running them as early as 2011/2012. By 2018, uptake was more widespread with roughly 10 countries running tenders (including Germany, Poland), doubling up to at least 20 European countries having trialed or validated tender schemes since then, from Scandinavian countries to the Baltic states down to Mediterranean rim countries. In the past 5 years, large volumes were awarded in tenders in Germany, Italy, Poland, the Netherlands, the UK, Spain and France

Their use worldwide is increasingly used to stimulate and regulate medium to large-scale systems across the world, either tendering access to support mechanisms, and land or electricity procurement contracts. They are also used to stimulate investment in specific types of systems, for example floating PV or, more commonly in the past few years, agrivoltaics. A European Commission report "on the performance of support for electricity from renewable sources granted by means of tendering procedures in the Union" published in November 2022 concludes "that introduction of tenders for renewables was a clear success for the European Union" and that they "reduced the support cost significantly compared to administrative schemes, enhanced the deployment of renewable capacities and provided a solid framework for technological improvement".

Initially, the first remuneration models in tenders were feed-in tariffs (FiT) where remuneration is based on a fixed price per kWh, and whilst they are still used in some countries for some segments, particularly commercial and industrial systems on buildings (Japan, Italy, Egypt), governments are steadily replacing them with feed in premiums or with Contract for Difference (CfD). A Feed-in Premium (FiP) is a fixed premium that is paid on top of the variable electricity wholesale market price, leading to variable remuneration. In 2023, Austria, transitioned their tendered feed-in tariffs to feed-in premiums, joining Germany, the Netherlands who used this mechanism already. Japan uses both Fit and FiP in its tenders, depending on system size. A Contract for Difference scheme (UK, Greece, France, Italy, Hungary, Australia and Spain) is a FiP that ensures constant remuneration by covering the difference between the expected remuneration and the electricity market price. Tenders have also been run with some or all of the remuneration based on green certificates (Australia) or some other form of "green" bonus on top of market remuneration (Flanders, Belgium).

In March 2023, the European Commission's proposed revision of the EU's internal electricity market design required "the use of two-way contracts for difference (CfDs) for new investments in low carbon generation where public funding is needed" as a means of curbing excessive generator revenues in times of volatile electricity markets.

In 2023, in the Middle East and North Africa, competitive tenders (open or for specific sites) were issued in the UAE, Israel, Algeria, Morocco, Tunisia, Saudi Arabia (3.7 GW) as well as Eritrea, Botswana, Mauritius, Namibia and South Africa (1.8 GW). In some cases, the tenders called for storage also (Panama). In North America the USA ran tenders at state or utility levels. In Latin America, Argentina, Chile, Columbia used tenders – with some significant volumes awarded, for example 5.7 GW in Columbia; in the Caribbean, Jamaica did too. In Asia, many countries continued with their tender schemes including India, Uzbekistan, Sri Lanka, but also the Philippines, Japan and South Korea . Australia, in the Pacific has tenders run by states and utilities.

Voted in May 2024, the European Commission's Net Zero Industry Act (NZIA) opens the path for support schemes that "promote high sustainability and resilience contribution(s) [...] by either providing additional proportionate financial compensation, or by conditioning the eligibility" (Art 28.1). Non-price criteria can be integrated into competitive tenders and auctions, and the resilience criteria allows governments to impose a diversification of sources of components to be used in a PV system to avoid dependency on a single supplier or suppliers of a single country. This criteria can be used to actively select for local content.

TRENDS IN TENDERS

As a tool to control and guide towards the type of PV system deemed desirable, governments have adopted new and continuing trends in tenders that include selection criteria or bonuses for local content (Spain), types of land usages or for being installed on buildings (France, Luxemburg), carbon content/footprint (France, South Korea).

Tender specifications can be used to push the development of specific market segments, whether it be in terms of size (between two thresholds, as in South Korea, France, Poland or in the type of PV mounting with separate tenders or designated volumes in tenders for PV on buildings and ground-mounted systems (France, Germany, Switzerland, Moldova). There is a clear trend to specific tenders or tender volumes for agrivoltaics France, Israel, Luxemburg in the past, and Italy in 2023). Tenders for floating PV included Portugal in 2022, India, Philippines, South Africa in 2023. It can also be used as a driver for innovation, allowing higher remuneration levels for innovative systems not quite ready for the market, as used in France, Germany.

Environmental or local content constraints are introduced to give an advantage to local companies or to favour a better environmental footprint of the products. Reserved volumes or segment bonuses promote specific technologies or impose additional constraints such as local manufacturing to boost the local industry. In several countries, a local content parameter has been discussed and acts as an additional primary or secondary key in the selection criteria (India, Malaysia, South Africa, Türkiye). This type of requirement aims at enabling the development of local solar module manufacturing. Türkiye, for instance, applies a premium for local content, on top of the normal FiT.

Tenders have mostly been used to frame PV development and PV costs on a national level. For regulators, this implies defining a maximum capacity and selecting the cheapest suitable plants to develop. However, they can be further developed and used to guide towards larger, long-term roadmaps on power capacity and segment development. By planning smartly with transmission grid operators, tenders can allow the development of specific capacities for defined technologies, optimize the grid and anticipate the energy transition as a tool to support local industry. They can also be tools to build public acceptance by setting criteria that satisfy public and social acceptability guidelines – such as reserving support to specific types of land usage.

Other elements that have been trialled include technology-neutral tenders. In this case, PV is put in competition with other generation sources. Some countries such as Canada, France, Germany, Spain and Italy have experimented with mixed auctions based on solar and wind in parallel with some technology-specific tenders.

In 2023, in the Middle East and North Africa, competitive tenders (open or for specific sites) were issued in the UAE, Israel, Algeria, Morocco, Tunisia, Saudi Arabia (3.7 GW) as well as Eritrea, Botswana, Mauritius, Namibia and South Africa (1.8 GW). In some cases, the tenders called for storage also (Panama). In North America the USA ran tenders at state or utility levels. In Latin America, Argentina, Chile, Columbia used tenders – with some significant volumes awarded, for example 5.7 GW in Columbia; in the Caribbean, Jamaica did too. In Asia, many countries continued with their tender schemes including India, Uzbekistan, Sri Lanka, but also the Philippines, Japan and South Korea. Australia, in the Pacific has tenders run by states and utilities.

PV MARKET DRIVERS AND SUPPORT SCHEMES / CONTINUED

COMPETITIVE TENDERS AND THE MARKET

Competitive tenders have driven the worldwide market, giving project developers the security of contracts backed by state support mechanisms to invest in increasingly large volumes, and providing governments with a tool to map and control solar energy capacity increases.

Tendered prices in competitive tenders were steadily decreasing up to 2021 when the downward price trend halted due to module price hikes resulting from a combination of COVID and demand impacts. Since bidders must compete with one another, they tend to reduce the bidding price to the minimum possible and shrink their margins. Developers with a large number of projects in previous tenders will have good visibility on price pressure and are most likely to be able to price their projects to winning bids.

The past years have demonstrated how low the bids can go under the constraint of competitive tenders. Low bids associated with FiT or CfD remuneration could be risky- many experts believe such low bids are only possible with extremely low capital costs, low component costs and reduced risk hedging. The shrinking profit margins, especially in super-competitive tenders, could become a threat to the long-term stability of some market actors, hence creating more market concentration. Because of strong competition, the most competitive (lowest) bids are also often costed on expected module price drops, leaving these projects fragile and potentially unable to remain economically viable when confronted with rising costs as was the case over 2021/2022.

Across all renewable energies, negative prices for tenders with FiP mechanisms have also been seen in recent years; in these cases, market sales or PPA's provide the project remunerations whilst the tenders framework provides other required keys such as grid capacity, security for debt financing....

Conversely, when module costs go up or market electricity prices go up, upper ceilings on tendered prices can be insufficient (either because they are below required remuneration levels or because they are less attractive than market prices). In this last case, for competitive tenders to remain attractive to project developers, they must once again provide benefits that cannot be found on the market – state backing of long-term contracts is the most obvious advantage, pleasing both equity and debt participants, but also landowners.

There have been many changes in the photovoltaics competitivity landscape over the past two years, from the rising costs in 2020/2021, to the significant drops in module prices in 2023 as electricity markets stabilised and market prices decreased. As a consequence, the dynamics of project profitability have varied, as has the attractivity of government-run tenders and PPA's.

EU POLICY FRAMEWORK

In December 2018, the revised European Renewable Energy Directive (RED II) set a 32% renewable energy target by 2030, up from a target of 20% in 2020[1]. In 2019 the European Green Deal was introduced, an action plan to boost the efficient use of resources by moving to a clean, circular economy and to restore biodiversity and reduce pollution. A pillar of the European Green Deal is a commitment to be climate neutral by 2050. In September 2020, the European Commission proposed raising the 2030 climate targets aiming at a 55% GHG reduction by 2030. The accompanying impact assessment[2] showed that such an increase in the climate ambition is realistic and economically feasible. The 55% GHG reduction target will require a share of renewable energy of approximately 38,5% according to the impact assessment.

In the European Union, solar energy and photovoltaics in particular were identified as one of the cornerstones of a rapid and more ambitious deployment of renewable energy technologies in order to meet the climate-neutrality objective in 2050 and a significant reduction of the EU's dependence on imported fossil fuels. Although the currently proposed measures include a strong component to diversify the source of fossil fuel imports, away from Russia, a path on how to phase out entirely their use is not yet so clear. The full implementation of the "Fit for 55" proposals would lower the Union's gas consumption by 30%, still requiring over 200 bcm, by 2030.

In 2022, the European Commission published the REPowerEU Communication and the Solar Strategy Communication respectively[3],[4].

1. European Commission, REPowerEU Communication, 08.03.2022, COM(2022) 108 final
2. European Commission, Solar Strategy Communication, 18.05.2022, COM(2022) 221 final
3. European Commission, REPowerEU Communication, 08.03.2022, COM(2022) 108 f
4. European Commission, Solar Strategy Communication, 18.05.2022, COM(2022) 221 final

REPowerEU aims to reduce net emissions by at least 55% by 2030 and the Solar Strategy called for an additional photovoltaic capacity of 450 GWp between 2021 and 2030, which would mean a roughly fourfold increase of the nominal capacity to over 720 GWp by 2030.

The European Solar Communication includes a number of building blocks to accelerate the deployment of PV in a timely manner. The following initiatives have been developed as tools to reach the target outcome:

European Solar Rooftops Initiative

Utility scale deployment including multi use of land (e.g. agri-PV, floating-PV, PV on noise barriers, etc.)

Solar value for buildings, districts and cities

Preparing the energy network for the efficient distribution of solar energy

Establishment of a resilient supply chain

Supporting investments regarding EU PV manufacturing (de-risking, funding)

Enacted in June 2024, the Net-Zero Industry Act[5] aims to create a favourable environment to scale up manufacturing of net-zero industries in the EU. One of the identified strategic net-zero technologies is PV. A simplification of the regulatory framework (permitting) for PV manufacturing and support for skills development are among the actions included in the Act that aim to help increase the EU PV competitiveness.

5. Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724 (Text with EEA relevance)

In this context, tenders have been under-subscribed (France, South Africa in 2022, Japan, South Korea, Poland, Serbia in 2023) – for example, when market conditions were more attractive - under-awarded when tendered rates were considered uncompetitive i.e. close to or over ceiling rates (France in 2020 and 2021 for some segments, Spain in 2022) or even over-subscribed where the security of investment and low modules costs made them more attractive (in 2023: Argentina, France, Germany, the Luxembourg/Finland cross border tender, the Luxembourg agrivoltaic tender, UAE).

In 2023 the lowest bids once again decreased, with Japan reaching bids under 8 Yen/kWh (55 USD/MWh) for the first time. The most competitive bids in 2023 were in the UAE at 16.2 USD/MWh (but ranging up to about double in India and more than triple in Europe), compared to 26 USD/MWh in 2022 (India, South Africa, Türkiye) and 60 USD/MWh (utility) to 90 USD/MWh (on buildings) in Western Europe (Germany, France).

Within this context, developers are comfortable looking to corporate clients to sell their electricity (corporate PPA's) (Germany, France, Spain, USA), or even directly to electricity markets (merchant PV) (Australia, Croatia, Germany, Romania, Spain).

TRADE OF GREEN CERTIFICATES AND SIMILAR SCHEMES

Green certificates and similar schemes based on Renewable Portfolio Standard (RPS) are only used in a few markets, explained by the greater complexity of this type of scheme. Green certificates with a set value can be issued within the framework of government or state support mechanisms (Belgium (residential systems), Australia, South Korea, Norway, UK). They can also be traded at market values between generators and utilities as part of RPS obligations (USA - predominantly but not only utility-scale systems). The regulatory approach commonly referred to as RPS aims at promoting the development of renewable energy sources by imposing a quota of RE sources. The authorities define a share of electricity to be produced by renewable sources that all utilities must adopt, either by producing themselves or by buying specific certificates on the market. When available, these certificates are sometimes called "green certificates" and allow renewable electricity producers to get a variable remuneration for their electricity, based on the market price of these certificates.

Green certificates can also be bought to satisfy voluntary social responsibility goals (in this case, most often Guarantees of Origin (GO) are attached to electricity sold to consumers with a surcharge for the guarantee). Their value can vary depending on the local markets and how active they are – but the 2023 trend was to

PV MARKET DRIVERS AND SUPPORT SCHEMES / CONTINUED

increased value. Some important markets include North America, UK. Depending on the local markets, trading GO's may or may not be cumulative with remuneration from government-financed support mechanisms.

PV DEVELOPMENT WITHOUT FINANCIAL INCENTIVES

An increasing volume of the market became independent of support schemes: this implies installations not financially supported and developed outside of tenders or similar schemes. This is a sign of the PV market becoming highly competitive. The increase in energy costs in 2021 and 2022, and specifically electricity prices, enhanced PV competitiveness in numerous countries. Whilst electricity prices dropped over 2023, so too did module prices; in parallel, consumers exposed to the volatile electricity market over the past years have increasingly turned to securing long-term supply contracts or generating their own electricity, financing PV outside of all support mechanisms.

POWER PURCHASE AGREEMENTS

Power Purchase Agreements (PPAs) are long-term private contracts between a PV producer and one or several off-takers: consumers (Corporate PPA) or electricity resellers (PPA). While FiT (or CfD, in the case of virtual PPA's) are paid in general by official bodies or utilities, commercial PPAs are contracts between the PV plant owner and an off-taker for the electricity produced, over a defined period. Such contracts guarantee a certain level of revenue and are increasingly popular for unsubsidized PV because the cost per kWh is negotiated between the parties. If built on a FiT model, in times of high electricity prices (2021, 2022), the PV producer has an advantage if the contract was negotiated in times of lower prices. PPAs imply sourcing of solar electricity without necessarily being physically connected to the power plant - a solution favoured more and more by large companies willing to decrease their GHG emissions through corporate PPA's. In the case of virtual PPAS's operating on a CfD, the off-taker pays the generator (or receives from the generator) the difference between the agreed-on price and the price sold on the electricity market sales; in this case, the off-taker carries the risk burden for the generator. Initially deployed in the wind industry, solar PPA's have outstripped wind PPA's in volume in 2023. PPAs have continued to grow in 2023 after strong growth in 2022 and 2021. Major information technology companies, online retailers and industry are significant clients for virtual CPPA's whilst mining companies are significant clients for PPA's from systems directly connected to consumption sites. The European Union incites member states to remove administrative barriers to long-term PPA and to facilitate their adoption. One of the principal barriers to developing PPAs is the multitude of risks, from low production to off-takers insolvency, and there is a small but growing market in risk hedging; France launched a credit guarantee scheme to support smaller actors for risk mitigation joining Spain and Norway who also have mechanisms in place. Whilst PPA contracts are mostly medium to long-term (10 to 25 years), the high electricity market prices in 2022 and early 2023 saw a surge in short-term (2 to 3 year) contracts as producers look to the highest returns.

In Europe, there was strong continued growth in the announcement of photovoltaic PPAs with both corporate and utility PPAs increasing. In 2023, Spain and Germany lead the PPA market that surpassed 10 GW in Europe, with active markets also in Denmark, Finland, France, Italy, the Netherlands, Poland, Sweden, and the UK. Solar PPA volumes contracted slightly in the USA, although this still estimated to represent nearly 50% of global PPA volumes. In South America, an emerging market for PPA's exists (over 500MW in Brazil and 244 MW in Chile). The Asia-Pacific region had PPA growth in South Korea (x 10 compared to 2022), Australia (where resource mining and heavy industry account for roughly 1/3 of Corporate PPAs in 2023) and Japan (where electricity charge increased and companies choose to select renewable energies) but also Bangladesh, Philippines, Chinese Taipei and Thailand. Countries that have been working towards structural changes to electricity markets to allow PPAs or corporate PPA's (Vietnam, Malaysia) were good to go in 2023. In the MENA region,

Whilst many PPA developers and buyers are industry specific, there is also a wide range of global energy players present, as discussed in Chapter 4.

MERCHANT PV

Merchant-based PV plants are expected to play a growing role in the development of the PV market. They are PV plants where the business model relies on sales on electricity markets. The design of the electricity market plays an important role in the emergence of this type of business model as the market should provide both short-term and long-term incentives. Whilst several countries experimented with merchant PV as long ago as early 2010 (unsuccessfully in Chile, for example), more recently competitive LCOE and the higher electricity prices on the European market in 2022/early 2023 encouraged project developers to investigate this option more seriously – it is now an option that has been used in Croatia, Italy, Germany, Norway, Portugal, Romania, Sweden and Spain, (where it is expected to become as common as PPA's in the near future) , as well as in the Philippines, Australia (a 2022 study indicated 18% of its then nearly 20 GW capacity exposed to spot markets) in Asia Pacific with projects underway or in the development phase in Botswana, Namibia, in Africa. In the USA as PPA contracts become shorter and shorter (under 10 years), merchant sales are becoming an integral part of the long-term economic viability of projects.

NON-INCENTIVIZED SELF-CONSUMPTION

Self-consumption ceases to need incentives when the revenue from the savings on electricity bills (the self-consumed part) and the revenue from the sale of excess PV electricity covers the long-term cost of installing, financing and operating the PV system. As retail and wholesale electricity prices rise and PV LCOE reduces, self-consumption has become an obvious choice in many markets – particularly in European and Australian markets or markets where electricity prices were disrupted due to the Ukraine conflict.

Where self-consumption becomes the norm, grid managers can become wary of transfers in the burden of grid costs between consumer/producer categories, or even revenue loss where revenue is proportional to consumption. In this context, fixed fees or self-consumption taxes and penalties can reduce the attractiveness of self-consumption and impact uptake. For example, concerns over such cost-shifting from PV to non-PV customers in the USA were cited as one of the main drivers of changes to California's net energy metering revision in 2022, where grid participation charges and minimum bills were initially considered. This in turn led to a rush of installation in California, as consumers rushed to remain eligible to the pre-reform mechanisms.

As grid capacity becomes saturated, triggering curtailment and balancing cost increases, consumers will increasingly look to alternatives, from storage to energy sharing through collective self-consumption or energy communities to improve the economic equation.

INNOVATING FINANCIAL SOLUTION SUPPORT

An increasing number of investment solutions have emerged for the financing of solar installations, these are even more relevant in the case of unsubsidized PV. The high upfront capital requirements are pushing different business models to develop, especially in the USA, and to a certain extent in some European countries. PV-as-a-service contributes significantly to the USA's residential market for instance, with the idea that PV could be sold as a service contract, not implying the ownership or the financing of the installation. These business models could deeply transform the PV sector in the coming years, with their ability to include PV in long-term contracts, reducing the uncertainty for the contractor. Such business models represent already more than 50% of the residential market in the USA, and some utilities in Germany, Austria, Sweden and Switzerland are starting to propose them. The USA remains innovative by the existence of pure players proposing PV as their main product, solving many barriers to financing and effective operations, as well as reducing the uncertainty in the long-term for the prosumer. It is possible that such services will further develop.

Similarly, pay-as-you-go financial models have been very successful in the deployment of Solar Home Systems (SHS) and solar kits in African countries in the past years and are expected to further drive the development of PV in the residential and off-grid segments. Pay-as-you-go models are directly inspired by prepaid mobile payment schemes; the users pay a monthly fee according to their needs and own the solar kit when enough credits have been paid.

PROSUMER AND ENERGY COMMUNITY POLICIES

SELF-CONSUMPTION IN REGULATORY ENVIRONMENTS

Prosumer (self-consumption) regulations are increasingly being implemented in different countries with the double goal of empowering consumers to play an important role in the energy transition and reduce the cost of support mechanisms for the development of renewable energies. Measures in favour of distributed generation are stimulating greater use of renewable sources with further positive effects such as a stronger penetration of electricity in final consumption, the reduction of transmission and distribution costs and new investments in integrated energy management projects (electricity, heat, efficiency, storage, etc.).

Self-consumption is allowed one way or another in many countries but the regulations in place differ significantly with both structured and ad hoc legal frameworks, although the physical principles of self-consumption are always the same: the electricity that is produced by the PV system and locally consumed reduces the quantity of electricity on the consumer's bill. However, this reduction is not implemented in the same way in all countries.

Mechanisms to promote or regulate self-consumption tend to address one or more of the following:

1. Initial grid connection and/or annual grid access fees
2. The right to inject excess and the remuneration of excess electricity.

Grid connection fees can be reduced or waived to promote self-consumption (especially when consumers are already equipped with electronic meters that require no direct intervention) (France, Finland, Netherlands) or on the contrary adapted to cover self-consumption. As in most countries grid access fees are calculated with at least part being proportional to consumption, a number of different approaches have been taken (or are under discussion) to diminish the impact on grid revenue for distribution service

PROSUMER AND ENERGY COMMUNITY POLICIES/ CONTINUED

operators. Some adaptations adopted or discussed include: modified grid tariff structures (increasing the fixed part and reducing the variable part linked to consumption (Australia, France, Switzerland); specific grid taxes to compensate for saved grid costs due to net-metering/billing policies (Israel, Spain, Belgium); minimum bills to ensure a minimum level of remuneration from the user (USA). It should be noted that states and utilities in Australia and the USA operate distinctly, and a variety of mechanisms have been used.

The right to inject excess electricity has required structural changes to many regulatory frameworks around the world as it intersects with generation and electricity sales on the one hand and balancing requirements on the other. In high penetration grids, or under-dimensioned grids, automatic rights to inject can also have serious consequences in terms of grid stability management when consumption is low and injections are high (Australia, Austria, some states in the USA, Vietnam). In these countries, limits on injection (injection capacity or time of injection) can be put in place; increasingly, distribution service operator-led dynamic curtailment of injection limits for distributed generation and prosumers is being investigated to ensure both grid stability and smooth development of PV (Australia, USA, Japan, Spain).

The excess electricity can be credited to the consumer (net metering) on a specific timestep (monthly, quarterly, annually) with unused credits either carried over or lost; it can be sold (net billing on short timesteps, from 5 minutes up to several hours or a day) to the utility, to support mechanisms buyers or on the market; it can also earn green certificates that can be traded. See above for more information.

Finally, third-party ownership (often synonymous with long-term leasing) allows the development of self-consumption even when consumers do not have access to the capital necessary for up-front costs – whilst it is common in some countries (USA), in others the complex regulatory environment means it is either not possible or requires changes to legislation (Denmark, France, Spain).

COLLECTIVE SELF-CONSUMPTION, ENERGY COMMUNITIES AND COMMUNITY SOLAR

Collective self-consumption, also called delocalized or virtual self-consumption, energy communities or community solar, is when the electricity from one or more generators is allocated to one or more consumers, either reducing or offsetting energy consumed from other suppliers through the grid. The energy flows can be physical (for example when a PV system injects to internal grids in multiple-tenancy buildings) or virtual (when generation is allocated via virtual metering and billing, using a predefined split key). The price of the electricity can be based on a negotiated per kWh fee or accessed after a share in the capital investment.

It began as a single system supplying on-site consumers with self-consumption; from there, collective self-consumption developed with the aim of widening the perimeter of self-consumption. This allows one or several PV producers (even utility-scale plants) to feed one or more consumers at a reasonable distance so that the use of the public grid is minimized. The perimeter, often initially limited to a building, has expanded in different countries to a geographical distance (10 km, 20km radius...or across a district, region or the whole country) or set on a transformer or substation level. In this sense, some schemes compensate for real energy flows, while others are compensating for financial flows. While details may vary, the basics are similar. This widening of the perimeter to the district or regional level to include several consumers and generators has advantages for participants that include increased self-consumption ratios and more equitable access to roofs and land for self-consumption purposes (Mexico, Brazil, France, Lithuania, USA).

The economic viability of collective self-consumption projects is built not only on retail and wholesale electricity prices and generation prices but also on the contributions participants must pay to grid access and the level of taxes on consumption and generation.

There has been strong interest in particular in Italy, France, Spain, the USA and to a lesser extent Portugal,, Austria, Canada, Norway Sweden, Switzerland, Germany.

In Italy, there are incentives for systems up to 1MW in groups behind the same substation. In Sweden, it had been allowed through microgrids in 2021. In France, virtual self-consumption operations can cover a perimeter of up to 20 km (rules apply) and there are simplified administrative and legal procedures for social housing operators running operations on multi-tenancy buildings; generators can access the FIT for excess electricity not immediately self-consumed within an operation's 30-minute compensation time step. In Germany, building owners can produce and sell electricity to their tenants which makes the investment more attractive. The UK has also implemented a favourable framework for collective prosumers. In Spain public policies and subsidies promote energy communities. Within the USA, the Inflation Reduction Act included significant tax credit bonuses for collective self-consumption projects that met certain size, location, and equitable distribution of benefits requirements; nearly half of the states have passed legislation enabling virtual collective self-consumption (referred to within the USA as "community solar"), with many including requirements for participation of low-income households. Other countries have some definitions, but these are not yet fully implemented. In Austria, electricity traded in energy communities benefits from tax exemptions. In Switzerland collective self-consumption is allowed by most DSOs, but consumers have to be contiguous and not use the public grid. In Norway, since 2023 consumers on the same property can share and self-consume electricity produced from a PV system of up to 1 MW, and discussion is underway to allow virtual self-consumption in industrial areas. In the USA and Australia community and edge-of-grid rural microgrids are emerging to reduce the cost of electricity consumption and provide local resilience through storage and backup power.

Network pricing regulations differ, and, in some countries, exemptions are used to encourage projects whilst in others full network charges must be paid even for locally transmitted electricity, which acts as a barrier to collective self-consumption or virtual net-metering.

These schemes create complex questions, especially regarding the use of the grid, the legal aspects and technical complexity related to compensating electricity between several meters and the innovative aspect of the scheme.

The opportunities opened up by such concepts are wide-ranging and could tend to increase consumer participation in market mechanisms and PPA participation. As an extension, consumption metering points could become virtual too - innovative schemes could allow charging an electric vehicle at the office with PV electricity produced at home or sharing the PV electricity in all public buildings in a small town between them depending on the consumption. Options are numerous and imply fair remuneration of the grid to be competitive for all. Using PV electricity in a decentralized location implies the use of the public grid, distribution or even transmission and would require putting a fair price on such use.

PROSUMER AND ENERGY COMMUNITY POLICIES / CONTINUED

in the EU context

While self-consumption is allowed in most European countries, Europe has decided to go a step further with the comprehensive update of its energy policy, the "Clean Energy Package". The European Union introduced new provisions on the energy market design and frameworks for new energy initiatives. Specifically, the actual recast of the renewable energy directive (REDII) and the electricity market directive (EMDII) provide basic definitions and requirements for the activities of individual and collective self-consumption. The European Union introduced the concept of Renewable Energy Communities (REC) and Citizen Energy Communities (CEC). REC should allow citizens to sell renewable energy production to their neighbours, while some crucial components are the definition of the perimeter and the tariffication for grid use. Those key components are defined in the national implementation in the member states that are being deployed across Europe. This concept of energy communities is expanding the existing PV market segments and allow cost reductions for consumers not able to invest in solar installation themselves. In Europe, the Federation of energy communities RESCoop has over 2000 member organizations representing more than 1.5 million citizens, testifying to the strong development.

in the USA

A different definition of an energy community is emerging in the USA as a result of the passage of the Inflation Reduction Act. It is now used to refer to communities that have been historically adversely impacted or are at risk of being adversely impacted in the future by the energy transition. The use of the term Community Solar in the USA is closer to the definition of collective self-consumption than the EU REC. Solar communities are growing under the impetus of IRA subsidies and state-led legislation – with often sharp crossovers joining community solar to energy communities; for example, Maryland, Minnesota and New Jersey have similar programmes that require community solar facilities to deliver a minimum percentage of their output to low- and moderate- income subscribers. By the end of 2023, community solar had an estimated capacity of 7.3 GW AC, with 75% of this power in just four states (Florida, New York, Massachusetts and Minnesota).

ENERGY TRANSITION LEVER POLICIES

SUSTAINABLE BUILDING REQUIREMENTS

The building sector has a major role to play in PV development and sustainable building regulations drive PV's deployment in countries where the competitiveness of PV is close. These regulations include requirements for new building developments (residential and commercial) but also, in some cases, on properties for sale. PV may be included in a suite of options for reducing the energy footprint of the building or specifically mandated as an inclusion in the building development.

The publication of the European Commission's Solar Strategy in 2022 is part of the REPowerEU package. It presents four initiatives to overcome the remaining short-term challenges and the first of them is promoting quick and massive PV deployment via the European Solar Rooftops Initiative. Member states are incorporating this initiative in different ways into their national regulations.

In Austria, the federal support schemes have a bonus for building integrated PV whilst many counties have regulations or incentives for building a PV system, with mandatory solar in Vienna and Styria for commercial and apartment buildings. France has mandatory solar or living roofs for commercial and industrial buildings or covered car parks. In Germany, in Berlin, solar will be mandatory on many new buildings by 2023 whilst in the Netherlands, buildings must aim to be nearly energy neutral since 2021, pushing solar. In Switzerland, mandatory solar is being rolled out across different cities for new and/or renovated buildings. In Belgium, Flanders introduced measures in 2014 with PV now on more than 85% of new buildings. In Denmark, the national building code has integrated PV to reduce the energy footprint, whilst in Italy, capital subsidies have been introduced to promote PV on public buildings in some regions. In Japan, Tokyo will be requiring solar on most residential buildings, and other smaller buildings from 2025. In South Korea, the NRE Mandatory Use for Public Buildings Programme imposes on new public institution buildings with floor areas exceeding 1000 square meters to source more than 10% of their energy consumption from new and renewable sources. In the USA, California has had mandatory solar for certain new residential buildings since 2020 and is set to extend this to non-residential and high-rise multifamily buildings in 2023 and expand the mandate to require a solar plus storage system, rather than just a solar system. In India, some states have mandatory solar supply policies for new buildings.

Beyond overall building performance regulations, rising questions around the public acceptability of utility-scale PV is pushing a number of governments to actively encourage or mandate solar in very particular segments – from Japan's program supporting research, guidelines and demonstrators for wall-integrated PV (including semi-transparent and perovskite cells) to France's mandatory solar on impermeable car parks. The goal of occupying low-conflict surfaces is pushing solar too.

ELECTRIC MOBILITY

The electrification of transport is accelerating in many countries and whilst the link between PV development and EVs is not yet fully understood, the growth of self-consumption policies and grid congestion limiting injections are factors to be considered. Charging EVs during peak load implies rethinking power generation, grid management and smart metering, and concepts such as virtual self-consumption could rapidly provide a framework for EV's as mobile storage for excess PV generation. With 14.2 million EVs sold in 2023 (+35% on 2022), electric vehicles sales are still accelerating in parallel, albeit at a different rhythm, to PV. Growth was particularly dynamic in some IEA PVPS countries including, Australia, Canada, China, Spain, Switzerland and Türkiye, Thailand, Malaysia. Non-IEA PVPS countries with strong growth markets include India and Brazil. In Europe, EU directives aim for 100% zero-emission vehicle sales by 2035 (2030 in Austria, the Netherlands, Denmark) and national and local-level actions exist to support EV deployment, both with incentives for those buying EV's or investing in charging stations, but also in terms of barriers for traditional internal combustion vehicles (France, Norway, Switzerland). In Austria, a federal program supports the purchase of electric vehicles for private – on the condition that it is supplied by 100% renewable energy. In Germany a support programme for solar for charging EV's launched in 2023 closed after its budget was depleted in just one day. Outside of Europe, many countries with dynamic PV markets also have strong financial incentives for electric passenger vehicles and charging stations (Japan, some states in Australia, India). In 2022, the USA implemented significant national incentives for the purchase of EVs via the Inflation Reduction Act and began the buildout of a national EV-charging network via the Infrastructure, Investments, and Jobs Act of 2021. In South Korea public entities may only purchase eco-friendly vehicles (electric or hydrogen), whilst local and national government support charging stations roll out and energy storage businesses with installed solar can now sell power directly to electric vehicle users.

Countries with higher penetration rates or good uptake, such as Norway, Sweden supported the roll out of electric vehicles for many years but have already stopped incentives. China no longer offered rebates in 2023 but maintained tax exemptions. Germany stopped its subsidies in 2023. In Australia, one state introduced a tax specifically for EV users to offset taxes no longer being collected through fuel levies in 2021; this tax was deemed unconstitutional in 2023 and will be reimbursed to EV owners.

HYDROGEN PRODUCTION

Solar fuels, storage and other hydrogen-based applications will require massive PV, wind and other RES development if hydrogen is to be "green". Distributed Hydrogen production could be driven by distributed PV as well, pushing for higher demand for distributed PV-H2 production. This still remains to be materialized in the future, however strong interest after the Ukraine conflict-hit gas and electricity prices in 2022 has been supported by strong government investment programs. In the USA, the Inflation Reduction Act financed a hydrogen hub program and supplies tax credits for hydrogen produced from renewable energies including solar. The European Commission expects green hydrogen to play a pivotal role in the decarbonisation of sectors where electrification might be less feasible and to bridge some of the gaps for seasonal variations of electricity generation (ie from solar). Funding programs promote research and a pilot project to reach the ambitious plan of between 15 GW and 40 GW of electrolysers in Europe by 2030. As member countries were required to submit updated National Energy and Climate Plans plans in 2023, nine member countries included funding and tax incentives for hydrogen projects;Spain tripled its 2030 targets for renewable-based hydrogen, Portugal doubled theirs. In China the biggest solar + hydrogen project was commissioned in 2023 and should produce 20 000 tons/year of hydrogen. In India competitive tenders for electrolysers for green hydrogen were launched in 2023, with a called capacity of 1.5GW of electrolyser capacity in the first round.

Large-scale renewable + hydrogen production projects finalised financing around the world in 2023: several each in Australia, Germany and France – whilst not exclusively solar-powered, cheap solar is an important part of the economic equation for these projects along with wind power.

ELECTRICITY STORAGE

The cost of storage is pursuing its steep decline after a short halt in 2022 - and storage is becoming more attractive in a growing number of markets. Due to the cost decline of storage, solar power plants with onsite storage are increasingly attractive for developers and residential customers as the combination with storage allows them

ENERGY TRANSITION LEVER POLICIES / CONTINUED

to smooth the power output, to deliver ancillary services or to reduce connection costs if peak injection is reduced.

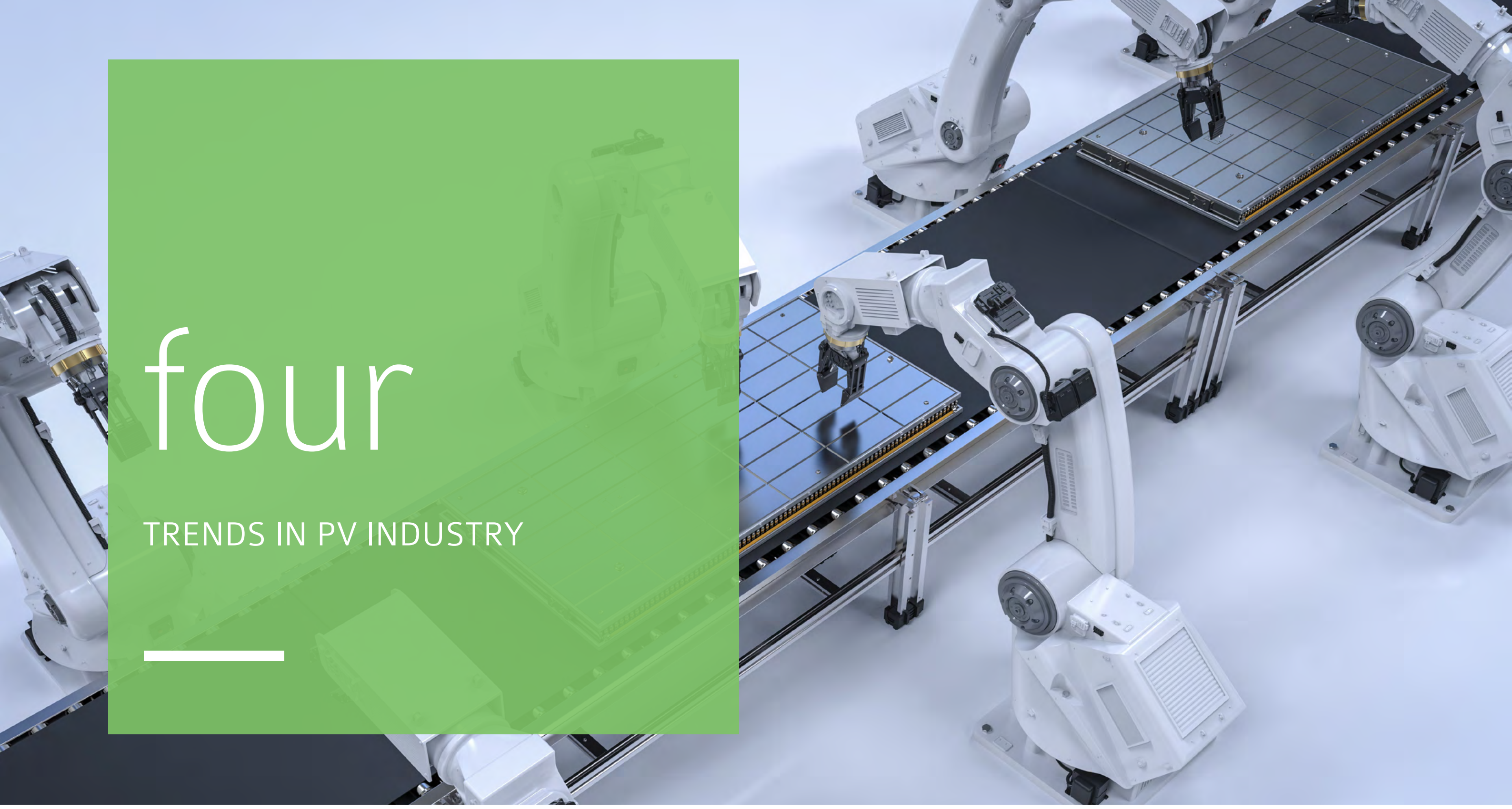
In China, capacity grew significantly in 2023 as in many provinces' storage is mandatory for new utility-scale solar, whilst commercial installation also grew due to changing time of use consumption tariffs and the availability of subsidies. Incentives for battery storage exist in a wide range of countries, including Austria, Japan and Romania whilst plans are being made for the near future (Italy, Hungary, Canada). Spain has launched a call for renewables + storage projects, subsidising storage for self-consumption projects; there are reserved volumes for projects on the Canary and Balearic Islands. In the USA tax credits are available as part of the Inflation Reduction Act, whilst multiple states have energy storage procurement goals or mandates, and in California solar + storage is now mandatory for many types of new commercial or multifamily dwellings. In Australia, households have access to rebates in some states, whilst in others time of use and power injection caps have given battery storage short payback times. Unattached to solar but enabling high PV penetration rates in the grid, Federal government support for Big Batteries continues with a revenue underwriting scheme (similar to CfD) and some states have grants and funds for market positioning and capacity building.
Storage is a key element of a carbon neutral energy system relying on RES electricity; therefore, the European Commission actively supports energy storage through research and innovation funds. Some consider that storage development for PV electricity will be massively realized through electric vehicles connected to the grid during a large part of the day and therefore, will be able to store and deliver energy to consumers at a larger scale than simple batteries. These vehicle-to-grid or V2G concepts are being explored and tested in several countries, with the Netherlands, Switzerland and Japan as front-runners, with at least one V2G project selling on the electricity market.

INDUSTRIAL AND MANUFACTURING POLICIES

COVID-led supply chain disruptions and increasingly ambitious climate change actions saw many initiatives favouring local manufacturing at various steps of the PV value chain in 2021 and 2022, with governments around the world supporting local manufacturing through policies, subsidies and regulations – from tax credits to direct subsidies to reduced administrative barriers for local content. However, the drastic reduction in module prices in mid-2023 as new capacity came online in China, well above the international market's ability to absorb, has made the future of many projects uncertain. Some of the most significant acts of the past decade were launched in 2022, including the Inflation Reduction Act (IRA) in the USA and the preparation of a series of EU-level policies in Europe. The IRA was promulgated in August 2022 and the generous tax incentives for local manufacturing, critical mineral refining, and recycling have triggered many announcements for new manufacturing capacity in the USA. In Europe a series of policies planned in 2022 but published in 2023 are intended as landmark acts in the EU Solar Energy Strategy (within the REPowerEU plan) - the Green Deal Industrial Plan (published in February 2023), the Net-Zero Industry Act (NZIA) and the Critical Raw Materials Act (both published in March 2023), and the Net Zero Industry Academies were enacted, stimulating and encouraging local manufacturing plans. Future changes to the Carbon Border Adjustment Mechanism may also have positive impacts in Europe. Amendments to the Temporary Crisis Framework at the end of 2022 lift limitations for the EU Member States to grant direct CAPEX support to new net-zero industry projects, with solar manufacturing being entirely eligible. Co-funded by the EU and launched in late 2022, the European Solar PV Industry Alliance aims to facilitate innovation-driven expansion of a resilient industrial solar value chain in the EU, particularly in the PV manufacturing sector. These EU level actions have been complemented by national measures planned over 2022 and 2023 in the Netherlands, Spain Italy, which came into action in 2024. In India, state financing for local manufacturing is available through the Production Linked Incentive Scheme that was continued in 2022, with three winners in Round 1 – and more than ten announced in further rounds in 2023, a first step to building dozens of GW of domestic manufacturing capacity capable of supplying a large proportion of the local, growing PV market. In Türkiye a new YEKA (Renewable Energy Resource Area) call for tenders is expected but not published in 2022 – the YEKA calls give priority to areas and RES projects that can be supplied with domestic manufacturing and have proved successful so far.

In China industry and government have acted to maintain their position as the pre-eminent manufacturer of PV, and with massive private investments over 2022 they have in fact triggered overcapacities in large-scale manufacturing, bringing down module prices to below cost in 2023 and creating a natural barrier to entry for new manufacturers in other countries.

Whilst there is a clear push to develop support for local manufacturing across the world, there is not always a clear understanding of the industry dynamics and the complexities of PV manufacturing, which will lead to fewer real projects than what some governments would like to see. In addition, as the proportion of global supply of specific raw materials (glass for example) devoted to PV increases, local manufacturing will require access to global value chains and the role of already existing global actors should not be neglected .



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TRENDS IN PV INDUSTRY

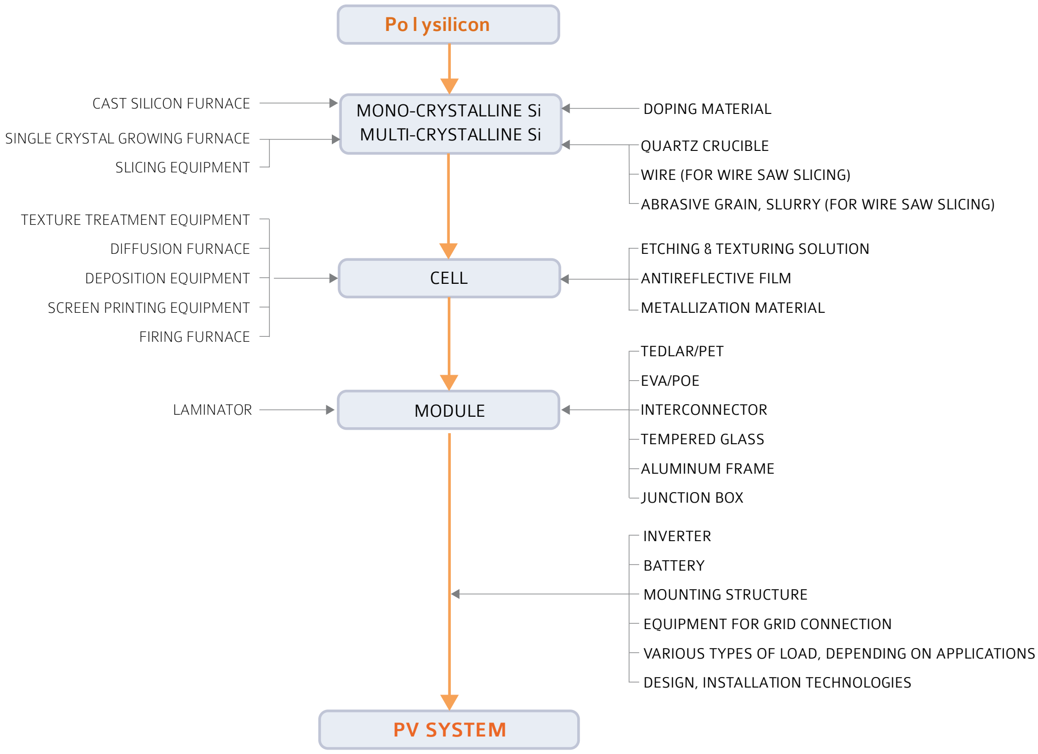
This chapter provides a brief overview of the upstream and downstream sectors of the PV industry intending to provide highlights during 2023 and the first half of 2024. The first part provides manufacturing activities of the upstream sector of the PV industry from feedstocks (metallurgical grade silicon, (MG-Si), polysilicon, ingots, blocks/bricks and wafers) to PV cells and modules described in Figure 4.1. The second part provides activities of the balance-of-system (BOS) sector that include components (inverters, mounting structures, charge regulators, storage batteries, appliances, etc.), and project development and operation and maintenance (O&M).

In 2023, the gaps between demand and manufacturing capacity affected lowering price trends along the value chain of PV modules. The speed of manufacturing capacity expansion surpassed the market growth and the increase of module inventories also affected price levels. The price of polysilicon dropped from 22.13 USD/kg at the end of 2022 to the 7 USD/kg range by the end of June 2023, and it remained below 10 USD/kg thereafter. PV module prices were 11-12 US cents/W as of the end of December 2023. While concerns about rising project costs in 2022 have been resolved, PV module suppliers have been facing lower margins and cost pressure.

Throughout the year, projects for increases in manufacturing outside of China have been reported in the USA, India and Europe. Due to the Inflation Reduction Act (IRA), it is reported that the USA production capacity of PV solar modules will exceed 100 GW/year in 2026. Projects for manufacturing inverters and trackers are also planned there. In India, due to the PLI, the solar module production capacity is expected to reach 60 GW/year by the end of 2025. Despite these projects, China remained the world's largest producer along the PV supply chain and further increases of manufacturing capacity in China were reported in 2023 whilst the Chinese production share increased in all of the value chain.

In 2023, production capacity increased to 1 103 GW/year from 717 GW/year in 2022. The production capacity figures include the capacities of aging and idle facilities that are not competitive anymore: consequently, the real, effective, production capacity is assumed to be on the level of about 700 GW/year to 800 GW/year in 2023. The speed of capacity enhancement is faster than the global PV market growth so the gap between demand and supply was wider in 2023 and PV module prices remained lower. If the gap is not bridged and inventories are not cleared, current price levels are expected to continue.

FIGURE 4.1: PV SYSTEM VALUE CHAIN



SOURCE IEA PVPS & OTHERS

THE UPSTREAM PV SECTOR

SILICON METAL PRODUCTION

Wafer-based c-Si technology remains dominant for producing PV cells. In that respect, this chapter focuses on the wafer-based production process. Silicon metal (Metallurgical grade Si) is used as a raw material for polysilicon, which is used to make ingots and wafers then processed to solar cells. Sustainability of the industry in terms of resources availability and fair business practices, and silicon metal production became focuses of the PV industry. In 2023, the world manufacturing capacity of silicon metal reached 8.54 million tons/year. Amongst the manufacturing countries, China has the largest capacity at 7 million tons/year (82%). As well as in the other steps of crystalline silicon solar cell manufacturing, China has the dominant position in this sector. In 2023, China produced 3.76 million tons of silicon metal, and domestic consumption was 3.19 million tons, of which 53% (1.825 million tons) was used to produce polysilicon. China foresees high growth in demand for silicon metal. Production in 2024 is expected to increase 20% year on year to 4.7 million tons in 2024. In China, Xinjiang has the largest share of production (48%) in 2023 followed by Yunnan (17%) and Sichuan (16%). Some major Chinese PV companies are planning to invest in production. For example, Tongwei group has a plan to establish two plants (360 000 ton/year and 400 000 ton/year) in Inner Mongolia. Trina Solar invested to build vertically integrated factories in Qinghai Province, including silicon metal (100 000 tons/year). Other companies such as Juhua Group are also reported as having new investment plans. Outside of China, new investment plans are reported reflecting the needs to diversify the PV supply chain. In India, Adani New Industries (ANIL) has raised $39.4 billion to set up vertically integrated factories for silicon metal, polysilicon, ingots, wafers and solar cell and PV modules (with a production capacity of 10 GW/year). In Australia, Solquartz is planning to produce MG-Si and polysilicon in the same area.

POLYSILICON PRODUCTION

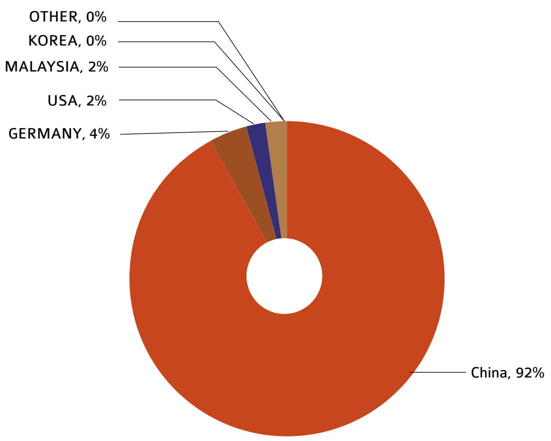
The global polysilicon production (including semiconductor grade polysilicon) in 2023 was about 1 608 000 tons, a 61% increase from the previous year. Production of polysilicon for semiconductors was about 38 800 tons. This means that more than 98% of polysilicon production was used for PV applications. Global polysilicon production capacity (including production capacity for semiconductors) increased by 83% from 1 354 700 tons/year in 2022 to 2 487 400 tons/year in 2023.

In China, five new companies entered into polysilicon production and Chinese total manufacturing capacity reached 2.3 million tons/ year, nearly double the previous year (1.16 million tons/year). China produced 1.47 million tons of polysilicon in 2023 and is expected to increase to 1.6 million to 1.8 million tons in 2024. According to the China Photovoltaic Industry Association, CPIA, China produced 1.06 million tons of polysilicon in the first half of 2024, a 60.6% increase on the previous period. Due to the continuous trends of lowering prices, some companies reconsidered capacity expansion and halted operation to ease the demand gap. Figure 4.2 shows the share of polysilicon production by country.

IEA PVPS member countries producing polysilicon are China, Germany, the USA, Malaysia, South Korea, Norway and Japan. Chinese production share in 2023 increased to 92% from 86% in 2020 .

Because of the rapid growth of manufacturing capacity and the gaps between demand and supply continuing, the price of polysilicon dropped from 22.13 USD/kg at the end of 2022 to the 7 USD/kg range by the end of June 2023, and it remained below 10 USD/kg thereafter. In January 2024, theprice level was 7 USD/kg and it further dropped to 4.36 USD/kg in June 2024. There are 17 polysilicon companies in China, but as of the end of May, at least nine of them have reportedly stopped operations at their factories for maintenance or other reasons.

FIGURE 4.2: SHARE OF PV POLYSILICON* PRODUCTION IN 2023 BY COUNTRY



*Production for semiconductors is included

Source: IEA PVPS, RTS Corporation

Consumption unit of polysilicon per W of solar cells dropped from 2.7 g/W in 2021 to 2.3 g/W in 2022. In 2023, it further dropped to 2.2g /W. Consumption per unit is declining due to the improvement of solar cell efficiency, thinner and larger wafers, and development of slicing technologies.

Most of the major polysilicon manufacturers use the Siemens process, conceived as a manufacturing process of polysilicon for the semiconductor industry. It is estimated that the Siemens process polysilicon accounted for 84% of the total production (1.35 million tons). Production of polysilicon from FBR process increased and accounted for 16.1%.

In 2021, the USA decided to ban imports of material from China-based Hoshine Silicon Industry that produces metallic silicon, a base material of polysilicon. Then, in December 2021, the Uyghur Forced Labor Prevention Act (UFLPA) was enacted. On June 21, 2022 the USA started to enforce the ban on the importation of goods that were manufactured wholly or in part with forced labor in China, especially from the Xinjiang Uyghur Autonomous Region. This measure combines with the IRA that provides tax credits for polysilicon production (3 USD/kg). In the USA, several production plans were reported. REC Corporation decided to start reoperation of polysilicon plants with the investment guaranteed by Hanwaha Solution of South Korea. Highland Materials, a USA manufacturer plans to set up a 16 000 ton/year solar-grade polysilicon plant. As was mentioned in the previous section, polysilicon production is planned in India, Australia. In the Middle East, several new manufacturing projects are reported. GCL Technology has announced a partnership with Mubadala Investment, a state-owned company of the United Arab Emirates (UAE), to establish the Middle East's first polysilicon plant in June 2024. United Solar Polysilicon (FZC) has broken ground on a polysilicon plant with a metallurgical process in SOHAR Port and Freezone, Oman. The current lower price level of polysilicon might affect the progress of these projects and China's dominant share is expected to continue for the time being.

INGOTS & WAFERS

To produce sc-Si ingots or mc-Si ingots, the basic input material consists of highly purified polysilicon. The ingots need to be cut into bricks or blocks and then sawn into thin wafers. In the past two types of silicon ingots were manufactured, sc-Si ingots and mc-Si ingots, but sc-Si has become the industry standard and had an almost 100% share in 2023 according to the International Technology Roadmap for Photovoltaic (ITRPV) 2024.

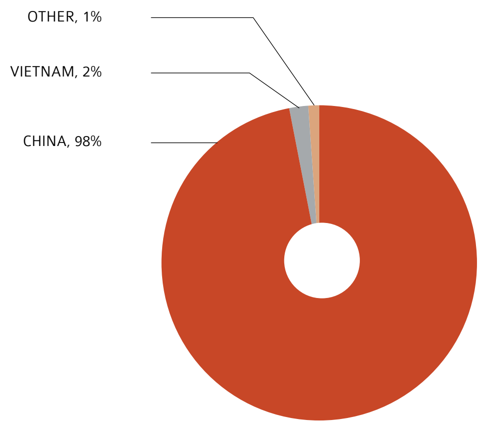
Global wafer production amounted to 682 GW in 2023, about a 79% increase from 381 GW in 2022. 291 GW/year of new capacity was added in 2023 and the global production capacity of wafers as of the end of 2023 increased from 683 GW/year in 2022 to 974 GW/ year. Production capacity is highly concentrated in China, with an

THE UPSTREAM PV SECTOR / CONTINUED

almost 98% share. Other major countries manufacturing wafers are Vietnam (18.5 GW/year), Malaysia, and Norway.

As shown in Figure 4.3, China has more than 98% of the global production of wafers. In 2023, China produced 668 GW of wafers, Of this total, around 70 GW of wafers were exported to other solar cell manufacturing countries such as Vietnam, Malaysia, Thailand, Singapore, Chinese Taipei and India. In Vietnam and Malaysia, major Chinese solar cell manufacturers have production capacity. In this segment, the Top 10 companies are all Chinese and combined they have a capacity of 831 GW/year, or 85.5% of the world's total production capacity. They produced approximately 668.3 GW, accounting for 98.1% of the world's production

FIGURE 4.3: SHARE OF PV WAFER PRODUCTION - 2023 BY COUNTRY



SOURCE: EIA PVPS, RTS Corporation

TABLE 4.1: PRODUCTION CAPACITY AND PRODUCTION AMOUNT OF TOP 5 WAFER PRODUCERS IN 20

RANK	COMPANY	FACTORY LOCATION	PRODUCTION CAPACITY (GW/YEAR)	PRODUCTION (GW)
1	TCL ZHONGHUAN	CHINA	155	133.7
2	LONGI GREEN ENERGY TECHNOLOGY	CHINA	167.4	124.9
		MALAYSIA	2.6	2.6
3	JINKOSOLAR	CHINA	78	69
		VIETNAM	7	7
4	GCL GROUP	CHINA	58.5	51.1
5	JA SOLAR TECHNOLOGY	CHINA	78.5	45.4
		VIETNAM	5	4.7

SOURCE: EIA PVPS, RTS Corporation

In addition to major ingot/wafer manufacturers, some PV cell/ module manufacturers also manufacture silicon ingots and wafers for their in-house uses. There was a trend for some of these major PV module manufacturers that established vertically integrated manufacturing to shift to procuring wafers from specialized manufacturers because of cost and quality advantages under the cost pressure. However, recently, some major companies have increased their in-house production capacity to reduce the risks associated with procurement. Table 4.1 shows the production capacity and production amount of Top 5 wafer producers

In 2023, the market share of n-type and p-type single crystalline Si was 30% and 70% respectively. It is expected that n-type will rapidly increase to approximately 63% in 2024. In 2023, market share of 182 mm (M10, square or rectangular) was 78% and 210 mm (G12) had a 20% of the total production. Share of 166 mm sized wafer decreased to less than 2% as large-sized wafers become the mainstream products. Wafer thickness further decreased in 2023. Average wafer thickness for p-type products in 2023 was 150 μm down by 5% in 2022. The average thickness of n-type wafers for TopCon was 125 μm. n-type is expected to be thinner and reach the 100 μm level in the short term. For cost reduction reasons, Tungsten wire is used as an alternative to diamond wire to allow thinner wafers.

The spot price of c-Si wafers generally follows the price of polysilicon. The price of 182 mm sc-Si wafers was 50.3 USD cents/ piece in December 2022 and the trend down continued into 2023 to reach a spot price at the end of December 2023 of 34.9 USD cents/ piece. This price decline was caused by the oversupply of wafers while the production capacity of large solar cells did not increase as much as that of wafers. In early 2023, short supply of quartz sand, the raw material for crucibles used in the production of ingots was reported, however process improvements meant it was no longer an issue in 2024.

In the first half of 2024, China produced 402 GW of wafers, a 58.6% increase on the same period of the previous year. Of this, 38.8 GW was exported to mainly ASEAN countries, where major PV manufacturers have solar cell manufacturing facilities. It is reported that more than half of the wafer manufacturing companies dropped operating intensity or halted production to narrow the supply and demand gap. Considering over capacity, plans for about 15 GW/year of new capacity were canceled or postponed.

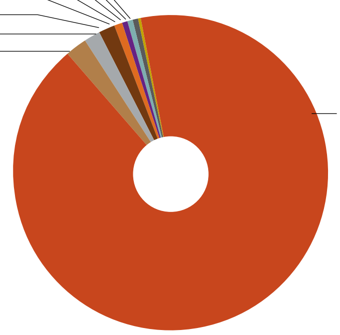
Outside of China, plans for new and expanded wafer production capacity were reported in 2023. In India, several companies are planning vertical production from wafers to PV modules using the subsidy under the Production Linked Incentive (PLI) scheme. It is reported that total wafer capacity in India will reach 56 GW/year by 2026. According to the USA's Solar Energy Industries Association, SEIA, a total 20 GW/year wafer production capacity was announced in the USA. A Norwegian company, NorSun is planning to have 5 GW/year capacity in Oklahoma (USA) and Hanwha is building a 3.3 GW/year ingot/wafer plant in Georgia (USA). NexWafe (Germany) that is building a 250 MW/wafer plant in Bitterfeld, Germany announced a plan to establish a 6 GW/year factory in the USA. However, it is unclear whether these plans will come to fruition due to the over-supply issues, and some reports of cancelled projects have already been already reported - Cubic PV cancelled its project of 10 GW/year in the USA. Given these circumstances, there is no doubt that China will remain the primary wafer supplier for the time being.

SOLAR CELL AND MODULE PRODUCTION

Solar Cell Production

Global solar cell (c-Si and thin-film solar cell) production in 2023 reached 644 GW, a 63% increase from 394 GW in 2022. Global solar cell manufacturing capacity was 1 032 GW/year as of the end of 2023, as for the first time it passed the 1 TW/year level. China's dominant position was further strengthened in this sector as China produced 591 GW of solar cells, and increased it's share of global production to 91.8% from 84% in 2022 as shown in Figure 4.4. China's solar cell manufacturing capacity was 930 GW/year at the end of 2023 with 424 GW/year of newly added capacity. In China, 310 GW of solar cells were produced in the first half of 2024, a 38.1% increase from the same period of 2023. Major countries other than China that reported production of solar cells in 2023 are Malaysia, Vietnam, Thailand, South Korea, India but also the USA and Japan. Figure 4.4 shows the share of solar cell production by country in 2023. Production in Vietnam, Malaysia and Thailand havs been increasing as demand for modules exempt from the USA's antidumping duties (AD) and countervailing duties (CVD) imposed on Chinese products grows. USA imported about 3.5 GW of solar cells from these countries. In the USA, solar cell production is mainly conducted by First Solar with CdTe thin-film PV technology.

FIGURE 4.4: SHARE OF PV CELL PRODUCTION - 2023 BY COUNTRY



SOURCE IEA PVPS, RTS CORPORATION

TABLE 4.2: GLOBAL TOP FIVE MANUFACTURERS IN TERMS OF PV CELL/MODULE PRODUCTION AND SHIPMENT VOLUME (2023))

RANK	SOLAR CELL PRODUCTION (GW)		PV MODULE PRODUCTION (GW)		PV MODULE SHIPMENT (GW)	
1	TONGWEI SOLAR	80.8	JINKOSOLAR	83.5	JINKOSOLAR	78.5
2	JINKOSOLAR	63.9	LONGI GREEN ENERGY TECHNOLOGY	72.8	LONGI GREEN ENERGY TECHNOLOGY	67.5
3	LONGI GREEN ENERGY TECHNOLOGY	62.3	JA SOLAR TECHNOLOGY	60	TRINA SOLAR	65.2
4	JA SOLAR TECHNOLOGY	45.5	TRINA SOLAR	58.9	JA SOLAR TECHNOLOGY	55.3
5	TRINA SOLAR	44.3	CANADIAN SOLAR	31.4	TONGWEI GROUP	31.1

NOTE: PRODUCTION VOLUMES ARE MANUFACTURERS' OWN PRODUCTION, WHEREAS SHIPMENT VOLUMES INCLUDE COMMISSIONED PRODUCTION AND OEM PROCUREMENT

SOURCE IEA PVPS, RTS CORPORATION

THE UPSTREAM PV SECTOR / CONTINUED

As shown in Table 4.2, the Top five solar cell manufacturers are Chinese companies.

In 2023, p-type PERC technology had the largest market share of about 64%, but a quick transition to n-type is expected to advance in 2024. According to CPIA, the share of n-type manufacturing capacity for TOPCon, silicon heterojunction solar cell (SHJ), back contact type (IBC), etc. is expected to reach 69% by the end of 2024. The share of TOPCon technology increased from 10% in 2022 to about 30% in 2023 and it is expected to increase to about 50% in 2024 and become the mainstream technology. SHJ's share in 2023 was 5% and IBC's share was 2%. The two principal technological developments that manufacturers are investing in is to achieve higher efficiency or to reduce silver (Ag) usage. According to the Silver Institute, demand for Ag for solar cells was up 64% from the previous year to 193.5 million ounces in 2023 and accounted for 16% of total silver demand (1.195 billion ounces).

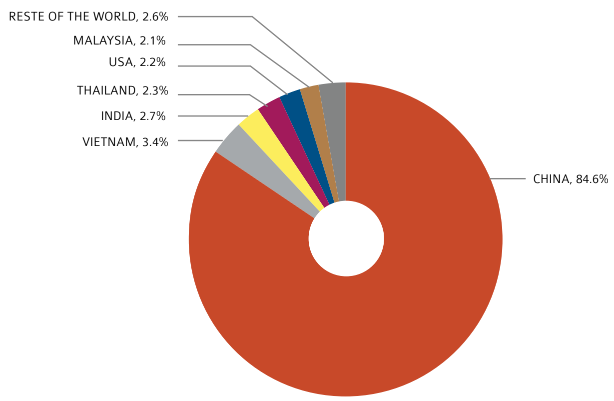
The spot price of solar cells has been changing, following wafer prices and the supply and demand conditions in the market, and the cell manufacturing segment is also affected by the demand and supply gap. In January 2023, the spot price of 182 mm solar cells was 10 USD Cents/W. It had changed according to the demand and p-type products dropped to around 4 USD cents/W in December 2023. N-type products (182 mm) in the same period had a higher price than p-type at 5.6 USD cents/W.

A diversification of solar cell manufacturing locations is expected in the future. In India, cell manufacturing capacity is expected to be more than 75 GW/year by the end of 2026. In the USA, a total of 43 GW/year of new capacity addition has been announced since the IRA was passed. In addition, plans to build solar cell manufacturing bases or capacity additions have also been reported in European countries such as Italy, France as well as Indonesia, Australia, Laos, Brazil, but also in the Middle East and Africa. As was mentioned before, given the current price and demand supply gap, it is uncertain if these plans will eventuate or not.

PV MODULE PRODUCTION

As well as solar cells, global PV module manufacturing capacity surpassed 1 TW/year in 2023 with 1 032 GW/year for the first time as 419 GW/year of new capacity was added. Global PV module production (c-Si PV module and thin-film PV module) reached 612 GW, an almost 62% increase from 324 GW in 2022. As shown in Figure 4.5, China continued to be the largest producer of PV modules in the world. China produced 510 GW of PV modules in 2023 from its 920 GW/year of production capacity. China's production share showed growth form 77.8% in 2022 up to 84.6%. In 2023, China recorded the highest exported amount of PV modules at 211.7 GW, a 37.8% increase from the previous year. As shown in Table 4.2, the Top five PV module manufacturers are Chinese companies. In the first half of 2024, China produced 271 GW of PV modules, up 32.8% year-on-year. Of this, 129.2 GW was exported. The export volume increased 19.7% year-on-year, while export value decreased due to price drops. Because of the rapid increase of supply capacity, most PV module producers have been facing thinner margins so that a reorganization of PV module players has started in China. Announced capacity additions and new entry business plans in China were cancelled or postponed because of the huge oversupply situation.

FIGURE 4.5: SHARE OF PV MODULE PRODUCTION IN 2023 BY COUNTRY



SOURCE IEA PVPS, RTS CORPORATION

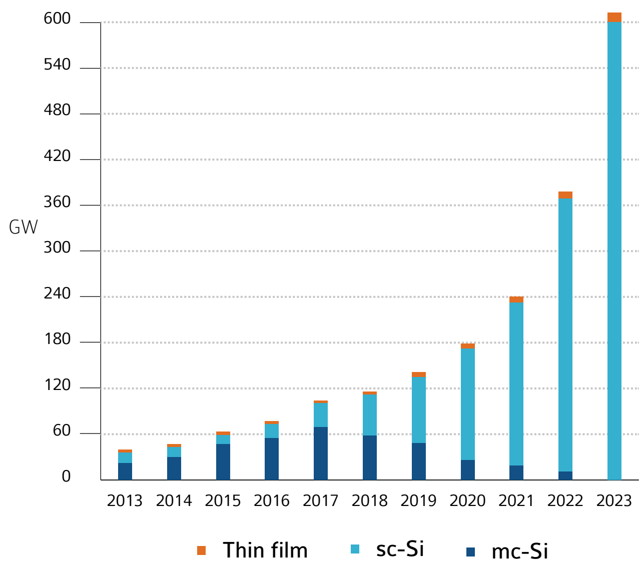
In 2023, the second largest PV module producing country was Vietnam (21 GW) followed by India (16.6 GW). Other countries producing PV modules are Thailand, Malaysia, USA. Canada, South Korea, Chinese Taipei, Türkiye, Singapore and some European countries are listed - but production amounts are smaller than those countries. In India, according to the Ministry of Renewable Energy (MNRE), PV module production capacity reached 64.5 GW/year and it could be 150 GW/year by the end of 2026. The Indian government promotes domestic production by introducing its certification program (ALMM) and Production Linked Incentive (PLI). In the USA, under its policy to guard domestic manufacturers with import duties and incentives under IRA, PV module production increased from 7.3 GW in 2022 to 13.5 GW in 2023, and 20 GW/year of new capacity was added by eight companies for a total manufacturing capacity of 35 GW/year. Further capacity increases are expected in the USA. Under the IRA, a total of 85 GW/year of new PV module manufacturing facilities have been announced. Plans for the regional production of PV modules are becoming active in Europe as well, driven by the demand for lower carbon footprint modules, economic stimulation, and to mitigate the risk of depending on specific production locations under the initiative by the European Union (EU). The Net Zero Industry ACT (NZIA) enforced in June 2024 is expected to promote local production. However, several European companies decided to enhance their capacity in USA instead of Europe due to more favorable conditions.

As well as other products in the supply chain, PV module price was affected by the supply and demand gap and increasing inventories in the market. In January 2023, the average spot price of 182 mm PERC PV modules with a nominal power of 550 W to 595 W was 0.223 USD/W. The price dropped to 0.187 USD/W in June then gradually decreased to 0.115 USD/W at the end of 2023. While dropping prices stimulate the demand, PV module manufactures are facing difficult situations. One of the major PV module manufacturers requested the Chinese government crackdown on companies selling at unfair prices and review the bidding rules which use price as the only selection criteria. It is reported that manufacturers are now exposed to the risk that product quality will decline if cost reductions are further prioritized, effectively creating a risk to final clients with regards to safety, reliability, and performance throughout the entire operational period of the PV modules. Because of the very competitive environment over prices, major companies are shifting their business to solutions or system integration businesses combining PV products with their inhouse batteries or inverters.

PV MODULE TECHNOLOGY

In 2023, 599.7 GW of c-Si PV module was produced. As shown in Figure 4.6, the share of c-Si PV module was 98%, a slight increase from 97.5% in 2022. It should be noted that the transition to sc-Si PV modules advanced in 2023, and mc-Si disappeared from the market. As mentioned in the section on wafers and cells, adoption of larger-sized solar cells further increased. For the utility-scale segment, 70% of the PV modules used had a surface area of 2.5 m^2 to 3.0 m^2 in 2023. In this segment, bifacial PV modules are also commonly used. While larger sized PV modules contribute to a reduction of the LCOE, the heavier weight sometimes becomes an issue as it increases the cost of trackers and construction. PV modules adopting half-cut c-Si solar cells are now mainstream, accounting for more than 90% of all the PV modules in 2023. PV modules with third-cut cells and further separated cells are manufactured as well. Shingled PV module technology (overlapping the edges of solar cells without ribbons) and seamless soldering technology were also adopted.

FIGURE 4.6: PV MODULE PRODUCTION PER TECHNOLOGY IN IEA PVPS COUNTRIES 2013 - 2023



SOURCE IEA PVPS, RTS CORPORATION

THE UPSTREAM PV SECTOR / CONTINUED

Thin film PV production in 2023 was 12.5 GW and the share of thin-film PV slightly decreased from 2.5% in 2022 to 2% in 2023. The majority of the thin-film PV modules were CdTe PV modules produced by First Solar (USA). First Solar shipped 11.4 GW of PV modules produced with 16.6 GW/year of capacity in the USA and Malysia. China had 540 MW/year of CdTe capacity with 3 companies, but production scale remains low in comparison to First Solar. Other thin-film technologies produced in 2023 were CIGS and amorphous-silicon PV modules.

EMERGING TECHNOLOGY

In several IEA PVPS member countries such as China, Japan, South Korea, USA, Germany, the Netherlands and Sweden, R&D efforts on emerging PV technologies are underway. In particular, since the conversion efficiency has been rapidly improved in a short period of time, efforts toward the practical application of perovskite technology have been continued in 2023. Perovskite solar cells are expected to have the potential for high conversion efficiency, low material costs, and a low carbon footprint process. Approximately 70 to 80 companies around the world are working on development with the aim of commercializing the manufacture of single-junction perovskite solar cells and tandem solar cells that combine perovskite solar cells with other technologies.

Several companies in China and Europe are operating pilot production lines. As of March 2024, there are two manufacturers commercially producing and selling perovskite solar cells: Hangzhou Microquanta Semiconductor of China, which produces flat glass modules, and Saule Technologies of Poland, which mainly produces perovskite solar cells for consumer products (such as for electronic shelf power supplies). Several other companies have begun shipping samples. Most companies, including those currently preparing for production, plan to begin commercial production around 2024 to 2026, after that some of those companies have plans to expand production capacity to GW/year level.

In China, about 20 companies have announced plans to produce perovskite solar cells. In the "Action Plan for Innovation and Development of the Smart Photovoltaic Industry (2021-2025)" announced in 2021, the Ministry of Industry and Information Technology of China (MIIT) announced a policy to promote the smartification of the entire PV industry. In this regard, advance research and industrialization of new solar cell modules, such as perovskite and tandem types are promoted. Development and application of building-integrated photovoltaics (BIPV) with long service life and higher safety is also promoted. Under these policies, glass-glass perovskite modules produced by the pilot lines have begun to be installed on roofs and walls of buildings as a demonstration project. Some companies have announced that they have passed the IEC 61215/61730 certification test. For example, in January 2023, Hangzhou Microquanta Semiconductor of China announced that its mass-produced perovskite solar cell module, "Microquanta Module-α" had passed all stability tests for the IEC 61215 and IEC 61730 standards by third-party testing organization VDE of Germany, becoming the first in the world to receive certification. In addition, UtmoLight announced in February 2024 that its commercial-sized perovskite solar cell module with an area of 0.72 m^2 had passed the IEC 61215/61730 certification test and obtained the first and only TÜV certification.

The practical application of tandem technology using perovskite solar cells and c-Si solar cells is also actively being carried out around the world. Oxford PV (UK) started small scale production of tandem cells using M6 (166 mm wafers) in their German factory and plan to start commercial scale production in 2024. In June 2024, the company announced that it had recorded a conversion efficiency of 26.9% for a PV module with an area of approximately 1.6 m^2 (1 m x 1.7 m) (measured by FhG-ISE CalLab) The construction of a pilot line is advance by Hanwha Solutions (Hanwha Q CELLS) (South Korea). The company established a pilot production line in Talheim, (Germany) in November 2022 through a consortium with the Helmholtz Center for Materials and Energy Research Berlin (HZB) and others. In May 2023, the company announced that it would invest $100 million for the construction of a new pilot production line for tandem solar cell modules at its Jincheon plant in South Korea. The plan is to start commercial production by the end of 2026. Tongwei Group (China) plans to establish a photovoltaic industry technology research and development center in Sichuan Province, China, including a 100 MW/year perovskite/HJT tandem solar cell research and development line, and reportedly received approval from the Sichuan Provincial Development and Reform Commission in January 2024. The company announced that it had recorded a conversion efficiency of 31.68% for its perovskite/HJT tandem solar cell in November 2023. Other major Chinese companies are also working on research and development of perovskite/c-Si tandem technology, although they have not announced plans to build pilot lines. In June 2024, LONGi Green Energy Technology (China) announced that it had recorded a conversion efficiency of 34.6% for its small area perovskite/c-Si tandem solar cell (measured by EU ESTI). The company also announced that it achieved a 30.1% of conversion efficiency using M6 standard wafers (measured by FhG-ISE). Jinko Solar is also working on research and development of tandem solar cells. In May 2024, the company announced that a perovskite/c-Si tandem solar cell with an n-type TOPCon structure recorded a conversion efficiency of 33.24% (measured by SIMIT, China).

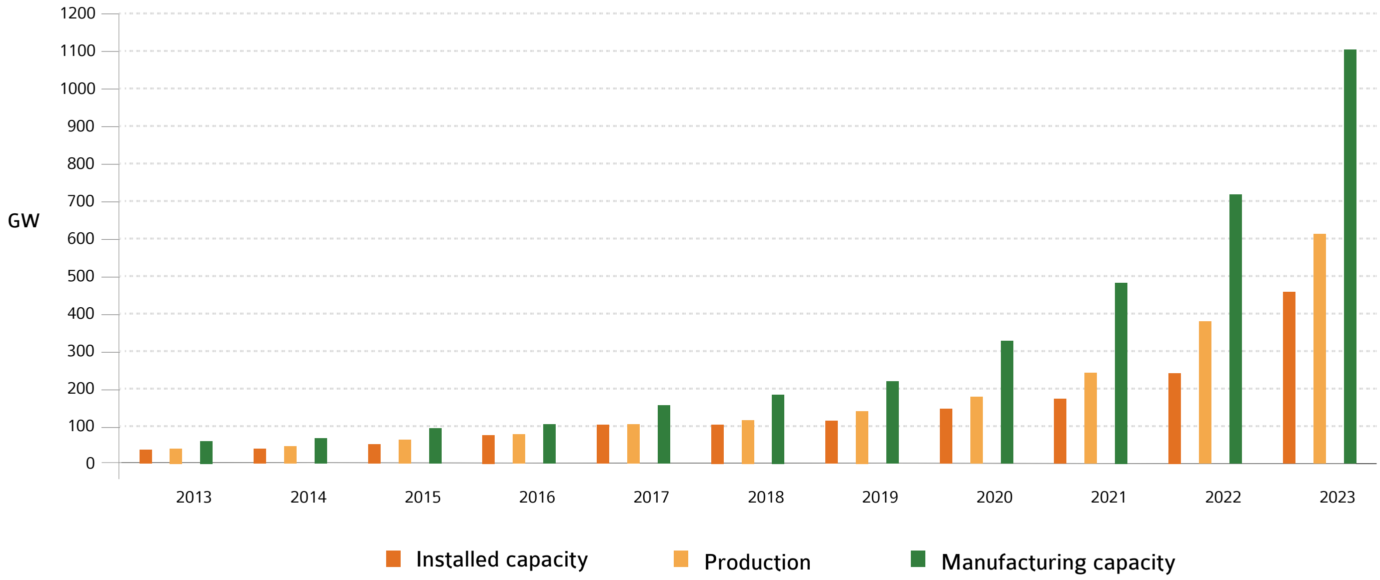
As mentioned above, research, development and demonstration of next-generation solar cells based on perovskite solar cells has been active, but neither single-junction nor tandem technologies have yet reached full-scale commercial production. It is necessary to improve conversion efficiency (to fill the gap between small-area cells and large-area modules), verify service life and stability, and establish a manufacturing process. In addition to overcoming these technical challenges, it is also necessary to identify target markets that take advantage of the characteristics of the technology, establish standardization (performance measurement and reliability evaluation), and product design as a system (construction method, etc.), as well as ensure environmental safety and respond to recycling efforts. For tandem types, durability and reliability must be verified before they can be introduced into the market of existing c-Si solar cells.

PRODUCTION CAPACITY EVOLUTION

Figure 4.7 and Table 4.3 show the evolution of global annual PV installed capacity, PV module production amount and PV module production capacity. In 2023, production capacity increased to 1 103 GW/year from 717 GW/year in 2022. The production capacity figures include the capacities of aging facilities and idle facilities that are not competitive anymore; hence the real effective production capacity is assumed to be on the level of about 700 GW/year to 800 GW/year in 2023. The speed of capacity enhancement is faster than the global PV market growth development so that the gap between demand and supply was widened in 2023 and PV module prices dropped. If the gap is not reduced and the inventory is not cleared current price levels are expected to remained.

THE UPSTREAM PV SECTOR / CONTINUED

FIGURE 4.7: YEARLY PV INSTALLATION, PV PRODUCTION AND PRODUCTION CAPACITY 2013-2023 (GW)



SOURCE IEA PVPS, RTS CORPORATION

TABLE 4.3: EVOLUTION OF ACTUAL MODULE PRODUCTION AND PRODUCTION CAPACITIES (MW)

YEAR	ACTUAL PRODUCTION			PRODUCTION CAPACITIES			
	IEA PVPS COUNTRIES	OTHER COUNTRIES	TOTAL	IEA PVPS COUNTRIES	OTHER COUNTRIES	TOTAL	UTILIZATION RATE
1993	52		52	80		80	65%
1994	0		0	0		0	0%
1995	56		56	100		100	56%
1996	0		0	0		0	0%
1997	100		100	200		200	50%
1998	126		126	250		250	50%
1999	169		169	350		350	48%
2000	238		238	400		400	60%
2001	319		319	525		525	61%
2002	482		482	750		750	64%
2003	667		667	950		950	70%
2004	1 160		1 160	1 600		1 600	73%
2005	1 532		1 532	2 500		2 500	61%
2006	2 068		2 068	2 900		2 900	71%
2007	3 778	200	3 978	7 200	500	7 700	52%
2008	6 600	450	7 050	11 700	1 000	12 700	56%
2009	10 511	750	11 261	18 300	2 000	20 300	55%
2010	19 700	1 700	21 400	31 500	3 300	34 800	61%
2011	34 000	2 600	36 600	48 000	4 000	52 000	70%
2012	33 787	2 700	36 487	53 000	5 000	58 000	63%
2013	37 399	2 470	39 868,5	55 394	5 100	60 494	66%
2014	43 799	2 166	45 964,9	61 993	5 266	67 259	68%
2015	58 304	4 360	62 664	87 574	6 100	93 674	67%
2016	73 864	4 196	78 060	97 960	6 900	104 860	74%
2017	97 942	7 200	105 142	144 643	10 250	154 893	68%
2018	106 270	9 703	115 973	165 939	17 905	183 844	63%
2019	123 124	17 173	140 297	190 657	28 530	219 187	64%
2020	156 430	23 044	179 474	289 581	37 095	326 676	56%
2021	213 032	29 346	242 378	410 500	71 500	482 727	50%
2022	329842	48758	378600	611124	105476	716600	53%
2023	550992	61208	612200	1030500	72500	1103000	56%

Note: Although China joined IEA PVPS in 2010, data on China's production volume and production capacities in 2006 onwards are included in the statistics.

SOURCE IEA PVPS, RTS CORPORATION

THE UPSTREAM PV SECTOR / CONTINUED

Balance of system (BOS) component manufacturers and suppliers represent an important part of the PV value chain and BOS components are accounting for an increasing portion of the system cost as the PV module price is falling. Accordingly, the production of BOS products has become an important sector of the overall PV industry.

INVERTER

With the growth of the PV market in China that achieved a minimum of 235.0 GW and probably up to 277.2 GW[1] of installed capacity in 2023, more than double from the previous year, Chinese inverter manufacturers had a dominant position in the global market. Their dominance was observed in both utility-scale and distributed PV markets. According to CPIA, the global shipment shares of China-made inverters in 2023 was 70%. Huawei and Sungrow, both Chinese companies have about 50% of the global shipment whilst the Top 10 manufactures had more than 80% of the global volumes shipped. However, regional difference remains - the Chinese market is dominated by Chinese companies, but in the PV market in the Americas and Europe, European manufactures have a more significant share.

Generally, inverters are categorized into three types: central inverters, string inverters, and micro-inverters called "MLPE, module level power electronics". In 2023, the share of central inverters (1 MW to 5 MW) used for large-scale utility projects above 10 MW was about 20%, down from 33% in 2022. The market share of string inverters used in utility-scale and small to medium-scale commercial PV systems was around 79%. The share of MLPEs remains low at about 1%, mainly for residential and small-scale commercial applications.

Inverter prices were under pressure so efficiency improvements have been advanced, achieving 99% and with the adoption of SiC or GaN, a reduction of the weight and size is observed. It is reported that new products achieved more than a 40% and 30% reduction of the volume and size respectively. In terms of the voltage,1 500V products had an almost 55% share in the global market. In 2023, for the first time, 2 000 V products were connected to the grid in the Mengjianwan project in China. With higher voltages, 2 000 V PV inverters reduce power losses in the system and improve efficiency, not just of the inverter but also the power efficiency of transformers and other equipment, while reducing the cost of materials. New grid codes require the active contribution of PV inverters to ensure grid management and grid protection. Grid forming, which requires sophisticated control and interactive communications functions with digital technologies and responds to inertia force is now being developed. While requirements are extended for inverter functions, serious concerns around cybersecurity are emerging, and addressing cybersecurity is now one of the major issues for energy security. Recently, US NIST published the draft guideline "Cyber security for smart inverters: Guidelines for residential and light commercial energy systems". Solar Power Europe and other trade associations are also working on these issues.

Along with the growth of the distributed market, hybrid products that support power storage for residential and commercial use are increasing, and applications for EVs and virtual power plants (VPPs) are expanding. For self-consumption, functions to optimize self-consumption have been equipped, supported by energy management solutions combining energy storage systems and EVs with smart monitors. Applications of AI and machine-learning for failure detection as well as optimization of electricity generation contributed to lowering operation and maintenance (O&M) costs.

MLPE is growing in specific markets. Microinverters and DC optimizers (working on a module level) have been mainly adopted in the USA residential market to respond to rapid shutdown requirement imposed by the National Electricity Code (NEC) but are also being pushed in other markets where shutdowns and AC wiring is considered desirable (public buildings in France, for example). MLPE can help achieve a higher output for PV systems affected by shading and a more efficient rapid shutdown can be made in case of fire. In 2023, it is reported that the MPLE market in Europe grew with the demand for decentralized PV.

Regarding the plans of establishing PV manufacturing bases in the USA as mentioned above, the production capacity of inverters in the USA is expected to increase. In August 2023, Siemens announced contract manufacturing in USA and Enphase extended contract manufacturing in several states. Under the IRA, incentives are also provided for inverter manufacturing, and the IRA's incentives are expected to increase demand for USA-made inverters, as there is a 30% investment tax credit (ITC) plus a 10% deduction for projects using domestic products.

1. A range of values is provided to account for uncertainty in AC/DC conversion ratios, in particular with regards to new utility-scale capacity in China, where the minimal annual volume considers official China reporting and the maximal annual volume considers a further 42 GW that could have been installed considering the uncertainty surrounding official conversion ratios from AC to DC of Utility-scale systems.

TRACKERS

Among other BOS segments, the market of single axis trackers has been growing. The installed capacity of single axis trackers of 2023 was around 70 GW. The largest tracker market is the USA, where more than 90% of the utility-scale projects adopted single axis trackers. Aside from the USA, the market for PV trackers is expanding in the countries where utility-scale PV projects are growing, China, India, Australia, South America, South Africa and the Middle East. Unlike other segments, the USA has the biggest share in tracker shipments accounting for more than 50% of the global single axis tracker shipments, but single axis trackers are also produced in demand areas such as China and Europe. Some of the principal companies (Nextracker, ArrayTechnologies and GameChange Solar) announced production capacity enhancements in the USA thanks to the dynamic and growing utility-scale market under IRA tax credits with a bonus for local contents. Besides utility-scale applications, trackers used for agriPV projects are developed and commercialized with specific designs to share solar energy with crops.

Companies doing business in the downstream sector have various origins: subsidiaries of electric utilities, subsidiaries of PV module manufacturers, companies involved in the conventional energy or oil-related energy business. Major PV project developers are accelerating their overseas business deployment and are active in business deployment in the markets such as Africa, the Middle East, ASEAN region and South America. The number of project developers active in the international business is increasing. Traditional energy companies are active in this field and TotalEnergies, Enel, Light Source BP, EDF Renewables and Iberdrola, etc. are developing PV globally. Chinese energy giants are also active in this field - Top 5 energy companies such as State Power Investment (SPIC), CHN ENERGY Investment Group, China Huaneng Group, China Three Gorges Renewables, and China Datang invested in around 80 GW of PV projects in 2023 in total. It should be also noted that several vertically integrated companies are present in the downstream sector. These companies produce PV modules or polysilicon, develop PV projects and provide EPC and O&M services. c-Si PV module manufacturers such as JinkoSolar, Trina Solar (both China), Canadian Solar (Canada), and Hanwha Solutions (South Korea) are also active in the downstream sector. On the other hand, in India, project developers entered upstream sectors to take advantage of PLI incentives. For example, in addition to PV cell and module manufacturing capacity, the Adani Group has plans to establish vertically integrated production from polysilicon to PV modules. In April 2024, a wafer and ingot manufacturing plant in Gujarat started operation.

THE UPSTREAM PV SECTOR / CONTINUED

Solar power remains the lowest-cost option in most countries, making it increasingly attractive to investors. While lowering PV module prices in 2023 stimulated the PV market, project developers need to consider recent inflation, rising interest rates, and increasing labor costs. In this situation, developers with strong credit and capital will likely become more competitive as they will have an easier time raising funds. Across the world, government tenders will need to consider recent inflation, rising interest rates, and fluctuations in product prices and devise flexible methods to continue to attract investment.

five

SOCIETAL IMPLICATIONS OF PV AND ACCEPTANCE

PV is bringing profound and undoubtedly long-lasting changes to modern society – with positive impacts across economic sectors, societies and the environment, it is a fundamental pillar without which the energy transition could not go ahead. As with all radical transformations, the acceptability – or even, the desirability – of the change is linked to perception of the attractivity or necessity of the change and understanding of the impacts it will bring. For photovoltaics, this covers subjects such as the number of jobs involved, the creation of new companies and the disappearance or transformation of others, the generation of new financial flows, the impact on the environment and local communities. Understanding these social aspects related to the development of PV is becoming essential for governments adding photovoltaics to increasingly ambitious clean energy targets.

In particular, as penetration rates increase and utility scale and building integrated systems become more visible in local communities some populations are becoming less accepting of PV, whilst in specific countries, organised resistance to PV, most commonly for ground mounted systems but sometimes for building applied systems, has become a reality despite a generally positive opinion from the general public.

This chapter aims at providing key elements and indicators that can be used to promote the desirability of PV as an element of the energy transition while highlighting essential aspects that remain as sensitive points.

ACCEPTANCE OF PV DEPLOYMENT

Acceptance can be defined as the willingness of stakeholders to approve, support, and engage themselves in the energy transition. This acceptance is fuelled by a positive perception of the changes and decreased by negative inputs. In the early days of the development of PV, up until the European boom of 2007-2009, PV benefitted from an overwhelmingly positive image; it was developed with small scale distributed systems on roofs and was not a significant generator of revenue or tension.

Drops in acceptability have tended to come after boom growth – for example, in Spain in 2007-2008 the local feed-in tariff was so popular that PV developed so fast that local authorities cut support mechanisms, in fear of economic and budget consequences for the country. Other countries that stepped into the FiT policies have also experienced major market development followed by a rapid halt. The EU was the epicentre of PV development until 2011-2012, and this happened across a number of other European countries like Spain, France, Belgium, Czech Republic, Greece, Bulgaria and Romania.

Opposition in these contexts most often came from sectors that perceived photovoltaics as a threat: traditional utilities and energy sector majors for example, were unable to accommodate photovoltaics in their traditional business plans and pushed poorly informed authorities to put the brakes on PV development. The PV community had built its reputation on its environmental advantages and had not yet had to work on a broad social acceptance and was unable to work with governments to create healthy dialogue.

ACCEPTANCE OF PV DEPLOYMENT / CONTINUED

The most recurring arguments motivating a lack of social acceptance for PV depend on the country and the market segments, however common themes can be found including:

- Unappreciation of the physical appearance of PV systems in natural or heritage landscapes.
- Unfavourable opinions on the financial flows generated by PV systems (seen as either "profiteering" by individuals or multinationals profiting from local resources without contributing to local economies).
- Fear that toxic and/or rare materials are used in the manufacturing process with no possibility of recycling and/or that such materials may leach into the environment over time.
- Worries that PV will supplant crops and pose a risk to nutrition and food sovereignty.
- Opposition to ground mounted systems on the grounds of impacts to biodiversity and local environments.
- Concerns that developers will fail to take community sentiments or needs into account during system design
- Fear around quality and reliability issues (fire and electrical risks, resistance to storms...)

Where PV penetration rates are low, these issues seem to remain in the background, and only become prominent as market penetration increases. For those countries/regions where they are present, the PV sector, independent or government agencies have organised communication and educational campaigns, made fact-checking tools available to debunk the more aggressive false claims against PV and created educational resources targeted to the general and specific publics. Communication campaigns tend to be targeted towards the general public, working to demonstrate best practices, illustrate community investment and governance, or even educate the public about their ability to participate and engage in planning and development processes.

SOCIO-POLITICAL AND COMMUNITY ACCEPTANCE

In many countries there is a gap between national socio-political acceptance and community acceptance. These are associated with relatively different concerns and should therefore be addressed separately.

National socio-political acceptance refers to the acceptance of a technology by politics, policy makers, key stakeholders and the public. It englobes how legal and regulatory frameworks are adapted to include PV, and takes into consideration subjects as diverse as who carries the financial burden for support mechanisms and grid capacity, jobs, industry development and local content. Socio-political acceptance is often lagging behind community acceptance in the early stages of PV development in a country.

Governments have demonstrated maturing levels of national socio-political acceptance through adapting planning legislation and procedures, reserving research budgets for community engagement or technology advancement, unrolling support for local jobs through deployment rules and local content. Examples Türkiye a hold on PV development until it was coupled with local value creation. In France, indirect local content requirements have been used in tenders for years, and local BIPV products were eligible for a FiT bonus over 2022 and 2023 – and in 2024 the two gigafactory projects for local manufacturing were declared Projects of National Interest. In the USA, recent funding programs improving community engagement in utility PV siting plans (R-STEP) and budgets specifically for research on community acceptance and opposition to solar (SEEDS) were implemented. In Japan, the 2023 meeting of the Agency for Natural Resources and Energy (ANRE) working group has developed recommendations for facilitating harmonious siting practices for local communities as well as provisions for suspending FiT and FiP for operators that did not respect all laws and regulations, working to reassure the general public of the accountability of generators.

Community acceptance is related to the acceptance by local stakeholders. It includes concerns over distributional justice (costs and benefits), procedural justice, and trust; NIMBYism (Not In My Backyard) sometimes occurs. It covers consideration of economic aspects: grid costs, Renewable Energy System (RES) fees, unequal access to PV, concentration of revenues between a limited number of big companies, social aspects (environmental, aesthetical impact), and specific opposition (e.g., farmers, hunters, lobbyists, etc). Many countries with well-developed utility scale markets are increasingly experiencing local and/or organised resistance to utility scale systems, with multiple factors cited as reasons for opposition, from the sealing of permeable lands to conflict of usage with agriculture or biodiversity reservoirs (Austria, France, Spain, Portugal, Sweden) – or even on the incompatibility of PV with the local cultural heritage (Italy). This opposition can be aimed at planning permits, but also become manifest in local planning regulations that restrict the siting of utility scale PV (USA, France, Italy, Netherlands).

Mandatory profit sharing of added value with local residents (France) is one type of action that can be taken to improve community acceptance, as is giving neighbours and community members the ability to participate in siting and planning procedures and consultations.

Challenges related to the acceptance of PV, even if they are directly influenced by the political, economic, geographical, social context in which PV installations are being deployed, are fairly similar across different regions and countries. This calls for a higher collaboration between countries on this topic based on the sharing of experience and exchange of good practices.

COMMUNITY ENGAGEMENT

Stakeholder engagement is an important way to improve acceptance and accelerate deployment. Stakeholders run across the value chain, from research down to permitting, construction and use – with stakeholder involvement important in some key areas such as permitting, grid connection and investment. Tools to increase involvement include public consultations in permitting procedures, self-consumption (encouraging all citizens to become generators), energy communities and collective ownership, open participation in the elaboration of climate and energy transition policies and targets or the provision of guidance and educational tools to end users.

The ability of local residents and communities to be involved in the process of zoning for solar, siting solar projects and the permitting procedure is now widely recognised as a lever for increasing community acceptance of large-scale projects. Accordingly, many governments have ensured that public consultations of local residents and communities are an integral part of the permitting procedures for PV projects, including in Austria, Japan, USA, France, UK. In Japan, from 2024 access to FiT and FiP for systems over a specific size or requiring forestry management authorisations is subject to a minimum number of public briefing sessions, and can include mandatory transparency on business plans. In the USA the government R-STEP (the Renewable Energy Siting through Technical Engagement and Planning) program will support the creation and/or expansion of state-based programs that improve renewable energy planning and siting processes for local communities. In France, public consultations are mandatory for ground mounted systems over 1MW. In Europe, the European Union adopted a series of new and updated guidance documents in May 2024 aimed at improving and streamlining permitting procedures to accelerate the deployment of renewables. These guidelines, recognising the importance of public participation for greater acceptability, recommend that "the needs and perspectives of citizens, local authorities and societal stakeholders should be taken into account at all stages of renewable energy projects from policy development to spatial planning and project development, deployment and operation."[1]

1. Commission Recommendation (EU) 2024/1343 of 13 May 2024 on speeding up permit-granting procedures for renewable energy and related infrastructure projects

Citizen participation in energy communities or citizen investment and governance of solar projects is an important lever for both empowering residents and citizens to initiate projects but also maintain economic flows to local communities. In Austria, trials

have been undertaken to involve citizens in energy planning and investment. In France, the government co-finances the promotion of citizen investment in renewables. Citizen investment is present in many countries such as Austria, Germany, France, Denmark, USA, Australia... where citizens can either participate in controlling the project or receive financial participations.

Information and guidance web platforms and brochures can be used to facilitate citizen engagement in self-consumption, guiding through administrative procedures or demystifying the technology and providing buyers guide. In Australia the Solar Consumer Guide is a government website to guide through the process from installing to monitoring after installation; in the USA the Solar Energy Technologies Office of the Federal Energy Department hosts the Homeowner's Guide to Going Solar website with the same goals; in France Photovoltaique.info is a government financed website providing guidance from planning to operations for both end-users and professional installers; Singapore has a similar system, the government entity "Energy Market Authority" created a website that provides guidance on the installation steps, payment schemes and selling excess electricity. The installation steps section contains a list of the qualified persons (architects or professional engineers) with the permissions to install a PV system.

More generally, involvement can be seen under various angles:

- Individual participation as the beneficiary of PV electricity: Prosumers are consumers producing part or all of their electricity with PV while maintaining grid connection. Countries with prosumers policies, especially self-consumption ones are described in chapter 3. Energy access in emerging countries has shown for a long time that the implication of the populations significantly increases the adoption of decentralized energy sources.
- Individual participation as group actions for the development and use of PV electricity: Energy communities, and the specific case of solar communities are involving communities in producing and managing energy, allowing a higher involvement of stakeholders.
- Collectives and groups participating in the development of PV: Companies and utilities involved in the PV business are known to become advocates of the energy transition, as are local authorities that adopt PV as a tool in their climate change mitigation strategies.

CLIMATE CHANGE MITIGATION

The paragraphs below highlight some key factual elements that can be used to improve the perception of PV in general, on economic, social and environmental aspects.

Climate change has become one of the key challenges that our societies has to overcome and PV is one of the primary solutions for reducing greenhouse gas emissions in the energy sector.

Global energy related CO_2eq emissions increased to 37 400 Mt[2] in 2023, up 1.6% on 2022, (compared to 0.9% from 2021 to 2022). Increasing the share of PV in the grid's electricity generation mix can significantly reduce the emissions from power generation. The global average carbon intensity of electricity was around 490 g CO_2/kWh[3] in 2023 (slightly up on 2022) whereas for 1 kWh produced by PV the CO_2 emitted, taken on a life cycle basis, can be as low as 15 g depending on technology and irradiation conditions.

For example, the IEA PVPS Task 12 report from 2024 indicates that for the analysed configurations, in the case of the PV plant installed in the south of Italy (with an annual irradiation of about 1,820 kWh/m2/y), the estimated greenhouse gas emissions are 17.1 g CO_2 eq. /kWh if the PV plant is equipped with mono-axial solar trackers and 20.7 g CO_2 eq. /kWh if the modules are at fixed angle (34°).

The total CO_2 emissions that are avoided by PV on a yearly basis can be calculated considering the amounts of electricity that can be produced annually by the cumulated PV capacities installed at the end of 2023 and considering that these amounts replace equal amounts of electricity that would be generated by the respective grid mixes of the different countries where these PV capacities are installed.

The annually produced PV electricity is calculated based on country-specific yields depending on the average yields of PV installations and irradiation conditions in each country. With increasingly significant PV penetration rates in a large number of countries, and an overwhelming dominance of China manufactured modules, some changes have been made to the methodology used to determine avoided $C0_2$ in this report, compared to previous years reports.

Because of the higher penetration rates, this report now considers that PV production replaces electricity with a CO_2 content of the countries average grid mix (in the past, the CO_2 content of marginal production has been considered). This has significantly reduced the "avoided" CO_2, as PV now replaces average electricity, not just the most polluting easily dispatched electricity. Additionally, the inherent emissions of PV installed from 2022 has been uniformly considered as monocrystalline China-manufactured modules, independently of the country of installation[4].

CO_2 avoided

923 MT CO_2eq

Using this methodology, calculations show that the PV installed capacity today avoids up to 923 million tonnes of CO_2eq annually. Thus, it avoids approximately 2.5% of the energy sector emissions. This is essentially due to the fact that PV is being massively installed in countries having highly carbon intensive grid mixes, such as China, India, Australia, Germany and Poland.

Figure 5.1 gives a view of the avoided CO_2 emissions in the first 30 countries in ranking of avoided CO_2 emissions, and which represent in total over 98% of global avoided emissions. This figure displaying the countries as a function of their installed PV capacities and grid mix carbon intensities clearly shows their differential contribution to the global avoided emissions and the high impact of their respective grid mix compositions. The more CO_2 the power mix in a country emits, the more positively PV installations will contribute to avoiding emissions.

2. https://www.iea.org/reports/co2-emissions-in-2023
3.https://ember-climate.org/insights/research/global-electricity-review-2024/

4. Had previous years methodology been maintained, avoided CO_2 would have been reported as 1 927 MT CO_2eq., however with this updated methodology it is now reported as 923 MT CO_2.eq

FIGURE 5.1: CO_2 EMISSIONS AVOIDED BY PV

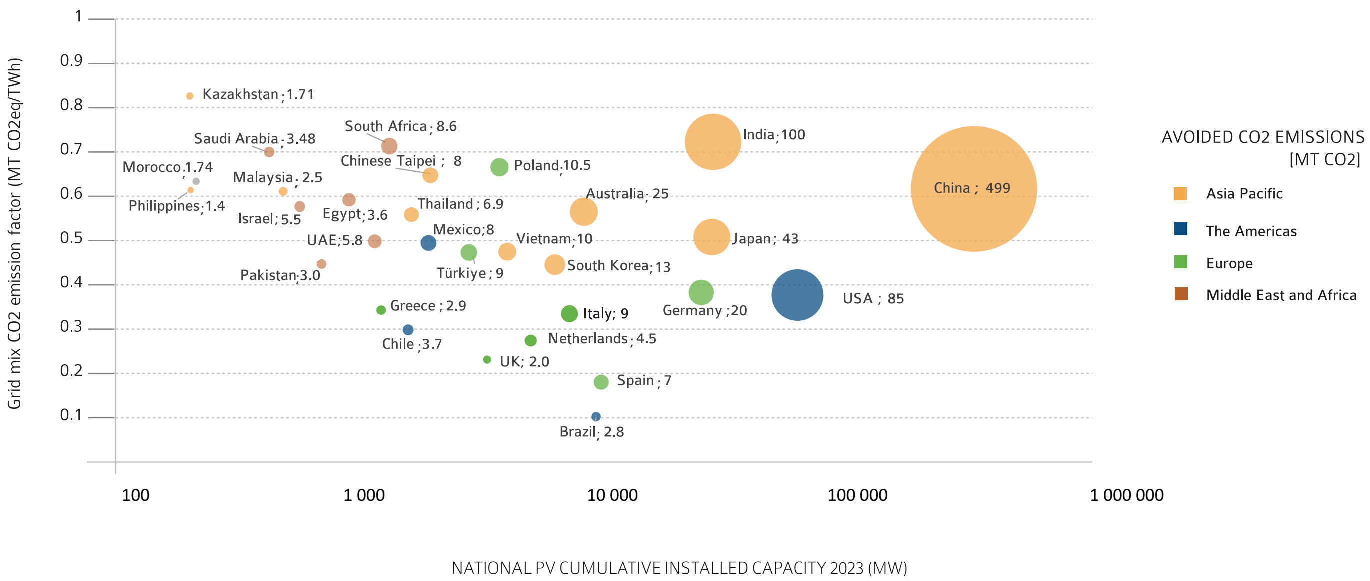
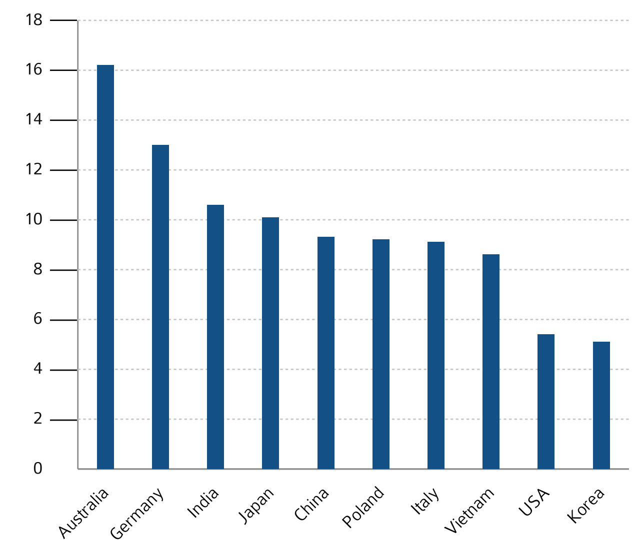
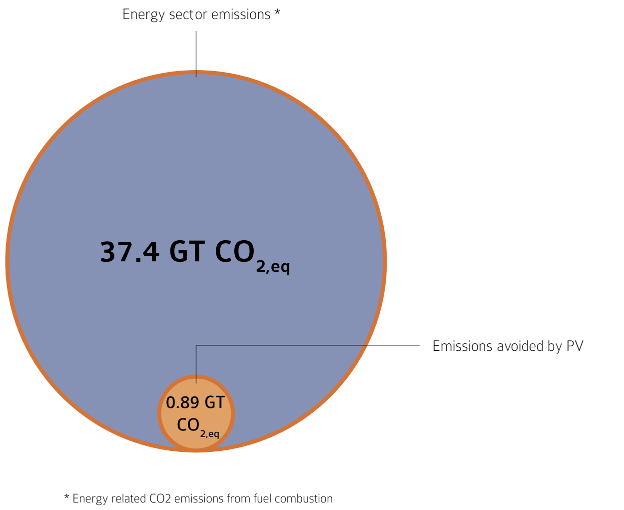


FIGURE 5.2A: AVOIDED CO_2 EMISSIONS AS PERCENTAGE OF ELECTRICITY SECTOR TOTAL EMISSIONS



SOURCE IEA PVPS & OTHERS

FIGURE 5.2B: AVOIDED CO_2 EMISSIONS AS PERCENTAGE OF ENERGY SECTOR TOTAL EMISSIONS



SOURCE IEA PVPS & OTHERS

VALUE FOR THE ECONOMY

The turnover of the PV sector in 2023 amounted to around 400 billion USD. This number has been calculated based on the size of the PV market (annual installations and cumulative capacities) and the average price value for installation and Operation & Maintenance (O&M) specific to the different market segments and countries.

Given the variety of existing maintenance contracts and cost, the turnover specifically linked to O&M has not been considered in detail. However, the global turnover related to O&M was estimated at around 15 billion USD per year. This estimate can be considered as a lower range value, due to the assumptions made for its calculations. It does not take into account either the material cost of replacement and repowering, which is hardly visible, or the value of recycling. O&M costs have decreased over time and a part of PV systems are not maintained through regular contracts (especially residential roof-top systems, unless they are monitored).

According to our estimates, in parallel to the growth of the annual market, the global business value of PV installations has increased by around 62%. The global value for O&M increased at least 50%. Between 2022 and 2023 the global business value increased an already considerable 25% - but this year's increase is well above that. Part of the increase is due to the reduction in system installation costs experienced in most markets in 2023 (even if the drop in module prices wasn't passed on to all markets in 2023), and part of it is due to the sheer size of the market increase. As in previous years, it is still important to note that this value increased less than annual new installed volumes increased (90%). It is worth noting that the O&M value is bound to grow further, powered by increasing volumes of centralised systems, aging plants and repowering operations.

Turnover PV

400 Billion USD

O&M

15 Billion USD

Global business value

+ 62% in 2023

For the purposes of this report, the value of the PV sector for the economy has been assessed based on the volume in MW of installations rather than by evaluating all the contributions of the complete value chain. The assessment of the business value of the industry is in general more complex, due to the decentralized production and the existence of transnational companies. However, a specific approximation of the industrial business value of PV was performed for IEA PVPS major PV manufacturing countries and is presented in a specific section below.

CONTRIBUTION TO THE GDP

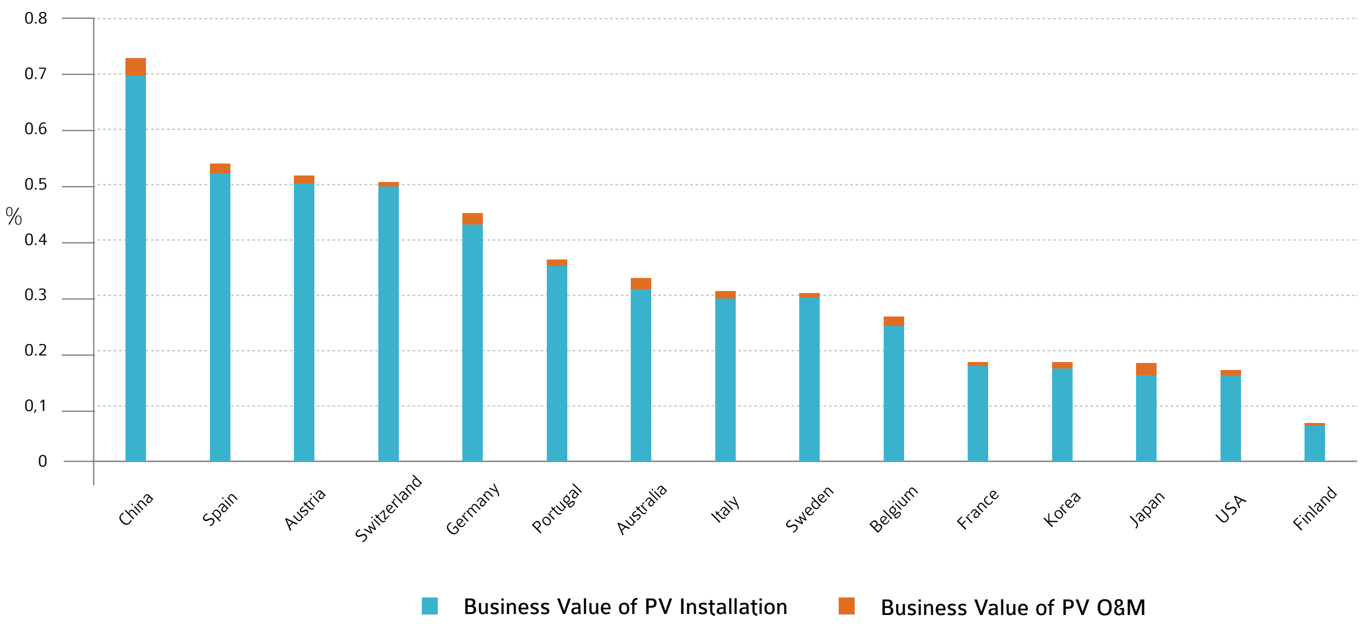
Figure 5.3 shows the estimated business value of the PV sector in IEA PVPS reporting countries as compared to their national GDPs. These values were determined based on the internal PV markets in each country, as described above, and hence they do not take imports or exports into account. Some countries benefited from exports that increased the business value they obtained through the internal PV market while huge imports in other countries had the opposite effect. However, as already mentioned, the market is integrated to the point that it would be extremely complex to assess the contribution from each part of the PV value chain.

As shown by Figure 5.3, the business value of PV compared to GDP is growing as national market sizes increase – China, Spain and Austria all hit above 0.5% of GDP (this is +0.1% for China and over +0.25% for Austria), whilst a further six of the selected countries are above 0.3%. On a global scale, PV business value represents around 0.40% of the GDP, up from 0.25% in 2022, compared to around 2.96% for energy investments.

This level of investment is very close to global investments in all other generating technologies – but there is still scope for more, recognising that in the same year, over 1 000 billion USD were invested in fossil fuels.

In the IEA PVPS countries, the top 3 countries by volume of investment (China, USA, Germany) each roughly doubled their investment level, as did Italy.

FIGURE 5.3: BUSINESS VALUE OF THE PV MARKET IN 2023 COMPARED TO GDP IN% IN 2023



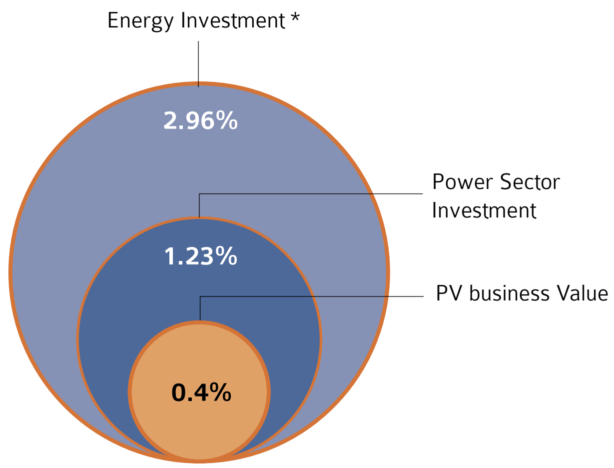
SOURCE IEA PVPS & OTHERS

TABLE 5.1: BUSINESS VALUE: TOP 10 COUNTRIES IN ABSOLUTE VALUE

RANK	COUNTRY	BILLION US$
1	CHINA	130
2	USA	44
3	GERMANY	20
4	SPAIN	8.5
5	JAPAN	7.5
6	ITALY	6.9
7	AUSTRALIA	5.9
8	FRANCE	5.4
9	SWITZERLAND	4.5
10	KOREA	3.1

SOURCE IEA PVPS & OTHERS

FIGURE 5.4: CONTRIBUTION TO GLOBAL GDP OF PV BUSINESS VALUE AND ENERGY SECTOR INVESTMENTS



*Investment in the power sector, fuel supply and end-use & efficiency

SOURCE IEA PVPS & OTHERS

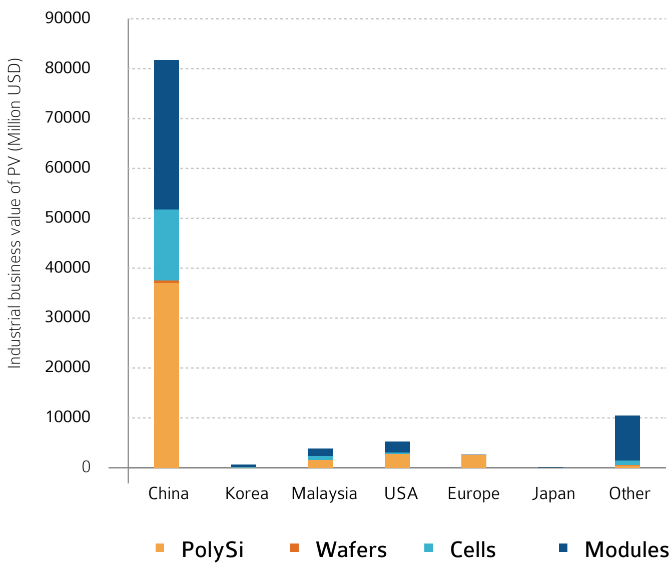
VALUE FOR THE ECONOMY / CONTINUED

Even though assessing the detailed contributions of the different parts of the whole PV value chain is hardly possible in this report due to the level of integration of the market, an approximate evaluation of the industrial business value of PV has been performed and the results detailed for IEA PVPS major PV manufacturing countries.

The evaluation was made based on the production volumes and manufacturing shares of countries for polysilicon, wafers, cells and modules, including thin film technologies, as detailed in Chapter 4, as well as on an average estimated price for each of these four segments. The prices taken into account are based on average prices reported by member countries. We consider that equipment and materials are included in this computed value. BoS, including inverters are not considered here.

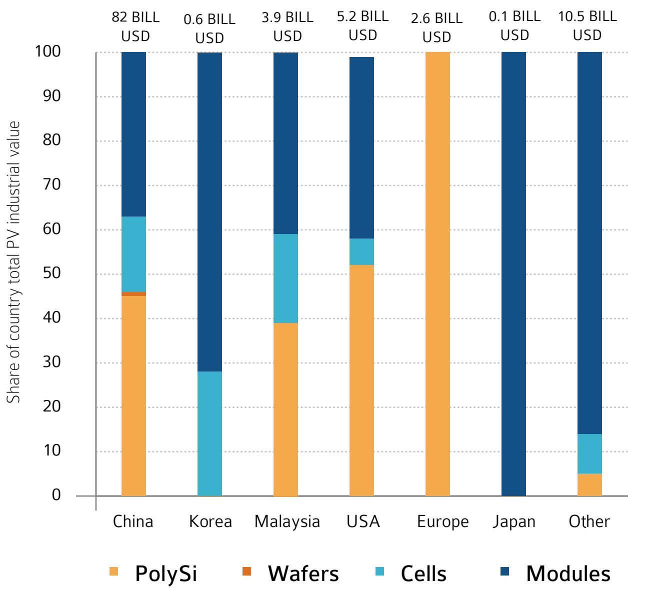
The estimated global industrial value of PV established itself at around 104.7 billion USD in 2023, up from 93.6 billion USD in 2022 (+12%). This relatively low growth is due to the significant price drop in average module and system costs in China (down to 0.14 USD/W or just 61% of the 0.23 USD/W cost in 2022). Figure 5.5A, 5.5 B and 5.5C show for IEA PVPS major PV manufacturing countries the estimated contribution of each step of the value chain in the PV industrial value for each country in absolute and relative terms as well as the comparison of this value to their GDP.

FIGURE 5.5A: ABSOLUTE PV INDUSTRIAL BUSINESS VALUE IN 2023



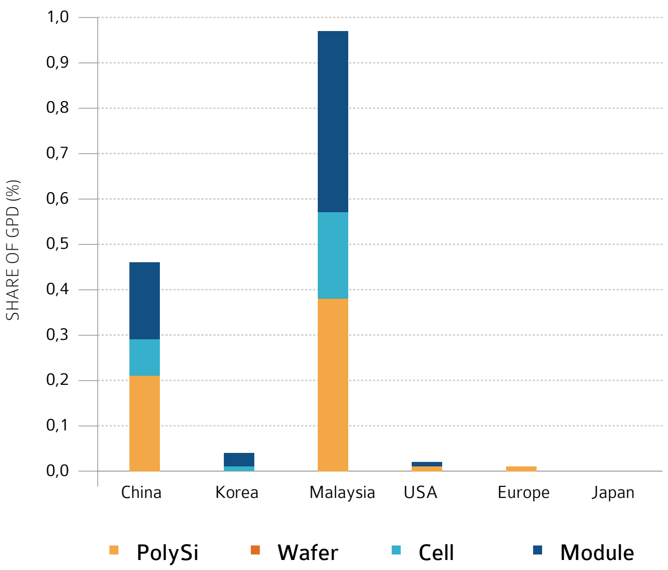
SOURCE IEA PVPS & OTHERS

FIGURE 5.5B: PV INDUSTRIAL BUSINESS VALUE ALONG THE VALUE CHAIN IN 2023



SOURCE IEA PVPS & OTHERS

FIGURE 5.5C: PV INDUSTRIAL BUSINESS VALUE AS SHARE OF GDP IN 2023



SOURCE IEA PVPS & OTHERS

China is by far the predominant manufacturing country in all steps of the PV value chain, with an approximate share of 0.46% of its GDP (up just 0.06% since 2022) represented by the PV Industry (polysilicon, wafers, cells and modules). As in previous years, despite much lower production volumes, the PV industry in Malaysia represents a significantly higher share of the country's GDP compared to China, stable at between 0.9% and 1%. As the many projects in the USA come online, the share in the USA is expected to become visible.

For the BoS, the industry is significantly more distributed, and production occurs in many countries. It is not counted as such here, with many local manufacturers and suppliers servicing the PV industry present across the world in cabling, supports and electrical protections; an analysis would make sense to grasp the extent of the PV industry impact on the countries' economic landscape but is not within the scope of this report.

SOCIAL IMPACTS

EMPLOYMENT IN PV

Figure 5.6 gives an overview of the total direct full-time equivalent jobs in IEA PVPS countries and India. Reported numbers have been established based on the IEA PVPS National Survey Reports and additional sources such as the IRENA jobs database. It should be noted that these numbers are strongly dependent on the assumptions and field of activities considered in the upstream and downstream sectors and represent an estimate in the best case and will diverge with those reported in other sources for this reason.

The methodology used takes data provided by reporting countries on the upstream (industrial) and downstream (distributed and utility scale PV installation and O&M) job numbers, then extrapolates to other markets depending on their respective market specifics. A distinction is made between countries in developed economies having a costly, low intensity work market and the emerging economies with an affordable work force, as well as economies somewhere between these two, where labour costs are mid-range. Manufacturing numbers are based on industry reports and additional sources and split according to the same methodology. Installation numbers are always an approximation.

This report estimates that the PV sector employed in the order of 7.2 million people globally at the end of 2023. An estimated 1.9 million were employed in the upstream part, including materials and equipment, while 5.3 million were active in the downstream part, including O&M.

PV sector employed an estimated

7.2 million people in 2023

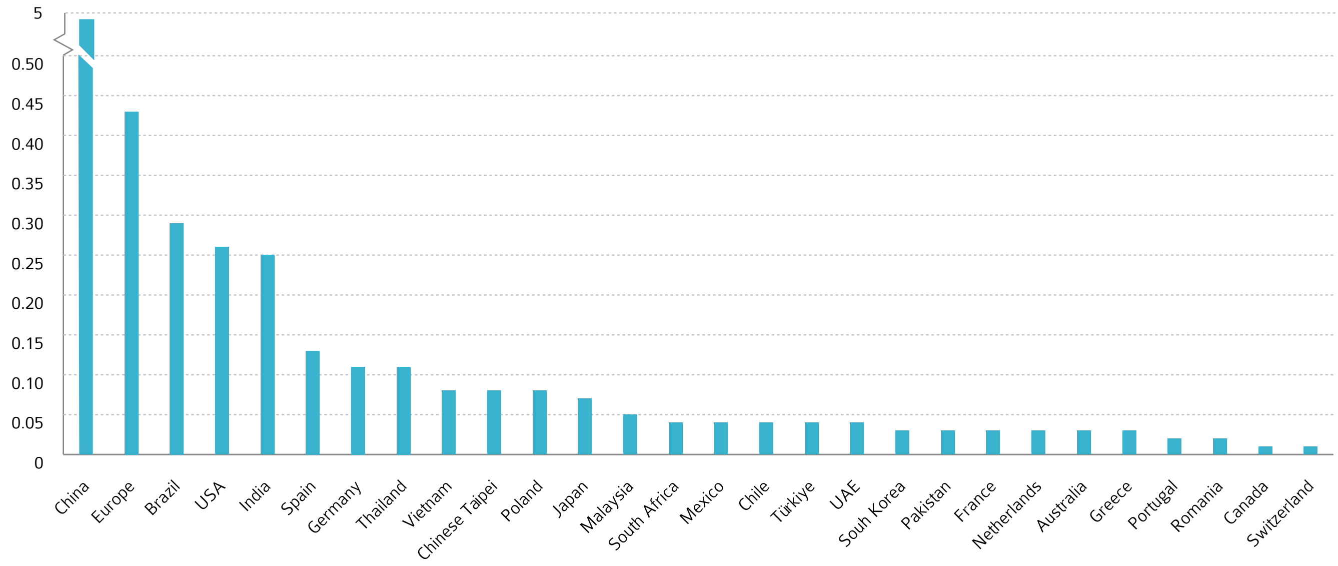
As the leading producer of PV products and the world's largest installation market by a long margin, China is markedly leading PV employment with around 5.1 million jobs in 2023, which corresponds to a significantly higher number of jobs than anywhere else. Lower by one order of magnitude, Brazil, the USA, and India follow, with between 250 000 and 300 000 FTE (Full Time Equivalent). There are an estimated 500 000 FTE in the European Union. Other countries with large workforces included Malaysia, Thailand, although estimations are difficult. Japan has a steady PV market and maintains approximately 70 000 jobs.

Generally, in good correlation with the market evolutions, PV employment expanded where the market developed. As the scale of manufacturing increases, so too does automation, reducing the job intensity per GW in the manufacturing sector. On the other end of the spectrum, residential (distributed) PV deployment has the highest job intensity along the value chain – although it varies significantly in intensity/MW between developing countries and developed countries.

When specifically focusing on development and installation activities, more labour intensive than manufacturing, on average the job intensity ranges from 3 FTE/MW for utility scale PV in developed countries with established markets, to up to 20 FTE/MW for distributed systems in developing countries.

SOCIAL IMPACTS / CONTINUED

FIGURE 5.6: GLOBAL EMPLOYMENT IN PV PER COUNTRY



SOURCE IEA PVPS & OTHERS

O&M generates many manual jobs while the entire PV value chain creates good quality jobs, from research centres to manufacturing.

With an estimated total of 7.2 million jobs in the solar PV sector worldwide in 2023, PV employs well above one third of the total renewable energy workforce and remains number one in the employment ranking of the global renewable energy sector, as new solar capacity additions largey outnumber other renewables sources, this is not expected to diminish.

LOCAL MANUFACTURING

The emergence of PV as a mainstream technology woke up appetites for local manufacturing and job creation at all levels of the value chain. Looking at IEA PVPS member countries only a few countries have pushed through different schemes for local manufacturing in recent years, namely Canada, Türkiye and the USA whilst others have at least initiated studies and advanced projects (France). Elsewhere, some countries have succeeded in bringing manufacturers to produce PV components in their country, for example in Malaysia, Vietnam, and Thailand. South Africa initiated local measures for partnerships with Chinese manufactures but have not yet been able to follow through. Other countries, such as Chile and Saudia Arabia seem to be thinking about it. With the disruptions in the PV value chain caused by the pandemic and the increased cost of shipment, the question of local manufacturing gained traction in 2021 and remained in 2022 despite shipping costs returning to pre-pandemic levels early in the year. Countries such as India and the USA, to name a few, are pushing hard to develop a local industry and increase their partial independence. However, over 2023, increasing volumes of new manufacturing capacity came online in China, and the market cost of modules plummeted due to significant oversupply. As the low module costs were sustained through the end of 2023 and into 2024, different planned manufacturing facilities in Europe were cancelled (Germany), as investors called on EU countries to be more reactive faced with the Chinese oversupply and the attractive incentives offered in the USA. New manufacturing capacities require skilled workforces – and it is increasingly becoming a potential barrier; for example, Europe has identified the need to train at least 100 000 new people over 3 years for the PV industry.

IMPACT ON ELECTRICITY BILLS

The impact of developing PV on electricity bills works through three separate mechanisms; the cost of support mechanisms; the cost of electricity on wholesale markets and the cost of grid access fees.

Whilst in the past these three elements were seen as burdens, the increasing competitivity of photovoltaics and the fluctuations of wholesale electricity costs over the past 3 years can allow one to consider them as opportunities:

Firstly, PV is reimbursing its support mechanisms: the impact of the increase in gas prices resulting from sanctions due to the war in Ukraine over 2022 and 2023 has resulted in PV (and other renewables) playing a much greater role in security of supply than intended so far. With spot market prices skyrocketing across Europe due to record high gas process, PV suddenly become not only competitive but desirable from an economical point of view. Those countries running support mechanism on Contracts for Difference even generated positive cash flow for governments, as renewable generators sold high on the market but reimbursed the state to reach agreed on contract levels for each MWh generated. In the UK, France, solar CfD contracts funnelled back millions of dollars to governments in 2022 (when market costs were exceptionally high) and in 2023 - despite market caps and reforms and lower market costs) in France, support mechanisms for solar raised 724 million euros (761 million USD) in 2022 and a further 81.3 million euros (88.9 million USD) in 2023 for the government and allowed the government to reduce taxes on electricity to contain prices for consumers. In Austria, fees to finance support mechanisms collected in electricity bills were cancelled in 2022. In the ACT in Australia, CfD contracts are anticipated to limited consumer electricity price to below inflation raises, under 5%, compared to a national average of over 20%.

Secondly, PV electricity generation is being sold on the markets in quantities sufficient to reduce market costs, especially in countries where peak consumption is concordant with solar generation. Numerous studies in various countries have shown that PV reduces wholesale market prices for electricity at the time of production – negative prices illustrate this and are most often seen when high solar (or wind) generation occurs at low load times. With the exception of Spain and Portugal , most of the Western European electricity markets saw dozens to hundreds of hours of negative prices in 2023, and are expected to see more in 2024 – with similar events in the USA, (South) Australia and China. The savings for electricity consumers and the society, in general, is difficult to compute but most studies conclude on significant savings and additionally, cost decrease in the distribution grid up to a certain penetration of PV. In the USA state of Texas's grid, it is projected that renewables will save $6 billion USD in net system operating costs in 2024[1].

Thirdly, solar, generally combined with batteries, has demonstrated its ability to provide key network stability services cheaper than fossil fuel plants can – for example, in the nuclear-reliant France, delayed maintenance of the nuclear portfolio in 2022 led the transmission grid manager to call on renewables to step up in supplying services necessary to the grid, in particular voltage stability – whilst coal, heavy oil and additional gas facilities could have supplied theses services, renewables were by far the most economical, and climate friendly, solution. In Australia, big batteries supply of frequency control ancillary services passed 50% in 2023, fast making traditional coal or gas services redundant, whilst distributed batteries are reducing service loads on turbine generation. In the USA, solar power plants across several different states and extreme weather events have been key generators during crises.

PV FOR SOCIAL POLICIES

Besides its direct value for the economy and the jobs that it creates, both making contribution to the prosperity of the countries in which it is being installed and manufactured, PV entails additional positive implications on the social level if leveraged with appropriate policies.

PV can be a competitive alternative to increase energy access in remote rural areas not connected to power grids. Improved energy access can benefit rural business performance, free up workers' time, provide more studying hours for children, improve health through cleaner cooking, and create or enhance jobs as a result. Electrification is a key factor to reduce poverty and increase education, with a direct impact on women's and children's life standards in many regions in the world. In that respect, PV would deserve a significant attention for electrification.

In an increasing number of countries with stable electricity networks and close to total electrification, programs are or have been established to assist low-income families to install grid connected solar, either through means tested rebates, loans or gifts from state agencies or private organisations including in the USA at the national, state, and local levels, as well as Australia, UK. The development of energy communities is also being used as a tool to provide cheaper solar electricity to in need consumers in some countries such as Italy, Portugal. With the combination of high and volatile electricity prices experienced across many countries in the past 3 years, self-consumption of increasingly cheap solar is more and more often seen as the best solution to maintaining electricity bill affordability.

Increasingly cheap solar and self-consumption regulations offer opportunities for social welfare programs aimed at alleviating energy poverty. The energy crisis of 2022 increased the competitiveness of PV to the extent that it could reduce the electricity bill of families, municipalities and companies, not only through direct self-consumption but also through delocalized (or virtual) self-consumption.

Some more specific examples of energy poverty programs involving solar include:

In Malaysia, rural electrification is still a priority of the government, with a projected 100% electrification rate by 2025. Rural electrification is done together with utilities as a form of public-private partnership. In remote Sarawak, the Sarawak Alternative Rural Electrification Scheme (SARES) has electrified almost 5 000 households in 192 villages since its launch in 2016 and has received

1. https://poweralliance.org/wp-content/uploads/2023/04/NERA-Astrape-White-Paper-20230405_Final.pdf

SOCIAL IMPACTS / CONTINUED

regional recognition in 2019. Solar PV and hybrid systems are often used in this scheme, as well as micro hydro-technologies.

In South Korea, with the financial aid from Seoul Metropolitan government, a non-profit organization, Energy Peace Foundation, and Solar Terrace company installed 30 kW of mini-PV systems for 100 energy-vulnerable households (300 W/household). This type of mini-PV installations is becoming popular in South Korea to reduce the electricity bill burden during the summer.

In Italy, the government has established a fund to finance self-consumption systems of between 2 kWp and 6 kWp for households in economic difficulty across 2024 and 2025; a municipality in Sardinia collaborated with an energy services operator in 2017 where the municipality purchased PV systems then sold on loan to families in energy poverty conditions, to make them benefit from PV self-consumption and thus reduce their energy bills. The revenues of the net-billing feed a public fund, in order to finance the maintenance of the plants or possibly the purchase of other plants for other families. The scheme has been replicated in other municipalities, and an energy poverty observatory has been set up.

In Australia, a number of measures were announced by State Governments in 2020 and have been maintained in 2023 going from interest free loans or even complete subsidies (Solar for Low Income Households for systems with an installed capacity up to 3 kW). Additional measures tackling rural electrification include a budget to support feasibility studies looking at microgrid technologies to replace, upgrade or supplement existing electricity supply and to finance the deployment of PV to reduce the use of diesel.

In France, rural electrification is addressed in overseas territories and isolated alpine areas through budgets available for off-grid electricity production, electric vehicle charging points, or grid-connection financing, whilst the widespread availability of micro-PV kits (1 or 2 modules) is leading to small investments by many low income families. Social housing organisations have been granted simplified conditions for managing collective self-consumption systems on social housing as an indirect incentive to allow low income families to benefit from self-consumption.

In the USA, the Inflation Reduction Act (IRA) contained 145 million USD in grants, 18 billion USD in loans, and carve-outs within the low-income bonus to the Investment Tax Credit for Tribal solar deployment to address disparity of electricity access for indigenous communities. The IRA also contained significant incentives for rural electrification, as well as measures targeted towards energy access for low-income communities, historically marginalized communities, and communities with higher rates of unemployment as a result of the energy transition.

In Brazil, the program "Luz para todos" was launched in November 2023, with the goal of improving rural electrification through renewable energies. In its new phase "Luz Para Todos Minha Casa Minha Vida", the program aims to install 500 000 solar panels in low-income households across the country. The primary objective of this new phase is to lower electricity costs while increasing access to renewable energy.

In Chile, the Energy inclusion program founded in 2018, brings together international collaboration and public-private funds to create concrete actions to improve the electricity conditions of vulnerable households under innovative business models adapted to their actual conditions, strengthening local economic development and labor insertion. One example of these projects includes the financial support to build a solar refrigeration center for a fishing village.

PV END-OF-LIFE

The volume of PV modules reaching the end of their useful (first) lifetime is still marginal compared to the volumes of new PV modules deployed in the market. However, as the PV market develops fast and often faster than anticipated, the same trends are expected to be witnessed for end-of-life PV module streams. Forecasting precisely end-of-life PV module streams is a complex exercise for several reasons. PV modules may reach the end of their useful lifetime for different reasons - significant performance degradations, premature failures from production defects, damages from transportation and installation or premature dismantling related to insurance claims, repowering, or revamping. These modules then enter end of life streams anywhere from after just one year or up to thirty years or more. A large disparity in useful lifetime is observed between distributed and centralized applications, with shorter useful lifetimes observed in centralized systems, mostly driven by economic considerations, i.e. the hardware is uninstalled due to financial lifetimes and not technical failures. The market for second-life PV modules is a further source of uncertainty in end-of-life PV module streams forecasts.

Depending on the country and region, end-of-life PV modules may be treated under PV-specific regulations or under general waste and disposal-related regulations.

In the EU, end-of-life PV module streams are regulated by the WEEE (Waste Electrical and Electronic Equipment) Directive since 2012. The Directive is based on the extended producer responsibility principle that stipulates those producers (the term broadly refers to manufacturers, distributors, sellers and importers) placing PV modules on the EU market (regardless of where the PV modules were manufactured) are liable for the costs of PV waste collection, treatment and monitoring. Producers can choose to operate their own take-back and recycling scheme or join existing ones. The WEEE Directive sets collection, recovery and preparation for re-use and recycle minimum requirements, which are expressed in percentage by mass.

Recycling requirements are currently typically achieved through mechanical processes which rely on

1. removal of some components (e.g., frame, junction box, cables),
2. mechanical shredding,
3. sorting into different material categories, taking advantage of physical property differences (weight, conductivity, density, ...) amongst the recovered materials (plastics, glass, metals).

These mechanical recycling processes are usually performed by incumbent recycling actors (e.g., EEE recyclers, metal recyclers, glass recyclers) who leverage existing recycling facilities, equipment and expertise, eventually reaching recycle at a relatively low net cost while enabling WEEE-compliant recovery rates. Processes based on delamination (mechanical delamination (e.g., hot-knife) or thermal delamination (e.g., pyrolysis, incineration)) also exist and are implemented at a commercial level in some rare cases only. Combined with some subsequent chemical process, such recycling routes have the potential to recover materials with higher levels of purity (e.g., glass, silicon) or to recover high-value or critical materials (e.g., silver). However, they are associated with higher net costs and the WEEE Directive requirements are not stringent enough to provide a regulatory-push for such processes.

In other regions, country specific approaches have been taken. In Asia, in China, two demonstration lines for PV waste recycling were set up after a 2019-22 national R&D program focused on recycling crystalline silicon PV modules, and in April 2022 the PV Recycle Industry Development Center in Jiaxing, Zhejiang province was set up as a public institution affiliated with the Ministry of Industry and Information Technology. In Australia, in some states, PV modules are banned from landfill and must be treated in the electronic waste streams. Limited facilities exist to undertake recycling, however a Solar PV Stewardship pilot project was opened first for decentralized PV waste and then utility scale waste in 2024. In Japan, from July 2022, setting aside of future cost of EoL PV systems became compulsory for solar power generation facilities with more than 10kW installed capacity under the FIT program. Owners of PV systems who fail to make reserves for dismantling and removal of PV modules may be subject to revocation of FIT. The Organization for Cross-regional Coordination of Transmission Operator, OCTT, is responsible for managing the reserves. Part of the reserve is expected to cover the cost of recycling of PV modules. In September 2021, the Agency for Natural Resources and Energy under the Ministry of Economy, Trade and Industry published a guideline. In the USA by early 2024 there were nearly 30 recyclers listed in an Office of Energy Efficiency & Renewable Energy website, built as part of the National PV Recycling Program founded in 2016.

PV END-OF-LIFE / CONTINUED

Thin film cadmium-telluride panels, which represent a smaller part of the solar market, undergo a specific recycling process with a USA manufacturer running dedicated recycling facilities for thin film panels which recover the semiconductor material (cadmium and tellurium) in addition to glass and copper. The Inflation Reduction Act also contained limited incentives for the construction of recycling facilities for renewable energy technology, and several announcements of recycling facilities have been made since its passage in August 2022.

six

COMPETITIVENESS OF PV ELECTRICITY IN 2023

The rapid price decline that PV experienced in the last years has already opened possibilities to develop PV systems in many locations with limited or no financial incentives. However, the road to full competitiveness of PV systems with conventional electricity sources requires answering many questions and bringing innovative financial solutions, especially to emerging challenges.

This section aims at defining where PV stands regarding its own competitiveness, starting with a survey of module and system prices in several IEA PVPS reporting countries. Given the number of parameters involved in competitiveness simulations, this chapter will mostly highlight the comparative situation in key countries. Prices are often averaged and should always be looked at as segment related.

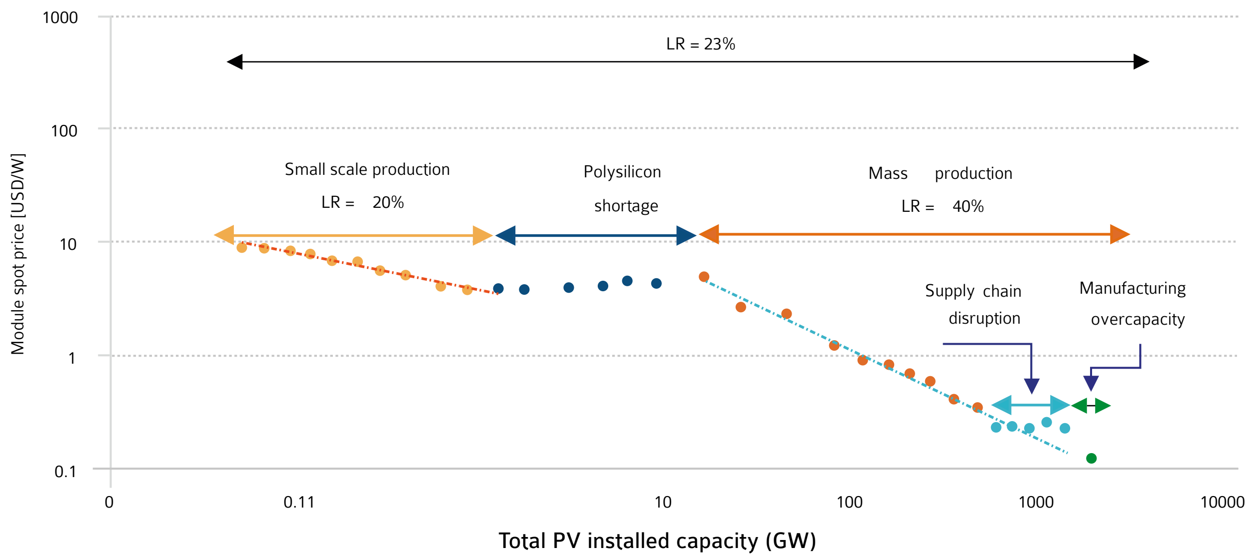
The question of competitiveness should always be contemplated in the context of a market environment created for conventional technologies and sometimes distorted by historical or existing incentives. The fast development of nuclear in some countries in the last 50 years is a perfect example of policy-driven investments, where governments imposed the way to go, rather than letting the market decide. The oil and gas markets are also perfect examples of policy-driven energies which are deemed too important not to be controlled. PV competitiveness should therefore be considered in this same respect, rather than the simple idea that it should be considered competitive without any regulatory or financial support. There are also further barriers, other than economic, for PV to become the obvious alternative to coal (rather than gas) for utilities. Currently, many already unprofitable coal power plants are still in operation because the regulatory and financial structure is not tailored for so many coal units to become stranded assets. In addition, the choice of alternatives to coal is frequently not motivated by pure economics but is biased towards an electricity price and market design that favour gas-fuelled electricity. Since all sources of electricity have benefited at some point from such support, the question of the competitiveness of PV should be considered carefully. Hereunder, we will look at the key elements driving the competitiveness of PV solutions.

MODULE PRICES

The very first period of PV market development can be considered starting from the first prototypes to small-scale production leading to a total PV installed capacity of around 2 GW. During this first phase, price reductions corresponding to a learning rate of 20% were achieved: this allowed the total PV installed capacity to continue growing further. At that point, prices stabilized until the total capacity reached around 10 GW: this period is known as the time of low availability of polysilicon that maintained prices at a high level. Then, a third period started which is still the case today, beginning with the mass production of PV, especially in China. During this period ranging from 10 GW to current levels, significant economies of scale have led to a learning rate of 40% - the supply chain disruptions due to COVID having slowed it slightly. The present price drops due to overcapacity have compensated in part for the stable prices in the post-covid period. In a few years it will be possible to better evaluate the impact of the significant manufacturing capacity increases that occurred in 2023 and 2024.

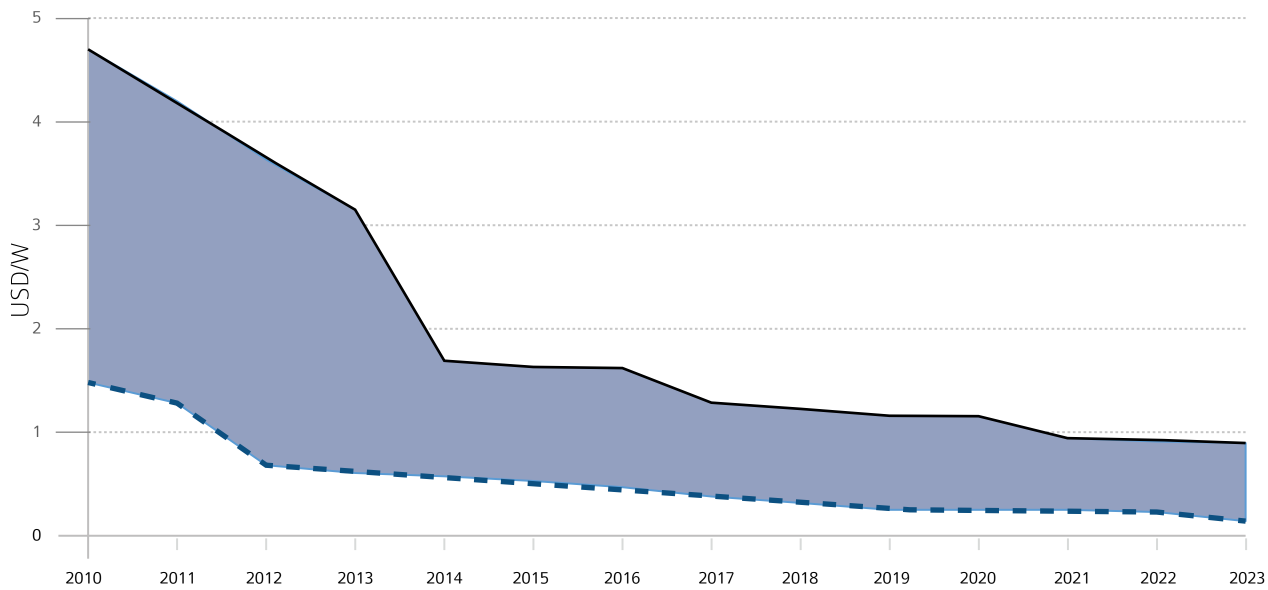
MODULE PRICES / CONTINUED

FIGURE 6.1: PV MODULES SPOT PRICES LEARNING CURVE (1992-2023)



SOURCE IEA PVPS & BECQUEREL INSTITUTE

FIGURE 6.2: EVOLUTION OF PV MODULE PRICES RANGE IN USD/W



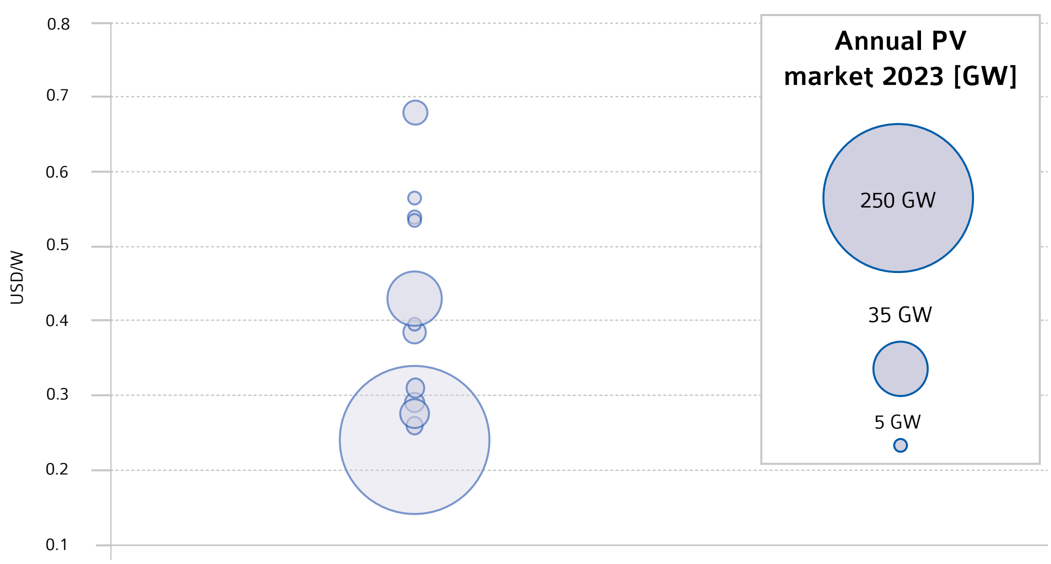
SOURCE IEA PVPS & OTHERS

On average, the price of PV modules in 2023 (shown in Figure 6.3) accounted for approximately 40% and 50% of the lowest achievable prices that have been reported for utility scale systems. In 2023, the lowest price of modules in the reporting countries was around 0.14 USD/W, significantly below anything ever seen before. This price is a direct consequence of the large volumes of manufacturing that came online in 2023, well above the market's capacity to absorb. Low as it was, prices continued to drop into 2024 and went under 0.10 USD/W.

Looking back to understand past and present price trends, the Chinese decision to strictly limit PV subsidies in May 2018 led to a new imbalance between production and demand, with dozens of GW of new production capacities added in 2017 and 2018 in all segments of the value chain while the global PV market was stagnating. The price decrease that followed accelerated some project development and can be considered at least partially responsible for the market growth in 2020. The year 2021 had seen the rise of multiple raw material prices. In particular, PV polysilicon average spot prices rose significantly during the year, up from around 10 USD/kg in early 2021. Other key raw materials such as PV glass, copper or aluminium maintained their high prices reached at the end of 2020 and the whole PV value chain was subject to increases in transportation costs. Costs and hence prices remained high through 2022, and manufacturers upgraded capacity through this time. By 2023 new manufacturing capacity was coming online as there was a polysilicon price drop that cascaded through to cells and modules, and with a surge in module availability, prices began to drop. By the end of 2023, and despite important efforts in China to stimulate the market enough to absorb the surge in manufacturing capacity, oversupply was impacting the module price for Chinese-made modules. The consequences of the policy decisions in the USA in years previous to the ramping up of manufacturing capacity meant the bulk of Chinese modules - that were not installed domestically - were exported to Europe. By late December 2023, mainstream modules had reached costs that analysts considered under manufacturing cost. Looking in depth at the revenues of some manufacturers among the most competitive, it appears that average sales are above these low prices. It can also be assumed that such prices are obtained with new production lines in which production costs are significantly lower than previously existing ones.

Higher module prices are still observed, specifically in the residential segment in countries with historically high prices such as Japan or France.

FIGURE 6.3: INDICATIVE MODULE PRICES IN SELECTED REPORTING COUNTRIES



SOURCE IEA PVPS & OTHERS

SYSTEM PRICES

Reported prices for PV systems vary widely and depend on a variety of factors including system size, location, customer type, connection to an electricity grid, technical specifications, and the extent to which end-user prices reflect the real costs of all the components. For more detailed information, the reader is directed to each country's national survey report on the IEA PVPS website (www.iea-pvps.org).

Figure 6.4 shows the range of system prices in the global PV market in 2023. It shows that around 75% of the PV market consists of prices below 1 USD/W. Large distributed PV systems start at around 0.70 USD/W while utility-scale PV saw prices as low as 0.42 USD/W. BIPV can be seen as a series of segments where the prices can significantly diverge. Off-grid applications suffer from a similar situation, with totally different cases illustrated at different prices. In general, the price range decreased from the previous year for all applications.

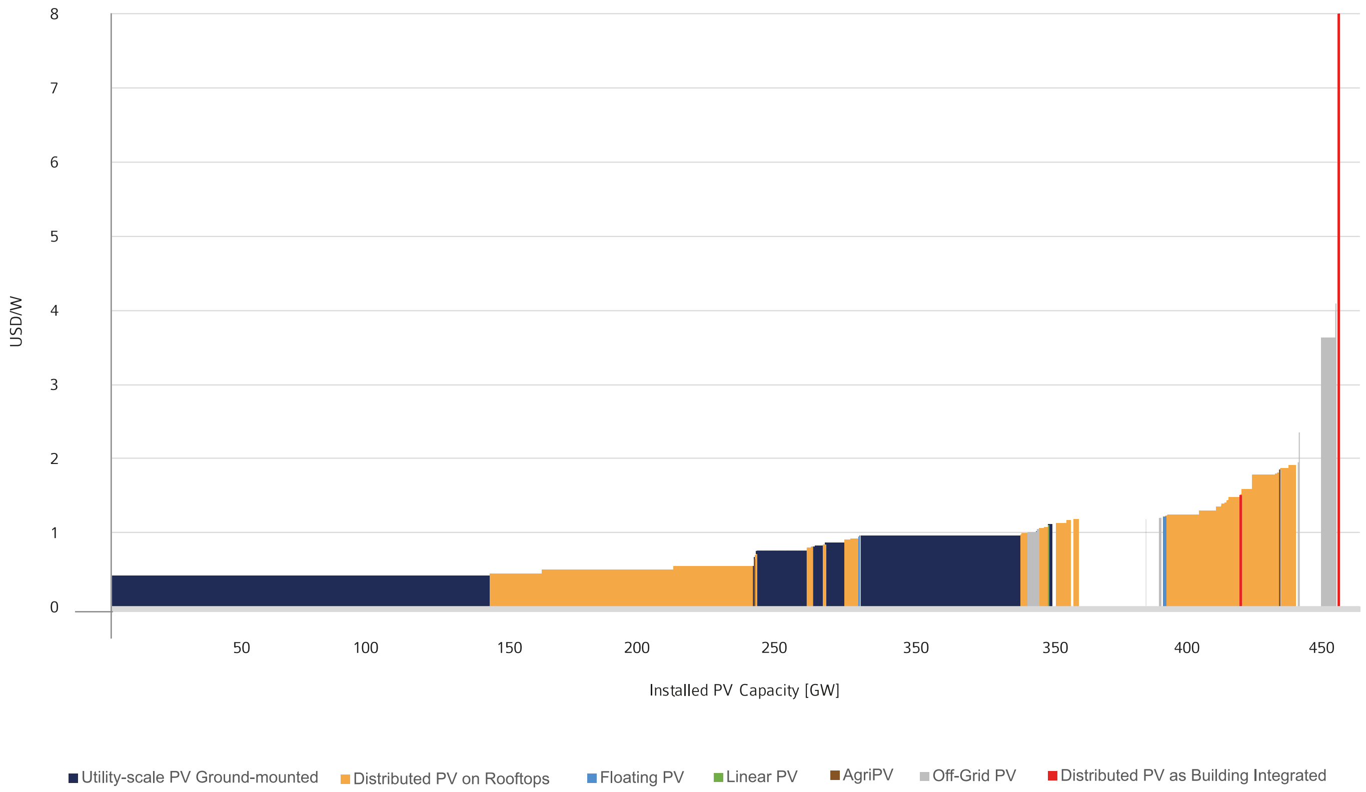
On average, system prices for the lowest-priced off-grid applications are significantly higher than for the lowest-priced grid-connected applications. This is mainly attributable to the relatively higher transport costs to access the sites. Indeed, large-scale off-grid systems are often installed in places far from the grid but also far from major towns and highways. Higher prices asked for such installations also depend on higher costs for the transport of components, and technicians, without even mentioning the higher costs of maintenance. In 2023, the lowest system prices in the off-grid sector, irrespective of the type of application, typically ranged from about 2 USD/W to 6 USD/W but prices for some specific applications can be higher. The large range of reported prices in Figure 6.5 is a function of the country and project-specific factors. The highest prices haven't been included in the figures given the very low level of installations: in general, off-grid prices have been averaged in the figures for readability reasons.

Four specific segments are developing that are likely to grow significantly in volume in countries with limited land. System prices in these segments can vary widely, both from local labour and material costs but also given the inherent constraints specific to the sites used.

- Floating PV – costs vary with anchoring for local weather, salinity, system size and grid connection.
- Linear PV systems along roads, trainline and canals – costs vary depending on size, electrical architecture and grid connection, and can be as low as ground mounted utility scale systems but tend to be higher.
- Parking canopies over commercial and industrial car parks – costs vary depending on the type of supports and system size, but are above ground mounted system costs.
- Agrivoltaics either in inter-row grazing or above crops – costs vary from as low as utility scale ground mounted systems when associated with grazing up to BIPV-level costs for specialised mobile systems above crops

More expensive grid-connected system prices are often associated with roof-integrated slates, tiles, building integrated designs or single bespoke projects: BIPV systems in general are considered more expensive when using dedicated components, however the drop in module prices is likely to impact some, but not all, BIPV products.

FIGURE 6.4: 2023 PV MARKET COSTS RANGES

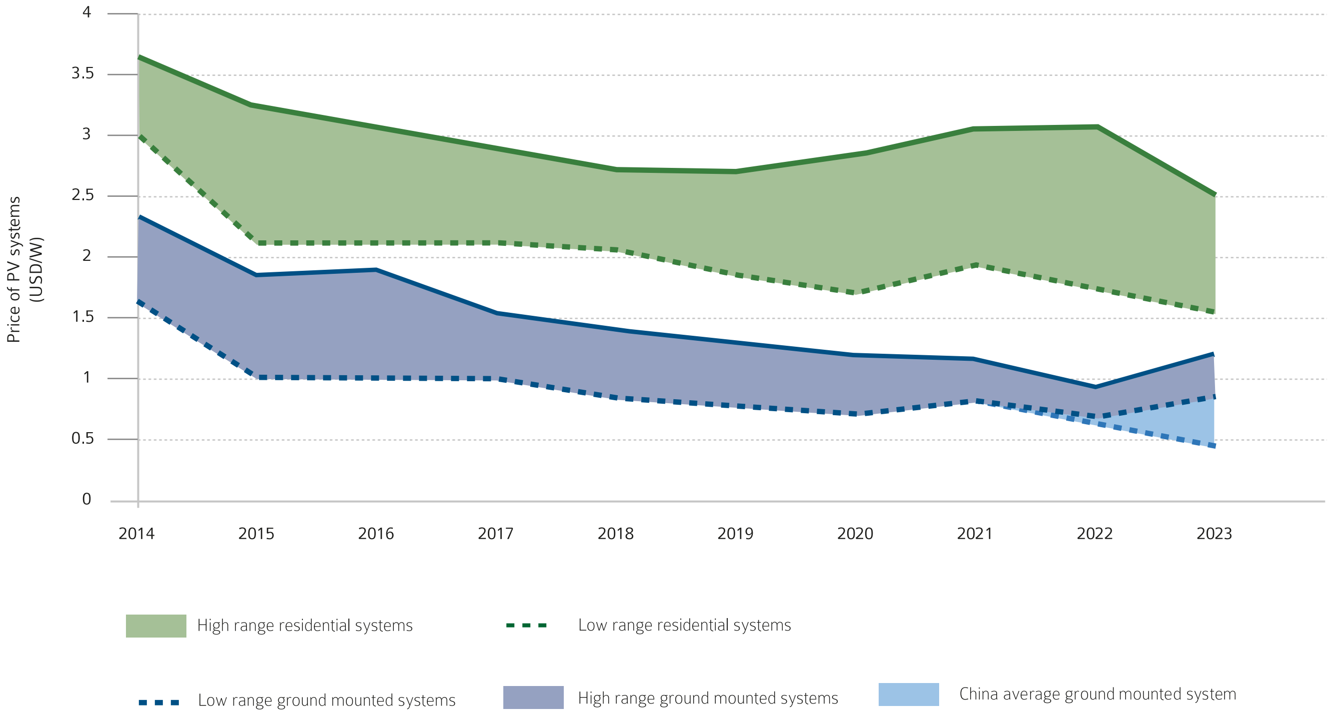


Note: Utility and distributed PV are distributed according to volumes and costs. Floating, Linear, AgriPV and Offgrid PV are indicative average maximum / minimum price points; the real costs are spread between these two points with outliers

SOURCE IEA PVPS 8 OTHERS

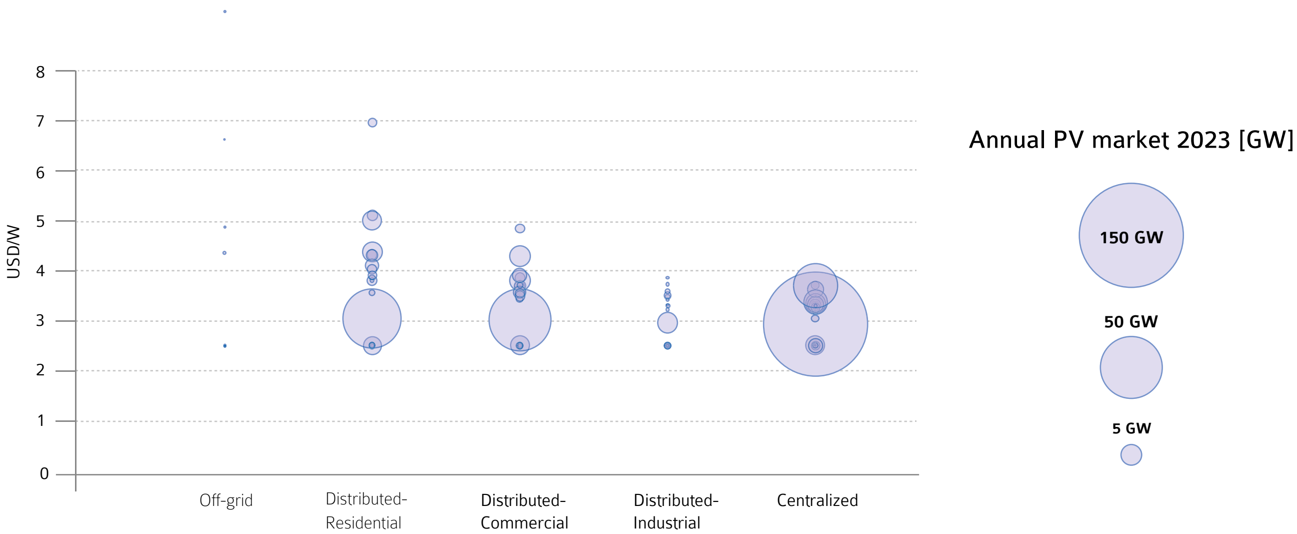
In 2023 residential PV systems price typically ranged from 0.78 USD/W to 2.6 USD/W (with costs in China below this and costs above this in Switzerland) while utility-scale PV systems prices typically ranged from 0.42 USD/W to 1.2 USD/W in 2023 according to the data collected – a wider range than in 2022, but expected given the module price drop between the beginning and end of the year. These typical price ranges give an overview of the market, but they don't consider the full range of prices practiced across the world – residential systems have, in reality, a much wider range depending on local contexts, with prices below this range depending on labour and administrative costs and the size of systems, and prices going above this range for systems using BIPV products, high end inverters and monitoring or simply scarce labour. Utility scale systems can also go beyond this, particularly on the bottom range, when project developers work aggressively to secure land or for particularly large systems.

FIGURE 6.5: EVOLUTION OF RESIDENTIAL AND GROUND MOUNTED SYSTEMS PRICE RANGE 2013 - 2023 (USD/W)



SOURCE IEA PVPS & OTHERS

FIGURE 6.6: INDICATIVE INSTALLED SYSTEM PRICES IN SELECTED IEA PVPS REPORTING COUNTRIES IN 2023



SOURCE IEA PVPS & OTHERS

The lowest achievable installed price of grid-connected systems in 2023 also varied between countries as shown in Figure 6.6. The average price of these systems is tied to the segment. Large grid-connected installations can have either lower system prices depending on the economies of scale achieved, or higher system prices where the nature of the building integration and installation, degree of innovation, learning costs in project management and the price of custom-made modules may be considered as quite significant factors. In summary, system prices for utility-scale PV mostly decreased by the end of 2023, following the trends of module prices and the balance of the system, while soft costs and margins remained stable, and interest rates rose. System prices below 0.6 USD/W for large-scale PV systems were common in very competitive tenders and in China. The question of the lowest CAPEX is not always representative of the lowest LCOE (Levelized Cost of Electricity): the case of utility-scale PV with trackers illustrates this, with additional CAPEX translating into a sgenerally lower LCOE.

Additional information about the systems and prices reported for most countries can be found in the various National Survey Reports.

COST OF PV ELECTRICITY

In order to compete in the electricity sector, PV technologies need to provide electricity at a cost equal to or below the cost of other technologies – unless other criteria are a determining factor. Obviously, power generation technologies are providing electricity at different costs, depending on their nature, the cost of fuel, the cost of maintenance and the number of operating hours during which they are delivering electricity.

The competitiveness of PV can be defined simply as the moment when, in a given situation, PV can produce electricity at a cheaper price than other sources of electricity that could have delivered electricity at the same time. Therefore, the competitiveness of a PV system is linked to the location, the technology, the cost of capital, and the cost of the PV system itself, which highly depends on the nature of the installation and its size. However, it will also depend on the environment in which the system will operate. Off-grid applications in competition with diesel-based generation will not be competitive at the same moment as a large utility-scale PV installation competing with the wholesale prices on electricity markets. In sum, the competitiveness of PV is connected to the type of PV system and its environment.

GRID PARITY

Grid Parity (or Socket Parity) refers to the moment when PV can produce electricity (the Levelized Cost of Electricity or LCOE) at a price below the price of electricity bought from the grid. While this is valid for pure players (the so-called "grid price" refers to the price of electricity on the market), this is based on two assumptions for prosumers (producers who are also consumers of electricity):

- That PV electricity can be consumed locally (either in real-time or through some compensation scheme such as local or delocalized net metering);
- That all the components of the retail price of electricity can be compensated when it has been produced by PV and locally consumed.

Technical solutions can be used to increases the self-consumption level (demand-side management including EV charging or direct use to heat water with heat pumps, local electricity storage, reduction of the PV system size, delocalized self-consumption, energy communities, etc.).

If only a part of the electricity produced can be self-consumed, even after actioning levers for increased self-consumption, as mentioned above, then the remaining part must be injected into the grid and should generate revenues of the same order as, at least, any centralized production of electricity. Today this is often guaranteed for small size installations by the possibility of receiving a FiT (or similar) for the injected electricity through net billing schemes. However, when grids are under strain, when local or regional generation exceeds demand, it is possible that excess electricity either cannot be injected into the grid (i.e. must be curtailed) or will not be financially compensated – as may soon be the case in parts of Australia, Austria, USA, amongst other countries experiencing grid constraints in the residential and commercial sectors.

The price paid for electricity by consumers is composed in general of four main components:

- The procurement price of electricity, on electricity markets plus the margins of the reseller;
- Grid costs and fees, partially linked to the consumption, partially fixed; the key challenge is their future evolution;
- Taxes;
- Levies (used among other things to finance the incentives for some renewable sources, social programmes, solidarity between regions etc.);

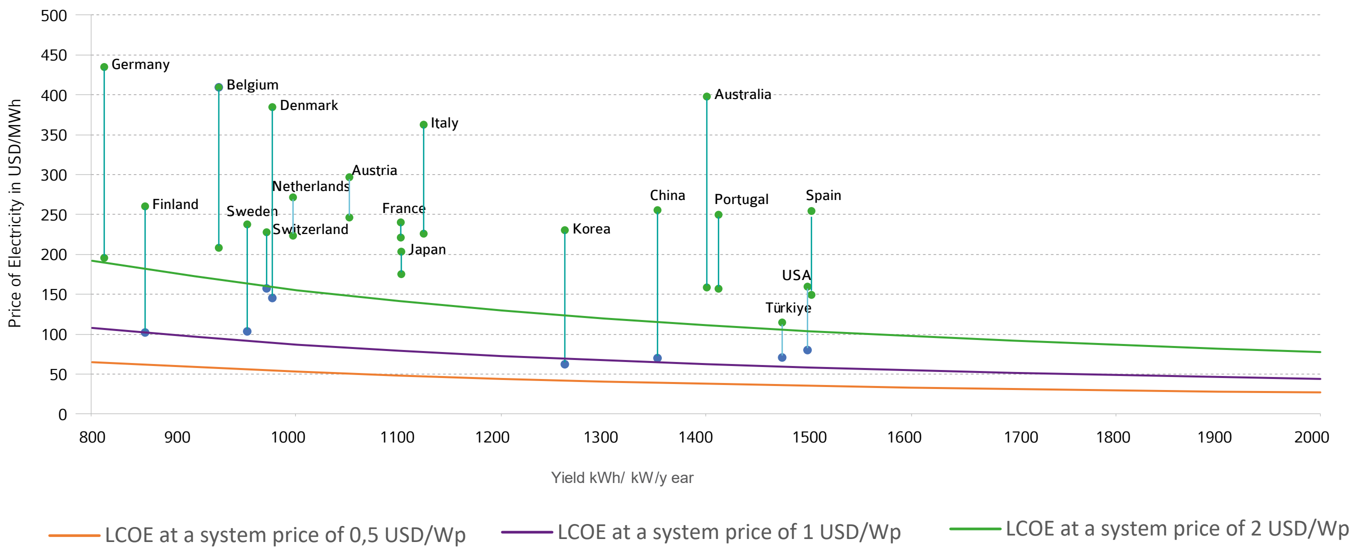
If the electricity procurement price can be compensated, the two other components require considering the system impact of such

COST OF PV ELECTRICITY / CONTINUED

measures: with tax loss on one side and the lack of financing of distribution and transmission grids on the other. While the debate on taxes can be simple, since PV installations are generating taxes as well, the one on grid financing is more complex. Even if self-consumed electricity could be fully compensated, alternative ways to finance the grid should be considered given the loss of revenues for grid operators - or a better understanding of PV positive impacts on the grid should be achieved.

Any support or compensation measures for the excess electricity after self-consumption should take into account these last elements and the question of equitable and ethical sharing of the cost burden for grids and supports schemes should become an increasingly important subject as PV penetration rates increase.

FIGURE 6.7: LCOE OF PV ELECTRICITY AS A FUNCTION OF SOLAR IRRADIANCE & RETAIL PRICES IN KEY MARKETS*



*NOTE: THE COUNTRY YIELD (SOLAR IRRDIANCE) HERE SHOWN MUST BE CONSIDERED AS AN AVERAGE

SOURCE IEA PVPS & OTHERS

THE LOWEST ELECTRICITY PRICES (RESPECTIVELY THE HIGHEST) DISPLAYED PER COUNTRY SHOULD BE SEEN AS AN AVERAGE VALUE FOR INDUSTRIAL CONSUMERS (RESPECTIVELY RESIDENTIAL CONSUMERS).

Figure 6.7 shows the range of retail prices in selected countries based on their average solar resource and the indicative PV electricity threshold for three different system prices (0.5, 1 and 2 USD/W, converted into LCOE). Green dots are cases where PV is competitive in most of the cases. Blue dots show where it really depends on the system prices and the retail prices of electricity.

The figure demonstrates how grid parity had been reached in most IEA PVPS countries through late 2022 and 2023, and how rising electricity costs and dropping PV costs are paving the way for more countries becoming competitive for PV. In this figure, the lower range of electricity prices is, with the exception of France, Türkiye for commercial and industrial consumer, whilst the higher is for residential customers. In 2022, retail and commercial/industrial electricity prices rose quite steeply in most countries, increasing the competitiveness of PV – and whilst in many countries, particularly in the EU, commercial electricity prices dropped slowly through 2023 and again in 2024, the drop in module prices means that competitiveness is here to stay.

In some specific segments, determining the competitiveness of a PV system is not just dependent on the system or electricity costs, but also on other avoided costs, as for BIPV, for example. The specific case of BIPV consists, for new or renovated roofs, to assess the competitiveness for the BIPV solution minus the costs of the traditional roofing (or façade) elements. The rest of the assessment is similar to any building under self-consumption using a standard BAPV solution. Of course, if the BIPV solution has to be installed on a building outside of any planned works, this doesn't apply. Metrics used for buildings can also be different, since the integration of PV components might be justified by non-economic factors or the perspective of an added value. For such reasons, BIPV competitiveness is in general assessed against the traditional building costs.

COMPETITIVENESS OF PV ELECTRICITY WITH WHOLESALE ELECTRICITY PRICES

In countries with an electricity market, wholesale electricity prices when PV produces are one benchmark of PV competitiveness. These prices depend on the market organisation and the technology mix used to generate electricity. In order to be competitive with these prices, PV electricity has to be generated at the lowest possible price. This is already achieved with large utility-scale PV installations that allow reaching the lowest system prices today especially when they come with low maintenance costs and a low cost of capital – although interest rates rose around the world in 2023, increasing the cost of capital. An increasing number of countries have had utility scale systems commissioned that sell directly on the market – including Croatia, Italy, Germany, Norway, Sweden, Portugal, Romania, Philippines, Spain, Australia and the USA; indeed, in these last three countries it is increasingly becoming a common option.

Energy-only markets are also likely to be soon completemented by grid services that could add additional revenues.

These types of business models, exposed to the market, remain riskier than conventional ones that guarantee prices paid to the producer over 15 years or more. The key risk associated with such business models lies in the evolution of wholesale market prices on the long term and the potential effects of what is known as price cannibalisation: large volumes of PV generated electricity reduce market prices during the midday peak when penetration becomes significant. However, with high penetration rates and the shift to electricity for transport and heating, it is unclear if price cannibalisation will be a real issue or not - either prices during PV production peaks will drop and impair the ability to remunerate investments, or low prices will attract additional electricity demand and will stabilise the market prices. At this point, both options remain possible. When a wholesale market doesn't exist as such, (in China for instance), the comparison point is the production cost of electricity from coal-fired power plants.

FUEL-PARITY AND OFF-GRID SYSTEMS

Off-grid systems including hybrid PV/diesel can be considered competitive when PV can provide electricity at a cheaper cost than the conventional generator. For some off-grid applications, the cost of the battery bank and the charge controller should be considered in the upfront and maintenance costs while a hybrid system will consider the cost of fuel saved by the PV system.

The point at which PV competitiveness will be reached for these hybrid systems takes into account fuel savings due to the reduction of operating hours of the generator. Fuel-parity refers to the moment in time when the installation of a PV system can be financed with fuel savings only. It is assumed that PV has reached fuel-parity, based on fuel prices, in numerous Sunbelt countries.

Other off-grid systems are often not replacing existing generation sources but providing electricity in places with no network and no or little use of diesel generators. They represent a completely new way to provide electricity to hundreds of millions of people all over the world.

PRODUCING COMPETITIVE GREEN HYDROGEN AND OTHER MOLECULES WITH PV

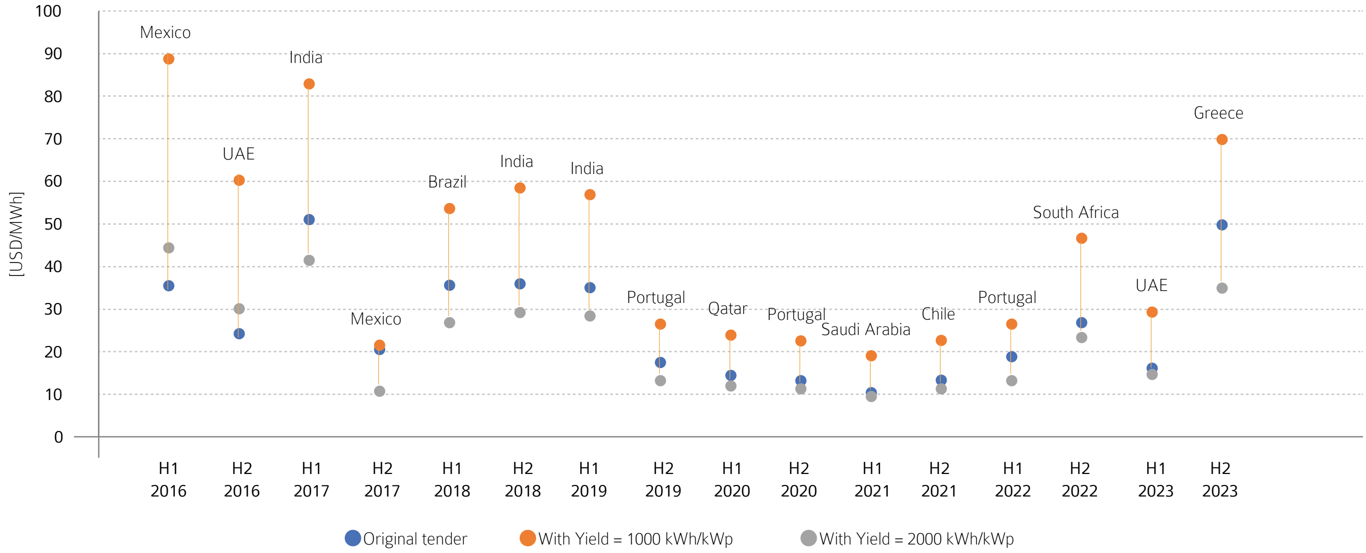
The declining cost of PV electricity opens the door for other applications such as green hydrogen and/or ammonia directly from PV (possibly in combination with wind). The cost of electrolysers is also decreasing as commissioned volumes of electrolysers increases; however, despite the increased gas prices after the war in Ukraine, competitiveness with "black" hydrogen is still only on the horizon and is not yet a reality. Different uses for hydrogen - industrial applications, transport, agriculture (through ammonia) - are expected to create a tremendous opportunity for PV to produce hydrogen without being connected to the grid.

Large projects have been announced around the world with several commissioned already including two systems in China with 150 MW / 300 MW of PV and a smaller project in Japan. The business model is being explored in a wide range of countries, with increasingly large multi-GW scale projects in preliminary phases across Australia, the USA, Brazil and Africa (Mauritania) and the Middle East (Oman, Egypt) - countries where high irradiance and low land costs are expected to allow for competitive conditions.

COST OF PV ELECTRICITY / CONTINUED

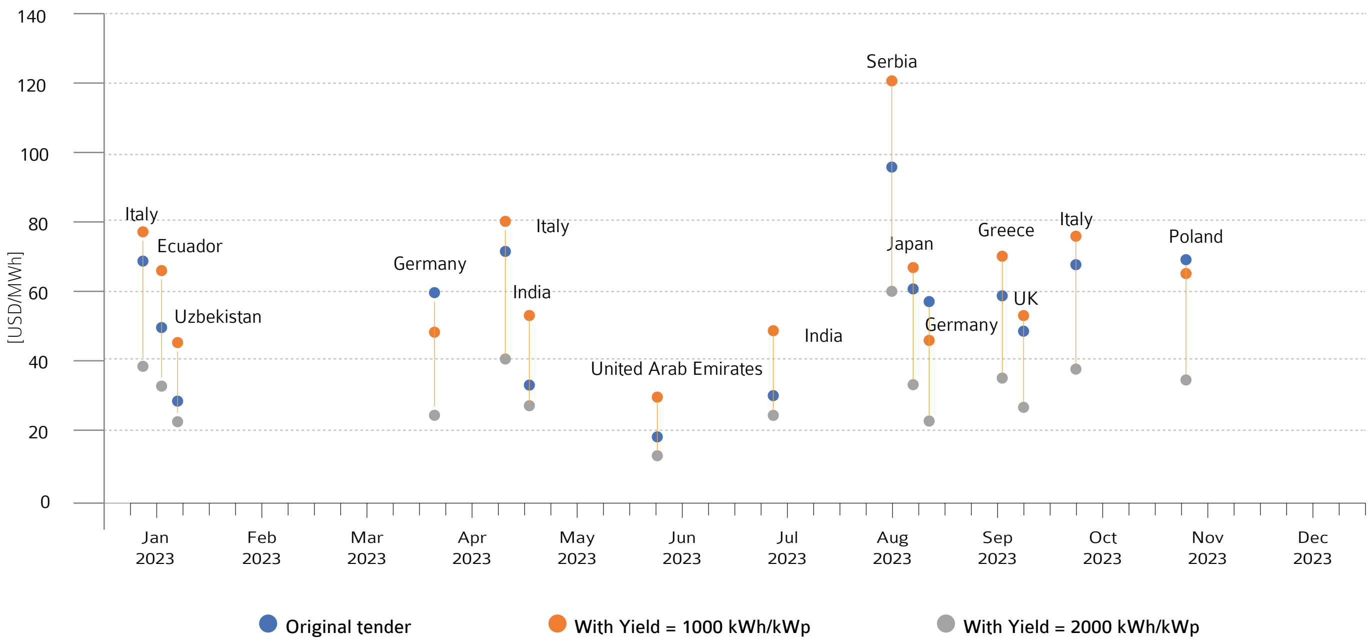
LOW TENDERS PRICES

FIGURE 6.8A: NORMALISED LCOE FOR SOLAR PV BASED ON LOWEST PPA PRICES 2016 - Q4 2023



SOURCE IEA PVPS & OTHERS

FIGURE 6.8B: NORMALISED LCOE FOR SOLAR PV BASED ON RECENT PPA PRICES 2023



SOURCE IEA PVPS & OTHERS

With many countries having adopted tenders as a way to allocate PPAs to PV projects, the value of these PPAs achieved record low levels in 2020 and some low prices in 2021 as well. In 2022 and 2023, because of the higher electricity market prices (Europe, USA, Australia) PPA's were negotiated at higher prices too. The high level of certainty when it comes to solar generation levels and operating costs has become attractive on markets where many industrial and commercial consumers were significantly impacted by the volatile electricity market prices of late 2022 and early 2023. It is increasingly worth paying a slight premium for the price stability. In parallel, solar is an increasingly attractive option for companies investing in renewable energy for renewable energy targets and corporate social responsibility goals such as the RE100 initiative.

Solar PPA prices seen in 2023 ranged from about 20 USD/MWh to 100 USD/MWh – a slightly wider range than in 2022, with a clear difference in regional evolution; they increased quarter on quarter through 2022 in Europe and the USA, and either stabilised or slightly decreased in 2023 (in Europe) whereas they continued to increase through 2023 in the USA. Whilst in the past most solar PPA's were for new and to be developed systems, in the coming years they will be for existing capacity reaching the end of current contracts under support mechanisms or initial PPA's.

COST OF PV ELECTRICITY / CONTINUED

TABLE 6.1: TOP 10 LOWEST WINNING BIDS IN PV TENDERS FOR UTILTY SCALE PV SYSTEM

REGION	CONTRY/STATE	USD/MWH	YEAR
MIDDLE EAST	SAUDI ARABIA	10.40	2021
EUROPE	PORTUGAL	13.20	2020
LATIN AMERICA	CHILE	13.32	2021
MIDDLE EAST	UNITED ARAB EMIRATES	13.53	2020
MIDDLE EAST	QATAR	14.49	2020
MIDDLE EAST	SAUDI ARABIA	14.80	2021
EUROPE	SPAIN	14.98	2021
EUROPE	PORTUGAL	16.02	2019
MIDDLE EAST	UNITED ARAB EMIRATES	16.20	2023
LATIN AMERICA	BRAZIL	17.50	2019

SOURCE IEA PVPS & OTHERS

TABLE 6.2: LOWEST WINNING BIDS IN PV TENDERS FOR UTILTY SCALE PV SYSTEM PER REGION

REGION	CONTRY/STATE	USD/MWH	YEAR
ASIA	UZBEKISTAN	17.9	2021
AFRICA	TUNISIA	24.4	2019
EUROPE	PORTUGAL	13.2	2020
LATIN AMERICA	CHILE	13.3	2021
MIDDLE EAST	SAUDI ARABIA	10.4	2021
NORTH AMERICA	MEXICO	20.6	2017

SOURCE IEA PVPS & OTHERS

seven

PV IN THE ENERGY SECTOR

PV ELECTRICITY PRODUCTION

TRACKING OF PV INSTALLED CAPACITY

Tracking PV installations in all the regions of the world can be challenging as many countries do not accurately keep track of the PV systems installed or do not make the data publicly available. Data published by IEA PVPS reports on new annual installed capacity and total cumulative installed capacity and is based on official data in reporting countries. For the purposes of this report, when individual countries do not publish any reporting data, estimated volumes have been made based on trade data (import volumes), and adjusted to take into account the delays between importing volumes and installation and commissioning.

Depending on reporting practices, cumulative capacity (the sum of new annual capacity) may outstrip operating capacity as systems are decommissioned. Repowered capacities not only replace some decommissioned capacity but also generally increase operational capacity, as the repowered capacity is higher than the initial plant capacity due to PV module efficiency improvements.

There is no standardised reporting on these subjects across IEA PVPS countries. Several countries already incorporate decommissioning of PV plants in their total capacity numbers by reducing the total cumulative number. Other countries report capacity in operation for that year, and do not include repowered volumes in new annual capacity or decommissioned volumes in operational capacity. Many countries do not track decommissioning or repowering with any consistency.

Repowering is still relatively unusual given the age of the oldest installations, but it is expected to increase in the near future - serial defects with backsheets manufactured in the period 2009 – 2011 is a good example, as the past 3 years have seen several hundred MW replaced. Module capacity that has been used to repower systems with defective or underperforming modules will appear in shipped volumes but not necessarily in new annual installations. Real decommissioning is expected to be rare, as land usage constraints and cheaper PV on buildings encourages repowering. Recycling numbers can provide a glimpse of what is happening with regards to repowering and decommissioning in countries where recycling schemes are active, however recycling volumes are underestimating decommissioning due to an active (and sometimes barely legal) second-hand market, especially towards Africa; also, reporting is often in tonnage and the availability of data must be improved before it can be used more generally.

IEA PVPS is following the dynamic evolution of decommissioning, repowering and recycling closely, however giving numbered estimates is not possible yet, so the expected impact on the installed capacity, market projections for repowering and the decline in PV performances due to ageing PV systems is not quantified.

ESTIMATING PV PRODUCTION

Estimating PV electricity production is easy to measure at a power plant but much more complicated to compile for an entire country. Not only the installed capacity must be accurately tracked, which requires an effective and consistent approach (especially for distributed, self-consumption and off-grid segments), but also, electricity production is impossible to accurately estimate from installed PV capacity for a given year, because estimations are based on the installed capacity without knowledge of when, during the year, that capacity was installed. A system installed at the end

PV ELECTRICITY PRODUCTION / CONTINUED

of the year will have produced only a small fraction of its theoretical annual electricity output.

Additionally, estimates are based on a theoretical annual production, and do not take into account different performance levels based on azimuth and inclination or even other factors such as system ventilation or shading., A system installed west facing will generate less over the year than one installed facing the equator. Performance losses due to aging of PV plants are not considered at this point. Some plants may have experienced production issues, due to technical problems or external constraints.

For these reasons, the electricity production from PV per country in this report is an estimate of what the minimal theoretical production should be the following year, when all the PV systems installed at the end of the year have generated electricity for one year.

To calculate this "next year's minimal theoretical PV production", an average solar yield in the country is used. Depending on the country, this value is either provided through National Survey Reports and is calculated as the total solar generation divided by total solar capacity, or is a representative value taken from geographical irradiance atlases – these yields are an approximation of the reality.

Nationally produced statistics on solar generation will in general reflect real production injected into the grid – consequently, in years with high new capacity additions, the theoretical value used here can be well above official statistics for the current year – and well below that of the next year. The real PV production in a country is increasingly difficult to assess even if tracked by transmission system operators (TSO's), as more and more volumes of generation are self-consumed (i.e. not metered) and storage enters into consideration, increasing self-consumption levels or curtailing generation to fit storage. IEA PVPS advocates for governments and energy stakeholders, including grid operators to create accurate databases and precisely measure PV production.

PV PENETRATION

PV electricity penetration can be three different indicators – either the installed capacity per capita, as seen in Chapter 2; or, as used here, the share of electricity cconsumption (or demand) or electricity production supplied by PV generation. Here it is the ratio between PV electricity production in a country and the electricity demand in that country and is expressed as a percentage. It is based on the theoretical electricity production from PV per country, calculated as indicated in the section above. Electricity demand is obtained via publicly available databases and via the IEA PVPS experts; when possible, it has been adjusted to consider self-consumption volumes.

The PV penetration rates here are an estimate and are likely to differ from official PV production and penetration numbers in many countries for the reasons detailed above - they should be considered as indicative, providing a reliable estimation for comparison between countries and do not replace official data.

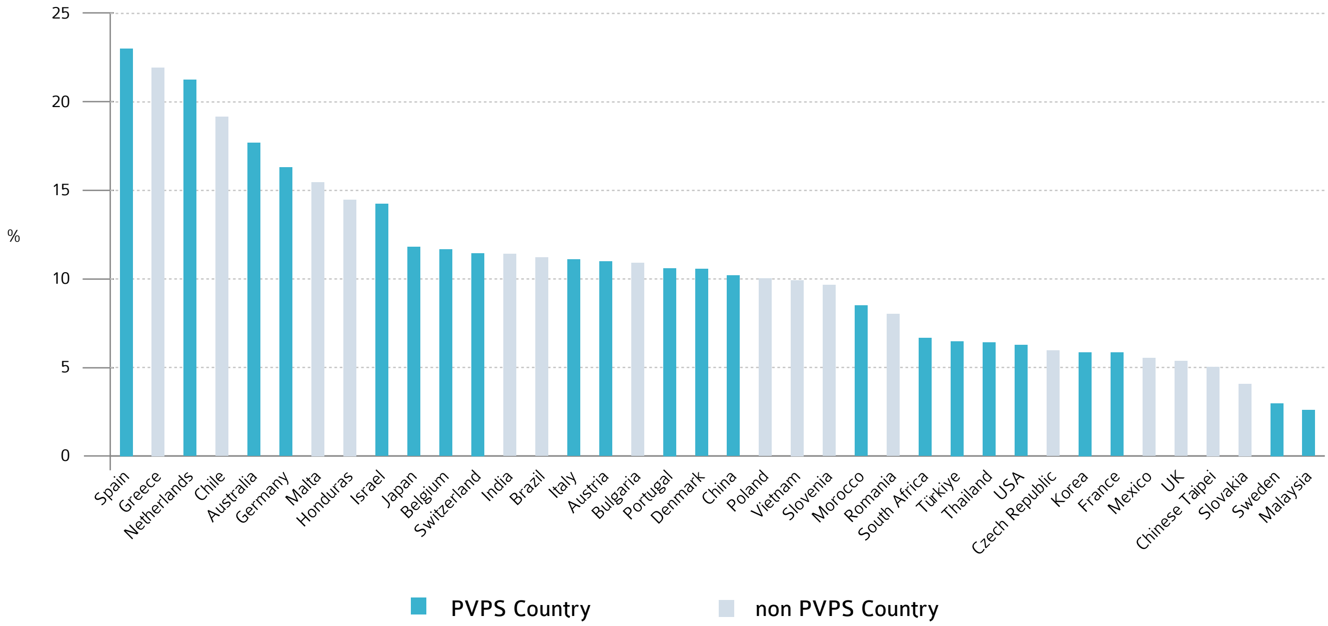
The PV penetration rate calculated based on electricity consumption will tend to be several points higher than when calculated based on electricity production, as losses from transport and transformation of centralised (fossil fuel) electricity generation have not yet been factored in.

To illustrate this divergence, the national TSO reported on production data in France, and gave the PV penetration at 5% for 2023, just above last year's IEA PVPS estimation of 4.9% but under estimations for this report at 5.8%. In Spain the TSO reported it as 14% for 2023, well below our estimated 19.7% last year and 22.3% this year. The difference from Spain is due to the fact that the TSO does not take into consideration the large volume of distributed PV in Spain – consequently, the divergence is expected.

Of the 41 IEA PVPS and non-IEA PVPS countries studied, all but one (Norway) produced at least 1% of their electricity demand from PV in 2023 – and 10 should be producing more than 10% next year.

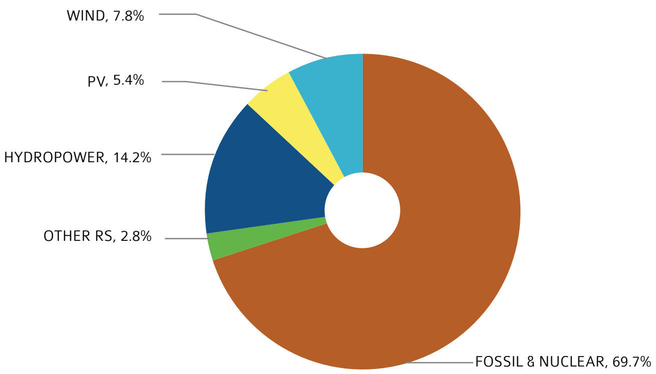
Concerning global PV penetration, with around 1 642.0 GW installed worldwide, PV could produce almost 2 136 TWh (see Table 7.1) of electricity on a yearly basis if an average yield of 1300kWh/kWp is considered. This represents around 8.3% of the global electricity demand covered by PV, up 2.1% on 2022 – with a wide range of differing contributions from one country to another, as demonstrated in Figure 7.1.

FIGURE 7.1: PV CONTRIBUTION TO ELECTRICITY DEMAND 2023



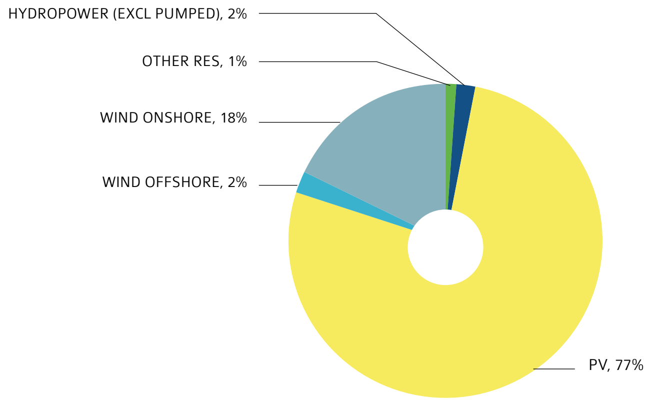
SOURCE IEA PVPS & OTHERS

FIGURE 7.2: SHARE OF RENEWABLE IN THE GLOBAL ELECTRICITY PRODUCTION IN 2023



SOURCE REN21, IEA PVPS

FIGURE 7.3: NEW RENEWABLE INSTALLED CAPACITY IN 2023



SOURCE REN21, "GWEC, IHA, IEA PVPS

PV ELECTRICITY PRODUCTION / CONTINUED

TABLE 7.1: 2023 PV ELECTRICITY STATISTICS IN IEA PVPS COUNTRIES

COUNTRY	FINAL ELECTRICITY ONSUMPTION 2023	HABITANTS 2023	GDP 2023	SURFACE	AVERAGE YIELD	PV ANNUAL INSTALLED CAPACITY 2023	PV CUMULATIVE INSTALLED CAPACITY 2023	PV ELECTRICITY PRODUCTION	ANNUAL CAPACITY PER CAPITA	CUMULATIVE CAPACITY PER CAPITA	CUMULATIVE CAPACITY PER KM2	THEORETICAL PV PENETRATION
	TWH	MILLION	BUSD	KM2	KWH/KWP	MW	MW	TWH	W/CAP	W/CAP	KW/KM2	%
AUSTRALIA	273	27	1 724	7 690 000	1 400	4 153	34 522	48	156	1 296	4	17.7%
AUSTRIA	61	9	516	83 883	1 050	2 603	6 395	7	285	700	76	11.0%
BELGIUM	79	12	632	30 688	925	1 806	9 955	9	153	842	324	11.7%
CANADA	598	40	2 140	9 985 000	1 150	823	7 340	8	21	183	1	1.4%
CHINA	9 150	1 411	17 795	9 634 000	1 350	277 176	691 241	933	196	490	72	10.2%
DENMARK	36	6	404	44 000	975	487	3 910	4	82	658	89	10.6%
FINLAND	80	6	300	338 432	850	318	1 008	1	57	181	3	1.1%
FRANCE	446	68	3 031	551 500	1 100	3 961	23 664	26	58	347	43	5.8%
GERMANY	408	84	4 456	357 588	808	15 005	82 305	67	178	974	230	16.3%
ISRAEL	71	10	510	20 770	1 797	1 150	5 657	10	118	580	272	14.2%
ITALY	306	59	2 255	302 070	1 122	5 255	30 319	34	89	516	100	11.1%
JAPAN	851	125	4 213	377 975	1 100	6 300	91 366	101	51	734	242	11.8%
SOUTH KOREA	594	52	1 713	100 401	1 261	3 306	27 619	35	64	534	275	5.9%
MALAYSIA	171	34	400	330 621	1 314	2 956	3 390	4	21	99	10	2.6%
MOROCCO	35	38	141	710 850	1 750	728	1 714	3	19	45	2	8.5%
NETHERLANDS	108	18	1 118	41 500	994	4 788	23 037	23	268	1 288	555	21.3%
NORWAY	126	6	486	323 806	760	303	657	0	55	119	2	0.4%
PORTUGAL	51	11	287	92 225	1 407	1 285	3 822	5	122	363	41	10.6%
SPAIN	254	48	1 581	505 990	1 500	8 987	38 986	58	186	806	77	23.0%
SWEDEN	135	11	593	410 000	950	1 688	4 215	4	160	400	10	3.0%
SWITZERLAND	54	9	885	41 285	970	1 641	6 375	W	185	720	154	11.5%
SOUTH AFRICA	195	60	378	1 219 090	1 733	2 965	7 504	13	49	124	6	6.7%
THAILAND	214	72	515	1 219 092	1 522	4 587	9 002	14	64	125	7	6.4%
TÜRKIYE	327	85	1 108	783 560	1 471	1 867	14 393	21	22	169	18	6.5%
USA	4 252	335	27 361	9 147 282	1 500	33 884	177 344	266	101	530	19	6.3%
IEA PVPS	**18 874**	**2 634**	**74 541**	**44 341 608**	**1 300**	**385 766**	**1 305 739**	**1 701**	**146**	**496**	**29**	**9.0%**
BRAZIL	508	216	2 174	30 530	1 506	12 446	37 817	57	58	175	1 239	11.2%
INDIA	1 320	1 429	3 550	357 172	1 625	13 020	92 645	151	9	65	259	11.4%
NON IEA PVPS	6 884	5 391	30 894	89 983 827	1 300	70 244	336 218	433	13	62	4	6.3%
WORLD	**25 758**	**8 025**	**105 435**	**134 325 435**	**1 300**	**456 010**	**1 641 956**	**2 135**	**57**	**205**	**12**	**8.3%**

SOURCE IEA PVPS 8 OTHERS

Renewable energies contributed more than 30% to global electricity production in 2023, up 0.4% on 2022. Whilst a significant part of new capacity was solar, (around 75%), with a lower capacity factor than wind or hydro power and a year with excellent wind in several large wind markets, its actual share in annual electricity generation decerased slightly to approximatly 5.5%.

PV INTEGRATION AND SECTOR COUPLING

THE ENERGY STORAGE MARKET

Energy storage can take different forms – when coupled with PV, the most common are batteries in standalone systems, generally found in residential systems far from the grid, however distributed residential batteries are increasingly used to improve self-consumption rates, whilst batteries are used to keep microgrids stable, providing both services and energy, and grid-scale batteries are slowly being deployed to provide system services.

In general, distributed battery storage is seen as an opportunity to solve grid integration issues linked to PV and to increase the self-consumption ratio of distributed PV plants to improve the payback time of PV systems. Despite their decreasing costs, such solutions are not yet economically viable in all countries and market segments – with some stand out countries such as Australia, China, Germany, Italy, and certain states in the USA. Around the world, the adoption of batteries is on the rise both in the residential segments and in the commercial segments as more and more consumers are willing to maximise their self-consumption and to optimize their consumption profile. In some countries, this is encouraged to relieve grid congestion or peak loads, either through subsidies (Australia, Austria, China, Spain, Japan, United States) or the terms attached to self-consumption policies such as time-of-use net billing and/or regulations on new building construction (both notably in use in California in the USA).

More large-scale PV plants are being built in combination with grid-scale batteries, which can be used to stabilize grid injection, reduce curtailment, and, in some cases, to provide ancillary services to the grid such as fast response voltage stability or peak power surges. New requirements for grid integration in tenders tend to favour the use of stationary batteries in utility-scale plants to smooth the output of the plant, reduce curtailment or reduce the need for grid capacity reinforcement, however this trend would require some more years to be confirmed.

Independently of PV systems, an increasing number of utility scale batteries are being installed around the world and their system size is increasing each year. The largest markets for utility scale batteries were China, USA, Europe (UK, Italy), Australia but also Japan and South Korea. In most of the markets, battery project developers are also developers of solar projects or energy majors. These grid-scale batteries provide services that would otherwise have been provided by turbine-based generation (coal, gas or hydro power), enabling higher PV penetration rates and a faster energy transition.

Globally, the largest part of batteries sold are used for transportation in EVs and stationary storage remains the exception with smaller volumes. However, the rapid development of electric mobility is driving battery prices down much faster than any could have expected in the stationary market alone, and is making storage increasingly an economically viable tool for increasing PV penetration rates.

THE ELECTRIFICATION OF TRANSPORT

The electrification of transport continues to advance around the world in parallel to the growth of solar. Charging EVs during peak load implies rethinking power generation, grid management and smart metering, and concepts such as virtual self-consumption could provide a framework for EVs as mobile storage for excess PV generation. In parallel, the use of transport infrastructure to support PV is opening up possibilities for future direct injection to transport networks (rail, tram) or for supplying vehicle charging stations (car ports and parking canopies, noise barriers).

THE ELECTRIFICATION OF HEATING AND COOLING

With the development of self-consumption, grid congestion and the need for peak shaving to relieve grid instability, the use of PV led heating and cooling is becoming increasingly common.

Heating with PV is mainly used to heat domestic hot water, as a way of increasing self-consumption, whether it be in response

From PV to VIPV and VAPV

With its distributed nature, PV fits perfectly with EV charging during the day when cars are stationed in commercial and office parking or at home. Such slow charging is also highly compatible with distribution grid constraints. Finally, the integration of PV in the vehicles themselves (VIPV), also offers opportunities to alleviate the burden on the grid, increase the autonomy of EVs, provide greater driver comfort and connects the automotive and PV sectors. The IEA PVPS Task 17 deals with this fast-emerging subject.

PV INTEGRATION AND SECTOR COUPLING / CONTINUED

to electricity consumption costs or grid capacity and congestion problems. Domestic hot water manufacturers now integrate devices to directly link extra PV production to the electric boiler. Specific recommendations exist for connection and metering of storage systems in Switzerland for instance.

In hot climates such as Australia, China, Japan, as well as the states of Florida and California (USA), PV has already been used to provide electricity for cooling for several years. However, as climate change intensifies and electricity costs go up whilst grid infrastructure becomes more fragile to heatwaves, the use of PV at the point of consumption to reduce grid loads whilst cooling needs are high is becoming more and more necessary. The electrification of heating and cooling through the increasing use of heat pumps will also increase demand for PV at the point of consumption.

For larger coupling, no real commercial products seem available. Nevertheless, designs of solar PV systems based on self-consumption are linked to some specific uses, for example of adapted water chillers including cold water storage. Commercial companies that intensively use cooling (especially in the food chain), and supermarkets are increasingly turning to PV installations on their buildings to reduce the electricity load of refrigerating units.

The use of solar energy (PV or thermal) for cooling is the subject of the IEA SHC Task 65 (https://task65.iea-shc.org/) that concluded in June 2024, which focused on innovative ways to adapt and develop existing technologies (solar and heat pumps) for sunny and hot climates.

GREEN HYDROGEN AND HYDROGEN DERIVATIVES

Green hydrogen refers to hydrogen produced from renewable sources, as opposed to hydrogen produced from fossil fuels or nuclear power. Hydrogen (or its derivatives such as ammonia) is increasingly seen as a partial answer to decarbonize some sectors such as heavy industry, agriculture, the maritime sector and long distance, heavy weight road transport. Early industrialization projects around the creation of green hydrogen (or other molecules) continue to be funded each year. Hydrogen, or its derivatives, produced by competitive PV can also be stored and used to produce electricity later, even if the overall efficiency decreases significantly. It is seen as a way of increasing PV capacity to supply electricity grids when there is a need, but also to store excess production when grid needs are lower, even if technological challenges remain. A number of very large PV projects are in the planning stages to power hydrogen electrolysers, particularly in the Middle East, China and Australia (see chapter 3 for policy developments and chapter 6).

ANNEXES

ANNEXE 1: CUMULATIVE INSTALLED PV CAPACITY (MWP) FROM 1992 TO 2023

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
AUSTRALIA	7	9	11	13	16	19	23	25	29	34	39	46	52	61	70	82	105	187	571	1 376	2 416	3 226	4 092	5 109	5 985	7 132	11 586	16 399	21 091	26 129	30 368	34 522
AUSTRIA	1	1	1	1	2	2	3	4	5	6	10	17	21	24	26	28	32	53	95	187	363	626	785	937	1 096	1 269	1 455	1 702	2 043	2 783	3 792	6 395
BELGIUM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	24	112	671	1 108	2 176	2 870	3 139	3 245	3 355	3 535	3 865	4 310	5 127	6 273	7 123	8 149	9 955
CANADA	1	1	2	2	3	3	4	6	7	9	10	12	14	17	20	26	33	95	281	559	766	1 211	1 843	2 519	2 665	2 913	3 130	3 388	3 713	5 752	6 517	7 340
CHINA	0	0	0	0	0	0	0	0	11	16	34	44	54	62	72	92	132	292	792	3 492	6 692	17 682	28 322	43 472	78 022	130 882	175 142	205 440	253 640	308 520	414 065	649 034
DENMARK	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	3	3	4	7	29	499	698	751	979	1 061	1 139	1 254	1 362	1 626	1 850	3 423	3 910
FINLAND	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	2	3	5	7	9	9	9	9	20	37	80	134	214	313	417	691	1 008
FRANCE	2	2	2	3	4	6	8	9	11	14	17	21	24	26	38	76	218	440	1 446	3 562	4 906	5 692	6 837	7 920	8 636	9 713	10 755	11 930	13 098	16 737	19 703	23 664
GERMANY	6	9	12	18	28	42	54	70	114	176	296	435	1 105	2 056	2 899	4 170	6 120	10 566	18 006	25 916	34 077	36 710	37 900	39 224	40 679	42 293	45 181	49 016	53 901	60 107	67 300	82 305
ISRAEL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	22	67	186	272	377	588	771	877	952	1 358	1 960	2 414	3 349	4 507	5 657
ITALY	8	12	14	16	16	17	18	18	19	20	22	26	31	37	50	100	496	1 277	3 605	13 141	16 796	18 198	18 607	18 915	19 297	19 682	20 108	20 865	21 650	22 594	25 064	30 319
JAPAN	19	24	31	43	60	91	133	209	330	453	637	860	1 132	1 422	1 708	1 919	2 144	2 627	3 618	4 914	6 632	13 599	23 339	34 151	42 040	49 500	56 162	63 192	71 868	78 413	85 066	91 366
KOREA	0	0	0	0	0	0	0	0	0	0	5	6	9	14	36	81	357	524	650	729	1 024	1 555	2 481	3 615	4 502	5 835	8 099	12 665	17 323	21 199	24 313	27 619
MALAYSIA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	4	34	145	213	273	352	401	793	1 292	1 800	2 308	2 680	3 390
MOROCCO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	205	206	206	699	986	1 714
NETHERLANDS	0	0	0	0	0	1	1	1	5	9	16	22	40	43	45	49	59	69	111	170	390	767	1 069	1 536	2 061	2 914	4 609	7 225	10 717	14 349	18 249	23 037
NORWAY	0	0	0	0	0	0	0	0	6	6	6	6	7	7	7	8	8	8	8	9	9	10	12	14	26	44	68	120	160	201	354	657
PORTUGAL	0	0	0	0	0	0	0	0	0	1	2	2	3	3	3	18	68	108	134	175	244	299	418	454	519	585	673	907	1 077	1 647	2 537	3 822
SOUTH AFRICA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	311	1 393	1 487	2 077	2 146	2 206	2 669	3 969	4 427	4 539	7 504
SPAIN	0	0	0	0	0	0	0	0	0	3	6	14	25	52	150	742	4 021	4 070	4 595	5 080	5 439	5 566	5 641	5 706	5 778	5 928	6 306	11 628	15 875	21 513	29 999	38 986
SWEDEN	1	1	1	2	2	2	2	3	3	3	3	4	4	4	5	6	8	9	11	15	23	42	77	125	184	269	429	707	1 107	1 606	2 527	4 215
SWITZERLAND	5	6	7	8	10	11	13	14	16	18	20	22	24	28	30	37	49	80	125	223	437	756	1 061	1 394	1 664	1 906	2 173	2 498	2 973	3 651	4 734	6 375
THAILAND	0	0	0	0	0	0	0	0	0	0	0	0	0	25	32	32	32	42	185	379	524	961	1 436	1 557	2 584	3 194	3 650	3 666	3 715	4 215	4 415	9 002
TÜRKIYE	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	32	64	358	1 175	4 206	7 339	8 551	9 424	10 917	12 526	14 393
USA	0	0	0	0	0	0	0	0	0	0	0	0	111	190	295	455	753	1 188	2 017	3 937	7 130	12 076	18 321	25 821	40 973	51 818	62 498	76 274	95 550	120 368	143 469	177 344
REST OF EU COUNTRIES	0	0	0	0	0	0	0	0	0	0	1	11	21	23	34	42	107	674	2 659	3 759	5 962	8 404	8 815	9 167	9 571	9 943	10 735	12 369	16 617	22 856	32 200	45 852
TOTAL IEA PVPS	50	65	90	115	150	206	271	372	572	784	1 143	1 566	2 698	4 116	5 552	8 013	14 884	23 036	40 132	70 067	97 580	132 214	167 718	209 701	276 832	360 931	445 838	529 068	642 200	778 094	968 976	1 329 105
BRAZIL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26	38	53	66	86	93	1 160	2 416	4 697	8 474	14 504	25 371	37 817
INDIA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	57	272	1 299	2 384	3 249	5 436	9 547	22 561	33 363	43 431	47 826	61 490	79 625	92 645
TOTAL NON IEA PVPS	0	0	0	0	0	0	0	0	1	8	14	24	34	46	67	94	139	249	576	2 304	4 781	8 049	12 800	21 588	31 076	50 086	69 006	99 291	131 515	169 087	216 970	312 852
TOTAL	50	65	90	115	150	206	271	372	573	791	1 157	1 591	2 732	4 162	5 619	8 107	15 023	23 285	40 708	72 371	102 361	140 263	180 518	231 288	307 908	411 016	514 844	628 359	773 715	947 180	1 185 946	1 641 956

SOURCE IEA PVPS & OTHERS

ANNEXES / CONTINUED

ANNEXE 2: ANNUAL INSTALLED PV CAPACITY (MW) FROM 1992 TO 2023

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
AUSTRALIA	7	2	2	2	3	3	4	3	4	4	6	6	7	8	10	12
AUSTRIA	1	0	0	0	0	0	1	1	1	1	4	6	4	3	2	2
BELGIUM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	18
CANADA	1	0	0	0	1	1	1	1	1	2	1	2	2	3	4	5
DENMARK	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
FINLAND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
FRANCE	2	0	0	1	2	2	2	2	2	3	3	4	3	2	12	38
GERMANY	6	3	3	6	10	14	12	16	44	62	120	139	670	951	843	1 271
ISRAEL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ITALY	8	4	2	2	0	1	1	1	1	1	2	4	5	7	13	50
JAPAN	19	5	7	12	16	32	42	75	122	123	184	223	272	290	287	210
KOREA	0	0	0	0	0	0	0	0	0	0	5	1	3	5	22	45
MALAYSIA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MOROCCO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NETHERLANDS	0	0	0	0	0	0	0	0	4	3	8	6	18	4	2	3
NORWAY	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	1
PORTUGAL	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	14
SOUTH AFRICA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPAIN	0	0	0	0	0	0	0	0	0	3	3	8	11	27	98	592
SWEDEN	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
SWITZERLAND	5	1	1	1	2	2	2	2	2	2	2	2	2	4	2	7
THAILAND	0	0	0	0	0	0	0	0	0	0	0	0	0	25	7	0
TÜRKIYE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
USA	0	0	0	0	0	0	0	0	0	0	0	0	111	79	105	160
REST OF EU COUNTRIES	0	0	0	0	0	0	0	0	0	0	0	10	10	2	11	7
TOTAL IEA PVPS	50	16	25	25	35	56	65	101	199	212	360	423	1 131	1 419	1 436	2 460
BRAZIL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INDIA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL NON IEA PVPS	0	0	0	0	0	0	0	0	1	7	6	10	10	12	21	27
TOTAL	50	16	25	25	35	56	65	101	200	219	366	433	1 141	1 430	1 457	2 487

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
AUSTRALIA	22	83	383	806	1 039	811	866	1 018	876	1 147	4 454	4 813	4 692	5 038	4 239	4 153
AUSTRIA	5	20	43	92	176	263	159	152	159	173	186	247	341	739	1 009	2 603
BELGIUM	88	559	437	1 068	694	269	106	110	180	330	445	817	1 146	850	917	1 806
CANADA	7	62	187	277	208	445	633	675	146	249	217	258	325	2 038	765	823
DENMARK	0	1	3	22	470	199	53	228	81	78	115	109	264	718	1 754	487
FINLAND	1	2	2	2	0	0	0	11	17	43	53	81	98	104	269	318
FRANCE	143	222	1 006	2 116	1 344	786	1 145	1 083	716	1 077	1 042	1 175	1 168	3 639	2 966	3 961
GERMANY	1 950	4 446	7 440	7 910	8 161	2 633	1 190	1 324	1 455	1 614	2 888	3 835	4 885	6 206	7 193	15 005
ISRAEL	1	21	45	119	86	105	211	183	106	75	406	602	454	935	1 158	1 150
ITALY	396	781	2 328	9 536	3 655	1 402	409	308	382	385	426	758	785	944	2 470	5 255
JAPAN	225	483	991	1 296	1 718	6 968	9 740	10 811	7 889	7 460	6 662	7 030	8 676	6 545	6 653	6 300
KOREA	276	167	127	79	295	531	926	1 134	887	1 333	2 265	4 566	4 658	3 876	3 278	3 306
MALAYSIA	0	0	1	2	34	111	67	61	78	49	517	499	508	372	1 068	710
MOROCCO	0	0	0	0	0	0	0	0	0	0	205	1	0	493	287	728
NETHERLANDS	10	10	42	59	220	377	302	467	525	853	1 695	2 616	3 492	3 632	4 200	4 788
NORWAY	0	0	0	0	1	1	2	2	11	18	25	51	40	41	153	303
PORTUGAL	50	40	26	41	69	55	119	36	65	66	88	234	170	571	959	1 285
SOUTH AFRICA	0	0	0	0	6	305	1 081	94	590	69	60	463	1 300	458	112	2 965
SPAIN	3 279	49	525	485	359	127	75	65	72	150	378	5 322	4 247	5 639	8 495	8 987
SWEDEN	2	1	2	4	8	19	35	48	59	85	160	291	400	499	921	1 688
SWITZERLAND	12	30	46	98	214	319	305	333	270	242	267	325	475	677	1 084	1 641
THAILAND	0	10	6	194	145	437	475	122	1 027	610	456	16	49	500	200	4 587
TÜRKIYE	0	0	0	0	5	26	32	294	818	3 031	3 133	1 212	874	1 492	1 610	1 867
USA	298	435	829	1 920	3 193	4 946	6 245	7 500	15 152	10 845	10 680	13 776	19 276	24 819	23 101	33 875
REST OF EU COUNTRIES	65	568	1 984	1 100	2 204	2 441	412	352	405	372	792	1 634	4 248	6 239	8 935	13 652
TOTAL IEA PVPS	6 871	8 153	16 958	29 935	27 517	34 634	35 503	41 983	67 131	84 099	85 032	83 245	113 133	136 252	191 779	360 128
BRAZIL	0	0	0	26	12	15	14	20	7	1 067	1 256	2 281	3 777	6 030	10 867	12 446
INDIA	0	0	57	214	1 027	1 085	865	2 186	4 111	13 013	10 803	10 068	4 395	13 664	18 135	13 020
TOTAL NON IEA PVPS	45	109	326	1 728	2 475	3 268	4 751	8 788	9 478	19 009	24 160	30 286	32 225	37 572	49 897	95 882
TOTAL	6 916	8 262	17 285	31 663	29 991	37 902	40 254	50 770	76 608	103 108	109 192	113 531	145 358	173 824	241 676	456 010

ANNEXES / CONTINUED

ANNEXE 3: CURRENCY EXCHANGE RATES

COUNTRY	CURRENCY CODE	EXCHANGE RATE IN 2023(1 USD =)
AUSTRALIA	AUD	1.506
BRAZIL	BRL	4.994
CANADA	CAD	1.35
CHILE	CLP	952.43
CHINA	CNY	7.075
DENMARK	DKK	6.89
EUROZONE	EUR	0.924
INDIA	INR	82.572
ISRAEL	ILS	3.687
JAPAN	JPY	140.511
KOREA	KRW	1338.93
MALAYSIA	MYR	4.61
MEXICO	MXN	17.733
MOROCCO	MAD	10.275
NORWAY	NOK	10.564
SOUTH AFRICA	ZAR	18.457
SWEDEN	SEK	10.613
SWITZERLAND	CHF	0.899
THAILAND	THB	34.802
TÜRKIYE	TRY	23.824
USA	USD	1

ANNEXES / CONTINUED

ANNEXE 4: COUNTRY AND MARKET GROUPINGS

COUNTRY/MARKET	SUB REGION	REGION
ALGERIA	AFRICA	MIDDLE EAST AND AFRICA
ARGENTINA	LATIN AMERICA	THE AMERICAS
AUSTRALIA	OCEANIA	ASIA PACIFIC
AUSTRIA	EUROPE	EUROPE
BELGIUM	EUROPE	EUROPE
BRAZIL	LATIN AMERICA	THE AMERICAS
BULGARIA	EUROPE	EUROPE
CANADA	NORTH AMERICA	THE AMERICAS
CHILE	LATIN AMERICA	THE AMERICAS
CHINA	ASIA	ASIA PACIFIC
CHINESE TAIPEI	ASIA	ASIA PACIFIC
COLOMBIA	LATIN AMERICA	THE AMERICAS
CROATIA	EUROPE	EUROPE
CYPRUS	EUROPE	EUROPE
CZECH REPUBLIC	EUROPE	EUROPE
DENMARK	EUROPE	EUROPE
ECUADOR	LATIN AMERICA	THE AMERICAS
EGYPT	AFRICA	MIDDLE EAST AND AFRICA
ESTONIA	EUROPE	EUROPE
FINLAND	EUROPE	EUROPE
FRANCE	EUROPE	EUROPE
GERMANY	EUROPE	EUROPE
GREECE	EUROPE	EUROPE
HONDURAS	CENTRAL AMERICA + CARIBBEAN	THE AMERICAS
HUNGARY	EUROPE	EUROPE
ICELAND	EUROPE	EUROPE
INDIA	ASIA	ASIA PACIFIC
INDONESIA	ASIA	ASIA PACIFIC
IRELAND	EUROPE	EUROPE
ISRAEL	MIDDLE EAST	MIDDLE EAST AND AFRICA

COUNTRY/MARKET	SUB REGION	REGION
ITALY	Europe	Europe
Japan	Asia	Asia Pacific
Jordan	Middle East	Middle East and Africa
Kazakhstan	Asia	Asia Pacific
Korea	Asia	Asia Pacific
Latvia	Europe	Europe
Lithuania	Europe	Europe
Luxembourg	Europe	Europe
Malaysia	Asia	Asia Pacific
Malta	Europe	Europe
Mexico	North America	The Americas
Morocco	Africa	Middle East and Africa
Netherlands	Europe	Europe
Norway	Europe	Europe
Pakistan	Asia	Asia Pacific
Panama	Central America + Caribbean	The Americas
Peru	Latin America	The Americas
Philippines	Asia	Asia Pacific
Poland	Europe	Europe
Portugal	Europe	Europe
Romania	Europe	Europe
Russia	Eurasia	Europe
Saudi Arabia	Middle East	Middle East and Africa
Serbia	Europe	Europe
Singapore	Asia	Asia Pacific
Slovakia	Europe	Europe
Slovenia	Europe	Europe

ANNEXES / CONTINUED

ANNEXE 4: COUNTRY AND MARKET GROUPINGS

COUNTRY/MARKET	SUB REGION	REGION
South Africa	Africa	Middle East and Africa
Spain	Europe	Europe
Sweden	Europe	Europe
Switzerland	Europe	Europe
Thailand	Asia	Asia Pacific
Türkiye	Eurasia	Europe
UK	Europe	Europe
Ukraine	Europe	Europe
United Arab Emirates	Middle East	Middle East and Africa
USA	North America	The Americas
Vietnam	Asia	Asia Pacific

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Technology Collaboration Programme

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IEA PVPS

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