Solar photovoltaic

Toward commoditization
February 2024

KEARNEY | Energy Transition Institute

Compiled by the Kearney Energy Transition Institute

Acknowledgements

The Kearney Energy Transition Institute wishes to acknowledge the following people for their review of this FactBook: Bernard Drévillon, professor at the École Polytechnique, former director of the Laboratory of Physics of Interfaces and silicon-based thin film, and director of the Mastère in Renewable Energy Technologies and Management (ETRE), as well as Dr. Adnan Shihab Eldin, Claude Mandil, Richard Forrest, Antoine Rostand, Erik Peterson, and Maria de Kleijn, members of the Kearney Energy Transition Institute board. Their review does not imply that they endorse this FactBook or agree with any specific statements herein. The review/assessment is based on own reviewers' views and opinions and does not necessarily reflect the views or positions of any entities they represent.

About the FactBook: Solar photovoltaic

This FactBook seeks to summarize the status of the solar photovoltaic (PV) industry, covering current and emerging technologies as well as solar PV system configurations. The report presents the market status and evolution, and also provides a global overview of ongoing policies and most frequent financing schemes. Figures about levelized cost of electricity are available, as is information about stakeholders across the value chain. Environmental and social impacts of solar PV are covered. Finally, information about innovation, research, and development in solar PV technologies and applications is presented.

About the Kearney Energy Transition Institute

The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economic perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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Agenda

1. Solar PV technology

Solar PV technology

Solar energy's technical potential is estimated between 2.6 and 80 times the world's primary energy supply in 2022. **Photovoltaic technology** enables the **conversion of solar energy into electricity**. It relies on the photovoltaic effect: a **semiconductor material** is excited by sunlight energy and releases an electron. The result is the formation of an electric current. A solar cell contains a semiconductor and additional components to retrieve and use this electricity.

There are two types of solar cells: **wafer-based** and **thin film**.

Wafer-based solar cells were the first photovoltaic technology to be developed. The cell is made of a rigid slice (called wafer) of a semiconductor crystal. **Crystalline silicon** (c-Si) is a wafer-based solar cell and is the most used solar technology. It has a record efficiency of 26.1%, average efficiency of ~20%, and cost around 0.25 USD/W.

Thin film is a technology that **deposits semiconductor on a flexible layer**. Despite a lower efficiency, thin film cells **require less material** and are **convenient to use,** cells are lighter, flexible, and color customizable. The most common thin film solar cell is the cadmium telluride (CdTe) solar cell with 22.1% record efficiency.

Cell conversion efficiency can be hindered by various phenomena **reducing the energy conversion** (light obstructed, not converted, or due to thermal loss). Additionally, cells are limited by **the Shockey Queisser limit**, which is the theorical maximum conversion rate of a solar cell (around 30% for crystalline silicon cells). Higher temperatures negatively impact cell performance.

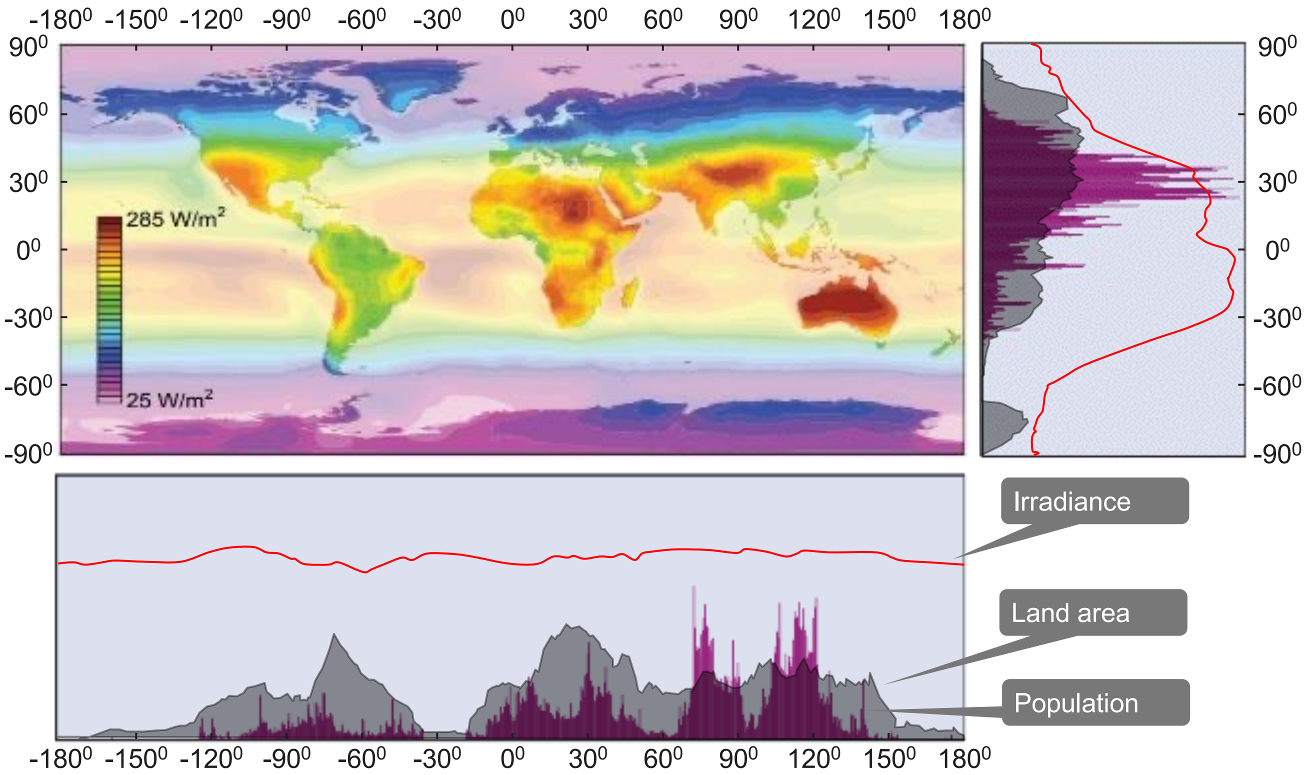
Technologies today are getting closer to the thermodynamical energy conversion limit, therefore new materials and new cell layout designs are developed to outperform today's efficiency. Cells can be built so that they **absorb light from both sides**, or **multiple cells are stacked** on each other to ensure maximum light conversion. **New materials are developed** to be cheaper and more efficient.

All advanced c-Si technologies are n-type with better performance in terms of efficiency and longer lifetime. In comparison, p-type cells offer lower costs and higher immunity to radiance but are not as durable as n-type cells and suffer from light-induced degradation effect.

Solar energy is relatively evenly distributed across the globe, despite temporal and geographic variability

Worldwide distribution of the solar resource

W/m^2 (Irradiance)



1.1 Solar resource

Variation in irradiance and its implications

Solar irradiance is of fundamental importance in the use of solar energy. It is considered good to excellent between 10° and 40°, South or North, although it can vary significantly at a given latitude.

The major causes of variation in solar intensity over time and across geographic location result from:

– The Earth's revolution around the sun (seasonal variation)

– The Earth's rotation about its own axis (diurnal variation) which are reflected in the changing obliquity of incoming solar radiation at different latitudes.

– The local changes in weather conditions

Nevertheless, the solar resource is, from a global perspective, one of the most evenly distributed energy resources available on Earth, as solar irradiance varies across heavily settled areas by no more than a factor of three.

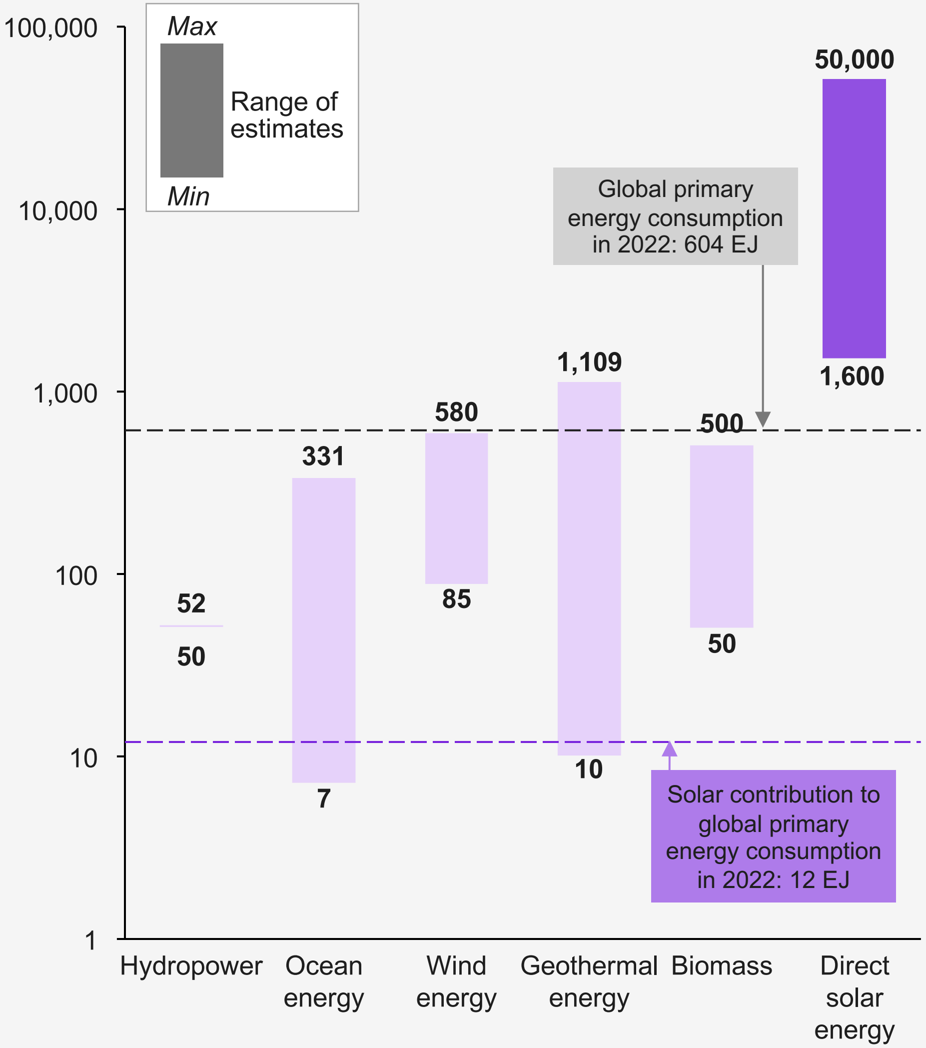
Sources: MIT, The Future of Solar Energy, 2015; Kearney Energy Transition Institute analysis

Solar is the most abundant renewable-energy resource in the world

The lower estimate for the technical potential of solar would be enough to supply 2.6 times the energy used in 2021 globally.

Ranges of global technical potential of energy sources[1]

Exajoule (EJ) per year, log scale



Global primary energy consumption in 2022: 604 EJ

Solar contribution to global primary energy consumption in 2022: 12 EJ

From sunlight to captured energy

The solar resource is larger than any other energy source available on Earth. Solar energy's technical potential is estimated between 2.6 and 80 times the world's primary energy supply in 2022. This estimate takes into account the fraction of land that is of practical use and realistic conversion efficiency.

Solar energy is transported through sunlight. The instantaneous amount of power from sunlight available at a particular location and at a given time is measured by the solar ***irradiance*** (in watts per square meter). Solar ***insolation*** (or ***irradiation***) is the resulting solar energy received at a given location during a specific period of time, measured in watt-hours per square meter.

There are two main methods of capturing energy from the sun:

- **Heat:** irradiative solar energy is transformed into heat through absorption by gases, liquids, or solid materials.
- **Photoreaction:** solar radiation is a flux of stream of photons which can promote photoreactions and generate a flow of electrons.

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[1] Technical potential corresponds to the capacity of a renewable energy technology available for development after accounting for topographic limitations, land-use constraints, and system performance.

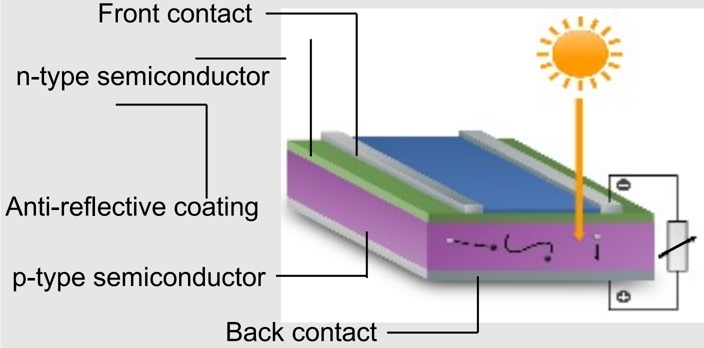
Sources: Energy Institute, Statistical Review of World Energy 2023; IPCC, Renewable energy sources and climate change mitigation, 2012; NREL, Renewable Energy Zones (REZ) toolkit, 2018; Kearney Energy Transition Institute analysis

Solar photovoltaic is one of the four main direct solar energy technologies

Direct solar energy technologies exclude natural solar energy conversions, such as natural photosynthesis for biomass.

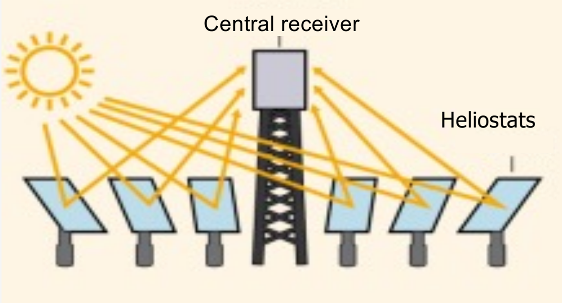
Solar photovoltaic (PV)

Electricity is generated via direct conversion of sunlight to electricity by **photovoltaic cells** (conduction of electrons in semiconductors).



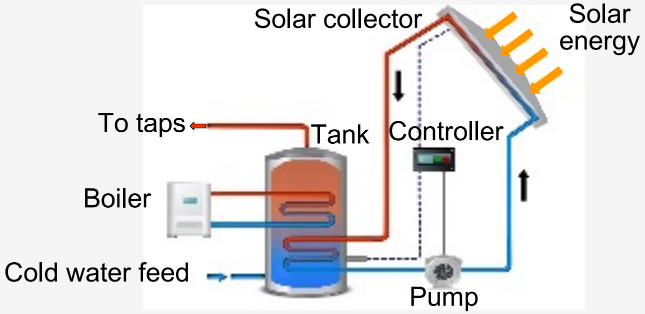
Concentrating solar power (CSP)

Electricity is generated by the **optical concentration** of solar energy, fluids or materials to produce steam to drive heat engines and electrical generators.



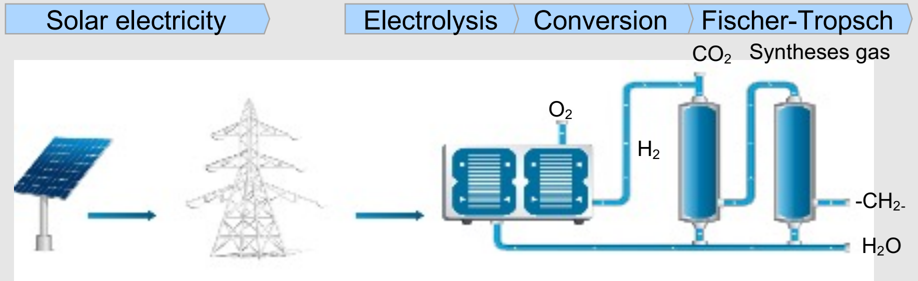
Solar thermal

Solar panels made up of evacuated tubes or flat-plate collectors **heat up water stored in a tank**. The energy is used for hot-water supply and, occasionally, space heating.



Solar fuels

Solar fuel processes are being designed to transform the radiative energy of the sun into chemical energy carriers such as hydrogen or synthetic hydrocarbons.



Sources: IPCC (2011), “Special report on renewable energy”; IEA (2011), “Solar Energy Perspectives”; SolarFuel (accessed July 2015); Kearney Energy Transition Institute analysis

While mitigating climate change, photovoltaic performance remains dependent on climate evolution

The direct climate impacts on solar power are small (around 5%) because irradiation changes remain small, and the negative effects of warming occur mostly at higher latitudes, which already have lower PV potential than low-latitude regions.

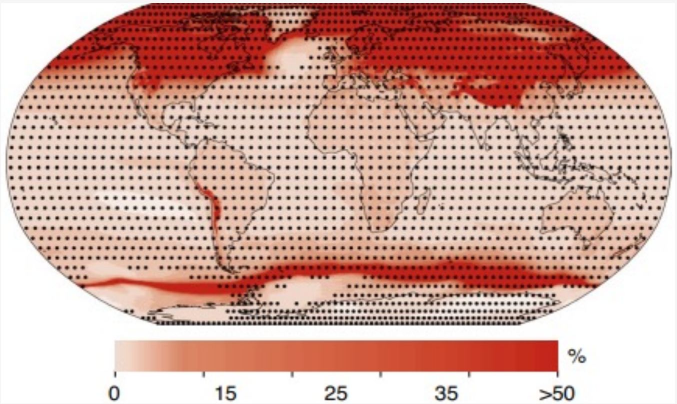
1.1 Solar resource

Climate change will redefine the world map of natural properties over time. Existing or ongoing solar projects may lose relevance after a few years. In fact, the efficiency of solar panels relies on irradiation, temperature, and other weather conditions.

Local natural phenomenon changing patterns can heavily hinder the expected yield of a solar project.
As the world will get hotter and natural phenomena more extreme, yield forecast will become more uncertain.

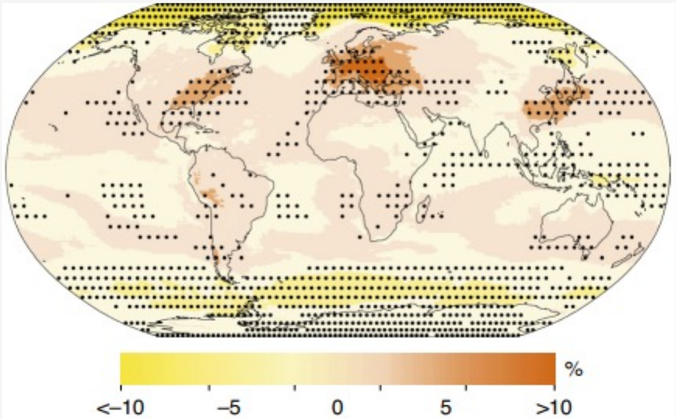
Expected temperature evolution due to climate change (2050 map)[1]

Temperature change (%)



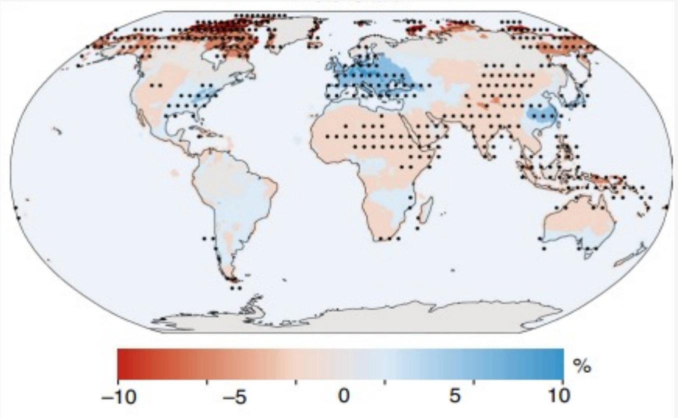
Expected irradiance evolution due to climate change[1]

Irradiance change (%)



Expected PV potential change due to natural phenomena evolution[1]

PV performance change (%)



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[1] All graphs show the evolution under RCP6.0 scenario (RCP is representative concentration pathways), a scenario estimated by the IPCC about the evolution of GHG emissions in the world depending on the effort made to limit emissions. RCP6.0 is the scenario with a medium stabilization of emissions before the end of the 21st century. All graphs show the state of the world in 2050. The dots on each map confirm that, statistically, the given prediction of the natural phenomenon is plausible.

Sources: Gernaat and al., Climate change impacts on renewable energy supply, 2021, Nature climate change 11; Observatoire national sur les effets du réchauffement climatique, 2015, Scénarios d'évolution des concentrations de gaz à effet de serre; Kearney Energy Transition Institute analysis

Using the photovoltaic effect, solar cells convert light into electricity

Solar cell components and electricity generation

- **Solar cells** are made of **semiconductors** (material with variable conductivity properties) of opposite doping.
- **Doping** is the phenomenon of inserting impurities inside the semiconductor to modify its conducting properties.
- A **p-type** semiconductor is doped with an excess of holes donating impurities (meaning a missing electron) and will be positively charged while an **n-type** is doped with electron-donating impurities and, thus, is negatively charged.
- An **electrical field is formed** at the junction of the two semiconductors inside the solar cell.
- When a carrier concentration gradient exists in the semiconductor, through random motion, carriers will have a net movement from areas of high carrier concentration to areas of low concentration by the **process of diffusion**. Hence, the carriers must easily diffuse to the electrical field region and diffusion length limits the maximum thickness of solar cell.
- When light meets a solar cell, photons transfer their energy to electrons. **Electrons** enter in an excited state and **move freely inside the semiconductors**. The electrical field created at the junction orients the movement of the electrons, resulting in **the creation of an electrical current.**

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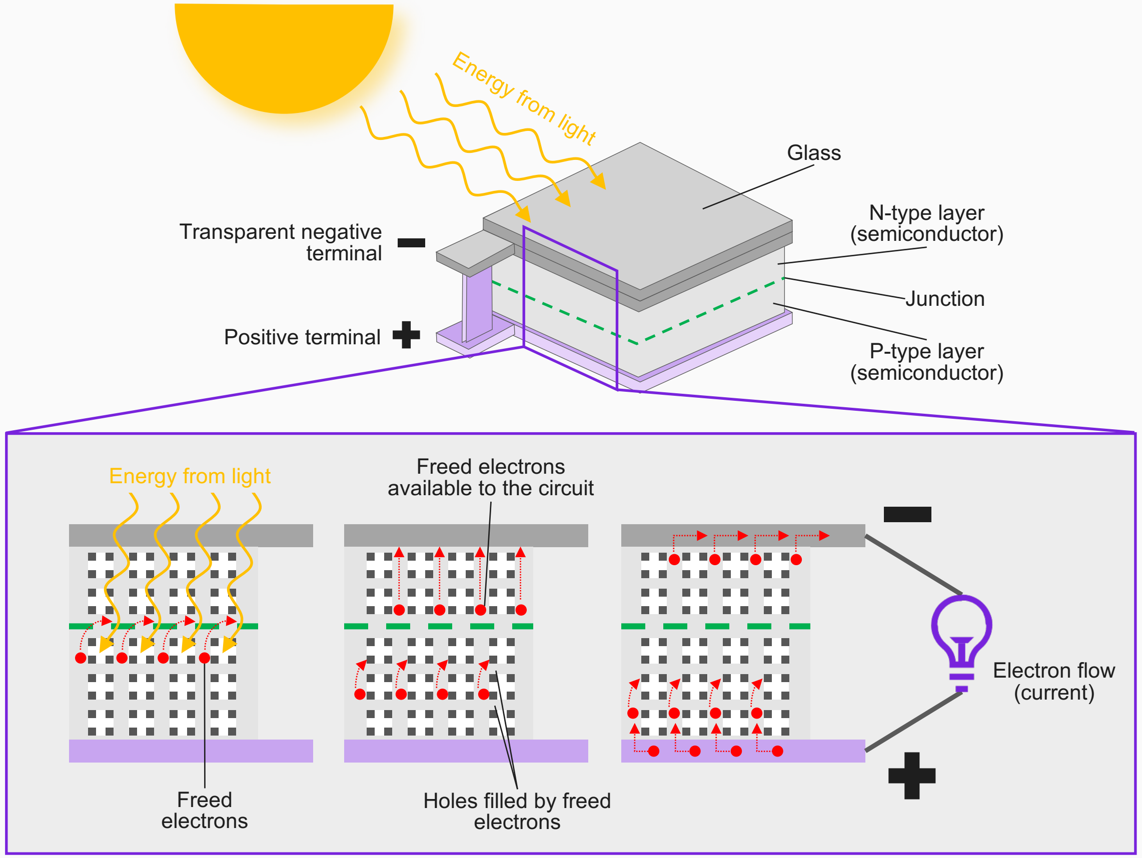
Photovoltaic effect principle



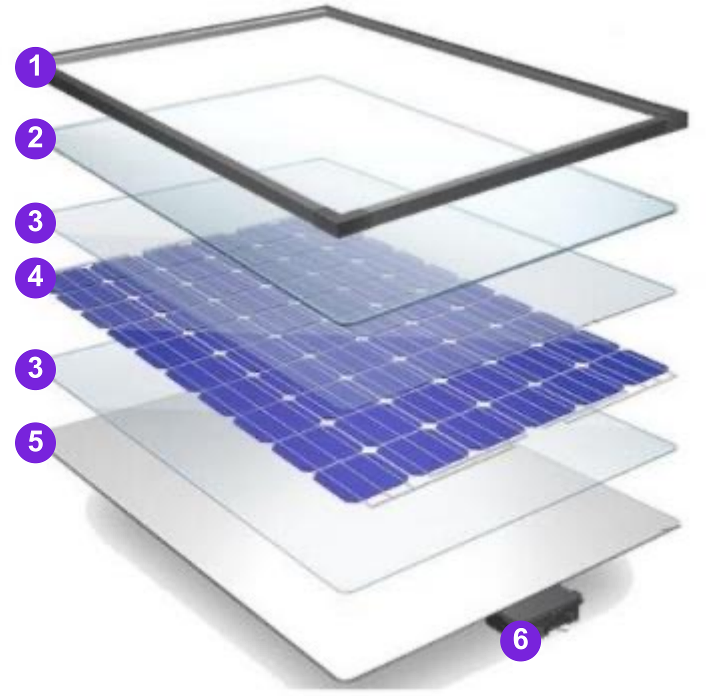
Sources: US Energy Information Administration, 2023, Solar explained Photovoltaics and electricity; American Chemistry Society; Kearney Energy Transition Institute analysis

Solar cells are then integrated to a solar module, commonly known as a solar panel

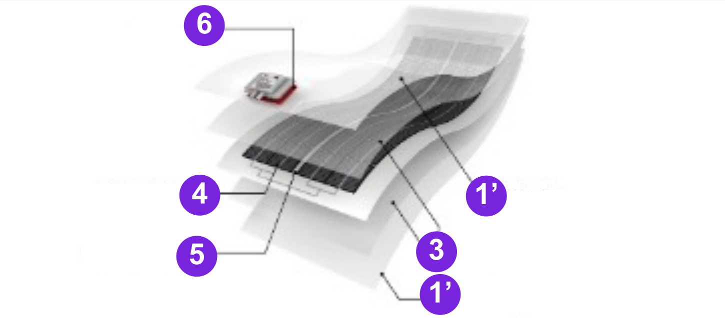
There are two types of solar cell: wafer-based and thin films. The difference relies on manufacturing process and a few properties.

1.2 Solar PV components and design

Wafer-based solar module components



Thin film solar module components[2]



1	**Aluminum frame** Protects the edges and provides rigid structure to the panel
1'	**Protective film** Film that encapsulates the flexible solar cells as a protection
2	**Tempered glass** Provides protection from falling debris and makes the panel waterproof
3	**EVA film**[1] Protects from temperature, moisture, and dirt and can act as a shock absorbent
4	**Solar cells**
5	**Backsheet or glass** Provides electrical insulation and mechanical protection
6	**Junction box** Houses cables for interconnection with other PV modules, etc.

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[1] Ethylene vinyl acetate film is a plastic film.

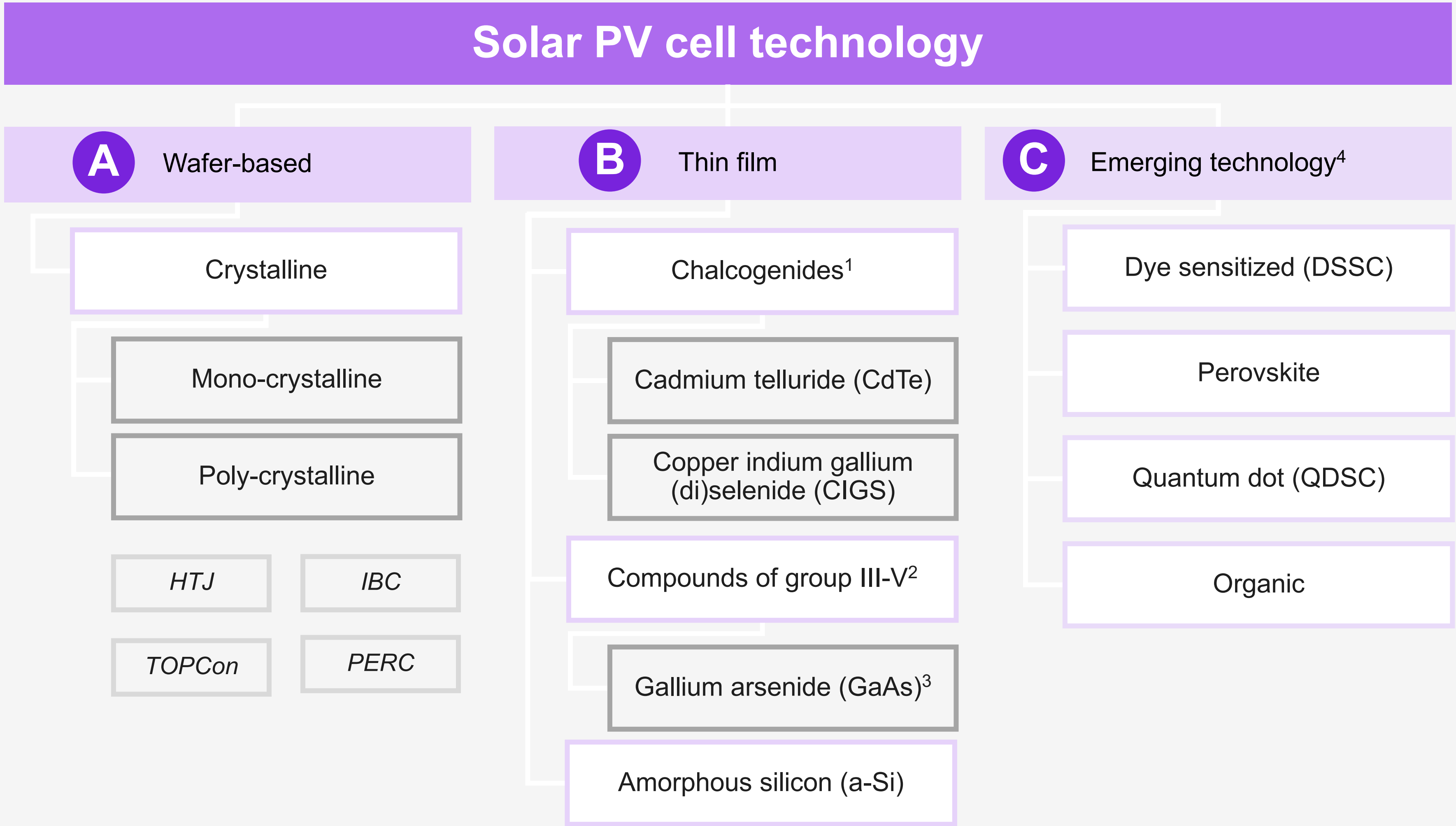
[2] Thin film technologies are developed and often used for their flexibility properties; however, they can be built as rigid panels.

Sources: Andalsolar, Clean Energy Reviews, 3M; Kearney Energy Transition Institute analysis

Depending on their manufacturing process, solar cells can be distinguished into three categories

Non-exhaustive

Classification of solar PV cell technologies



Solar PV cell technology

- **A** Wafer-based
  - Crystalline
    - Mono-crystalline
    - Poly-crystalline
  - *HTJ*
  - *IBC*
  - *TOPCon*
  - *PERC*
- **B** Thin film
  - Chalcogenides[1]
    - Cadmium telluride (CdTe)
    - Copper indium gallium (di)selenide (CIGS)
  - Compounds of group III-V[2]
    - Gallium arsenide (GaAs)[3]
  - Amorphous silicon (a-Si)
- **C** Emerging technology[4]
  - Dye sensitized (DSSC)
  - Perovskite
  - Quantum dot (QDSC)
  - Organic

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[1] Chalcogenides are a category of materials: they are salts of located in the antepenultimate column of the periodic table.

[2] Compounds of group III-V are semi conductors made from alloys between elements of the column IIIA and VA of the periodical table of element

[3] GaAs solar cell is traditionally considered as wafer-based, but recent improvements make GaAs more as a thin film.

[4] Emerging technology are new thin film technologies that are still in research state.

Sources: T. Ibn-Mohammed and al., 2017, "Perovskite solar cells: An integrated hybrid lifecycle assessment and review in comparison with other photovoltaic technologies", Renewable and Sustainable Energy review; Jean, Brown, Jaffe, Buonassisi and Bulovic´, 2015, Pathways for solar photovoltaics; Kearney Energy Transition Institute analysis

1.3 Solar PV classification

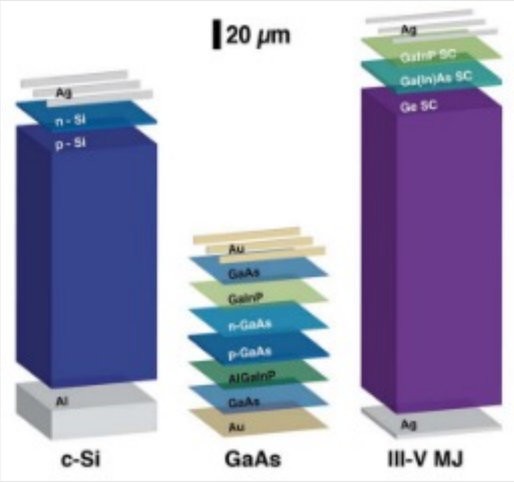
Some cells are built upon a rigid support, known as wafer-based

- **A** Wafer-based
- B Thin film
- C Emerging

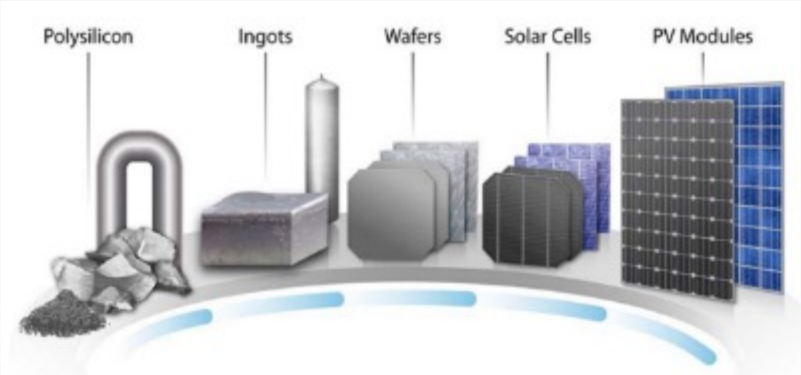
1.4 Solar PV technologies

Wafer-based solar cells

Wafer-based cells are cells built upon a **slice of a crystal ingot** (known as the wafer), on which additional layers are deposited. The most common wafer-based cell is **the crystalline silicon (c-Si)**, but there are also high-efficiency cells based on **III-V materials** (for example gallium-arsenide, GaAs).[1,2] However, those materials are extremely expensive and are designed for outer space purposes. Wafer-based cells are usually **thicker** than other technologies but are **more efficient**.



Wafer-based manufacturing



NREL analysis of manufacturing costs for silicon solar cells includes bottom-up cost modeling for all the steps in the silicon value chain.

Silicon (or any other III-V materials) is purified then molten into ingots. Wafers are then cut from those ingots to become solar cells. The assembly of solar cells will result in a solar module.

Technologies vary depending on the **type of crystal** (mono or poly crystalline), the **doping method,** and the **added materials.**

All advanced c-Si technologies are n-type with better performance in terms of efficiency and longer lifetime.

[1] II-V MJ stands for III-V multijunction; it refers to III-V cells with several layers

[2] GaAs cells are traditionally wafer-based solar cells, however, today, we usually find GaAs in the form of a thin film solar cell.

Sources: NREL, 2020, Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and Cost Reduction Road Map; Jean, Brown, Jaffe, Buonassisi and Bulovic´, 2015, Pathways for solar photovoltaics; Freiberger; Kearney Energy Transition Institute analysis

There are four sub-categories of silicon wafer-based technologies that differ by their components

Wafer-based technologies in a nutshell (2022 numbers)

	PERC	TOPCon	IBC	HJT
Description	Based on a p-type c-Si cell on which a passivation layer is added; it helps re-emitting non-absorbed light and prevent electron hole recombination	Evolutionary upgrade of PERC rear contact passivated with a thin silica layer, with higher efficiency potential based on n-type monocrystalline silicon wafers	IBC cells are made from c-Si n-type wafers in which all contact grids are put at the back; there is no more obstruction on the front surface	HJT cells are made from monocrystalline silicon n-type wafers and amorphous polysilicon
Crystal type	Mono/polycrystalline silicon	Monocrystalline silicon	Crystalline silicon	Monocrystalline silicon
Doping method	P-type (boron or gallium) silicon	N-type (phosphor) silicon	N-type (phosphor) silicon	N-type (phosphor) silicon
Added materials	– Silver – Aluminum, SiNx, Al_2O_3 – Phosphorus	– Silver – SiNx, Al_2O_3 – Boron	– Silver – SiO_2 – Boron	– Sliver – Amorphous polysilicon – TCO
Efficiency record	24.5%	26.7%	26.3%	26.5%
Lifespan	25–30 years	30 years	30 years	30 years
Manufacturing	Crystalline silicon process	Crystalline silicon	Specific process	Crystalline + amorphous processes
Maturity[1]	●	◑	◔	◕
Market share	85%	10%	<1%	4%

1: Emerging, 2: Development/demonstration 3: Deployment, 4: Mature
Sources: NREL, Spring 2023, Solar Industry update, PV magazine; Kearney Energy Transition Institute analysis

Thin-film cells are manufactured on flexible layers which gives these panels more versatile applications

- A Wafer-based
- **B Thin film**
- C Emerging

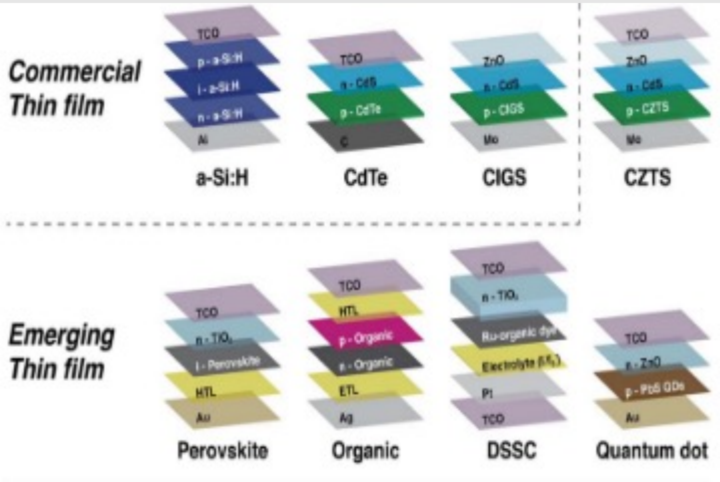
1.4 Solar PV technologies

Thin-film solar cells

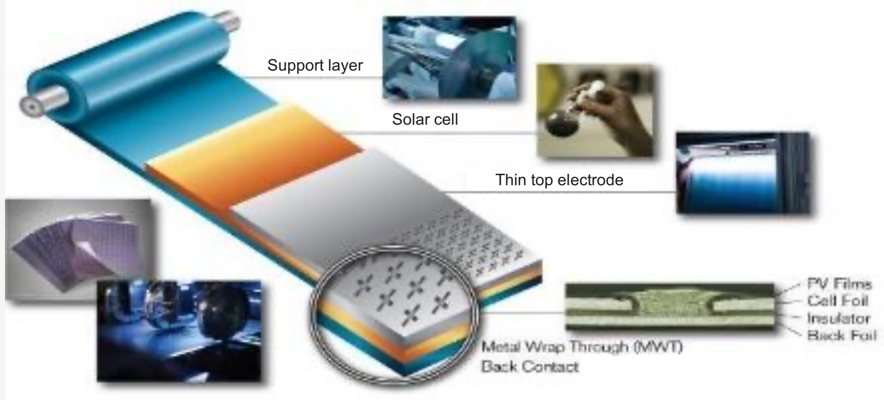
Thin-film solar cells work in the exact same way as wafer-based cells: electrons are excited thanks to the energy exchange from the photovoltaic effect. However, thin-film differs from wafer-based in the way they are produced and the material they rely on.

There are numerous thin-film technologies and they have been on the market for a long time, but no manufacturers have managed to increase production capacity due to **costs and efficiency issues**.

Thin-film solar cells are **thinner** than wafer-based, **flexible**, and **require less materials**.



Thin-film manufacturing



Thin-film cells are made from a **substrate** (that can be flexible, usually glass, metal, or polymers), on which **several layers are deposited**.

Layer deposition can be realized with different methods: direct current sputtering, physical vapor deposition, chemical bath deposition, chemical vapor deposition, or co-evaporation process. Cell **properties and doping** are dependent on the materials used for each layer.

Sources: J. Jean et all, 2015, Pathways for solar photovoltaics; DOE, Copper Indium Gallium Diselenide; Kearney Energy Transition Institute analysis

Thin-film technologies vary, with different states of maturity and different material requirements

Thin-film technologies in a nutshell (2022 numbers)

	CdTe	CIGS	a-Si	GaAs[3]
Description	Solar cell relying on a layer of cadmium (Cd) telluride (Te) band. Most common TF technology.	CIGS solar cells are the second most common TF technology, but they are still in deployment	Amorphous silicon is a mature technology made of hydrogenated silicon thin film deposited on a substrate.	GaAs solar panels are very efficient but expensive panels. They are mainly used for space vehicles.
Added materials	– Cadmium – Telluride	– Copper (Cu) – Gallium (Ga) – Indium (I) – Selenide (Se)	– Silicon	– Gallium – Arsenide
Efficiency record	22.1%	23.6%	14%	29.1%
Lifespan	25–30 years	25 years	10–20 years	25–30 years
Manufacturing[1]	VTD	VTD	PECVD	MOVPE - MBE
Maturity[2]	●	◐	●	●
Market Share	85%	15%	<1%	N/A

[1] Manufacturing methods are numerous and always improving, but we have listed the main ones. VTD is vapor transport deposition. MOVPE is metal-organic vapor phase epitaxy. MBE is molecular beam epitaxy. PECVD is plasma-enhanced chemical vapor deposition.

[2] 1: Emerging; 2: Development/demonstration; 3: Deployment; 4: Mature

[3] As previously mentioned, GaAs technology can be considered wafer-based as well as thin film. Recent developments tend to be thin film.

Sources: Fraunhofer ISE, 2022, Photovoltaics report; Papež, Dallaev, Ţălu, and Kaštyl, 2021, Overview of the Current State of Gallium Arsenide-Based Solar Cells; Jean, Brown, Jaffe, Buonassisi and Bulovic´, 2015, Pathways for solar photovoltaics; NREL, PV magazine; Kearney Energy Transition Institute analysis

Emerging technologies can overperform silicon crystalline cells in the future

A Wafer-based
B Thin film
C Emerging

1.4 Solar PV technologies

Perovskite is a new silicon-compound crystal material that is said to be efficient, cheap, and easy to manufacture. These cells are said to be highly customizable and convenient to use. However, perovskite degrades quickly.

Info	Top efficiency: 26.1%
	Highly tunable
Pros	Low cost
	Lightweight material
Cons	Toxic material
	Short lifespan

Dye sensitized (DSSC) are made from semiconductors that are electrochemically dyed. The solar cell contains a liquid electrolyte inside, making its usage more challenging because of temperature concerns.

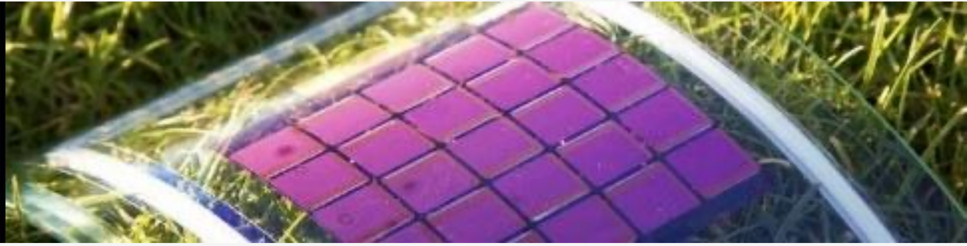
Info	Top record: 13%
	Versatile usage
Pros	Low cost
	Works under low light
Cons	Can freeze or dwell
	Toxic compounds

Quantum dots are used to replace the absorbing material (as silicon or CdTe). They are made from semiconducting particles and have a customizable absorption bandgap.

Info	Top record: 18.1%
	High SQ limit[1]
Pros	Highly tunable
	High efficiency potential
Cons	Toxic material
	Short lifespan

Organic solar cells rely on a polymer-based absorbent; semiconductor is carbon-based. The manufacture is cheap with abundant and nontoxic materials and have a very convenient usage.

Info	Top record: 19.2%
	Abundant resources
Pros	Low cost
	Eco-friendly technology
Cons	Air degradation
	Short lifespan



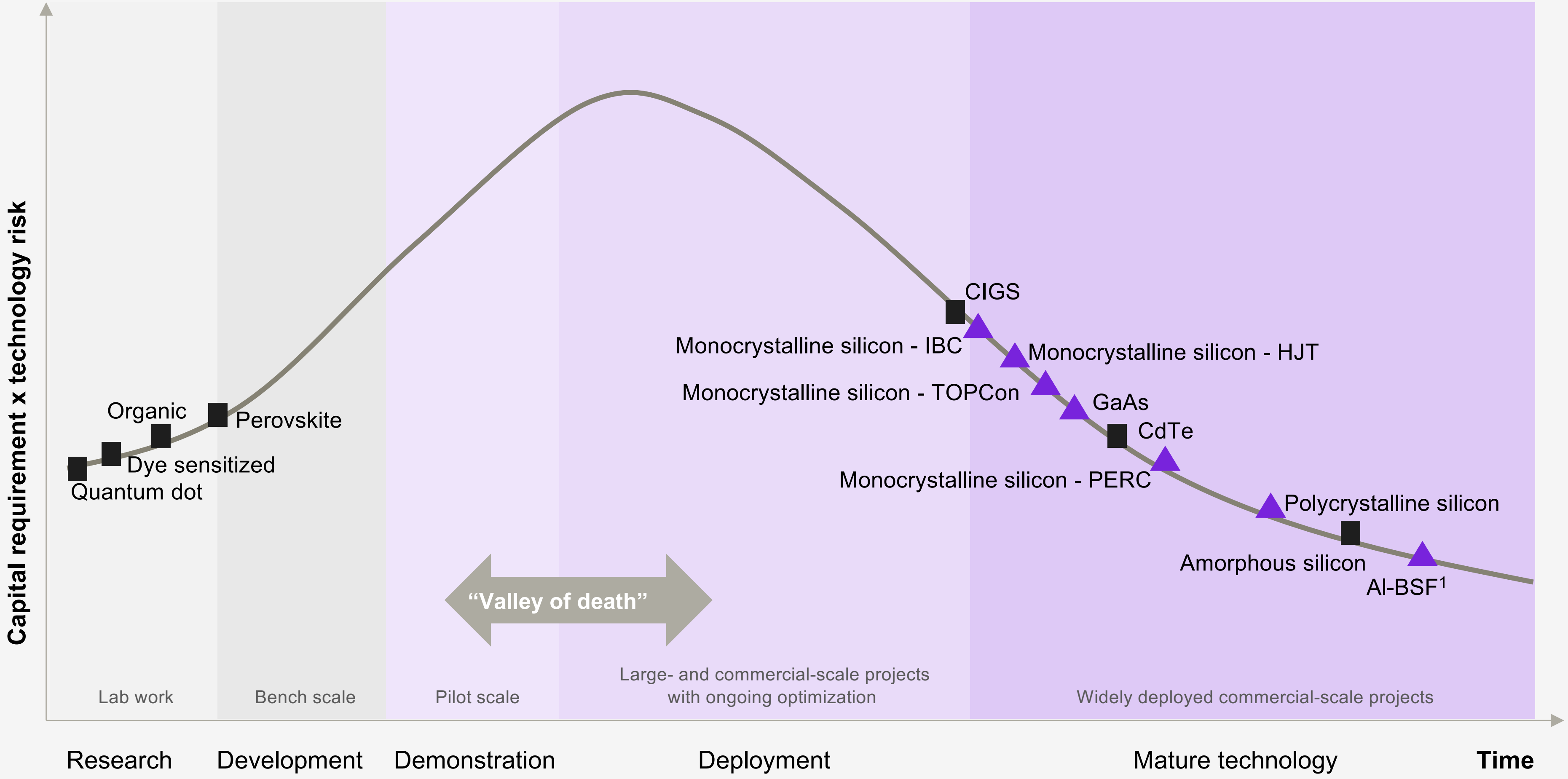
[1] SQ limit: Shockley Queisser limit, see slide 22

Sources: MIT, 2022, Explained: Why perovskites could take solar cells to new heights; NREL, 2013, Quantum Dots Promise to Significantly Boost Solar Cell Efficiencies; Maalouf and al., 2023, A comprehensive review on life cycle assessment of commercial and emerging thin-film solar cell systems; Kearney Energy Transition Institute analysis

Most solar cells are either mature and developed or in an emerging phase

Non-exhaustive

Solar cell technology maturity curve



▲ Wafer-based

■ Thin film

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[1] Al-BSF stands for aluminum back surface field, which are solar cells with a full aluminum layer on the rear of the cell to increase solar cell performance.
Source: Kearney Energy Transition Institute analysis

1.5 Technology curve

Comparative table of different solar cell technologies

Non-exhaustive

		Thickness	Material	Lifespan	Mass per area	Efficiency record	Avergae module price (USD/W)	Maturity[1]
Crystalline silicon	**PERC c-Si**	~200 µm	Rigid	25–30 years	500 g/m²	24.5%	0.25 $/W	4
	TOPCon c-Si			30 years		26.7%	0.23 $/W	3
	HJT c-Si					26.5%	0.27 $/W	2
	IBC c-Si					26.3%	0.27 $/W	1
Thin film	**CdTe**	~1 µm	Flexible	25–30 years	10 g/m²	22.3%	0.28 $/W	4
	Amorphous Si			10–25 years		14.0%	N/A	4
	CIGS			25 years		23.6%	0.48 $/W	2
	GaAs			25–30 years		29.1%	100 $/W	4
Emerging	**Perovskite**	~500 nm		1 year	5 g/m²	26.1%	0.38 $/W	1
	Dye sensitized	~10 µm		5 years	50 g/m²	13.0%	N/A	1
	Organic	~100 nm		10 years	5 g/m²	19.2%	N/A	1
	Quantum dot	~10 nm		< 1 year	5 g/m²	18.1%	N/A	1

[1] 1: Emerging; 2: Development/demonstration; 3: Deployment; 4: Mature

Sources: NREL, 2018, Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and Cost Reduction Road Map; NREL, 2020, Photovoltaic (PV) Module Technologies: 2020 Benchmark Costs and Technology Evolution Framework Results NREL, 2023, Best Research-Cell Efficiency Chart; intechopen.com; Wiley online library; Jean, Brown, Jaffe, Buonassisi and Bulovic´, 2015, Pathways for solar photovoltaics; Kearney Energy Transition Institute analysis

Minimizing energy loss inside a solar cell requires improving cell architecture to limit energy loss

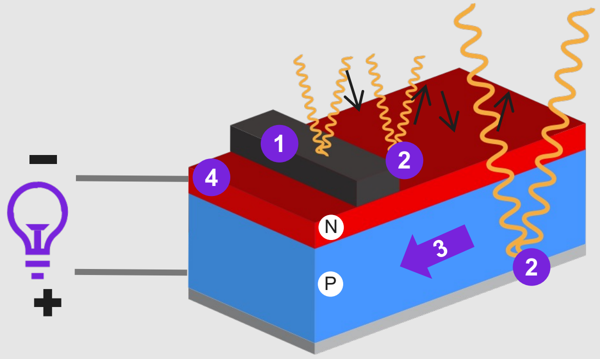
The **conversion efficiency** of a solar cell is defined as the ratio of the output power from the solar cell by unit area (W/cm²) to the incident solar irradiance.

Improving efficiency means **reducing energy loss** during the conversion of light into electricity.

The main losses are:

1. **Obstruction loss**: light does not reach the solar cell
2. **Reflection loss**: light is not converted into electricity

Schematic view of solar cell losses



3. **Thermal loss:** light is converted into heat
4. **Electrical loss**: due to electrical resistance of current flow and voltage drop

Solar cell efficiency limitations and improvements

Solar cell efficiency is theoretically limited by physics laws: it is called the **Shockley Queisser (SQ) limit**.
For a single junction solar cell, this limit is around 30%.

Therefore, to reach higher efficiency records, solar cell innovations are focused on **limiting energy loss**.
To maximize light conversion, **new layers are added,** and **cell architecture is redesigned**.

Some of the major improvements include:

- A **buffer layer** is added to enhance light absorption
- A **passivation layer** is added to prevent electron-hole recombination
- **Bifacial solar cells** absorb light from each of their surfaces
- Some cells have their **contact grid at the back** of the cell to maximize incoming light

Sources: Ehrler and al., 2020, ACS Energy Letters, 'Photovoltaics Reaching for the Shockley–Queisser Limit'; Bruno Lorenzi, Maurizio Acciarri, and Dario Narducci, 2018, Journal of Materials Engineering and Performance, 'Experimental Determination of Power Losses and Heat Generation in Solar Cells for Photovoltaic-Thermal Applications'; Kearney Energy Transition Institute analysis

1.7 Solar cells efficiency

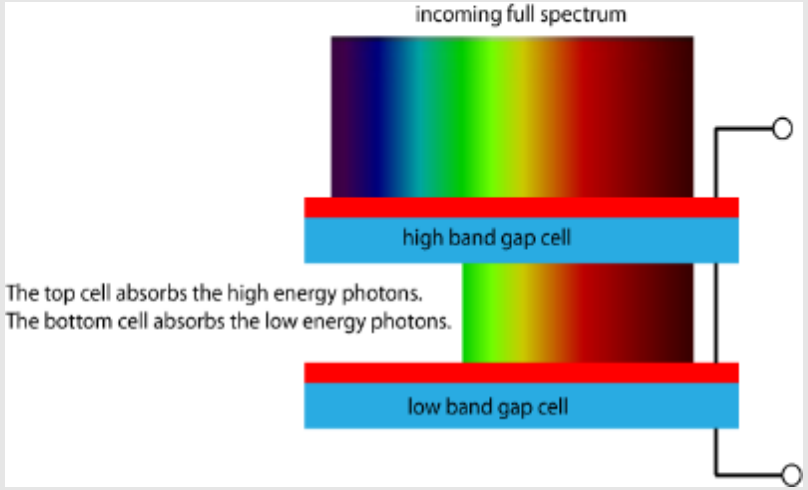
To absorb maximum incoming light, tandems and multi-junctions have been developed

Tandem solar cell principle

Because of physics principles, solar cell efficiency is limited (SQ limit): materials inside a **solar cell can only absorb specific light frequencies.**[1]

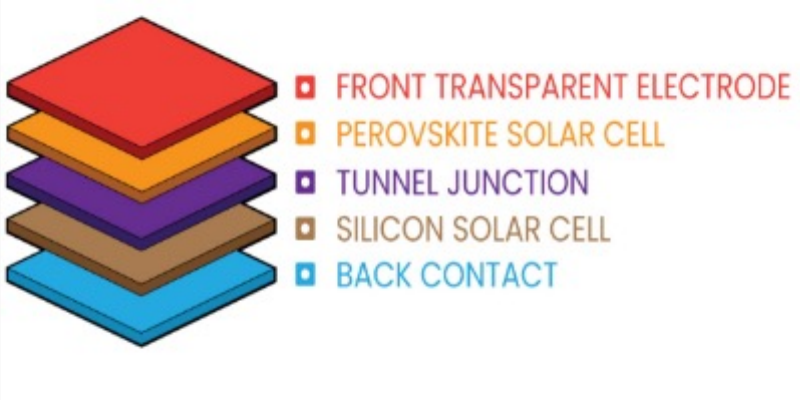
Tandem solar cells combine **solar cells with different absorption bandgaps**: several p-n junctions are stacked together so that most of the light can be converted into electricity (**tandem** refers to two junctions, **multi-junction** is for 3 or more).

Ranges of light absorption and cell bandgap



The top cell absorbs the high energy photons.
The bottom cell absorbs the low energy photons.

Perovskite-silicon tandem solar cell layout



Tandem technology enables reaching much higher efficiencies than single junctions. Fraunhofer ISE obtained in 2022 **a breakthrough efficiency of 47.6%** with a III-V/III-V tandem solar cell. Several technologies on a single cell means that the final panel will be much more expensive (up to 7 times the price of regular panels): multi-junction solar cells are still **designed for spatial purposes** (with GaAs/GaInP tandem cells). However, new materials and technologies, such as **perovskite**, are promising to make tandem with silicon affordable for commercial purposes.

1.7 Solar cells efficiency

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[1] SQ limit: Shockley-Queisser limit, see slide 21

Sources: Fraunhofer ISE; NREL; Jean, Brown, Jaffe, Buonassisi and Bulovic´, 2015, Pathways for solar photovoltaics; Kearney Energy Transition Institute analysis

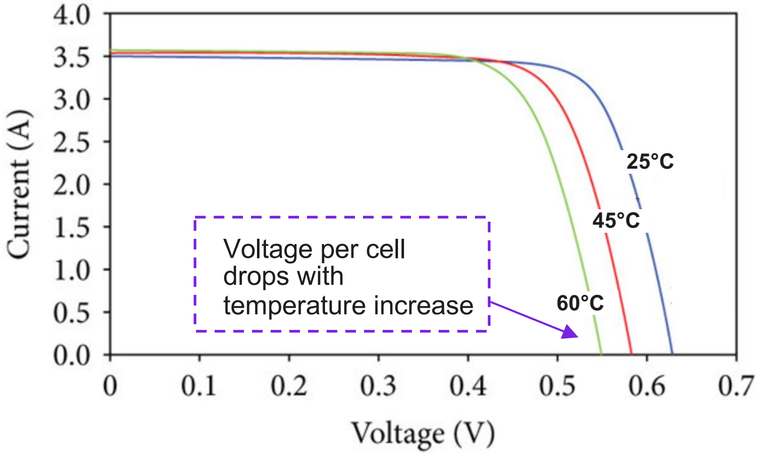
High temperatures have limiting effect on the solar cell parameters and performance

Effect of temperature on solar panel efficiency

Solar panel efficiency is negatively affected by temperature increases. Photovoltaic modules are defined at standard test conditions where the module's nameplate power is determined.

The panels then operate in real conditions which affect their performance. The temperature effect on solar cell performance is attributed to the temperature-dependent band-gap energy, charge carrier mobility, and charge carrier lifetime.

Impact of temperature on current and voltage of a solar cell



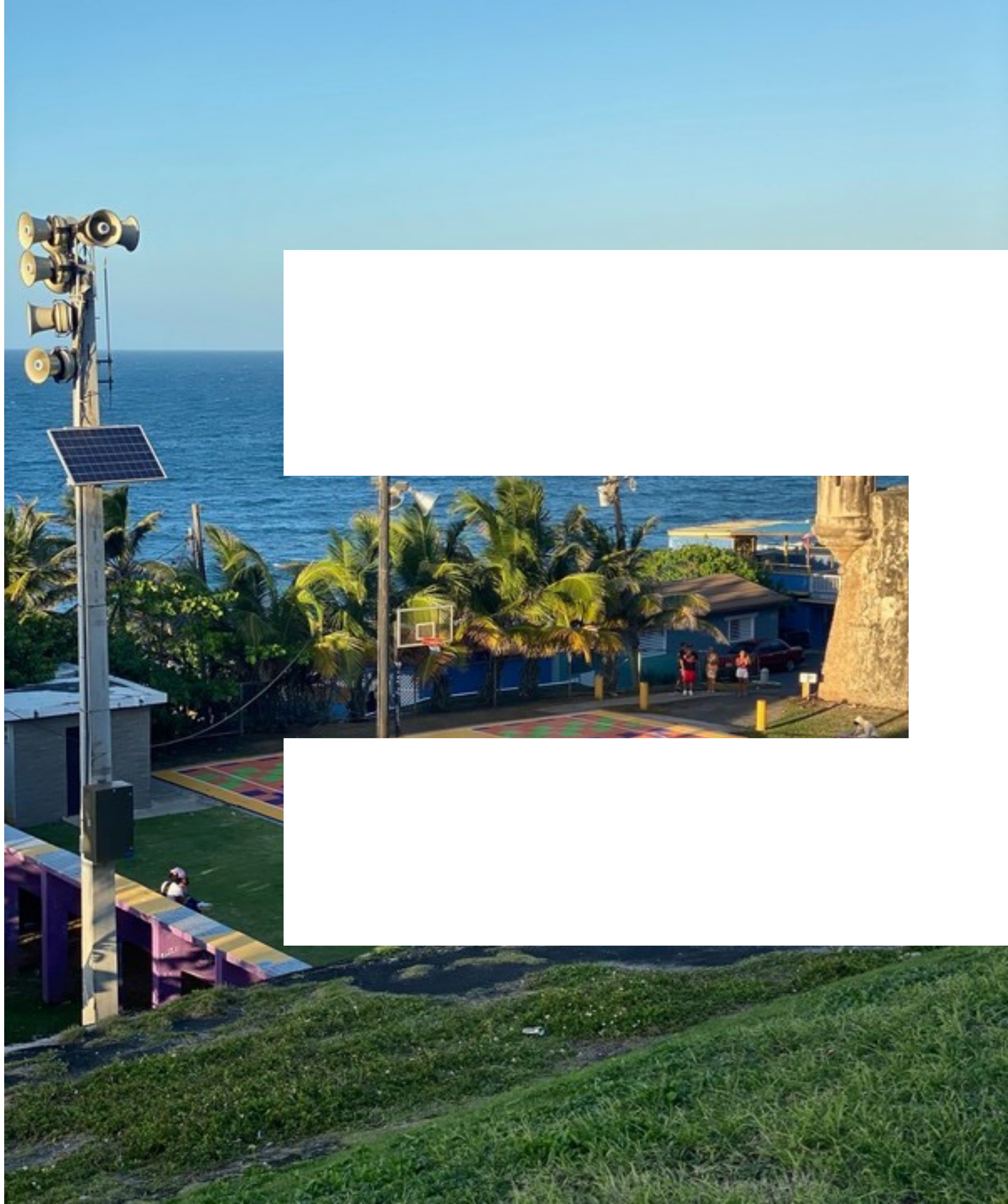
Measures to mitigate the impact of temperature increase

- Install panels to allow air circulation (i.e., proper spacing) and construct them a few inches above the roof so convective air flow can cool the panels. Optimal angle and orientation can maximize their exposure to sunlight while reducing the likelihood of overheating.
- Use cooling techniques, both active (water based and forced air circulation) and passive (heat sinks, reflective coatings with light-colored materials), to reduce heat absorption.
- Select PV panels with a low-temperature coefficient.
- Take advantage of innovations in solar panel materials and designs such as bifacial solar panels which have lower temperature sensitivity.

1.7 Solar cells efficiency

Sources: Hossain et all, 2020, New Design of Solar Photovoltaic and Thermal Hybrid System for Performance Improvement of Solar Photovoltaic, press search; Kearney Energy Transition Institute analysis

2. Solar PV systems



Applications and grid integration

The electricity produced by the solar panels is retrieved through the **balance of system** (BOS) components and sent to the grid or the consumer. **External losses occur** in wiring and BOS devices.

There are many different PV plant designs possible; they can be **on-grid or off-grid**. PV plants can be tied to the power grid (on-grid) or built independently from the power grid (off-grid).

Utility-scale PV plants are the most common PV plant design. Numerous panels are installed on large surfaces. Panels are often built with sun tracking devices, ensuring a direct irradiance from the sun during most of the day, maximizing the electricity output (up to 30%). The largest utility-scale plants have around **2 GW capacity**. Utility-scale PV plants have a considerable land footprint. Therefore, new designs are made to build plants on already used lands or surfaces.

These designs include **building-integrated PV,** panels designed within a building for self-consumption; **shades** which are built to provide cover from the sunlight; **agrivoltaics**, which combine the construction of a PV plant on crops, enabling agricultural development as well as electricity production; and **floating PV,** which was developed to generate electricity on water bodies.

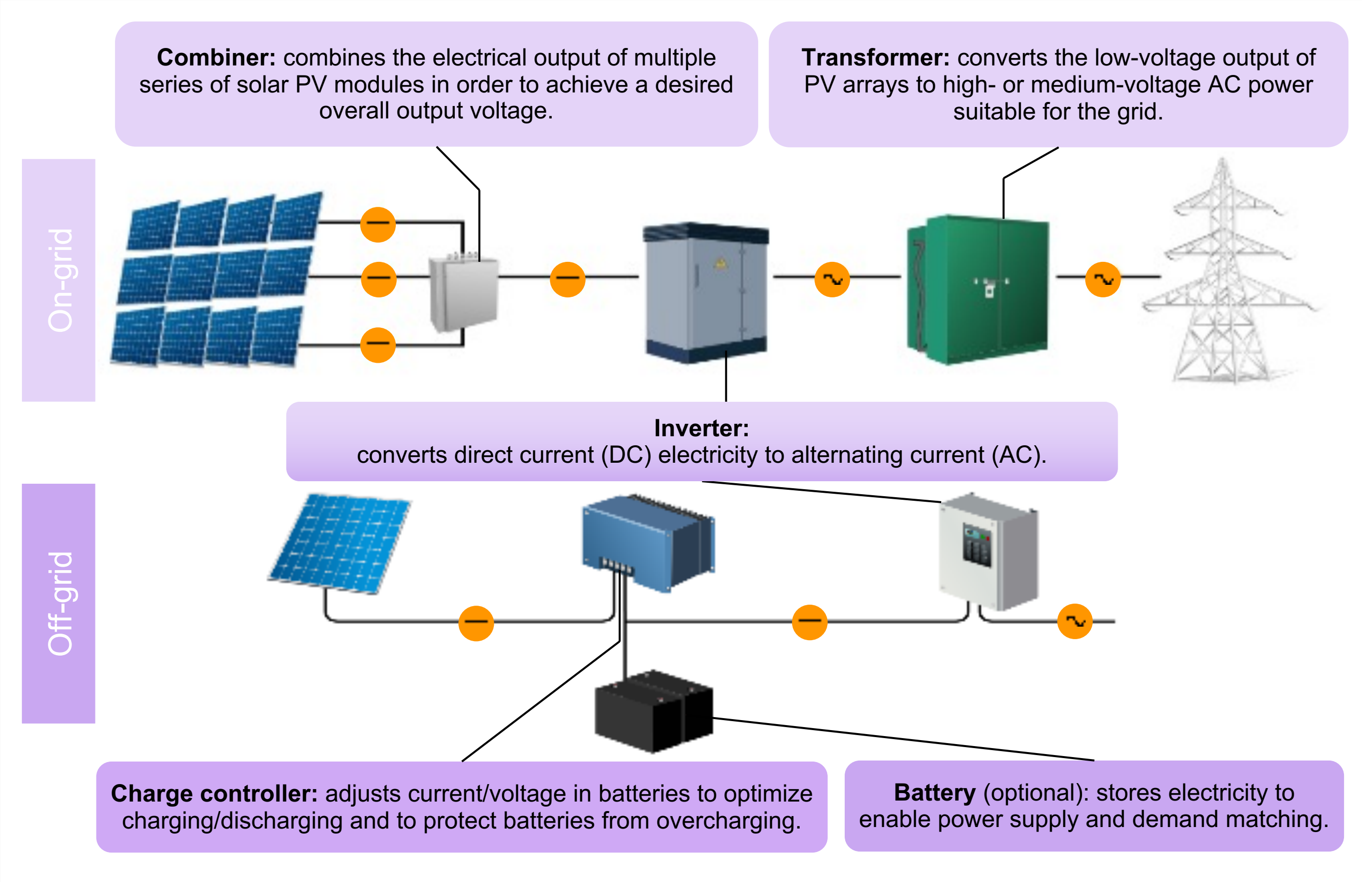
Off-grid applications correspond to PV systems that can come as **stand-alone** or **mini-grid**. These configurations offer **autonomy** and provide **electricity to remote areas, but at the expense of energy security** (intermittency of local supply).

As a variable electricity source, solar PV can be complemented with other technologies to ensure a more stable electricity supply—for example, with **wind power or an electricity storage facility**.

Photovoltaic panels can be allied to other devices to serve a specific purpose reducing greenhouse gas emissions. **Water pumps, desalination plants, and heat pumps** require electricity to operate; solar PV is an alternative to ensure they operate without emissions.

PV panels are integrated into power circuits with various electrical components

Main electrical components of PV systems



Combiner: combines the electrical output of multiple series of solar PV modules in order to achieve a desired overall output voltage.

Transformer: converts the low-voltage output of PV arrays to high- or medium-voltage AC power suitable for the grid.

Inverter: converts direct current (DC) electricity to alternating current (AC).

Charge controller: adjusts current/voltage in batteries to optimize charging/discharging and to protect batteries from overcharging.

Battery (optional): stores electricity to enable power supply and demand matching.

Electrical equipment is a critical component of solar PV balance-of-system (BOS). Its purpose is to collect power from the PV modules and transfer it to the grid or to the point of use in a reliable and safe manner.

On-grid solar panels are linked to the electrical grid. PV panel owners can share the excess electricity produced to the grid and use electricity from the grid when there is no sun. **Off-grid** systems work independently from the power grid and usually store electricity in batteries. Depending on the configuration, **different electrical components will be required.**

Electricity collection and conversion necessarily means energy loss.
The main losses inside a solar PV system are:

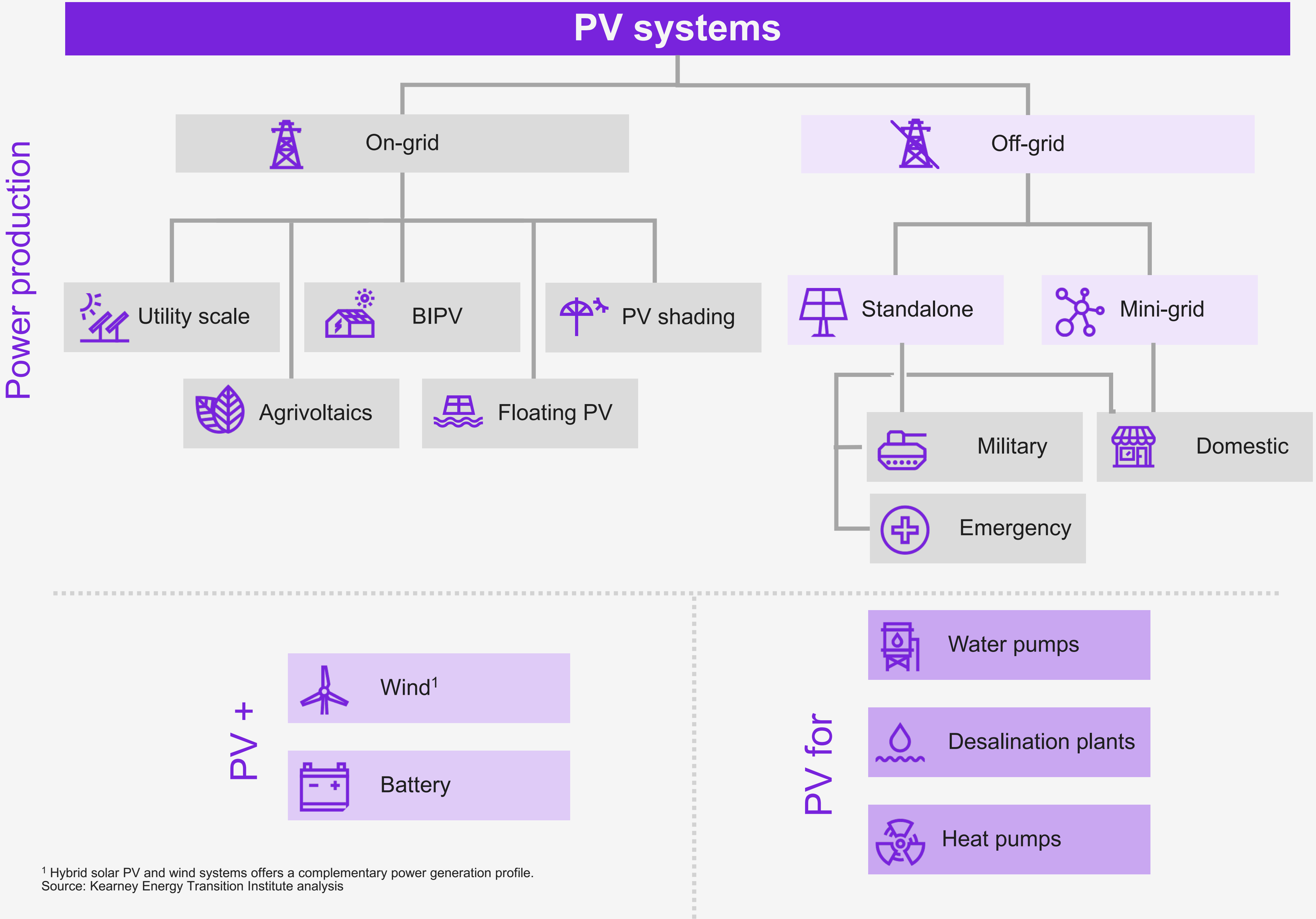
– Energy loss due to panel assembly
– Heat loss in wires
– AC/DC conversion loss
– Grid transformation loss
– Electricity storage loss

Sources: MIT (2015), “The Future of Solar Energy”; Rocky Mountain Institute (2010), “Achieving Low-Cost Solar PV”; IEA (2014), “Technology Roadmap Solar Photovoltaic Energy”; Energy.gov (accessed June 2015), “Balance-of-System Equipment Required for Renewable Energy Systems; Kearney Energy Transition Institute analysis

There is a wide range of solar PV systems; these have different applications and uses depending on local needs

Solar PV technology offers a high degree of **scalability and modularity** suiting varied customer demands ranging from smaller individual solutions (including pico-solar devices and residential rooftops) to commercial installations to large utility-scale projects.

2.1 PV applications



PV systems

Power production

- On-grid
  - Utility scale
  - BIPV
  - PV shading
  - Agrivoltaics
  - Floating PV
- Off-grid
  - Standalone
    - Military
    - Emergency
    - Domestic
  - Mini-grid
    - Domestic

PV +

- Wind[1]
- Battery

PV for

- Water pumps
- Desalination plants
- Heat pumps

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[1] Hybrid solar PV and wind systems offers a complementary power generation profile.

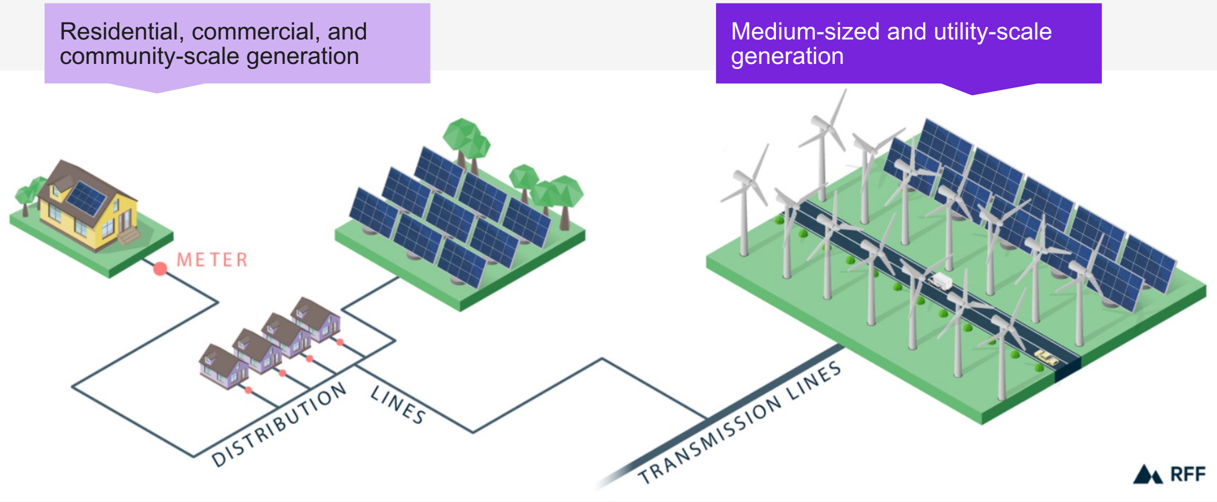
Source: Kearney Energy Transition Institute analysis

On-grid systems are designed in various forms to ensure power to the end users

On-grid PV systems are systems connected to the power grid. This configuration allows users to benefit from the **electricity grid** when there is no sunlight availability. Moreover, with **net metering devices**, systems can provide the electricity produced in excess back to the grid.

On-grid systems can be found under **two forms** depending on the proximity and purpose of the power plant: centralized or distributed.

Schematic view of centralized and distributed PV systems



Residential, commercial, and community-scale generation

Medium-sized and utility-scale generation

Share of on-grid system type, 2022

- **Centralized systems** are large-scale plants built in non-urban areas, where there is good resource availability to generate a large amount of power. Thanks to their size, these plants benefit from return to scale effect. Over a certain capacity (depending on countries or companies), plants are considered utility scale, and these can be presented in different forms including traditional ground mounted or other innovative structures such as floating and agrivoltaics.[1]
- **Distributed systems** are systems intended to produce electricity near the site of consumption. They are often built on roofs or near residential/commercial/industrial areas and have lesser output that centralized (usually <1MW) due to space constraints. Systems can be integrated in buildings or installed in rooftops but can also be small plants close to consumption areas.

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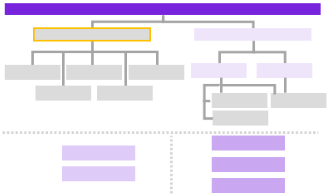
[1] Most references define utility scale with capacity from 1MW to 50MW. The most common definition is 1MW from SEIA and 5MW from NREL.

Sources: IEA PVPS, 2023, Trend in photovoltaic applications; The Wood Institute – Stanford, 2010 Distributed vs centralized power generation; Kearney Energy Transition Institute analysis

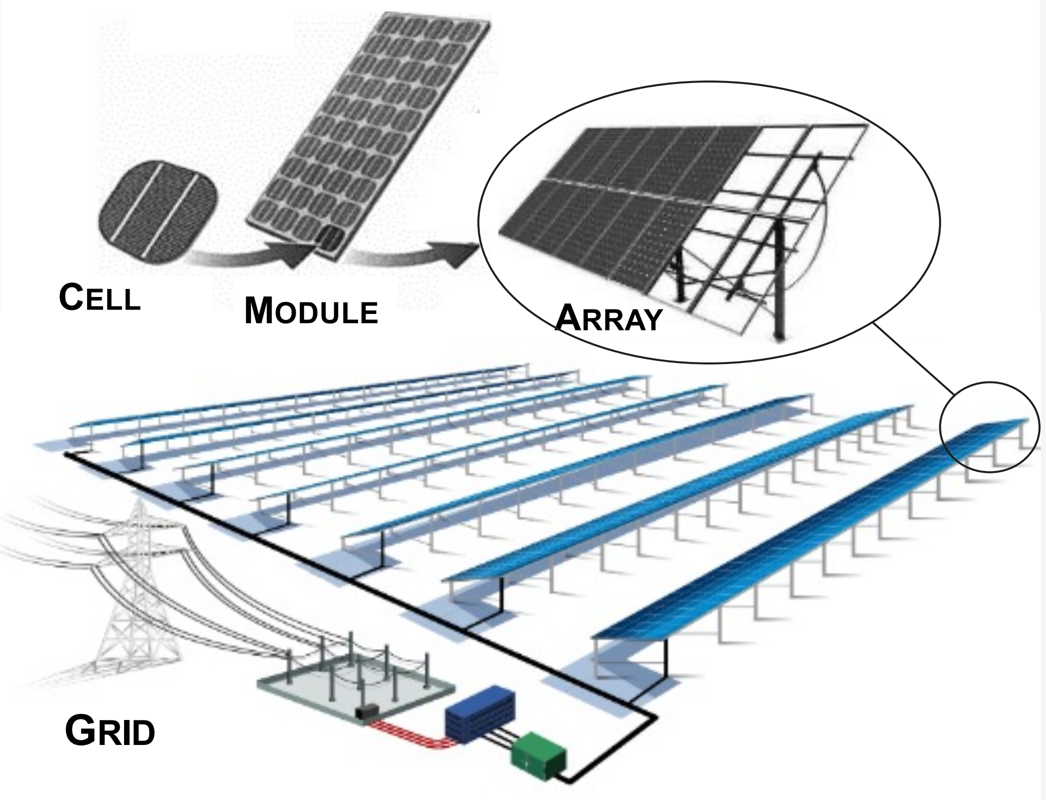
PV modules, made up of cells, form a PV system once combined with application-dependent system components



Wp or **watt peak** represents the maximum power output of a solar panel under standard solar irradiation.

2.1 PV applications

Main components for grid-connected PV systems



The main components of solar PV systems are photovoltaic solar cells, modules, and application-dependent components, known as balance-of-system. BOS encompasses both the structure supporting the modules (support track) and the electrical system required to collect, convert, and transfer the electricity to the grid or to the point of use (e.g., switches, inverter, wires…).

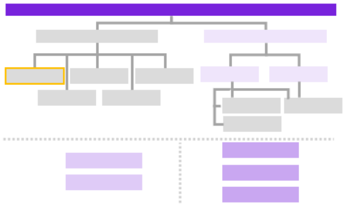
BOS structural components vary depending on system configuration. Systems can be ground-mounted or installed on a rooftop and can include a system to follow the sun (tracking) or can be fixed. Similarly, electrical components vary, depending on whether the solar panels are off-grid or grid-connected.

Solar cells typically have a size of 15cm x15 cm and produce 4–6 watts under peak illumination.[1] Solar cells are interconnected to form a PV module to gather the collective output. Typically, a module consists of 60–70 solar cells, forming a 1mx1.6 m solar panel. These panels generally have efficiencies around 18–23%, with an output from 350 to 450 Wp and a 25- to 30-year lifespan. Modules are then connected to form arrays.

[1] Solar irradiance of 1 kW /m², air mass 1.5 and a PV cell temperature of 25°C

Sources: MIT (2015), "The Future of Solar Energy"; IPCC (2011), "Special report on renewable energy"; IEA (2011), "Solar Energy Perspectives"; Kearney Energy Transition Institute analysis

Utility-scale projects are the main projects built worldwide



- Utility-scale PV are large projects generating electricity to the grid. These power plants have a **capacity of at least 1 MW** (according to NREL standards). In 2023, a total of **434 GW** of solar farm were installed.
- In 2023, utility-scale PV plants are expected to represent **about 55% of the total PV installed capacity**. Most power plants use crystalline silicon solar panels with **solar tracking technology (~90%).**
- Utility-scale PV is usually built on large, plane, and unused lands (this type of panel is called **ground-mounted**). However, criticisms arise because of the waste of land; new plants are now designed to **synergize with other land usage**.

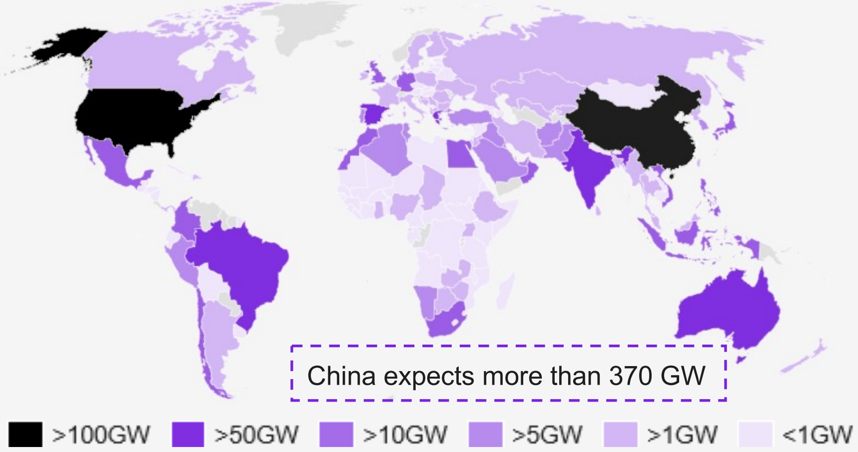
World's largest solar parks (2021)[1]

Solar park name	Country	Capacity (MW)
Bhadla	India	2,245
Huanghe Hydropower Hainan	China	2,200
Pavagada	India	2,050
Benban	Egypt	1,650
Tengger Desert	China	1,547

Ground-mounted utility-scale plants are directly fixed to the ground, often requiring large spaces.

Upcoming solar PV utility-scale capacities

GW



China expects more than 370 GW

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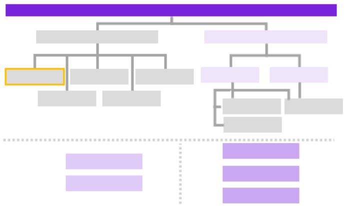
[1] Commissioning is hard to obtain exactly; here, we only give an estimation of operating capacity.

Sources: IEA, Renewables 2023, 2024; Global Energy Monitor, 2023 Global Solar Power Tracker; ISE Fraunhofer, 2023, Photovoltaics report; NREL; Kearney Energy Transition Institute analysis

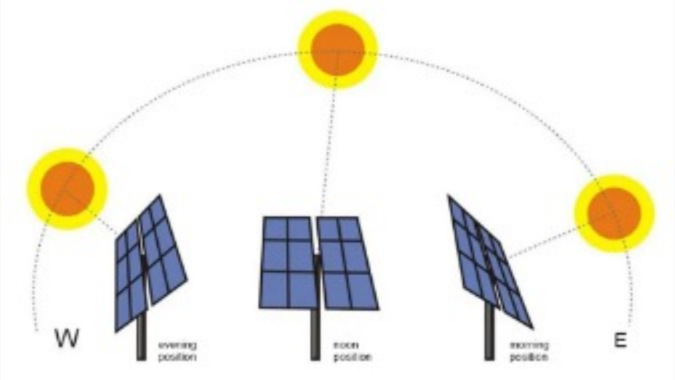
Solar tracking systems are numerous and improve power generation



Solar cell/panel efficiencies are given for ideal solar conditions. Under real conditions, **light incidence varies during the day**; ideal irradiance for a fixed panel lasts only for a limited moment during the day.

Solar tracking devices help collect the maximum incident light

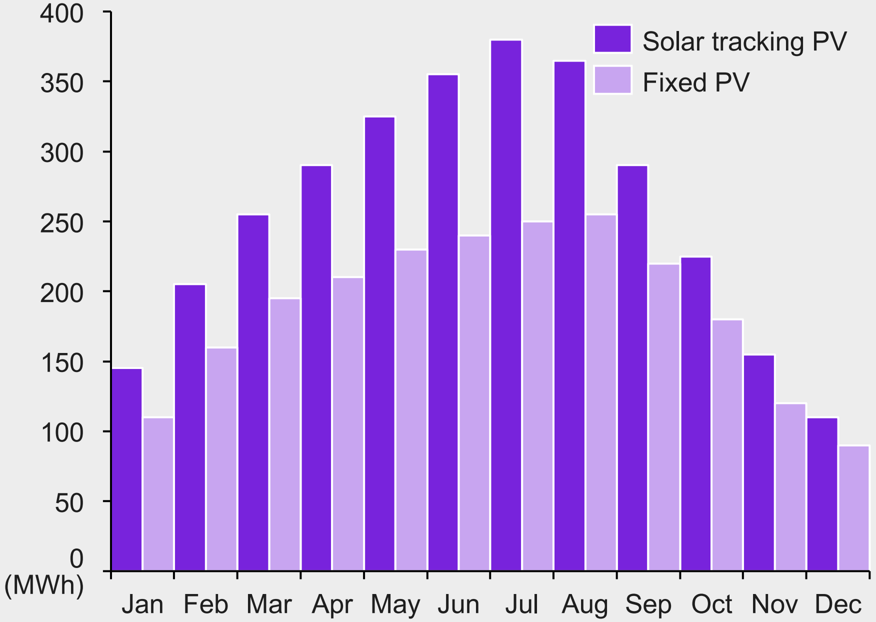
Solar tracking devices can be used to enable **the panel to follow the movement of the sun during the day** so that it constantly faces the sun.



However, tracking systems have constraints such as **high cost**, **supplementary maintenance**, and tracking is **not suitable for all topographies or weather.**

Conventional solar panel and solar tracking panel

Comparison in energy generation between fixed and solar tracking PV[1]



Several different solar tracking systems exist and adding these tracking devices can **increase solar panel efficiency up to 30%**; the more incident light reaches the panel, the more light can be converted.

Installing such tracking systems represents additional expenses which are estimated to **increase the cost of a solar power plant between 20% and 30%** compared to the fixed panel cost. The economic benefit of these solutions should be assessed on LCOE basis.

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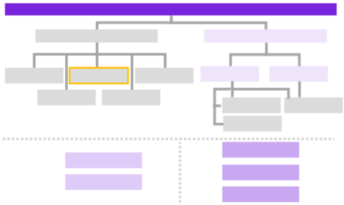
[1] The comparison is made between fixed panels and a dual axis solar tracking panels in Spain.

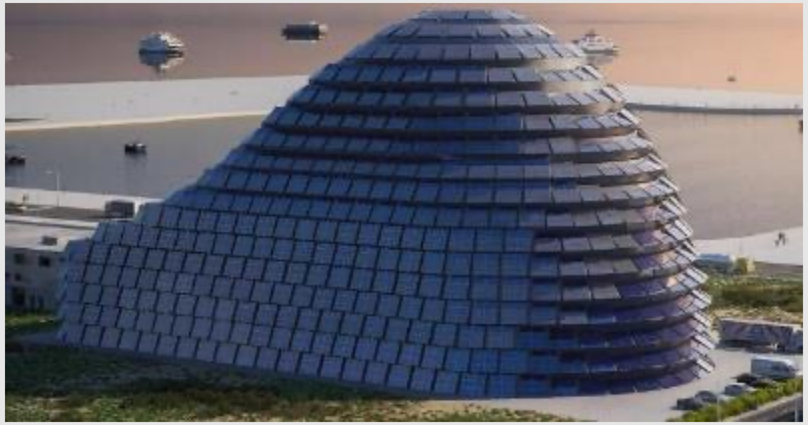
Sources: Fraunhofer ISE; Naval and Yusta, 2022, “Comparative assessment of different solar tracking systems in the optimal management of PV-operated pumping stations”, Renewable Energy; NREL; Kearney Energy Transition Institute analysis

Building-integrated PV (BIPV) is a common way to use PV in urban areas and reduce land footprint



BIPV technology can be integrated by replacing elements of a building. However, **BIPV efficiency is maximized when it is designed for the building from the beginning**.

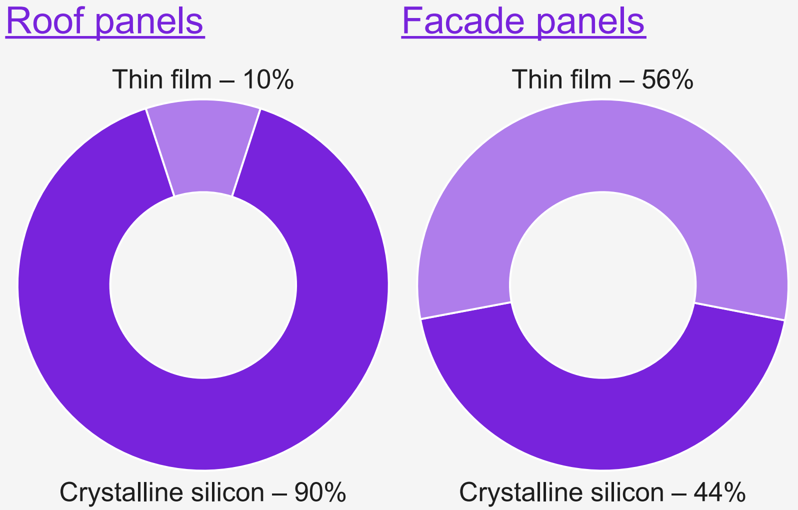
Buildings can be entirely covered by solar panels



- Building-integrated photovoltaics (BIPV) are developed to make buildings more energy-autonomous by producing their own electricity. Solar PV are built in, **replacing some components of the building** such as facades, windows, roofs, or sunshades. To note, we speak about building-added PV (BAPV) when PV are added to a building (but do not replace a part of the building).

- As the solar PV panels become the exterior layer of buildings, their purpose is not limited to electricity production and carbon footprint reduction—they also **help with sound and thermal insulation while providing shading for the building.**

Share of solar cell technology according to final usage



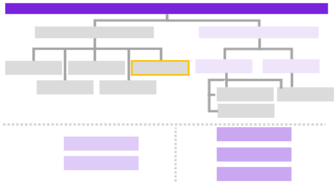
Roof panels

Facade panels

- Due to different definitions companies and countries give to BIPV, it is hard to have a clear estimation of worldwide installed capacity. Becquerel Institute estimated that **10 GW BIPV were installed in 2018**.
- Because new buildings can have some specific and unconventional designs, **thin-film technologies are generally used because of their flexibility and highly customizable properties** (especially for facades, where shapes are not necessarily flat and colors are wanted).
- In 2021, the **US BIPV market** was estimated to be **81% of roofing**.

Sources: BIPVBoost, 2019, Update on BIPV market and stakeholder analysis; Becquerel Institute & SUPSI, 2020, Building Integrated Photovoltaics: A practical handbook for solar buildings' stakeholders; SEIA; Kearney Energy Transition Institute analysis

PV shades are an alternative method to produce electricity and provide shade without using new spaces

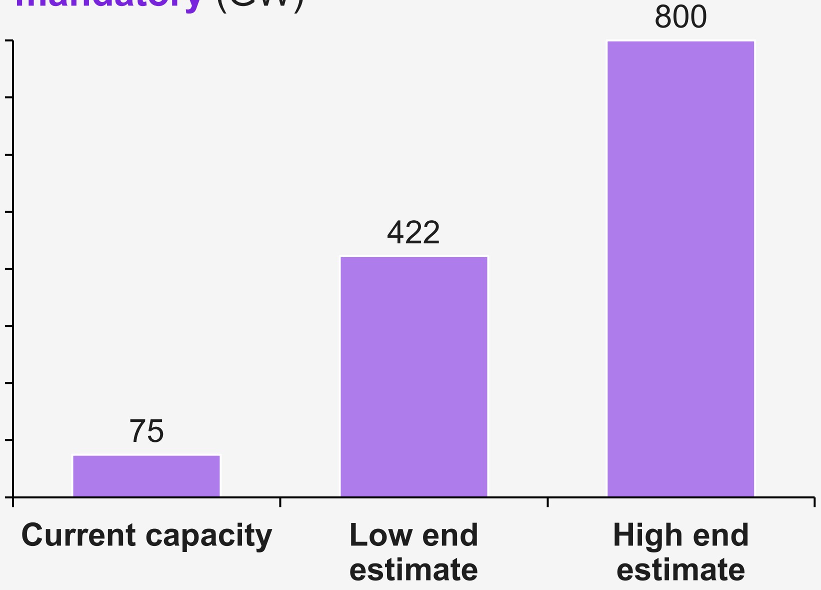


2.1 PV applications

- PV shades, also known as PV canopies, **generate electricity while providing shade** on human-built surfaces, such as parking or bus stops.
- These photovoltaic canopies have a high potential as they do not require modification of new natural land. **Canopies give to spaces additional properties**: shades from panels offer sun and rain protection and can also provide a recharge access to electric vehicles. Their major constraint is the **supplementary upfront cost of the installation**.

A growing number of parking lots are designed or repurposed with solar carports

Capacity estimation if US made carports mandatory (GW)



- To utilize built surfaces, some countries such as France have made **mandatory the deployment of solar carports for parking with a minimum surface.**[1]
- As parking represents a significant area of big cities, numerous carports can be installed to directly supply a city with electricity.
- PV canopies are easier to deploy than solar rooftop projects as they are **not constrained by weight limits and regulation**.

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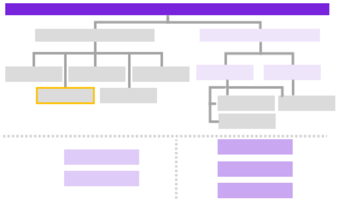
[1] Since March 10, 2023, France has made solar carports mandatory for parking with size greater than 1500 m².

Sources: PV Magazine, 2022, France introduces solar requirement for parking lots; Time Magazine, 2022, The Overlooked Solar Power Potential of America's Parking Lots; Kearney Energy Transition Institute analysis

Agrivoltaics integrate the use of solar PV production in the premises of agricultural production (1/2)



Definition

- **Agrivoltaic**, or agri-PV, is defined as **the design and use of solar panels on the same field as agricultural activities.**
- Agrivoltaics can limit the impact of traditionally ground-mounted solar PV on agricultural lands and limit energy–food competition.
- These PV systems produce electricity along with the growth of crops, vegetables, and fruits or for managing grazing, beehives, and greenhouses.
- The largest agrivoltaic plant is in the **Ningxia Province in China,** with a **capacity near 1 GW**.

Benefits and synergies of agrivoltaics

Benefits and synergies between crops and solar panels include:

- **Prevent soils from drying** (minimizing evaporation effect and limiting wind erosion)
- **Protect crops from extreme weather** events
- **Improve yields for some crops under PV**
- **Reduce irrigation demand** by 20%
- **Allow rainwater collection**
- **Cool panels** thanks to convection effect
- **Increase bifacial panel efficiency** thanks to increased spacing for crops

Studies show that the full potential of agrivoltaics can be reached in **hot and dry climates**.

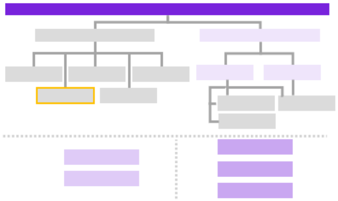
Agrivoltaics contribute to **biodiversity conservation** and reduce herbicide usage. The technology also allows for **integration of crops with animal breeding and grazing.**

---

[1] Agrivoltaics includes many different uses. Agrivoltaics can be installed in the same basic row layout as traditional large-scale solar plants, or they can be modified to provide extra space for light, animals, or farm equipment to move under and between them.

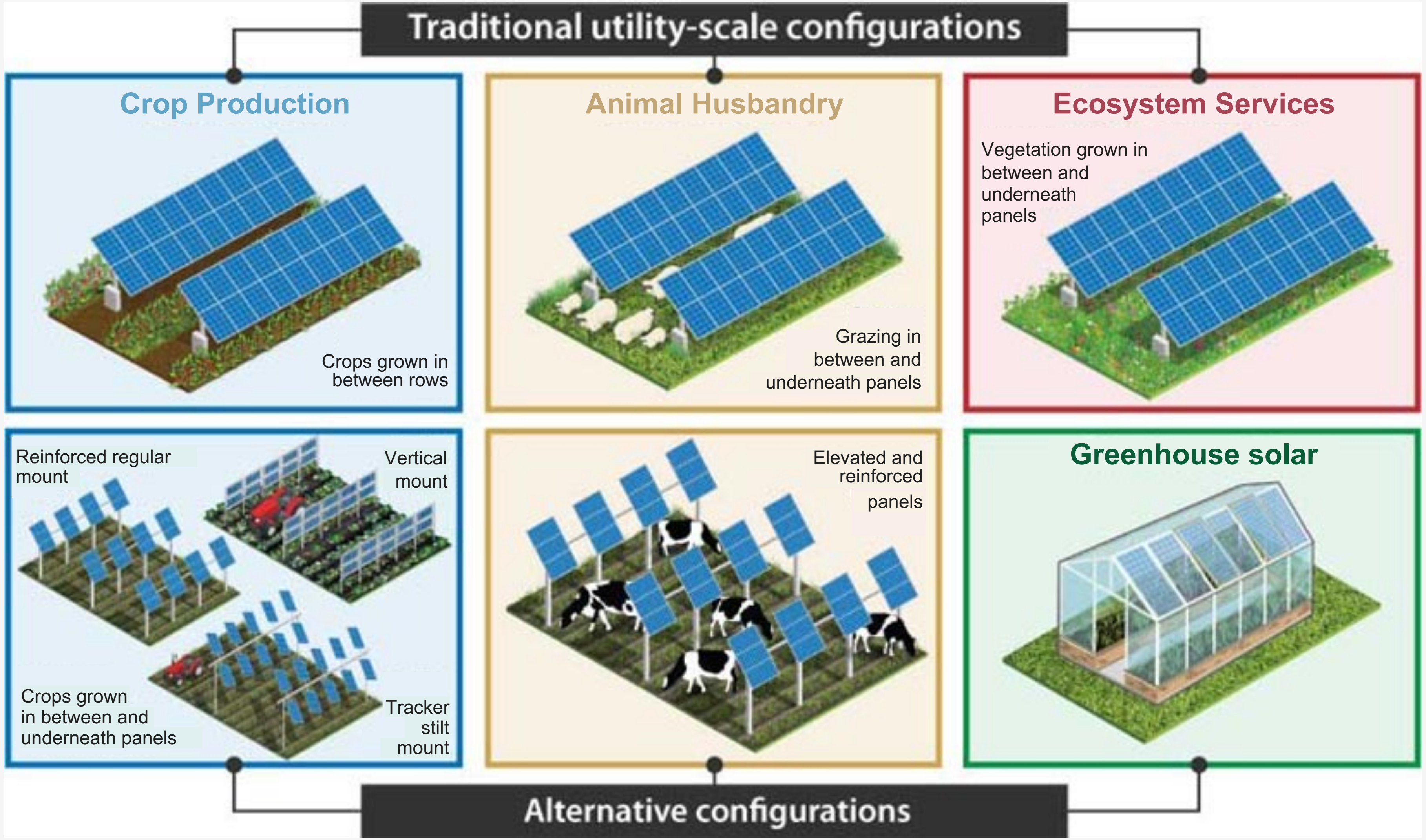
Sources: NREL, 2022, Growing Plants, Power, and Partnerships Through Agrivoltaics; Fraunhofer ISE, 2022, Agrivoltaics: Opportunities for Agriculture and the Energy Transition; Engie, 2022, Agrivoltaïsme, de la compétition à la complémentarité; Kearney Energy Transition Institute analysis

Agrivoltaics integrate the use of solar PV production in the premises of agricultural production (2/2)



In 2023, operating **agrivoltaics capacity** reached around **18 GW.**
It is estimated that **turning 1% of global cropland into agrivoltaics would meet total global energy demand.**

Agrivoltaics design depending on land usage[1]



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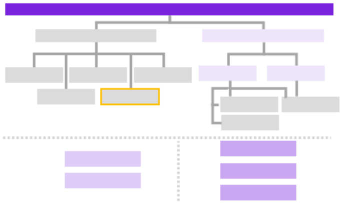
Floating photovoltaics is an alternative that uses the available surface of water bodies (1/3)

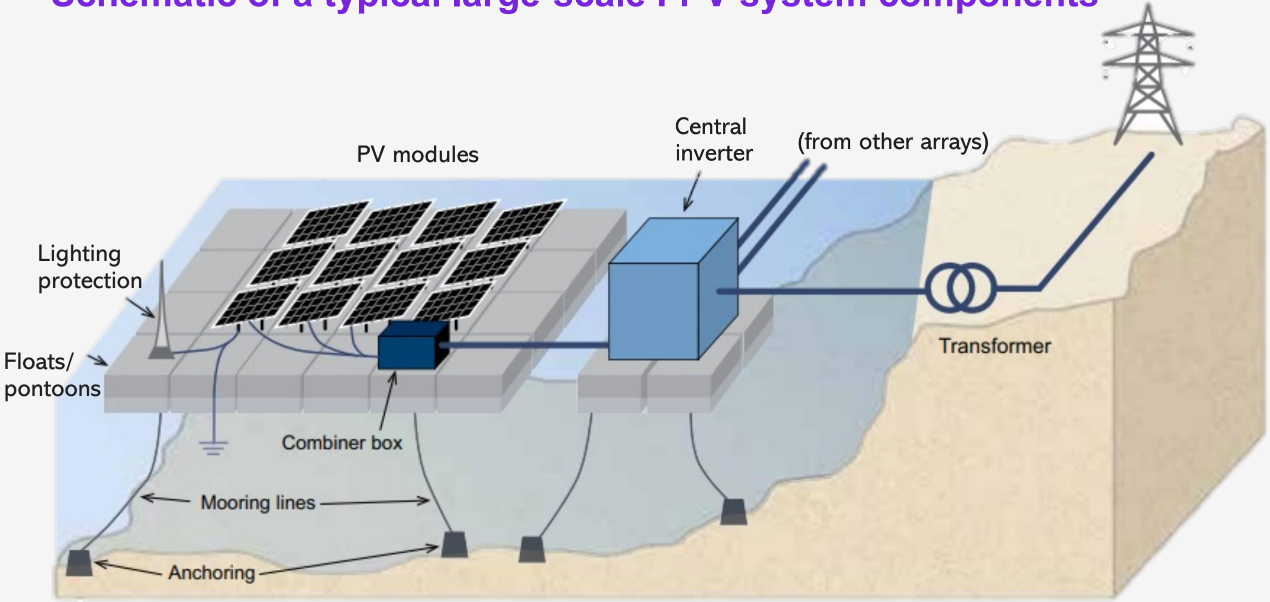


Floating PV can minimize land usage in countries/areas with scarce land and/or land where ground-mounted PV cannot be built (e.g., mountains), and water bodies are often closer than suitable lands.

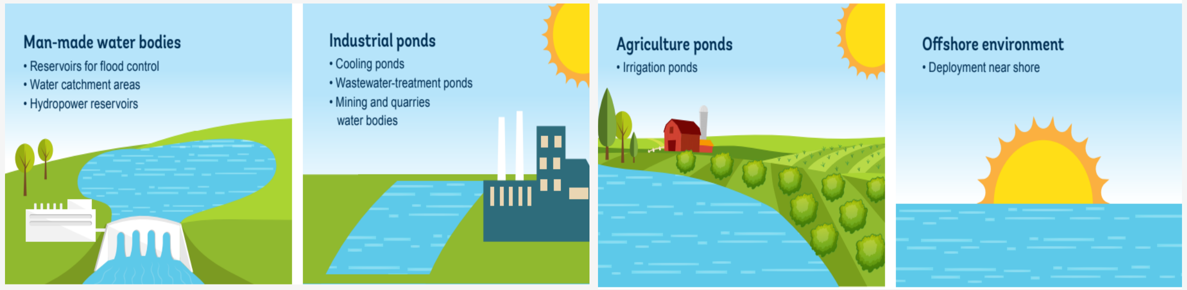
2.1 PV applications

Floating PV (FPV) correspond to photovoltaic panels built upon floating devices and deployed on water bodies (natural or artificial). These water bodies can be lakes, rivers, reservoirs, hydroelectric dams, industrial and agricultural ponds, water treatment tanks, submerged mines, and even near shore sea. Further, the cooling effect of water bodies makes solar panels more efficient.

Schematic of a typical large-scale FPV system components



Possible floating PV applications

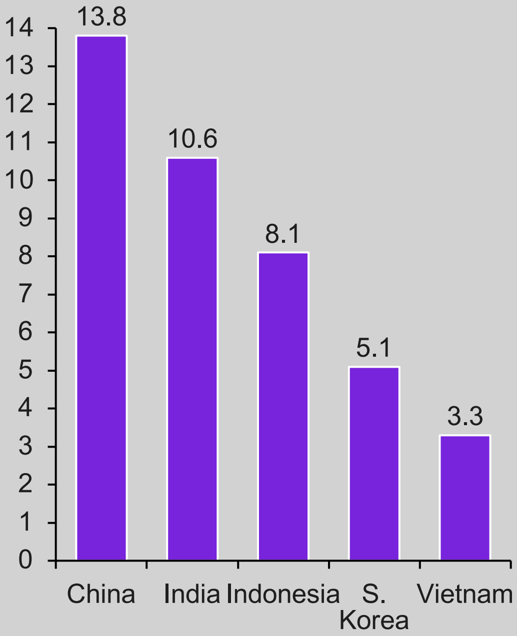


Sources: DNV, 2022, The future of floating solar: Drivers and barriers to growth; World Bank, 2019, Where Sun Meets Water - floating solar market report; E. Cuce and all, 2022, Floating PV in terms of power generation, environmental aspects, market potential and challenges, Kearney Energy Transition Institute analysis

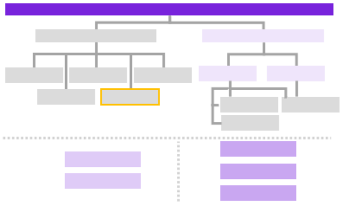
Floating PVs were developed first in Asia in countries with limited space and usable lands (e.g., Japan and South Korea). In 2023, **worldwide operating floating PV capacity** reached around **3 GW**. Most **floating PV projects are announced for Asia.**

Forecast total floating PV capacity

GW, 2031



Combining water bodies and solar panels has several synergies (2/3)



The usage of solar panels on water bodies can help **enhance water quality** while **solar panels highly benefit from the presence of water** beneath.

Influence of water

- **Solar panels are naturally cooled** thanks to presence of water and wind, **making them more efficient.**[1]
- Floating panels that do not require anchoring or mooring are **easier to install than ground-mounted panels**.
- Water body areas are often less dusty than land areas, **preventing panels from shading losses**.

Influence of PV

- By covering part of incoming sunlight and wind, **solar panels reduce water evaporation** (which can represent up to 40% water loss).
- The reduction of incoming sunlight from solar panels leads to a reduction of water temperature. **Both reductions help prevent algae growth**, increasing water quality.

Floating solar PV is still a **new technology, long-term effects are still uncertain,** and its installation comes with various challenges:

- Floating devices have higher costs. These projects are only designed for **utility-scale size.**
- **An anchoring and mooring system** can add additional installation costs because of the potential high variability of water level and currents.
- Floating PVs require **additional operation and maintenance**.
- Floating solar panels have **electrical safety issues** because of water immersion.
- Floating systems have a **shorter lifespan than traditional ground-mounted PVs** due to humidity and salinity (for off-shore/near shore FPV).

Dezhou Dingzhuang, the largest floating solar farm in China, has 320 MW capacity

2.1 PV applications

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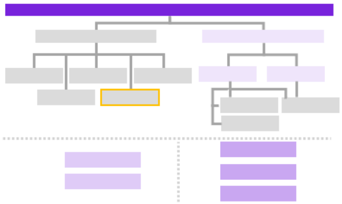
[1] Most solar cells lose efficiency when heated

Sources: DNV, 2022, The future of floating solar: Drivers and barriers to growth; World Bank, 2019, Where Sun Meets Water - floating solar market report; Kearney Energy Transition Institute analysis

Offshore floating PV benefits from the immense ocean surface, but requires it to endure conditions due to tidal, wind, and salt (3/3)



Several companies are exploring this new alternative to deploy solar PV all over the world. Companies like Solarduck, Tractebel, Ocean of Energy, Tokyu Land Corporation, and RWE have started finalizing designs and operating pilot plants.

Off-shore floating

Floating PV benefits from spaces with ideal irradiance and cooler temperature, ensuring a better electricity production.
Offshore PV has additional advantages such as vast space availability, good average irradiance due to improved conditions, and increased cooling effect due to streams.
However, offshore PV panels must be designed to **resist high waves and strong wind as well as corrosion from salt,** which is expected to increase their cost and maintenance.

SolarinBlue – Sun’Sète

The Sun’Sète project, deployed in the Mediterranean Sea in France, is designed to withstand 12-meter waves and 200 km/h winds.

The first module was launched in March 2023, and when the installation will be completed with 25 modules, the plant will reach a 300 kWp capacity and occupy a surface of half a hectare.

The estimated production should reach 400 MWh/y.

CIMC Raffles

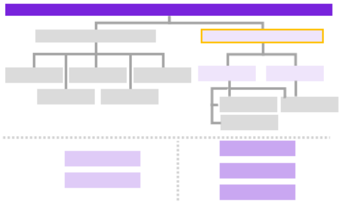
China is the country with the largest onshore floating PV capacity and has now entered the test deployment phase for its offshore PV plants.

CIMC Raffles, a Chinese company, has launched its offshore solar plant. It is the first semi-submersible floating offshore PV plant in Yantaï City, in China.

One platform consists of 4 arrays of ~2,000 m², with capacity of 400 kWp, withstanding 6.5m tidal and 120 km/h wind.

Sources: PV magazine, 2023, Floating solar tech for harsh offshore conditions; Taiyang News; CIMC website; Kearney Energy Transition Institute analysis

Off-grid PV systems are autonomous systems producing electricity for specific purposes



Off-grid telecom sites can feature solar alone or also include a Genset and use solar to offset diesel/propane costs.

This is especially useful in Africa where infrastructure is lacking.

2.1 PV applications

Off-grid PV systems use solar panels to provide electricity without relying on the power grid. Those systems form **a cluster to provide electricity for a specific device or purpose**.

Off-grid systems offer consumers **autonomy** toward power grid or fuel resource. Also, off-grid systems give an electricity **solution to remote areas or for nomad applications**.
However, the energy production is dependent of **incoming sunlight**. Thus, some systems **integrate batteries to store the excess electricity** produced and ensure energy availability when there is no sunlight.

In 2023, about **3 GW of solar PV capacity for off-grid systems** were installed worldwide, especially in **emerging countries**, facilitating access to electricity for millions of people.

Off-grid ensures affordable electricity in developing countries

Mini-grids are self-reliable power systems

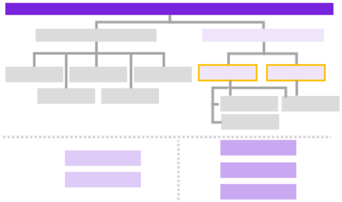
Mini-grids are **small-scale power systems** designed to **power a specific location or purpose**, with the possibility of being connected or islanded from the general grid. Small mini-grids are also called **micro-grids**.
With solar PV panels, PV mini-grids have **numerous applications**, from powering buildings and remote off-grid sites to supplying power during emergencies and military purposes.

Batteries are often added to mini-grids to ensure **power reliability** anytime despite the time of day and the weather.
In 2020, **half of mini-grid projects were solar powered**.

Mini-grids offer reliable power to places where grids don't reach

Sources: IEA PVPS, 2019, Optimal Integration of Photovoltaics in Micro-Grids that are dominated by Diesel Power Plants; IEA PVPS, 2011, Social, Economic and Organizational Framework for Sustainable Operation of PV Hybrid Systems within Mini-Grids; MIT, 2012, "The microgrid"; Mini-grids partnership, 2020, State of the global mini-grid market ; Kearney Energy Transition Institute analysis

Despite being a niche industry, off-grid PV systems offer electricity to areas where power lines do not reach



United Nations Sustainable Development Goal 7 (SDG7) aims for universal electricity access by 2030.

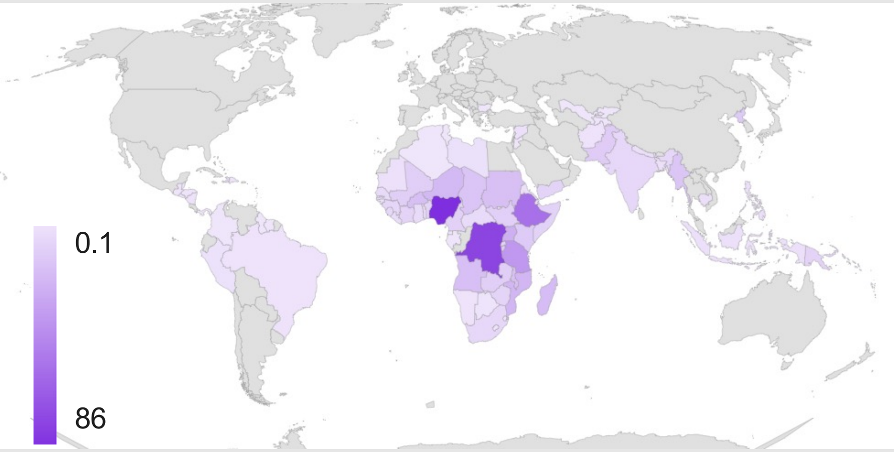
In 2022, around 785 million people did not have access to electricity according to the World Bank definition of electricity access[1]. It was the first time in years that this number increased.

In 2021, **about 100 million people had electricity access thanks to off-grid PV.**

Those devices can be financed with different payment methods; usually people pay the PV system through monthly installments.

Number of people without access to electricity[1]

In millions, 2021



Solar PV power generation in remote area in Africa

In 2023, off-grid PV represented about **8.5 GW worldwide, mainly in emerging countries**.

Off-grid systems help populations access additional devices to ensure greater comfort.

Most wanted appliances and features[2]

- More light
- TV
- Fridge
- Fan

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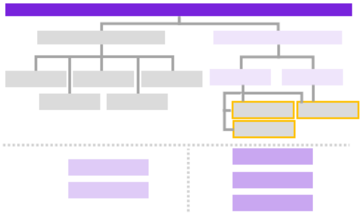
[1] World Bank defines the access to electricity as having at least 22kWh yearly consumption for task lighting and phone/radio charging.

[2] Wanted devices are given for three regions: East Africa, West Africa, and South Asia.

Sources: IEA, 2023, Guidebook for Improved Electricity Access Statistics; World Bank; SDG7; IRENA, 2022, Off-grid renewable energy statistics 2022; Kearney Energy Transition Institute analysis

PV has big potential to power remote or excluded places, for specific interventions or emergencies



With its transportability, autonomy, and resource availability, solar panels have numerous applications; PV are very useful after natural disasters or for military purposes. They help address operational vulnerability in situations where fuel supply can be difficult/challenging.

2.1 PV applications

PV for military proposes multiple benefits:

- Solar panels offer power autonomy from the grid, **minimizing human or natural threats on army bases** (due to grid connection).
- Furthermore, military bases often have **vast unused spaces** that can be converted into solar farms.
- New **self-powered equipment respond to the needs of army missions in** remote places.

US Department of Defense has heavily invested in micro-grids, representing around **30% of the micro-grids market in the US**.

Several armies have renewable energy strategies

Portable solar panels can be deployed everywhere

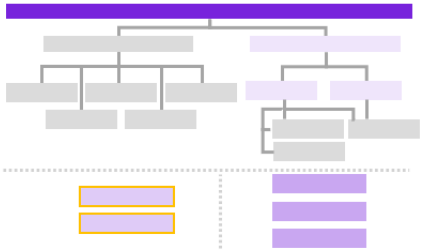
Photovoltaic portable devices can power supply during **emergencies or** after natural disasters.

Portable PV can replace grid as a **power backup solution** in the event of **power outages**. These can power **shelters, telecommunications, refrigeration units, water pumping or lighting,** among others**.**

Such installations can also be used in the **context of humanitarian aid, reducing fuel wood and cook stoves.**

Sources: REN21, 2022, Renewables 2022 Global Status Report; US Department of Defense, 2022; Le Figaro, 2023; Meister, 2013, Solar PV emergency and resilience Planning; World Economic Forum, 2018, Solar power is being used for disaster relief. Here's how; Kearney Energy Transition Institute analysis

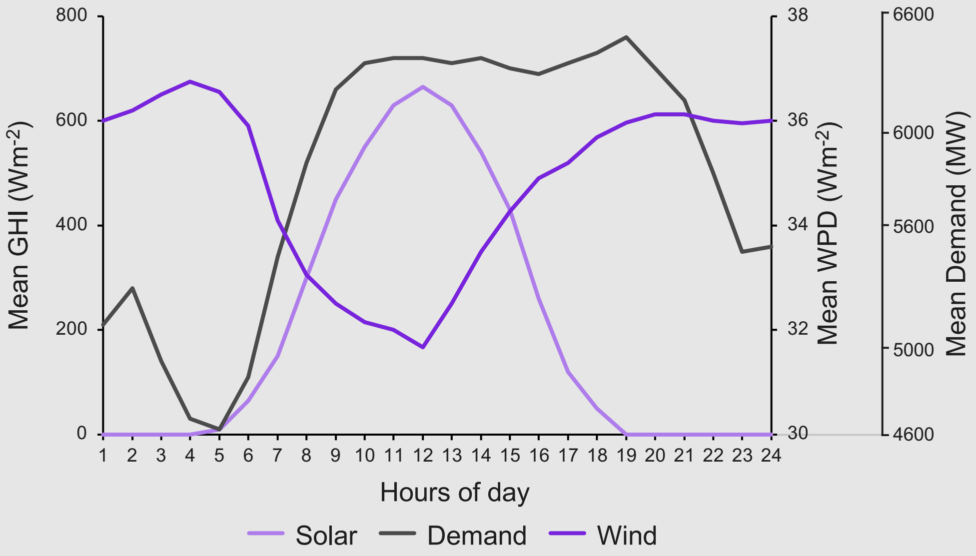
When there is no sunlight there are complementary solutions to store or produce electricity



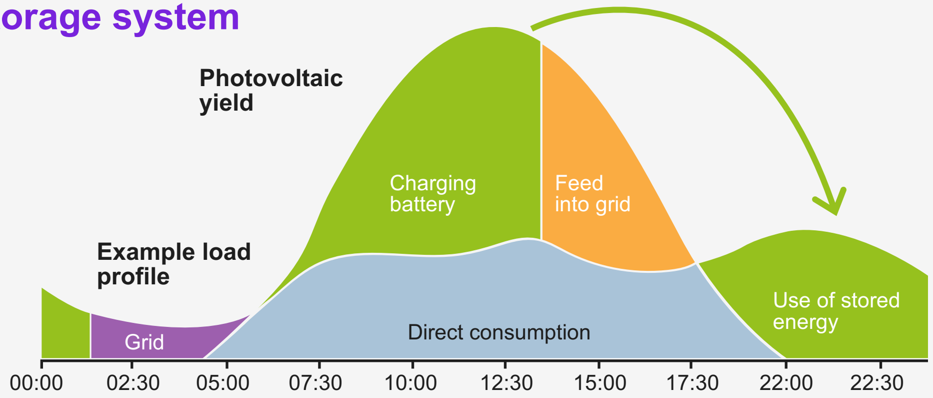
Solar and wind cycles tend to be complementary as there is usually more wind during night-time and winter. Colocation of wind turbines and solar PV plants **increases electricity generation while offering a more stable, predictable, and dispatchable output**.

Building both solar and wind farms can reduce **parts of the balance of system costs such as land, grid interconnection infrastructure, or even permitting procedures. Cost saving can reach up to 13% for capex and 16% for opex.**

Wind and solar daily cycle



Example of electricity management from a PV + storage system



Because solar panels only generate electricity during daytime, adding a **battery gives the opportunity to have electricity around the clock by storing the excess electricity produced.**

PV + battery systems could **increase self-consumption and reduce the electricity bill from 30% up to 60%.** However, it comes with additional investments and environmental costs (energy payback time is increased by 21% compared with PV only).[1]

2.2 PV synergies

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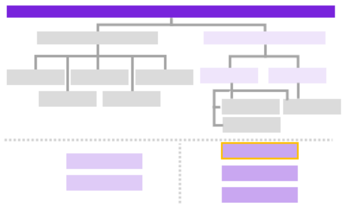
[1] Energy payback time (EPBT) represents the time required for the device to produce the equivalent amount of non-renewable energy necessary to the device production.

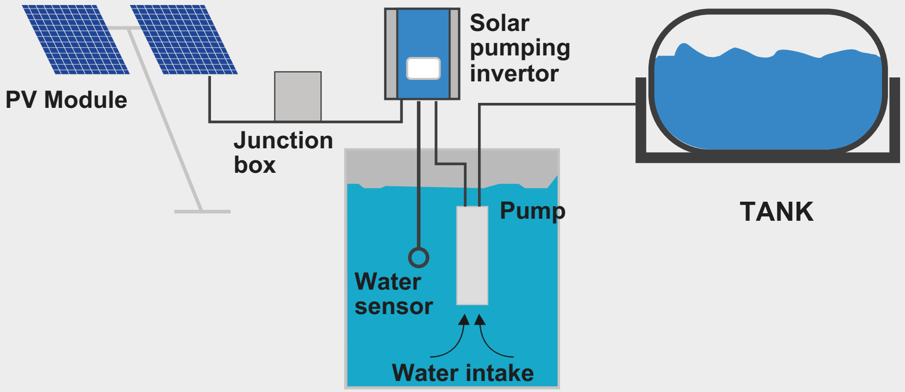
Sources: Stanford Precourt Institute for Energy; GreenBusinessWatch; NREL, 2021, Potential infrastructure cost savings at hybrid wind plus solar PV plants; NREL, 2022, Wind and Solar Hybrid Power Plants for Energy Resilience; Kearney Energy Transition Institute analysis

PV can power appliances with specific purposes such as water-pumping devices



Water pumps are usually motor-based, functioning with fuel, thus emitting GHG. Electric pumps are an alternative that, combined with PV systems, can **provide water while ensuring a reduction of carbon emissions**.
Recent solar PV cost reduction and electric pump improvements make **solar pumping systems more affordable and efficient**.
Despite its **higher cost of acquisition**, solar pumping systems **remain cheaper** in the long run, with less operating and maintenance costs required compared to traditional diesel systems.
To ensure water availability all day, photovoltaic pumping systems are often **built with water tanks.**

Solar pumping systems use solar panels to power a water pump

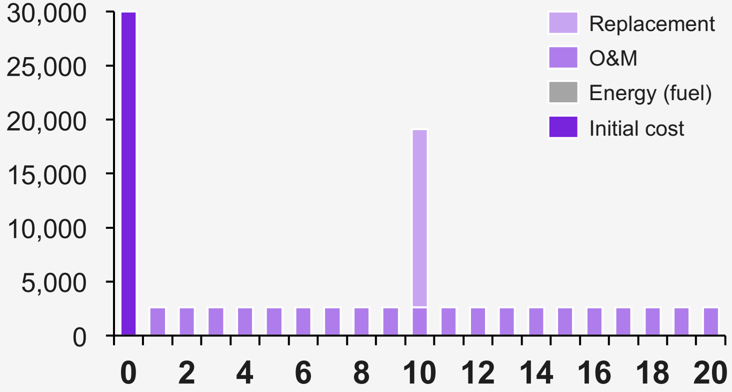


The following theoretical analysis shows that investing in **a PV pumping device can be up to half the price of fuel-based systems** in the long run.

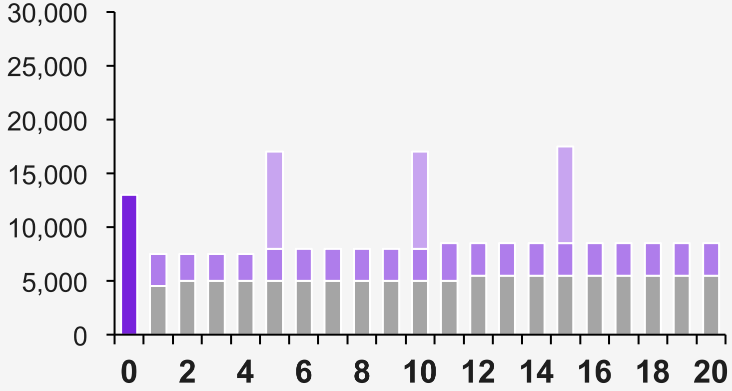
Theoretical cost analysis between PV and fuel-pumping devices

Annual cost (USD), by expenses type

PV pumping device

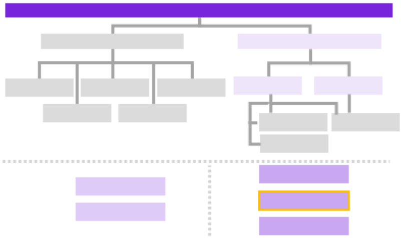


Traditional fuel-pumping device

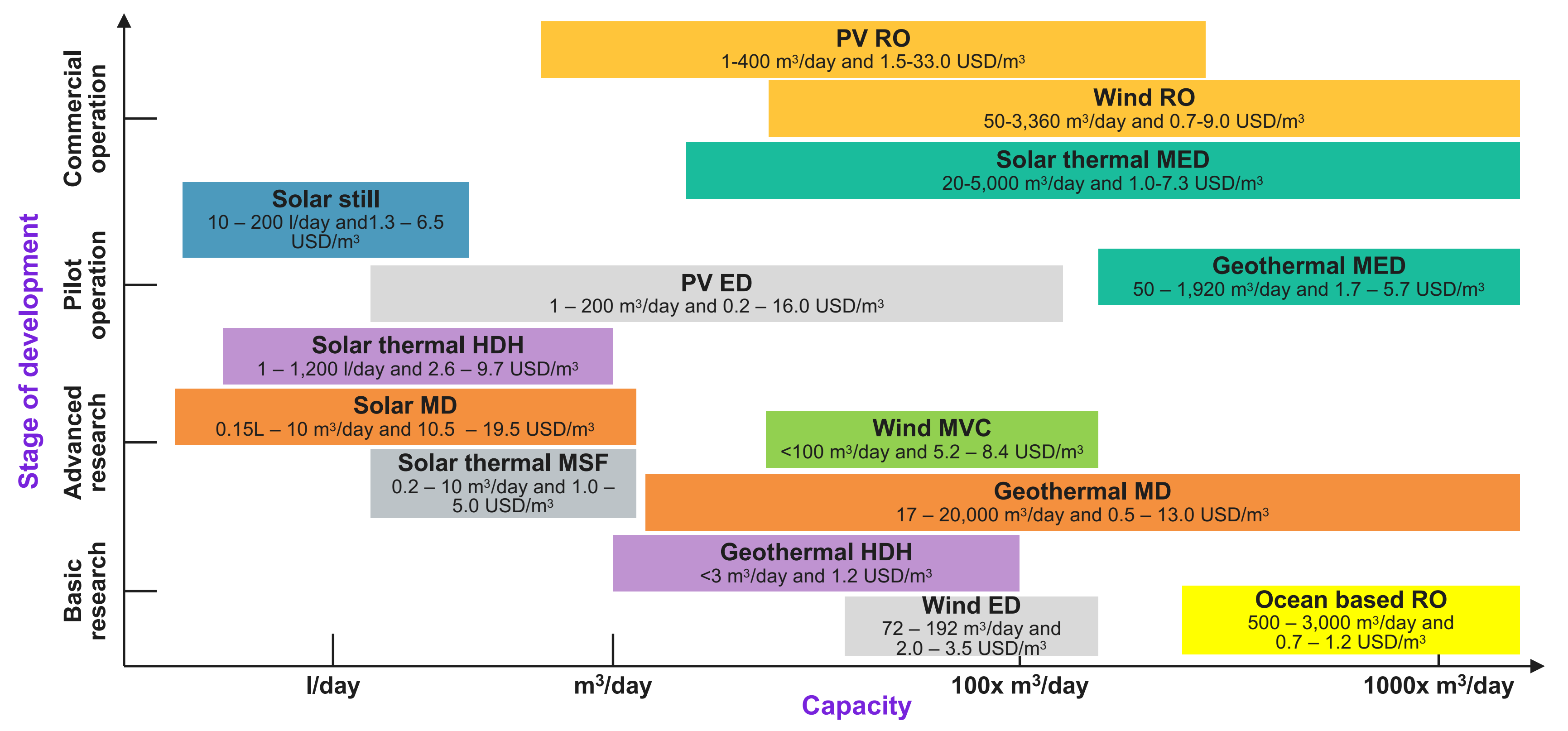


Sources: Solar Power Europe; UNICEF, 2022, UNICEF water pumps: a source of life, health and resilience; World Bank, 2018, Solar Pumping 101: the what, why, and the how; World Bank, 2018, Solar pumping The Basics Kearney Energy Transition Institute analysis

PV desalination supplies countries with a limited access to fresh water



Capacity *versus* stage of development of desalination technologies



PV RO
1-400 m³/day and 1.5-33.0 USD/m³

Wind RO
50-3,360 m³/day and 0.7-9.0 USD/m³

Solar thermal MED
20-5,000 m³/day and 1.0-7.3 USD/m³

Solar still
10 – 200 l/day and1.3 – 6.5 USD/m³

Geothermal MED
50 – 1,920 m³/day and 1.7 – 5.7 USD/m³

PV ED
1 – 200 m³/day and 0.2 – 16.0 USD/m³

Solar thermal HDH
1 – 1,200 l/day and 2.6 – 9.7 USD/m³

Solar MD
0.15L – 10 m³/day and 10.5 – 19.5 USD/m³

Wind MVC
<100 m³/day and 5.2 – 8.4 USD/m³

Solar thermal MSF
0.2 – 10 m³/day and 1.0 – 5.0 USD/m³

Geothermal MD
17 – 20,000 m³/day and 0.5 – 13.0 USD/m³

Geothermal HDH
<3 m³/day and 1.2 USD/m³

Wind ED
72 – 192 m³/day and 2.0 – 3.5 USD/m³

Ocean based RO
500 – 3,000 m³/day and 0.7 – 1.2 USD/m³

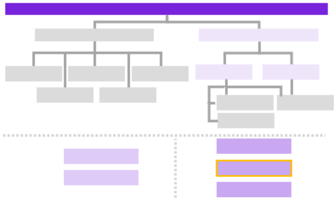
- Water desalination is a method of **removing the salt from sea water.** Some coastal countries do not have access to clear water and can only rely on this method for water self-production.
- There are a few different desalination methods, but **distillation** and **reverse osmosis** are the main ones (both technologies represent 90% of the market share).[1,2]
- These processes are highly energy demanding thus traditional plants pollute a lot. In fact, using **reverse osmosis techniques consumes around 3 kWh** to purify one metric cube of sea water.

RO: Reverse osmosis | MED: multi-effect distillation | ED: electrodialysis | H/DH: humidification/dehumidification | MSF: multi-stage flash distillation | MVC: mechanical vapor compression

[1] Method consisting of heating water and recovering the purified steam; [2] Method consisting of pressuring water through filters to remove impurities

Sources: IRENA, 2012, Water Desalination Using Renewable Energy; Ahmadi, McLellan, Mohammadi-Ivatloo and Tezuka, 2020, Sustainability, 'The Role of Renewable Energy Resources in Sustainability of Water Desalination as a Potential Fresh-Water Source: An Updated Review'; Kearney Energy Transition Institute analysis

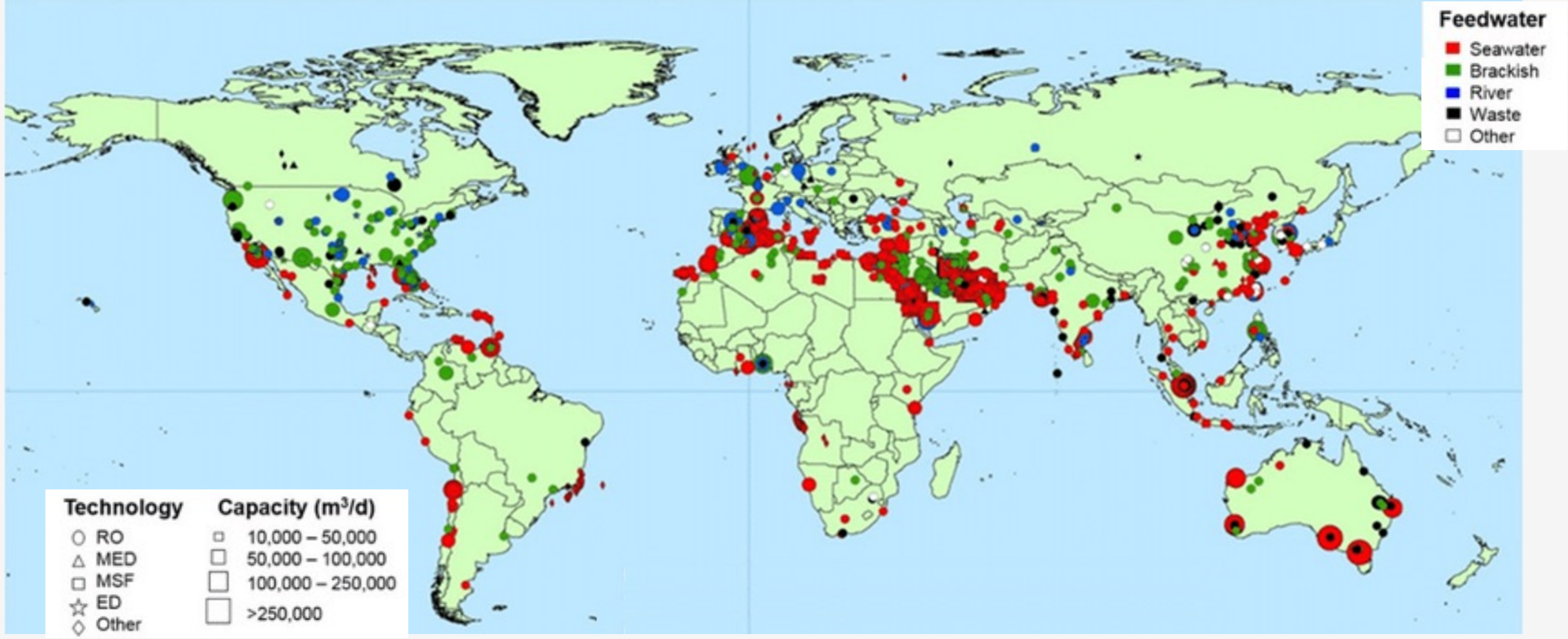
PV desalination supplies countries with a limited access to fresh water



Because of the important need for energy, solar panels could help reduce desalination carbon emissions. This combination is optimal as water-stressed areas are often located in sunny areas.

2.2 PV synergies

Desalination plants across the globe



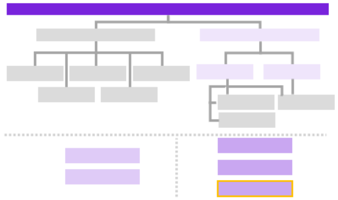
- Among all renewable technologies, solar is the most advanced as well as the most suited for large desalination plants. Most of the largest plants are in the UAE and Saudi Arabia, producing between **500,000 and 1 million cubic meters of water each per day**.
- Middle Eastern countries are planning to supply **90% of their water demand with desalination plants by 2030**.
- The largest PV desalination plant is the Al Khafji plant in Saudi Arabia, **supplying 60,000 cubic meters of water per day**.

[1] Method consisting of heating water and recovering the purified steam

[2] Method consisting of pressuring water through filters to remove impurities

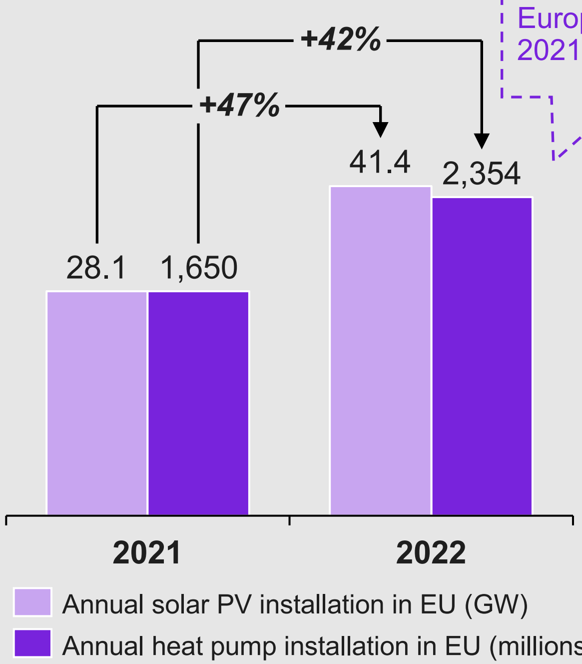
Sources: IRENA, 2012, Water Desalination Using Renewable Energy; Ahmadi, McLellan, Mohammadi-Ivatloo and Tezuka, 2020, Sustainability, 'The Role of Renewable Energy Resources in Sustainability of Water Desalination as a Potential Fresh-Water Source: An Updated Review'; Kearney Energy Transition Institute analysis

While solar PV helps produce energy, heat pumps help save energy



Installed capacity and sold units evolution

GW and million units, 2022



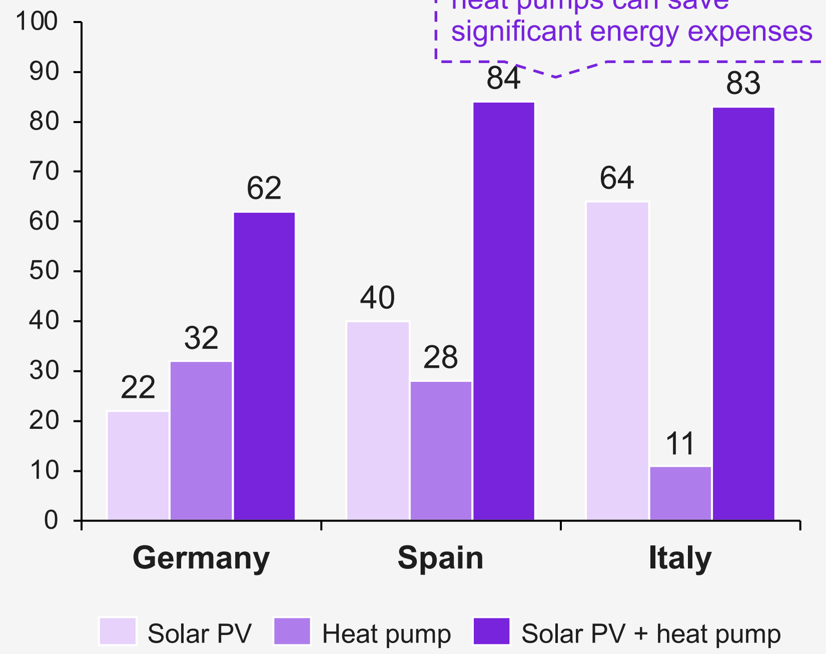
Similar evolution in Europe between 2021 and 2022

- Heat pumps are devices that transfer thermal energy (heat, or cold) between two different areas. Compared to traditional heaters, **heat pumps need less energy to operate and do not emit carbon emissions**.
- Combining heat pumps with solar panels creates **a device powered by solar energy and capable of heating and cooling buildings**.

Sources: Solar Power Europe, 2023, Solar Powers Heat; Kearney Energy Transition Institute analysis

Share of energy bill savings

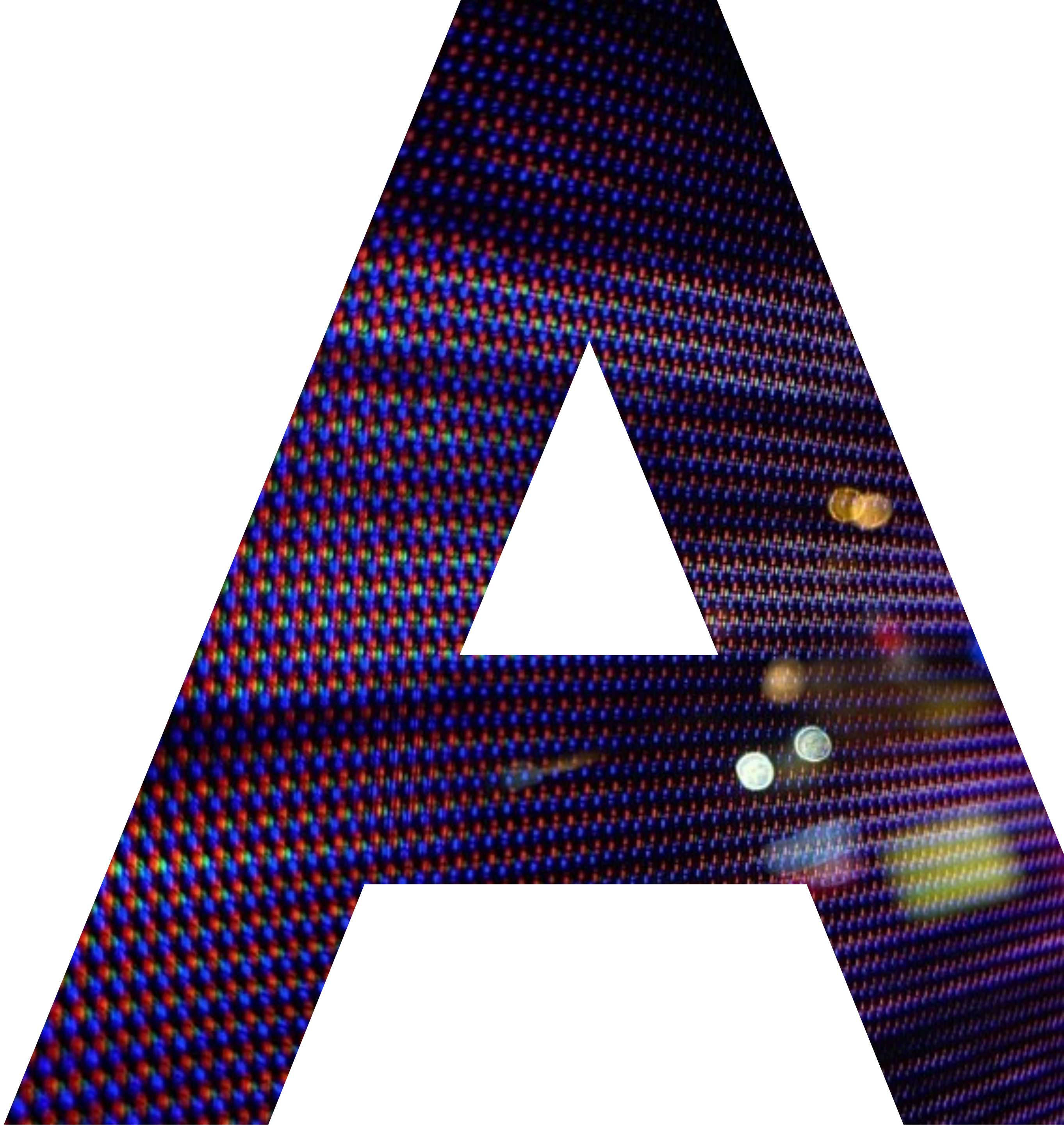
%, 2022



Combining solar panels and heat pumps can save significant energy expenses

- The combination of PV and heat pumps helps reduce electricity consumption from the grid. Estimates indicate that **energy bill savings could reach EUR 3,700 annually in Europe**
- Solar PV and heat pumps seem to have the best efficiency in **climates with hot summer and warm winter.**

3. Market status and projections



Market status and projections summary

Solar PV's commercial development began in the 1990s with the first programs supporting residential solar PV. Since the mid 2000s, it has been accelerating every year, led by Germany and Japan first, then by Europe and the United States. However, **since 2016, solar PV's growth is indisputably led by China**. **In 2022**, the **world added 240 GW** of solar PV capacity, **to exceed 1TW** for the first time. Between 2012 and 2022, solar PV's cumulative capacity grew by 28% each year on average. After China, the largest markets in 2022 were the European Union, the United States, India, and Brazil.

Solar PV's importance compared to other renewables grew too, as its share of total new renewable power **capacity additions increased threefold since 2012**, to 70%. Solar PV's share in the generation mix is growing faster than other renewables (from 9% in 2012 to 31% in 2022).

Solar PV's **load factor has remained around 17%** in the past decade. This is lower than for other renewables (39% for wind). There are strong variations in capacity factor by country, ranging from 28% in Chile to 10% in Germany.

Solar PV's **penetration rate** was multiplied by 12 between 2012 and 2022, **reaching 6.2% of global electricity generation**. There are now nine countries with more than 10% of their electricity coming from solar PV, including countries with low solar irradiance such as the Netherlands and Germany.

Over the past four years, a clear trend has emerged in favor of **monocrystalline PV modules** (**96% market share** in 2022). Meanwhile, thin-film has been stable since 2016, around 5%.

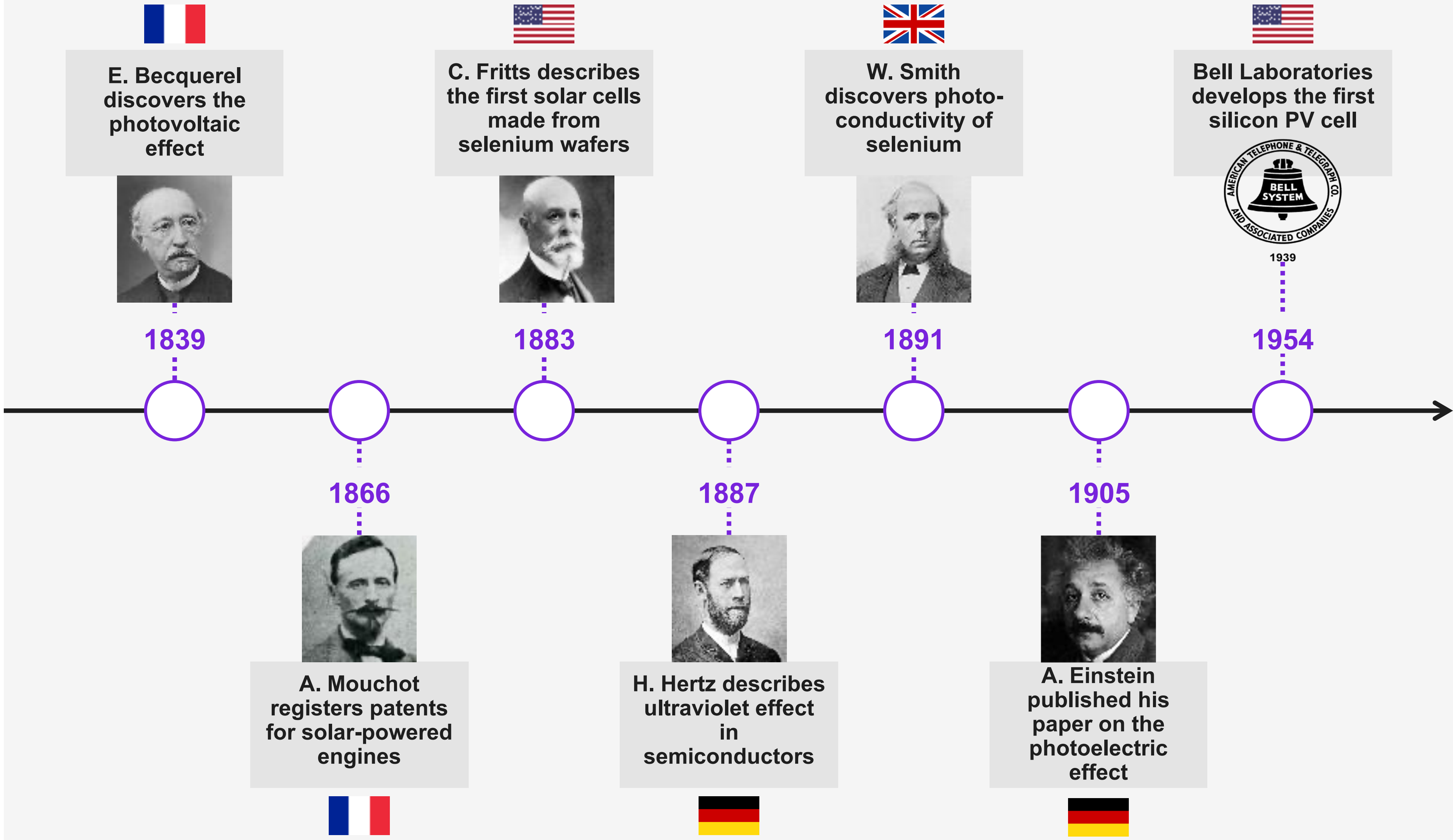
The vast majority of **PV capacity is connected to the grid (>99%)**. However, off-grid solar PV answers needs unmet by other PV applications, notably in remote or low-income areas. Grid-connected PV can be further split into centralized and decentralized (or distributed). While 52% of 2021's PV market was centralized, decentralized PV's share has been growing since 2016.

According to the IEA's predictions, by 2050 solar PV and fossil energy will weight the same in the total energy supply mix (18%). For electricity, solar PV is projected to make up **more than a third of the electricity mix** by 2050.

3.0 Summary

The technology behind solar PV was explored from the first half of the 19th century and the first PV cell was produced in 1954

Solar PV technology timeline: from the first discovery to the first PV cell

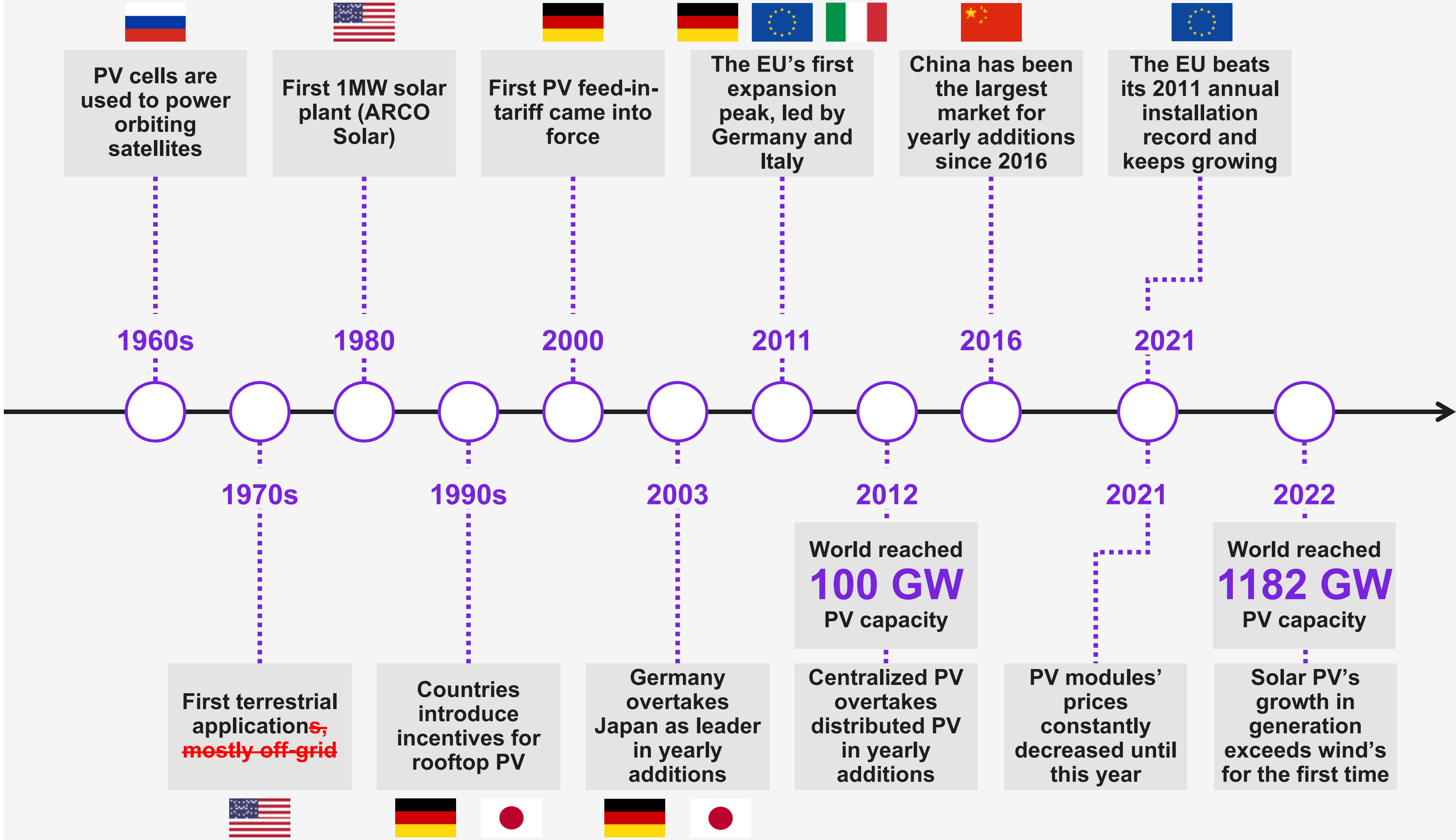


Source: Kearney analysis

3.1 History of solar PV

Solar PV development started in the late 1990s and sped up considerably from the 2010s, led by China

Solar PV development timeline: from the first application to today



1960s – PV cells are used to power orbiting satellites

1970s – First terrestrial application~~s, mostly off-grid~~

1980 – First 1MW solar plant (ARCO Solar)

1990s – Countries introduce incentives for rooftop PV

2000 – First PV feed-in-tariff came into force

2003 – Germany overtakes Japan as leader in yearly additions

2011 – The EU's first expansion peak, led by Germany and Italy

2012 – World reached **100 GW** PV capacity; Centralized PV overtakes distributed PV in yearly additions

2016 – China has been the largest market for yearly additions since 2016

2021 – The EU beats its 2011 annual installation record and keeps growing

2021 – PV modules' prices constantly decreased until this year

2022 – World reached **1182 GW** PV capacity; Solar PV's growth in generation exceeds wind's for the first time

Sources: Kearney; IEA PVPS, 2023, Snapshot of Global PV Markets; IEA, 2023, Solar PV; Kearney Energy Transition Institute analysis.

3.1 History of solar PV

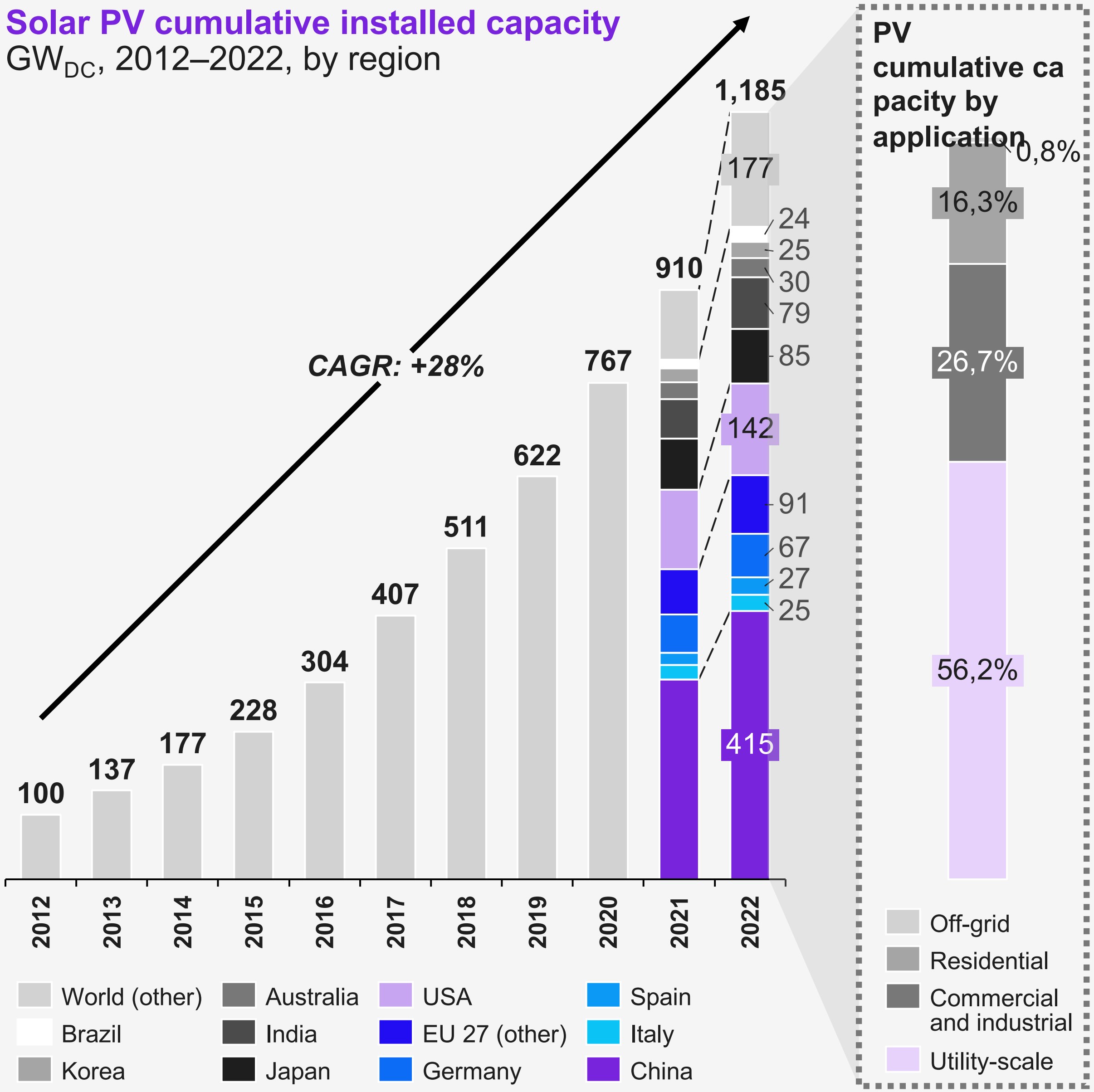
Solar PV capacity reached 1TW in 2022 after growing at 28% yearly for a decade, with China leading, followed by the EU and the US

Solar PV capacity is concentrated in a few countries, especially in China.
China has 35% of total capacity, the rest of the top 5 has 31% and the rest of the top 10 only 11%. The rest of the world has 23%.

3.2 Installed capacity

Solar PV cumulative installed capacity

GW$_{DC}$, 2012–2022, by region



Note: The installed capacity is the sum of the maximum power output of every PV cell in the region/country considered, usually measured in direct current (DC) in watts (W).
Sources: IEA PVPS, 2023, Snapshot of Global PV Markets; IRENA, Accessed July 2023, Data and Statistics; Kearney Energy Transition Institute analysis.

The rise of solar PV

Solar PV capacity has grown by 28% per year on average since 2012, reaching 1,185 GW in 2022.

China dominates the market with 35% of all capacity. The United States is second, just below 12%.

More than 99% of current capacities are on-grid installations, largely utility-scale plants, followed by commercial and industrial and residential.

The share of off-grid in solar PV additions is marginal (0.3%), below 1% every year except one since 2008. It represented 8% of global installed capacity in the year 2000.

However, off-grid systems cannot be ignored as they **answer to specific needs, ensuring electricity access in remote areas.**

Solar PV development is accelerating across the globe, with 240GW in capacity additions in 2022, led by China

The world had 23 countries adding at least 1GW of solar PV capacity in 2022, from only 7 in 2012.

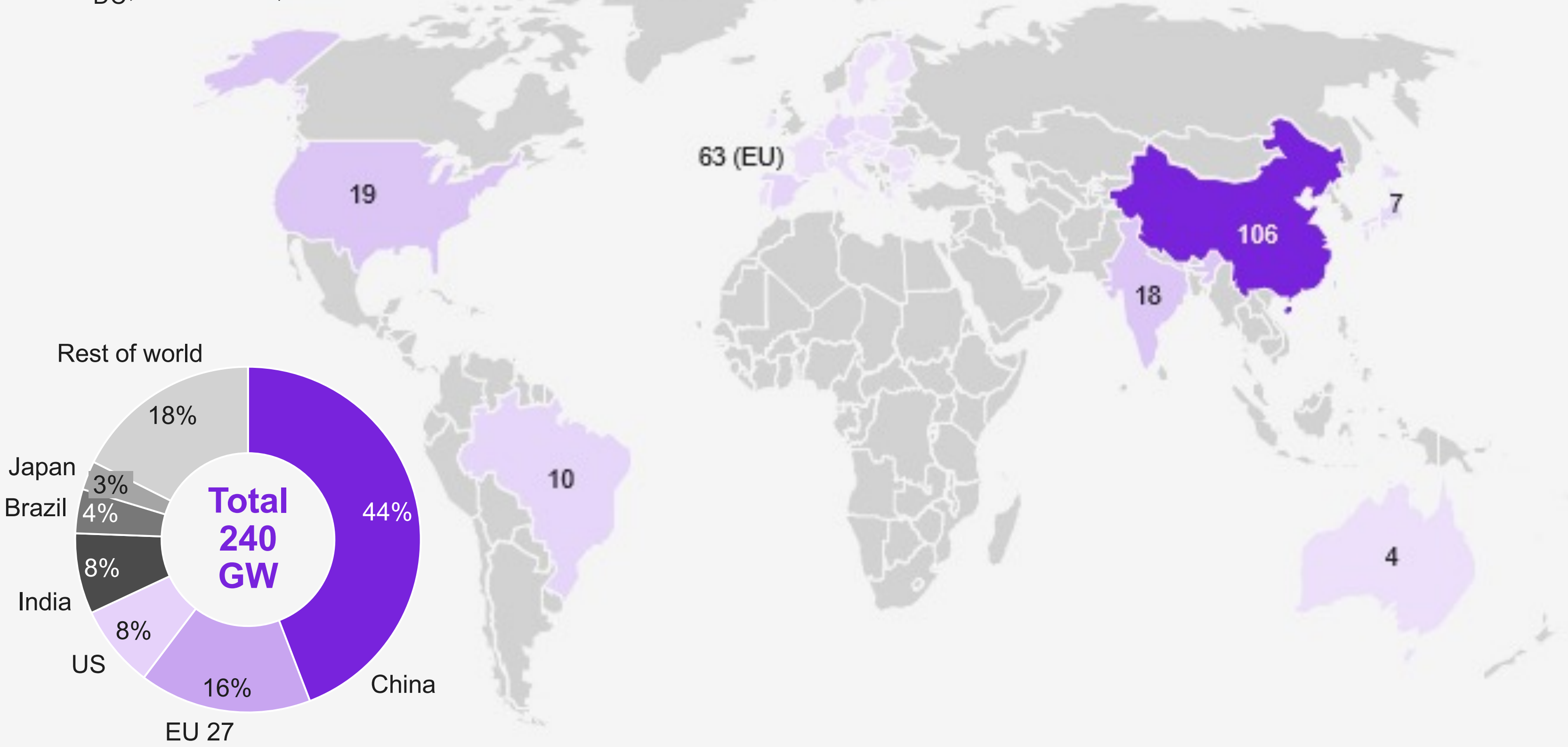
In 2022, **world capacity increased by over 25%.**

PV world capacity is expected to increase by 380 - 400 GW in 2023.

3.2 Installed capacity

Solar PV yearly capacity additions by country

GW$_{DC}$, share %, 2022



Countries installing more than 1GW of capacity in a year

(Decreasing order: top to bottom, left to right, 2012–2022)

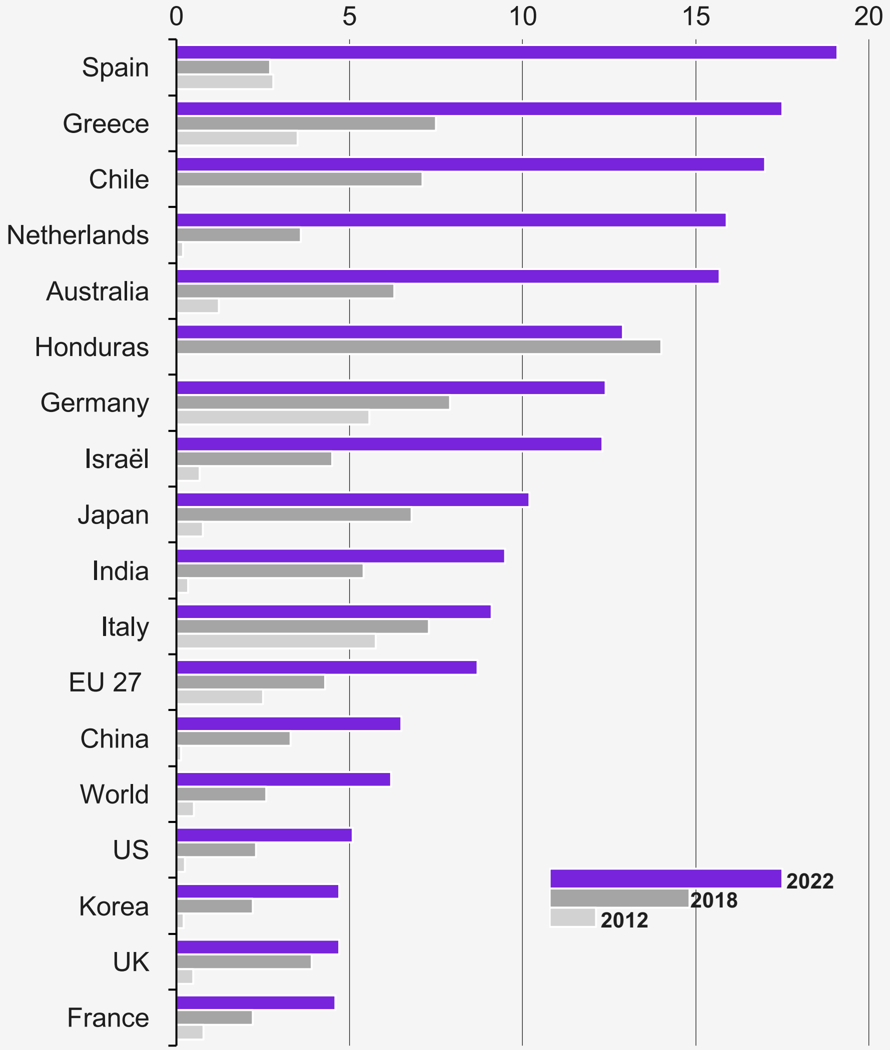
Sources: IEA PVPS, 2023, Snapshot of Global PV Markets; IEA, Renewables 2023, 2024; Kearney Energy Transition Institute analysis.

Solar PV's penetration rate has more than doubled in many countries across the world in the past four years, even in countries with lower irradiance

Solar PV produced 6.2% of electricity worldwide in 2022. This is up from only 0.5% in 2012.

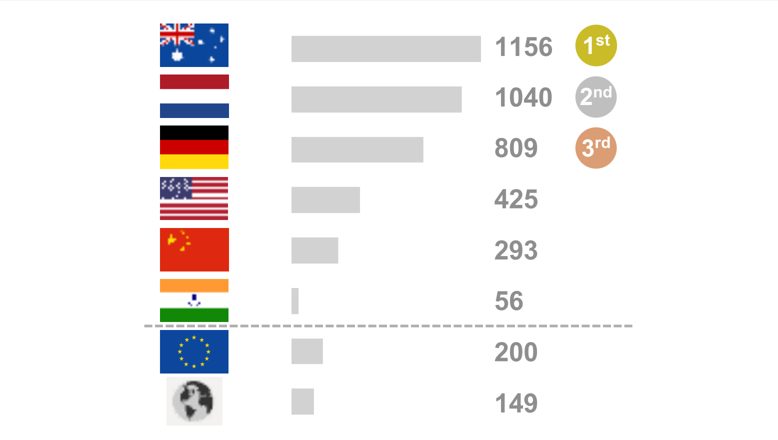
Solar PV penetration rate[1]

Share (%), 2012–2022, by region



Solar PV capacity per capita

W/capita, 2022, by region



- Solar PV's capacity growth significantly **increased its contribution to the electricity mix**, reaching 6.2% at the global level in 2022 from 2.6% just 4 years before and 0.5% in 2012.
- Also, there are now 9 countries with penetration rates above 10% compared to only Honduras in 2018.
- **High penetration rate is not only dependent on strong solar irradiance.** Indeed, the Netherlands (4th) and Germany (7th) are in the top 10 by penetration rate worldwide, thanks to policy support and albeit low irradiance.

[1] Theoretical penetration rate is the percentage of solar PV electricity generation in the total electricity mix of a specific country/region.

Sources: IEA PVPS, 2023, Snapshot of Global PV Markets; IEA PVPS, 2019, Snapshot of Global PV Markets; IEA PVPS, 2013, Snapshot of Global PV Markets; World Bank, accessed July 2023, DataBank Population estimates and projections; Kearney Energy Transition Institute analysis.

Solar PV's capacity factor has evolved little over the past decade; however, it has strong variations by country

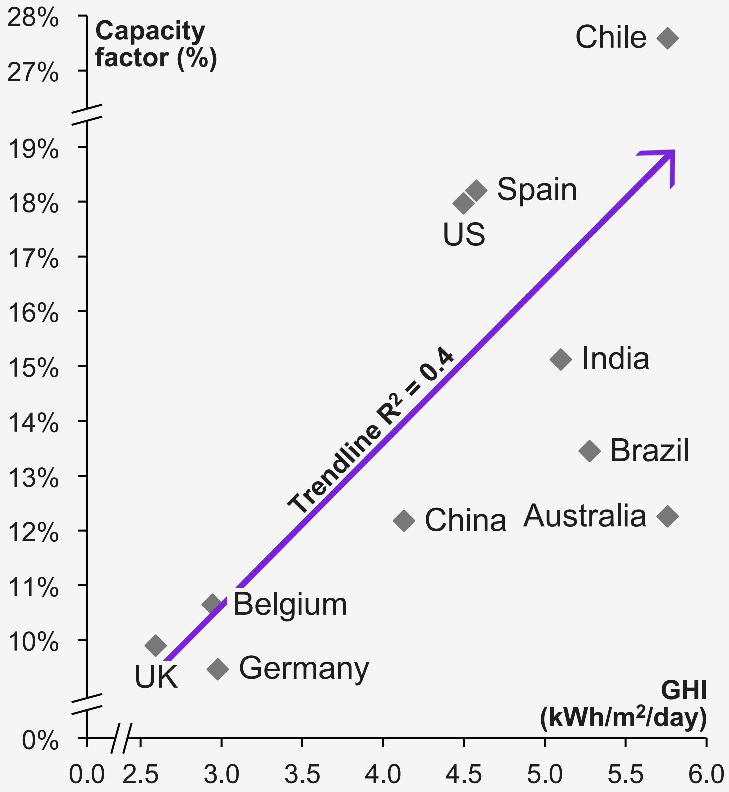
Capacity factor's variance by country is partly explained by differences in solar irradiance.

Solar PV's capacity factor has increased slightly over the past decade thanks to the expanded use of trackers.

3.2 Installed capacity

Capacity factor by average GHI[1]

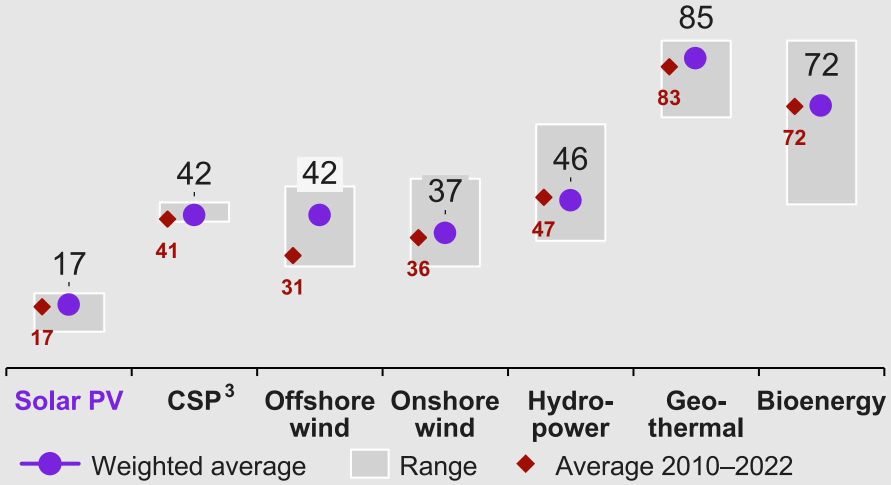
Capacity factor (%), GHI (kWh/m²/day), 2021



$$\text{The capacity factor is what percentage of the theoretical maximum power generation is actually produced} = \frac{\textit{Total generation in one year (GWh)}}{\textit{Total cumulative capacity (GW) * number of hours in a year (h)}}$$

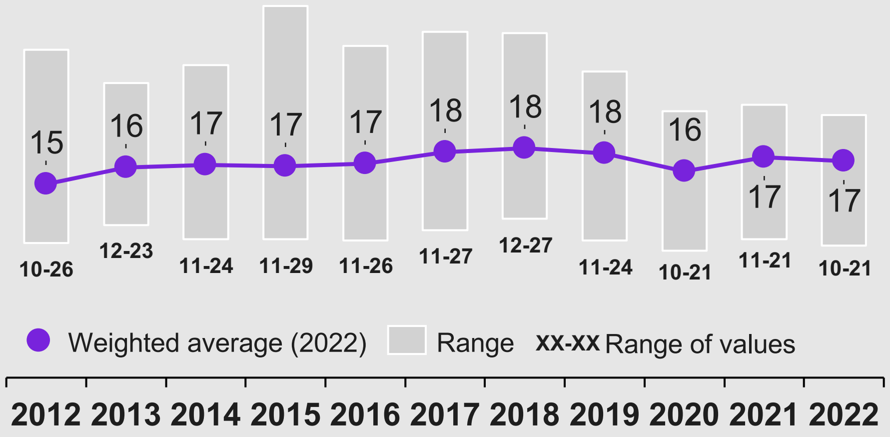
Global capacity factor by renewable technology[2]

%, 2022



Capacity factor of new solar PV, by year

%, 2012-2022, global



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[1] The GHI (global horizontal irradiance) is the theoretical potential of PV. The values are for 2020.

[2] Capacity factor for new capacity additions in that year

[3] CSP values are from 2020, as 2021 only had one project, with a capacity factor of 80%.

Sources: IRENA, 2023, Renewable Power Generation Costs in 2022; IRENA, 2022, Renewable Power Generation Costs in 2021; IRENA, Accessed July 2023, Data and Statistics; Global Solar Atlas, 2020, Global Photovoltaic Potential by Country; Kearney Energy Transition Institute analysis.

Solar PV evolution in the global electricity mix has steadily progressed

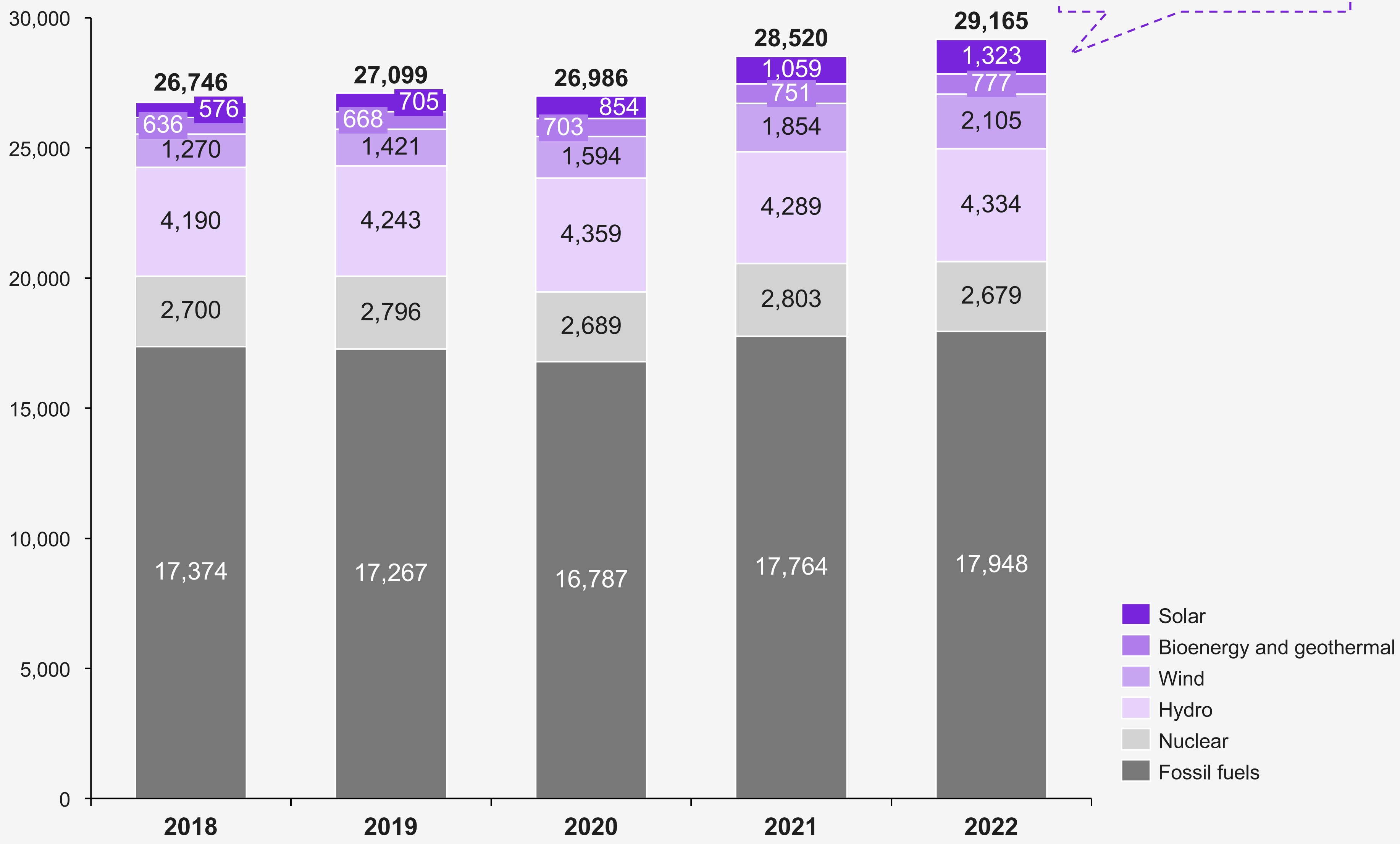
Solar power includes electricity generation from solar PV and concentrated solar power (CSP).

Solar PV represents more than 98% of the solar power generated, with CSP playing a marginal role.

3.2 Installed capacity

Solar power evolution in the global electricity mix
TWh, 2018–2022, global

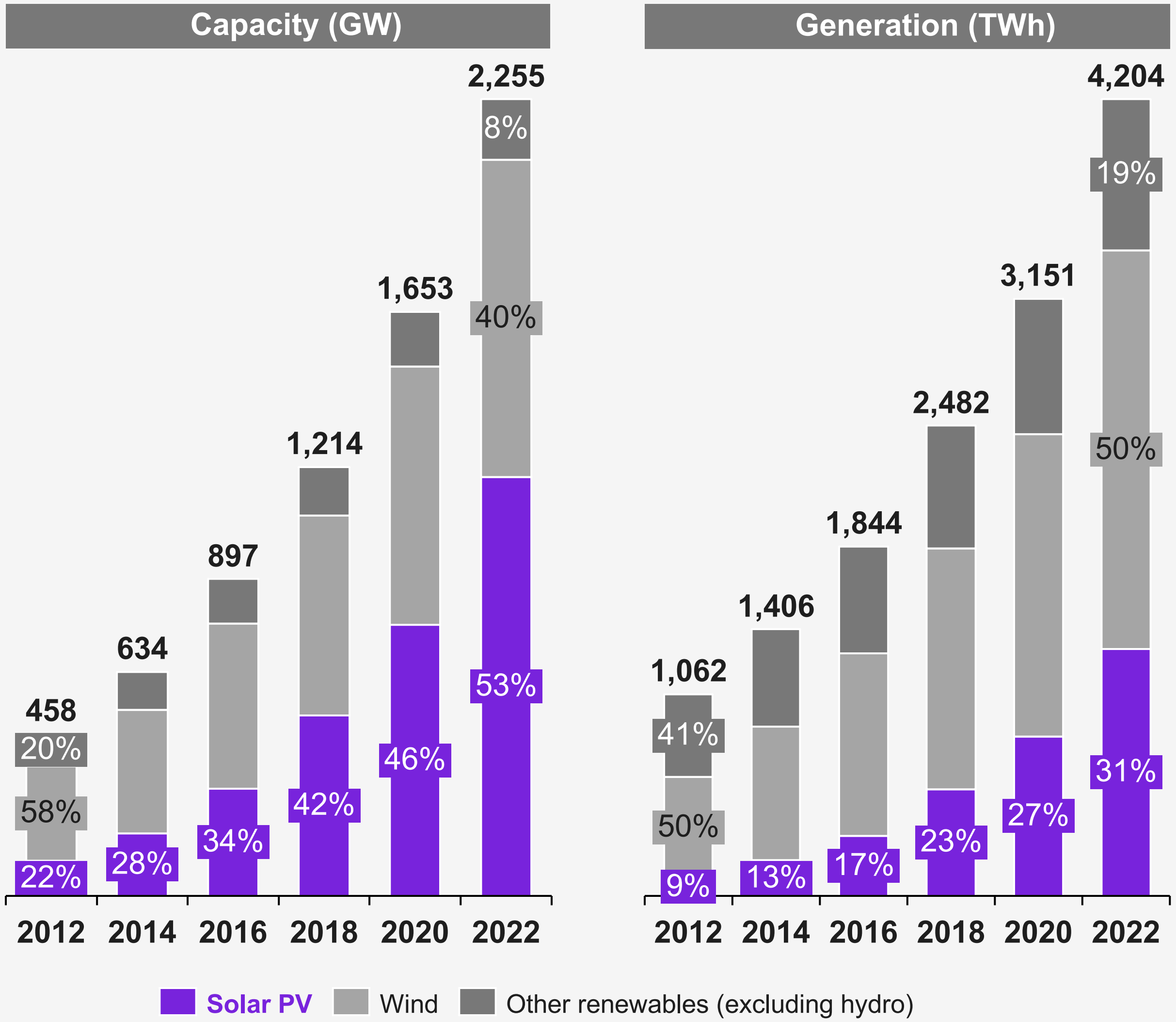
The annual growth rate for solar power has been **18%**



Sources: Energy Institute, Statistical Review of World Energy 2023; Kearney Energy Transition Institute analysis

Among renewables, solar PV is the fastest growing technology, representing more than half of this capacity

Global renewables' cumulative installed capacity and generation, excluding hydropower
GW, TWh, 2012–2022



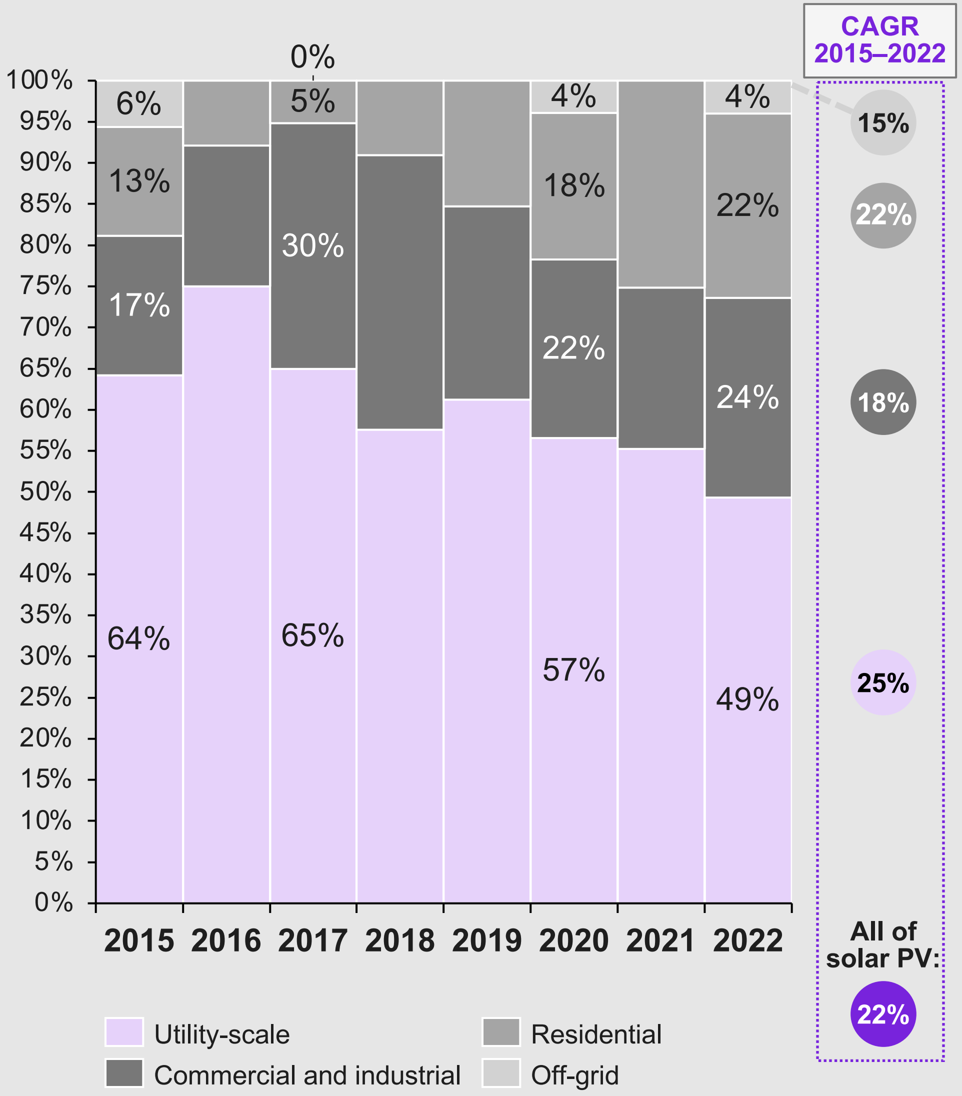
- **Solar PV capacity overtook wind in 2018** but it still generates less.
- **Solar PV's total generation has grown 14% faster than its installed capacity between 2012 and 2022**, thanks to better average capacity factors due to technology and location.
- **Other renewables have better capacity factors:** they generate more electricity for the same installed capacity.
- Despite a good performance compared to other renewables, **solar PV produces « only » 6.2% of electricity globally.**
- Solar PV supplies 2% of global energy demand.

Sources: Energy Institute, Statistical Review of World Energy 2023; IRENA, accessed July 2023, Data and Statistics; IEA PVPS, 2023, Snapshot of Global PV Markets; Kearney Energy Transition Institute analysis.

The vast majority of PV capacity is connected to the grid, with decentralized PV playing a growing role once again

Global annual PV capacity additions by type

Share (%), 2015–2022



Solar PV deployment started mostly as off-grid applications**. However, today 99% of the PV market is for grid-connected applications**.

These grid-connected applications have evolved in the past years driven by market dynamics and policy support:

- **Historically, utility-scale PV** expanded rapidly until 2016 and although it has been losing market share since then, it is still around 50% in 2022 and is responsible for driving PV growth.
- Within distributed PV, **residential PV has taken over from 2020**. The share of commercial and industrial additions has been decreasing since then.

3.3 Technology market share

Note: CAGR is calculated based on the absolute annual capacity additions and not the share evolution of each type of PV installation.
Sources: IEA PVPS, 2023, Trends in Photovoltaic Applications; IEA, 2023, Solar PV power capacity in the Net Zero Scenario; Kearney Energy Transition Institute analysis

Solar PV is predominantly made up of two application segments with established and emerging sub-segments

2022 cumulative installed capacity in GW and % of total installed capacity

XXX GW
XX%

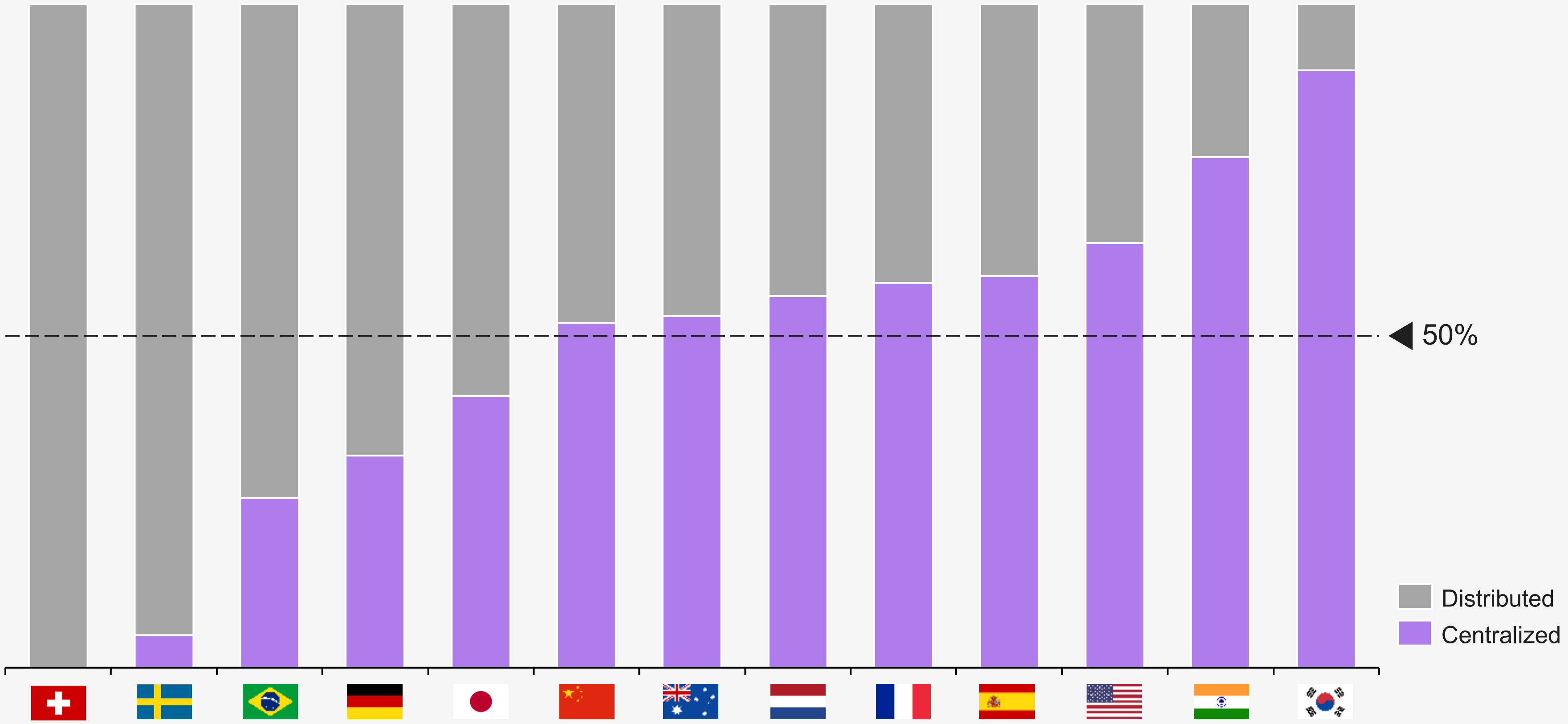
	Established	Emerging
Centralized (58%)	**Utility scale** Utility scales are all professional solar installations that aim to produce energy in order to sell all of it. 658 GW 56% Ground-mounted	**Floating solar** Solar panels mounted on a structure that floats on a body of water, typically a reservoir or a lake. 3 GW 0.3% **AgriPV** Simultaneously use an agricultural space for solar energy production and for agriculture. 18 GW 1.6% Water-/ground-mounted
Distributed (42%)	**Residential system** The Residential system is the set of solar panels used by individuals. Solar panels are not integrated into the structure. 191 GW 16% **Commercial and industrial system** The C&I system is the set of solar panels used by professionals of which a part or the totality is used for self-consumption. Solar panels are not integrated into the structure. 313 GW 26% Rooftop Ground-mounted	**Building-integrated photovoltaics (BIPV)** Solar panels are integrated inside the structure of the building. <1 GW <0.1% **Vehicle-integrated photovoltaic (VIPV)** Solar panels mounted on mobile systems (such as cars) and used for self-consumption. <1 GW <0.1% On vehicles Rooftop On wall

Sources: Kearney; IEA, 2022, Solar PV power capacity in the Net Zero Scenario; Fraunhofer ISE, 2023, Agrivoltaics; Fraunhofer ISE, 2023, Floating photovoltaics; Woodmac, 2023 Global floating solar to top 6 GW threshold by 2031; Kearney analysis.

The large variations across countries in the share of solar PV applications are driven by economic drivers and policy choices

Capacity additions by application type and by country

Share (% MW), 2022



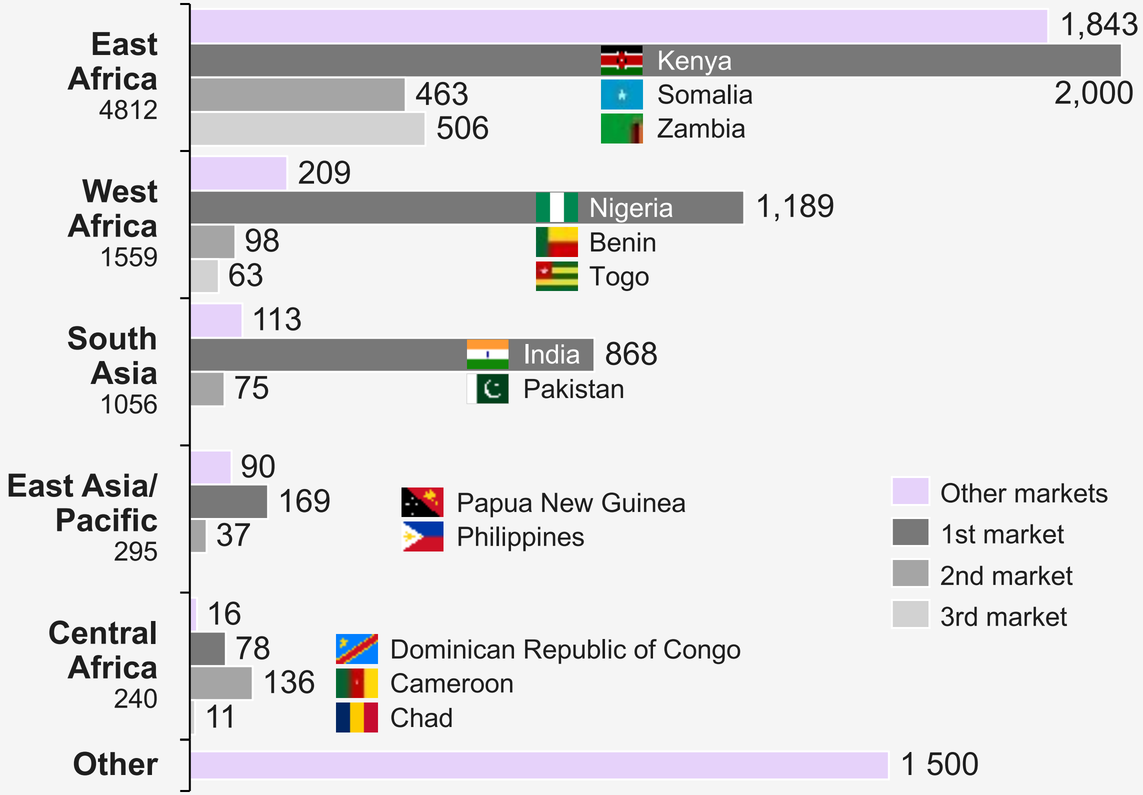
Sources: IEA PVPS, 2023, Trends in Photovoltaic Applications; Kearney Energy Transition Institute analysis

3.3 Technology market share

Off-grid solar PV answers needs unmet by other PV applications, notably in remote or poorer areas

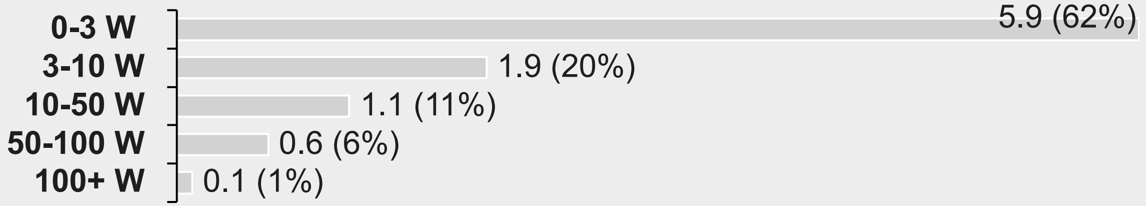
Off-grid solar PV products sold by region

Thousand units, 2022, by region/country



Off-grid solar products sold by size

Thousand units and share (%), 2022



Sources: GOGLA, 2022, Global Off-Grid Solar Market Report Semi-Annual Sales and Impact Data; World Bank, 2022, Off-Grid Solar Market Trends Report 2022; IRENA, Accessed July 2023, Data and Statistics; Kearney Energy Transition Institute analysis

Off-grid PV addresses different needs than on-grid PV

Only 0.4% of new PV capacity in 2022 was off-grid, but **off-grid PV is sometimes the only solution for remote locations.**

It is estimated that in 2022 there are 104 million people living in a household with improved energy access thanks to off-grid PV.

PV is preferred to wind for off-grid applications as it is easier to install and maintain.

Among the 9.5 million off-grid PV products sold worldwide, the **largest markets are in Kenya, Nigeria, and India.**

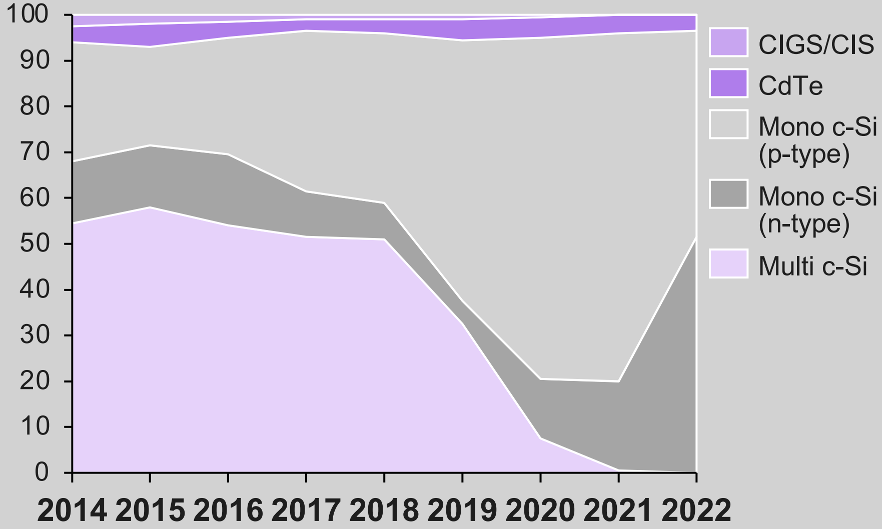
Most products sold are lanterns and phone chargers (<10 W). There are also larger “solar home systems” (>10 W) which are often coupled with appliances like TVs.

The main barrier to off-grid PV deployment is financing. **Pay-as-you-go solutions can ease the financial burden**. It represents 37% of off-grid PV sales in 2022.

Over the past four years, mono c-Si PV modules have strengthened their global lead to reach a 96% market share today

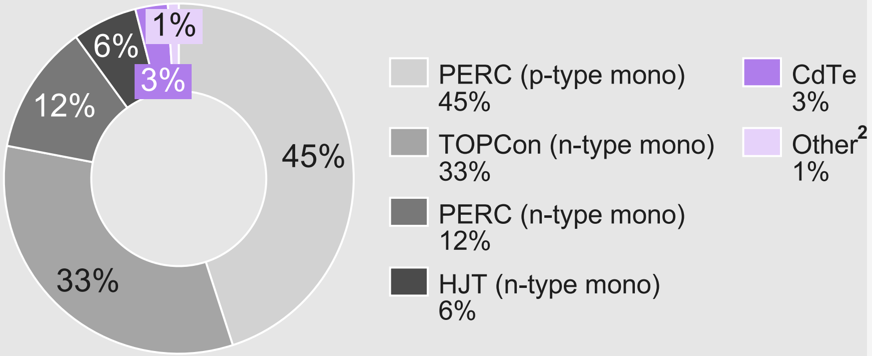
Global PV technologies' share of shipments

Share (%), 2014–2022



PV technologies share of 2022 shipments[1]

Share (%), 2022



Monosilicon modules dominate the market

Monocrystalline c-Si is the dominant technology in 2022: it increased its market share to 96% compared to 35% in 2015, while multi c-Si's share fell bellow 1% globally. This is **due to the higher efficiency of mono c-Si** and better performance in very warm conditions.

For mono c-Si modules, **the share of n-type grew (5% in 2019 to 51% in 2022) and the share of p-Type decreased (57% in 2019 to 45% in 2022).** In 2022 and for the first time, p-type has a smaller market share than n-type.

More precisely among mono c-Si cells, the leading cell type globally was mono PERC (p-type), followed by TOPCon, mono PERC (n-type), and HJT.

Thin-film technologies such as CdTe remain stable with a few points of market share

China is leading in module shipments

In 2022, 283 GW of PV modules were shipped, up 46% from 2021. **Three-quarters of the increase came from China.**

China's share grew from 1% in 2004 to 71% today. Other Asian manufacturing centers—Malaysia, Vietnam and South Korea—grew from 0% to 23% in the same timeframe.

3.3 Technology market share

[1] See section 1 of this FactBook for explanations about each technology.

[2] "Other" comprises a-Si, CIS/CISG, TOPCon (p-type mono), Multi PERC, IBC (n-type).

Sources: NREL, 2023, Spring 2023 Solar Industry Update; Baghel and Chander, 2022, Performance comparison of mono and polycrystalline silicon solar photovoltaic modules under tropical wet and dry climatic conditions in east-central India; Kearney Energy Transition Institute analysis

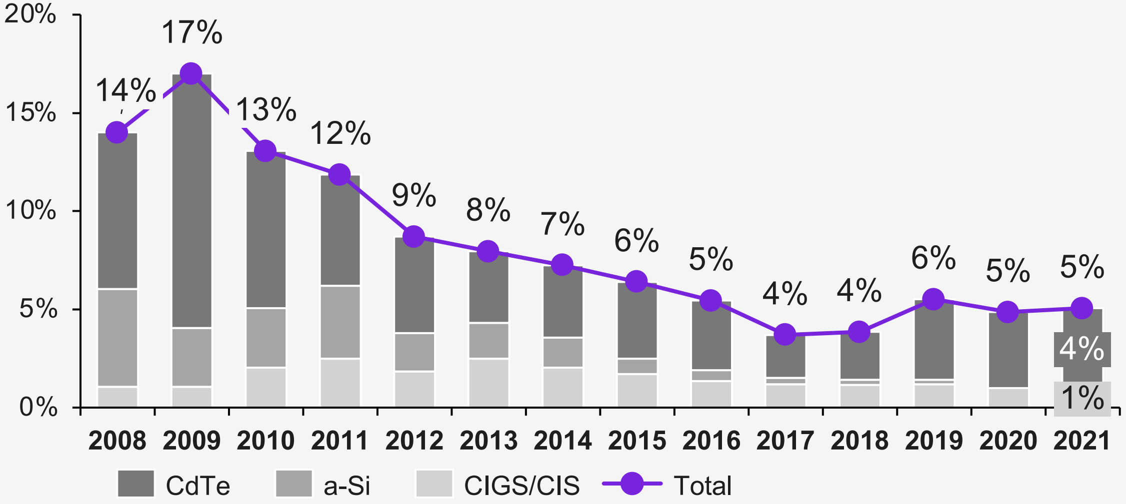
The market share of thin-film technologies has decreased since 2009 and stabilized around 5% since 2016, but total production is still increasing

In contrast with traditional panels, thin-film solar modules are much more adaptable to agricultural applications due to their flexible and lightweight design.

3.3 Technology market share

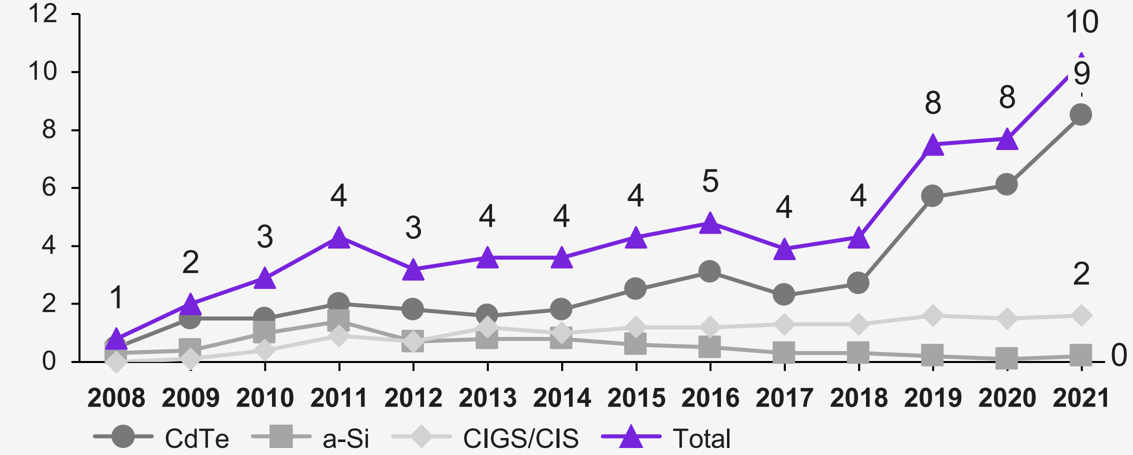
Share of thin-film technologies in total PV production

Share (%), 2008–2021, global



Global thin-film module production by technology

GW, 2008–2021, global



Sources: Fraunhofer ISE, 2023, Photovoltaics report; Benda and Černá, 2020, PV cells and modules – State of the art, limits and trends; Kearney Energy Transition Institute analysis

Thin film in the PV market

Thin film's share in the global PV market has decreased to 5% since its 17% peak in 2009.

Thin film's lower efficiency and higher production cost makes it **significantly more expensive per W than silicon PV**.

Despite these limitations, thin-film PV **has maintained a 5% market share due to its advantages:**

- **More resistant to changes in temperature**, which makes it suitable for places with very high solar irradiance
- **Easier to install and shape thanks to its flexibility and lighter weight**, making it more adapted for building-integrated PV (BIPV)

Thin film's production keeps growing in absolute terms thanks to the growth of cadmium telluride (CdTe) cells.

Solar PV's growth will be uneven between countries and backed by a strong growth in manufacturing

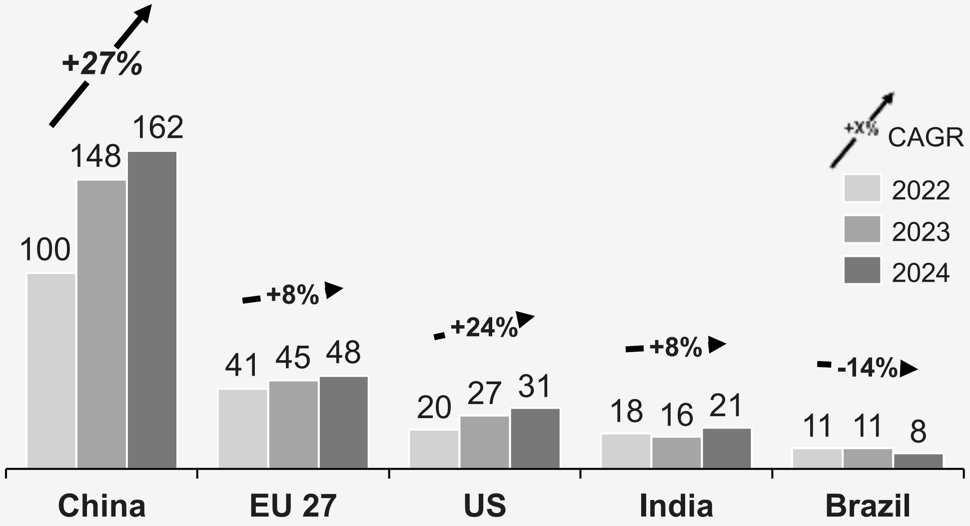
Projection

Xx.x Increase in manufacturing capacity from 2022 to 2024

3.4 Projects pipeline and projections

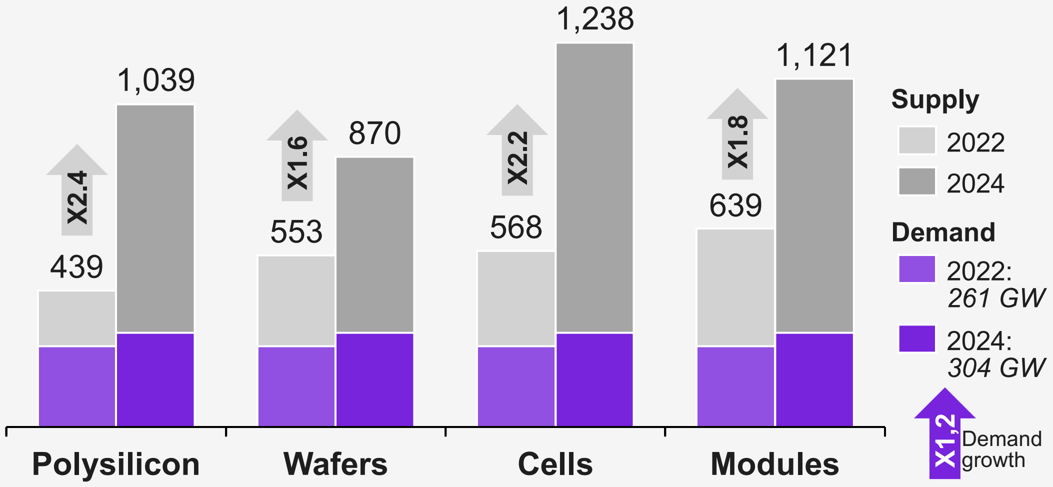
Solar PV capacity addition projections

GW, 2022–2024, IEA main case scenario



Solar PV manufacturing capacity by segment

GW, 2022–2024, global



Sources: IEA, 2023, Renewable Energy Market Update June 2023; Kearney Energy Transition Institute analysis

The IEA's main scenario predicts an 18% growth in annual PV installations for the next two years, but **this growth is unevenly distributed**:

China will reinforce its lead with a 27% CAGR, backed by a strong manufacturing base.

India will decline slightly in 2023, before growing again in 2024. This initial decline is due to lower auction volumes and supply chain issues, caused by India's domestic production push which increases costs and decreases supply in the short term.

Manufacturing growth

Looking at the global level, pledges by the main manufacturers indicates that **production capacity along the supply chain will double from 2022 to 2024**, while demand will increase by only 120%. Suppliers will be ready to absorb a faster than expected solar PV expansion.

Solar PV is projected in main scenarios to NZE by 2050 to produce about a third of global electricity demand

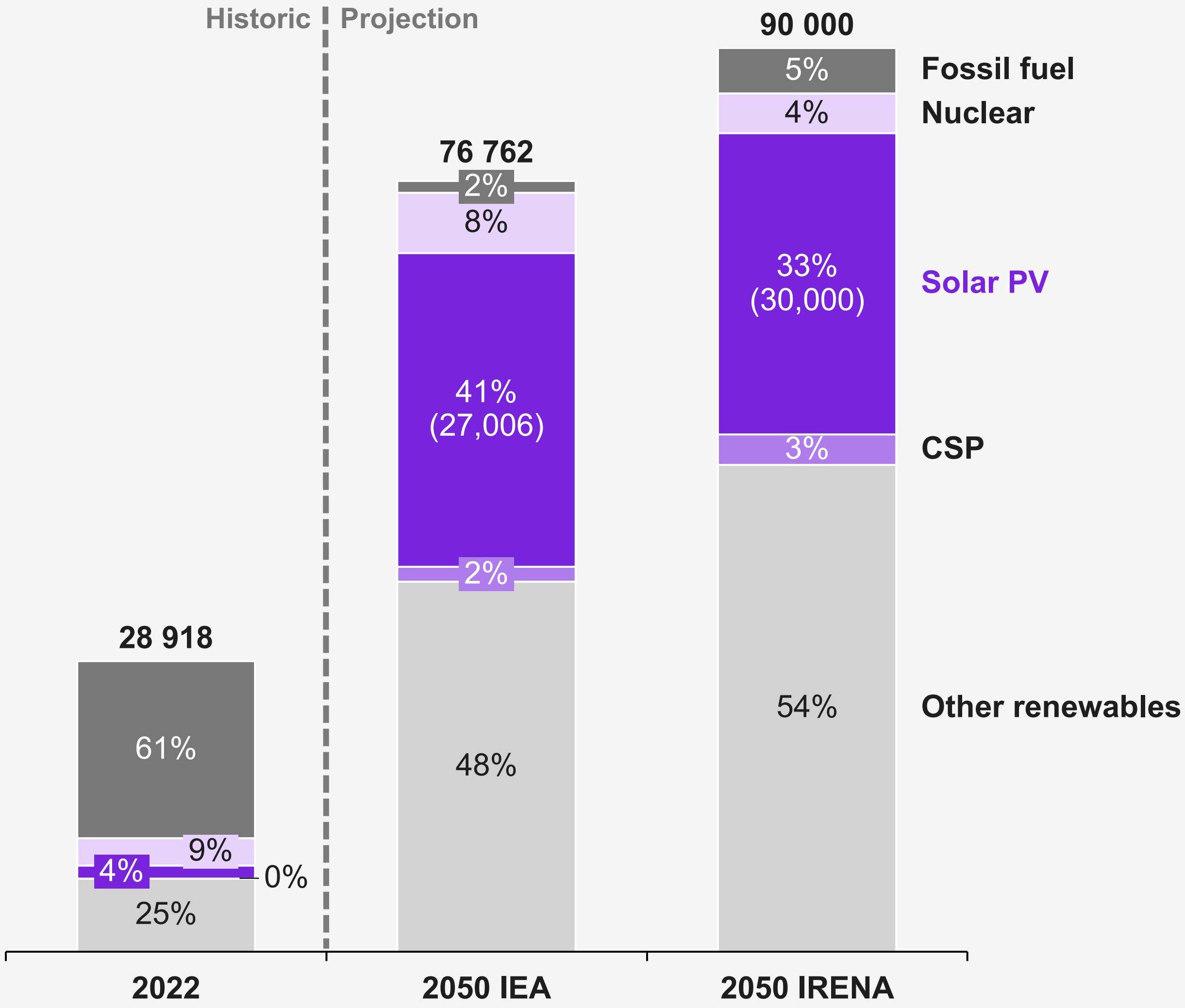
Projection

IRENA and the IEA say up to 37% of electricity generation could come from PV in 2050.

Note: long-term scenarios can be inaccurate and should be used with caution. They have underestimated PV's growth in the past.

3.4 Projects pipeline and projections

Global electricity generation mix scenarios[1]
TWh, 2022 vs. 2050



Solar PV is projected to become the most-used (37%) source of electricity according to the IEA, and the second largest source (33%, behind wind) according to IRENA, from only 4% today. To achieve this growth, **yearly investment in solar PV** between 2023 and 2050 will need to average between USD 267 billion and USD 333 according to BNEF and IRENA, respectively.

Investments in solar PV have gone up recently from USD 138 billion in 2018 to USD 307 billion in 2022[2]. It is close to IRENA's predicted requirement, and above BNEF's. **The question is whether or not this level of investment can be sustained for nearly 30 years.** Among the key clean energy technologies, **only solar PV has enough announced projects to be on track for net zero** by 2050 according to the IEA.

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[1] These scenarios are projecting the trajectories energy supply will follow to reach net zero CO_2 emissions by 2050 in two scenarios limiting global warming to 1.5°C.
[2] REN21 data

Sources: IEA, 2023, World Energy Outlook; IRENA, 2023, World Energy Transitions Outlook; IEA, 2023, Energy Technology Perspectives 2023; REN21, 2023, Renewables 2023 Global Status Report collection Renewables in Energy Supply; BNEF, 2023, Wind and Solar Propel Net-Zero Power Supply Investment; Kearney Energy Transition Institute analysis

By 2050, solar PV and fossil energy will weight the same in the total energy supply mix, just behind modern bioenergy

Projection

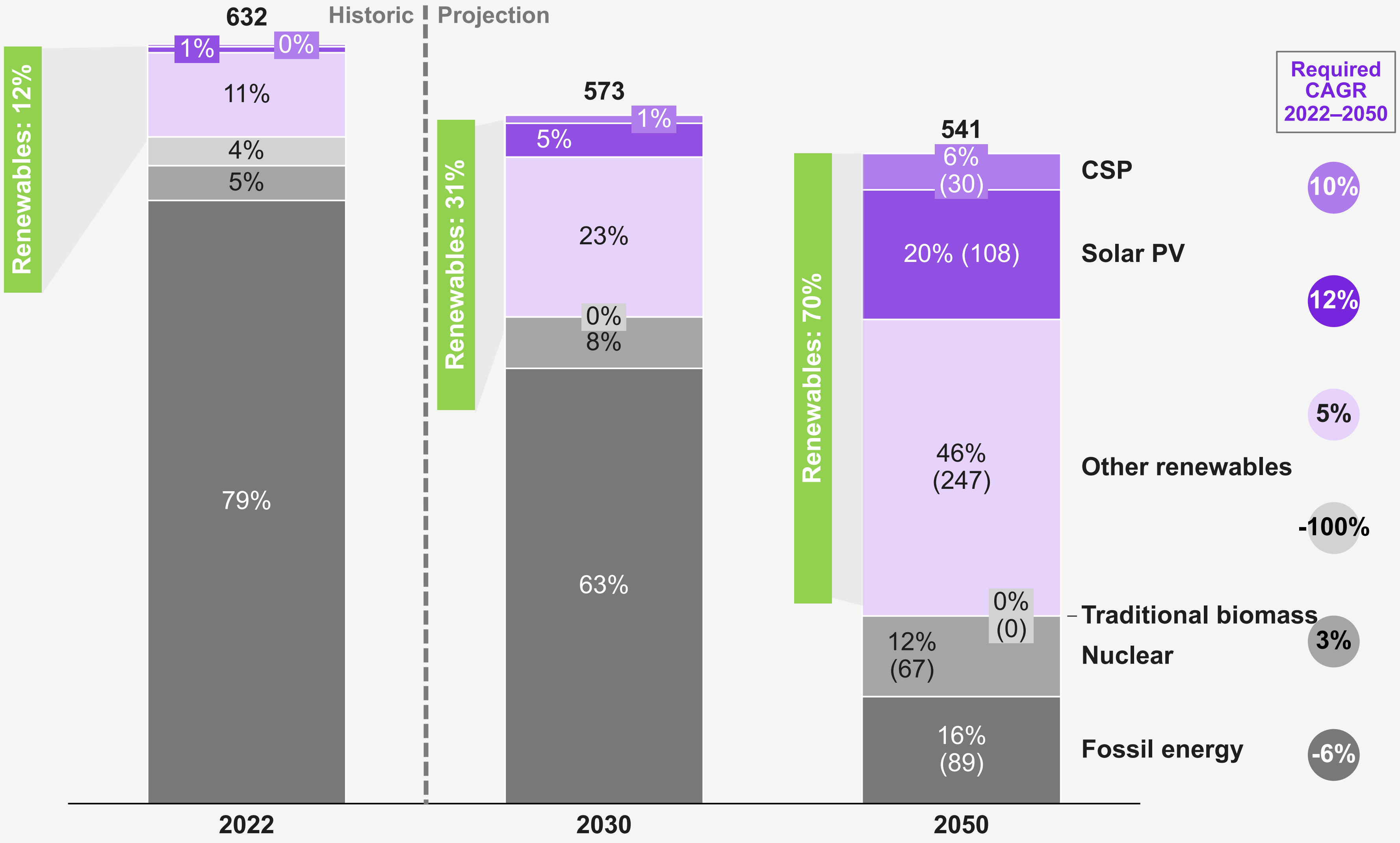
Solar PV produced less than 1% of total energy supply in 2022.

The IEA predicts that solar PV will have the fastest growth among all main energy sources, at 12% per year until 2050, to reach a share of 18%.

3.4 Projects pipeline and projections

Global energy supply, IEA Net Zero scenario[1]

Share (%), EJ, 2022



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[1] The Net Zero Emissions by 2050 scenario (NZE scenario) relies on the deployment of a wide portfolio of low-emissions technologies and emissions reduction options to reach net zero CO_2 from the energy sector by 2050

[2] Traditional biomass is no longer part of the energy mix from 2030.

Sources: IEA, 2023, World Energy Outlook 2022; Kearney Energy Transition Institute analysis.

4. Policies and financing schemes

Policies and financing schemes

Policies and regulations targeting solar PV are defined by a multitude of stakeholders to incentivize solar PV deployment. Policies can be price-based or quantity-based instruments, or indirectly by affecting related stakeholders and processes.

Among the most commonly used price-based instruments to encourage the adoption of solar PV, direct **feed-in-tariffs (FIT)** have **progressively decreased, from representing 86%** of the support mechanisms in 2010 **to only 28%** in 2021. FIT are **being replaced by auctions and calls for tenders** to promote the most competitive PV. **In markets** where there is no more direct policy support, PV is usually provided **through off-take agreements**. Quantity-based instruments define mandates through targets and standards to influence solar PV electricity production. Although most countries have defined general renewable targets, only **39 countries have explicitly mentioned solar PV goals**. Targets have **different levels of enforcement**, going from a simple political statement to a legally binding engagement.

To **accelerate the energy transition while ensuring competitiveness of markets**, countries and regional entities have recently defined a combination of mechanisms to **boost solar PV competitiveness** and **secure domestic supply chains**.

Solar PV offers flexible combinations of project scale, investors, and contracting types, which need to be properly tailored to optimize the power solutions for customers. Direct sales of PV electricity is growing and is usually achieved through power purchase agreements (PPAs). More and more **corporations are driving PPA growth** thanks to their net-zero pledges. This type of market-driven procurement is expected to contribute to solar PV expansion in 2023–2024. Other solar PV business models defined to reduce grid dependency (**net-metering and net-billing**), while others are exclusively defined for off-grid systems (**PAYGo or cash only**).

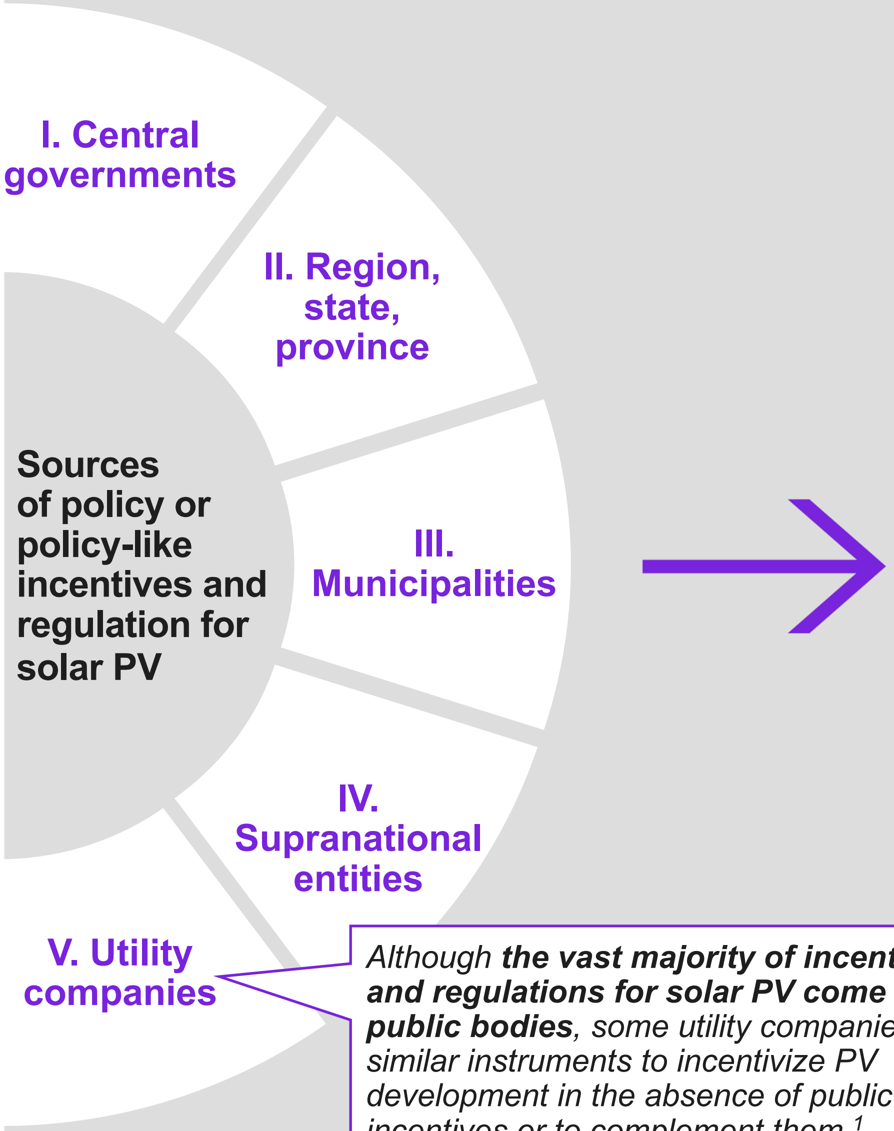
In terms of **investment**, solar PV has the **fastest growth rate among all renewables** and concentrates about 60% of global renewable power and fuel investment, reaching **USD 308 billion** in 2022 and is expected to reach **USD 380 billion** in 2023.

4.0 Summary

Many actors regulate and incentivize solar PV, following a variety of goals from decreasing CO_2 emissions to local job creation

4.1 Policies overview

Policy intervention sources



Sources of policy or policy-like incentives and regulation for solar PV

I. Central governments

II. Region, state, province

III. Municipalities

IV. Supranational entities

V. Utility companies

Although ***the vast majority of incentives and regulations for solar PV come from public bodies****, some utility companies use similar instruments to incentivize PV development in the absence of public incentives or to complement them.*[1]

Policy intervention goals

1 **Environmental goals**
- Reducing greenhouse gas emissions

2 **Energy sovereignty**
- Reducing the reliance on foreign fossil fuels

3 **Cheaper solar PV**
- Making solar PV competitive with other sources of energy
- Reducing electricity poverty

4 **Local economic development**
- Creating local jobs and companies along the solar PV value chain
- Training workers with new skills

5 **Grid and market stability**
- Maintaining grid reliability and stability
- Adapting electricity markets to PV’s variability

6 **Improved land use**
- Favoring distributed PV
- Regulating new models of self-consumption

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[1] The main example is in Switzerland.

Sources: IEA PVPS, 2023, Trends in Photovoltaic Applications ; Kearney Energy Transition analysis

Policies can target solar PV directly with price-based or quantity-based instruments, or indirectly by affecting related stakeholders and processes

Tenders and auctions are used by **public bodies to enact** many of the listed **policies.**

4.1 Policies overview

Policy options[1]

Price-based instruments	Influences solar PV electricity generation by altering prices faced by stakeholders
Feed-in tariffs (FITs)	Guarantee electricity will be bought at a certain price per kWh over a long time period (typically 20 years).
Market premiums	Support producers by paying them based on the quantity of electricity generated (feed-in premium (FIP)) or the capacity built.
Contracts for difference	The producer sells electricity on the market and receives or refunds the gap between market price and a predetermined price (sort of FIP).
Tax incentives or credits	Provide tax breaks or accelerate the depreciation of assets to reduce the cost for investors.
Direct subsidies	Refund developers a percentage of investment costs in cash to reduce the initial investment and improve returns.
Net metering	Offers credits for PV injected into the grid which can be used later by the producer. Does not adjust for daily price fluctuations.
Net billing	Electricity injected into the grid generates a monetary amount for the producer, related to the market price at the time of injection.

Caution: the definitions of these policy options are general indications, as details of similarly named policies can vary from country to country, and sometimes from state to state.

Quantity-based instruments	Influences solar PV electricity generation by mandating quantities and standards
Binding targets	Set a binding share or quantity of renewable energy sources for electricity producers or suppliers (ex: renewable portfolio standard).
Quotas with tradable certificates	Set minimum targets for renewable energy generation, with tradable renewable energy certificates. It aims to produce more efficiently.
Tenders and auctions	Used by public bodies for common procurement. They contract a set quantity of PV energy and attach incentives.
Non-binding targets	Set a target share or quantity of solar PV in the energy mix to give visibility to stakeholders.

Indirect instruments	Influences solar levels by influencing the surrounding stakeholders and processes
Grid access and market policies	Give priority to clean electricity fed into the grid, enforce curtailment limits, ensure grid improvement.
Permitting/ regulatory adjustments	Accelerating the permitting process, facilitating self consumption models, or even including solar PV in building requirements.
Supply chain support/ mandates	Favor local manufacturing, set up reskilling programs for workers, or support the growth of downstream supply chain segments.

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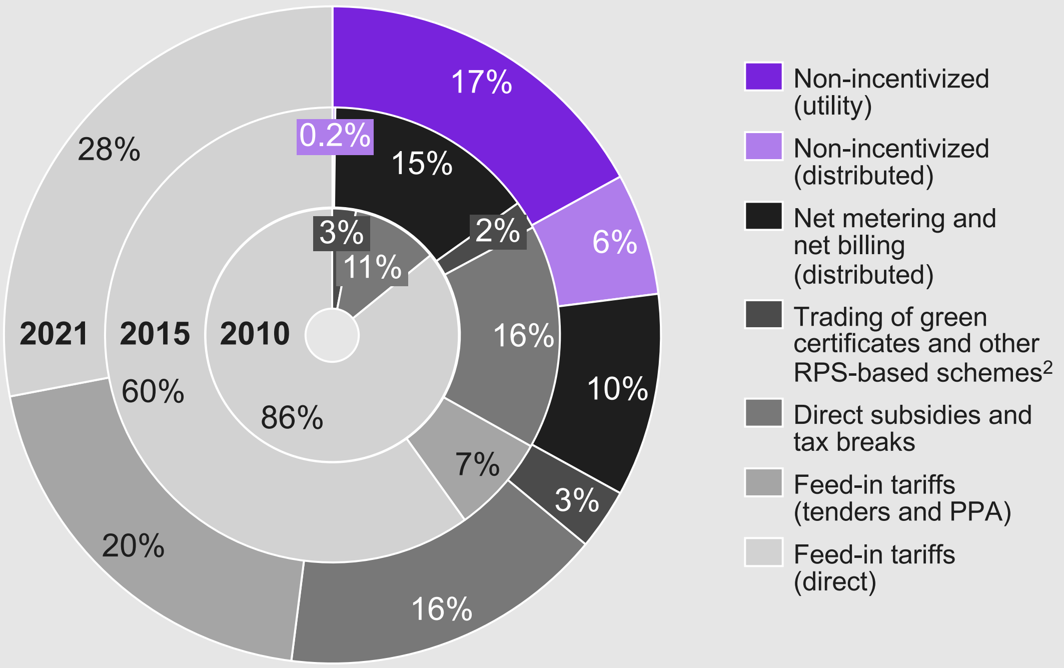
[1] This is not an exhaustive list but covers most of the policies implemented globally. There may be some overlap between different policies listed above, and in some cases the same name can mean different things depending on the country or even state.

Sources: IEA PVPS, 2023, Trends in Photovoltaic Applications; Kearney Energy Transition Institute analysis

The preferred type of policy support for solar PV has evolved gradually away from feed-in-tariffs and the share of non-incentivized production has increased

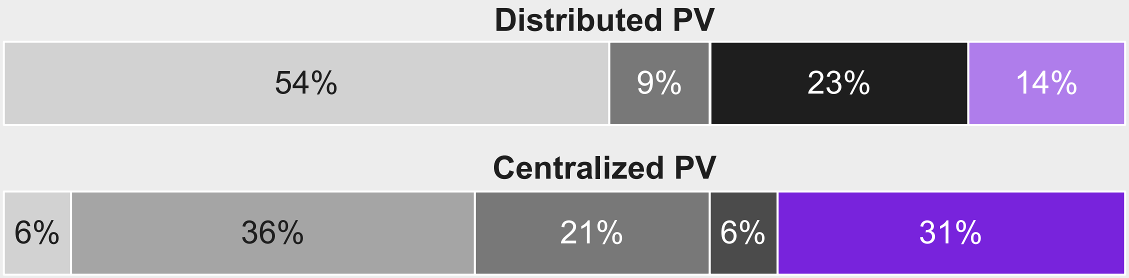
Main drivers of solar PV over time and by application

Share (%), 2010–2021, global[1]



Main drivers of solar PV by application

Share (%), 2021, global[1]



The role of policy with the appearance of competitive PV

There are now many locations where PV systems with limited or no financial support are operating, due to the competitiveness of solar PV.

However, this competitiveness is not yet guaranteed in all locations and segments. Thus, policy incentives may still be needed for years to come.

Several support policies are evolving:

- Feed-in-tariffs are being replaced by auctions and calls for tenders to promote the most competitive PV.
- When there is no more direct policy support, PV is usually provided first through PPAs, then through direct sale on market.
- For distributed PV, there is a shift from net metering to net billing, premiums, and FIT.

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[1] There is always overlap between policy drivers. This data shows the main driver and should be used as a general indication of the main PV drivers.
[2] RPS is renewable portfolio standard.

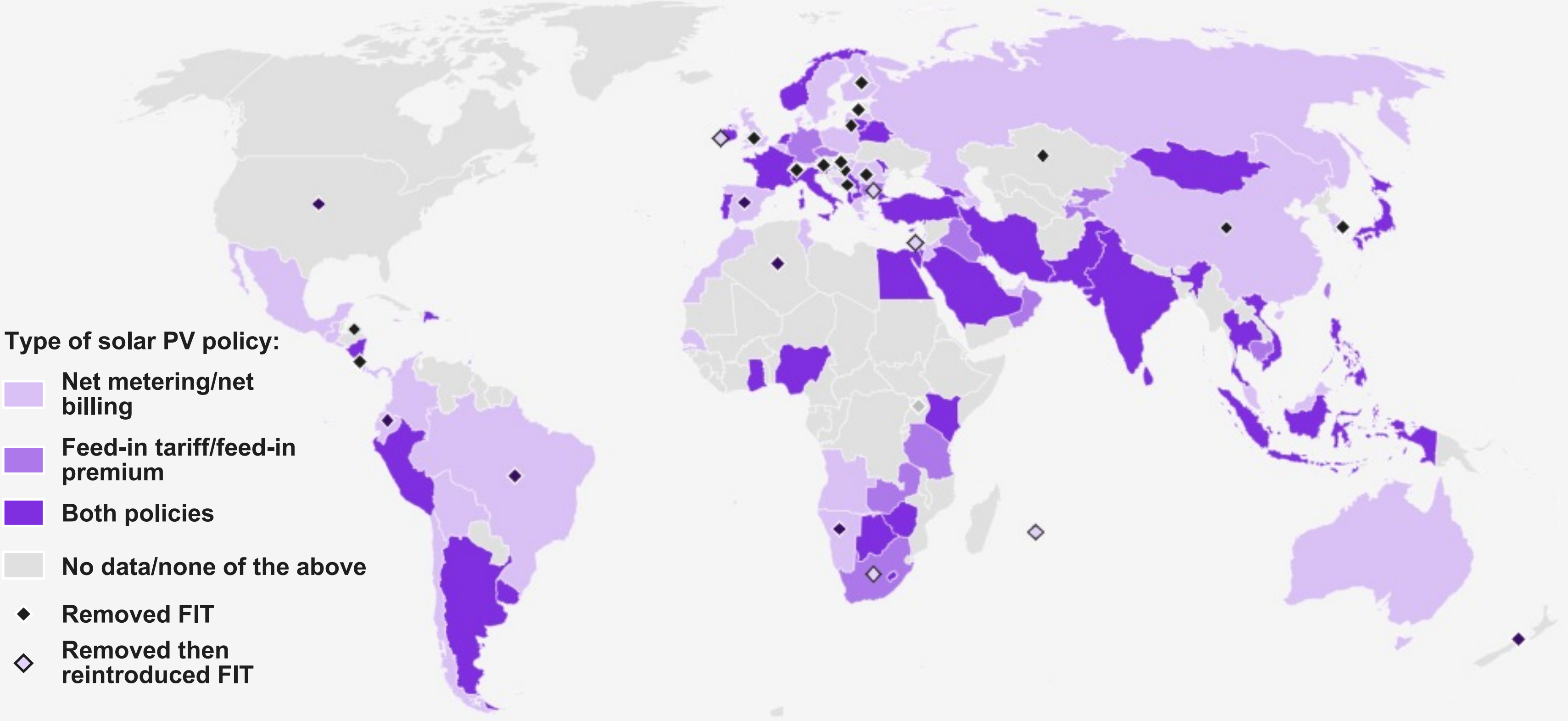
Sources: IEA PVPS, 2022, Trends in Photovoltaic Applications; Kearney Energy Transition Institute analysis

Feed-in tariffs and net metering are widespread and support the global growth in solar PV despite their drawbacks

Non-exhaustive

Countries by type of policy provided by central governments for solar PV

Type of policy, 2022, global



In 2010, 86% of policies supporting solar PV were **FITs**, and they still are the **largest source of support in 2021, at 48%.**[1] They are more used in distributed (54%) than centralized (6%) PV.

The decrease in the share of FITs is partly due to their **inability to adapt to quickly changing costs of PV**. If the FIT remains the same and PV costs decline, it will strain public budgets.

Net metering is broadly used to support distributed PVs (23%), by **compensating prosumers for the electricity they inject in the grid** through credits or monetary transfer (net-billing).

Note: In the US, there are some of the above policies, but only at a state level and not in every state.

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[1] FIT: Feed-in Tariff

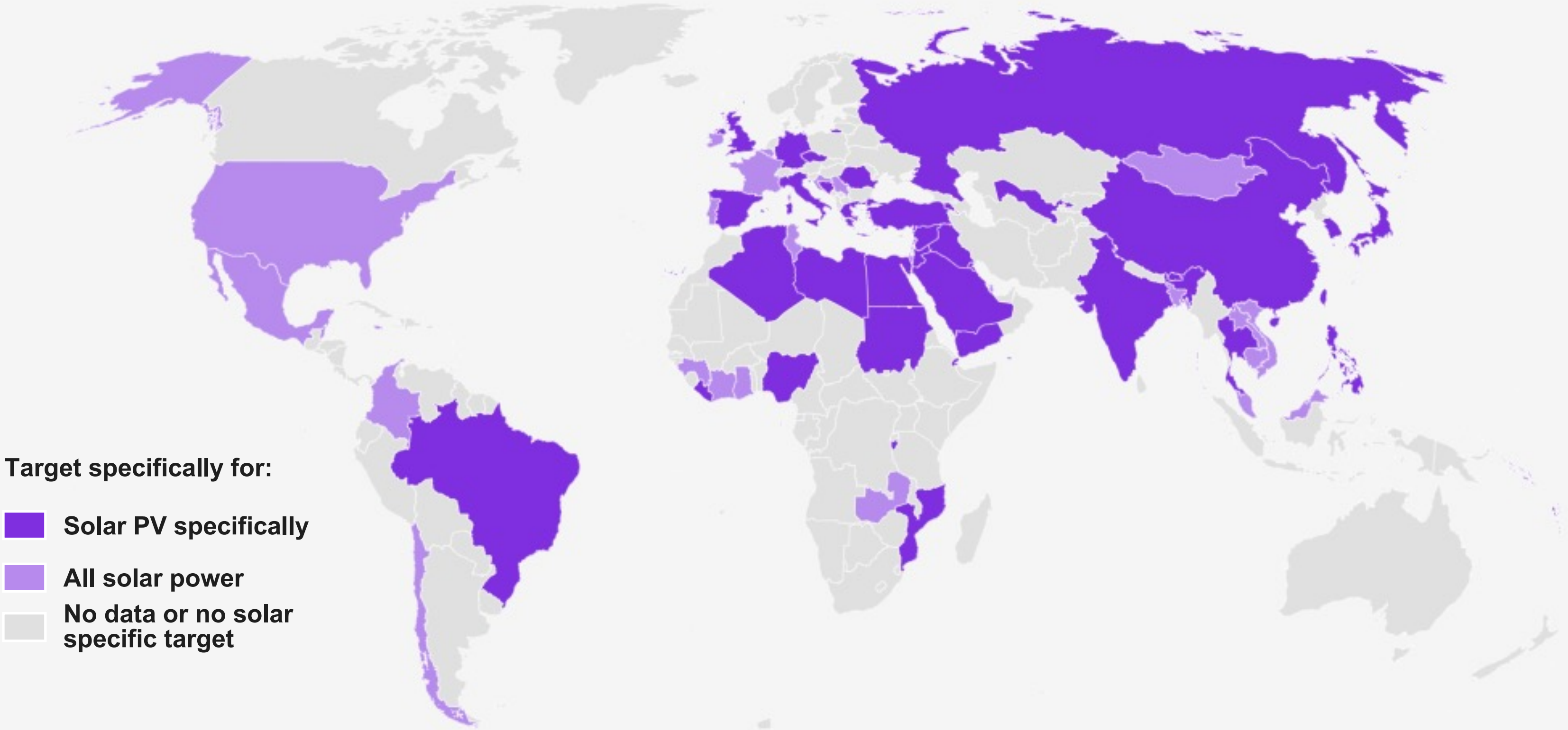
Source: REN21, 2023, Global Status Report 2023 Data Pack; IEA PVPS, 2022, Trends in Photovoltaic Applications ; Kearney Energy Transition Institute analysis.

National targets for solar PV are becoming more popular and are crucial to provide guidance to all stakeholders

Non-exhaustive

Countries by type of solar energy target

Type of target, 2022, global



Many countries do not have targets specifically for solar PV. However, **the number is growing, with 8 new ones in 2022**. Most countries have more general renewable targets.

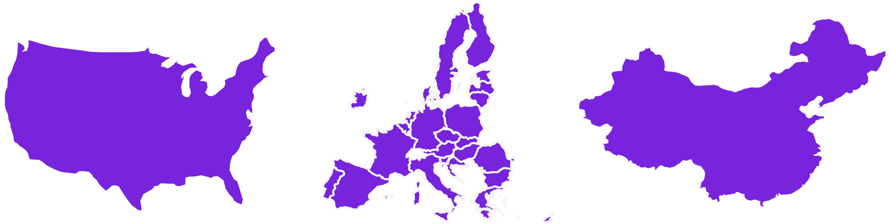
Targets vary greatly in strength, from simple political statements to detailed strategies to roll out renewables or solar PV specifically, to legally binding commitments.

Targets may not be enough to spur investments immediately, but they **indicate the general direction that the country is taking** and the kind of concrete policies that can be expected.

4.2 Policies country focus

Sources: REN21, 2023, Global Status Report 2023 Data Pack; IRENA, 2022, Renewable energy targets in 2022: a guide to design; Kearney Energy Transition Institute analysis

While China reduces incentives for solar PV, the US and the EU use a mix of instruments to secure their supply chains



Non-exhaustive

US

Category	Policies
Price-based mechanisms	
Tax credits	The federal **Energy Investment Tax Credit** finances solar PV installations.
Direct subsidies	The **Solar Manufacturing Incubator Funding Opportunity** finances solar PV R&D.
FIT	Not federal, some states have FIT.
Quantity-based mechanisms	
Quotas with tradeable certificates	Many states have **renewable portfolio standards**, and some require solar specifically.
Indirect instruments	
Supply chain support	The **Inflation Reduction Act** includes the **Advanced Manufacturing Production Credit** which gives tax credits for US-made PV components.

European Union

Category	Policies
Price-based mechanisms	
Subsidies	**REPowerEU** finances PV projects.
Quantity-based mechanisms	
Tenders and auctions	Some states use renewable energy **tenders** which favor low carbon PV.
Binding targets	**REPowerEU** sets targets for solar PV capacity by 2030 (600GW).
Indirect instruments	
Permitting/ regulatory adjustments and supply chain support	Several indirect measures support solar PV development such as the **European Solar Rooftops Initiative**, for faster and simpler permitting, **EU Solar Skills Partnership**, the **Critical Raw Materials Act** and the **EU solar PV industry alliance.**

China

Category	Policies
Price-based mechanisms	
Net metering	Since 2013 a net metering system is in place. Its value decreased significantly over the years to reach its current minimum.
Feed-in tariffs	**China stopped subsidizing solar** projects through feed-in tariffs from 2021. Solar PV electricity providers sell at market prices.
Indirect instruments	
Regulatory adjustments	Among other things, the **Buildings Energy Efficiency and Green Building Development Plan** mandates PV installation on 50% of rooftop space of new buildings by 2025.

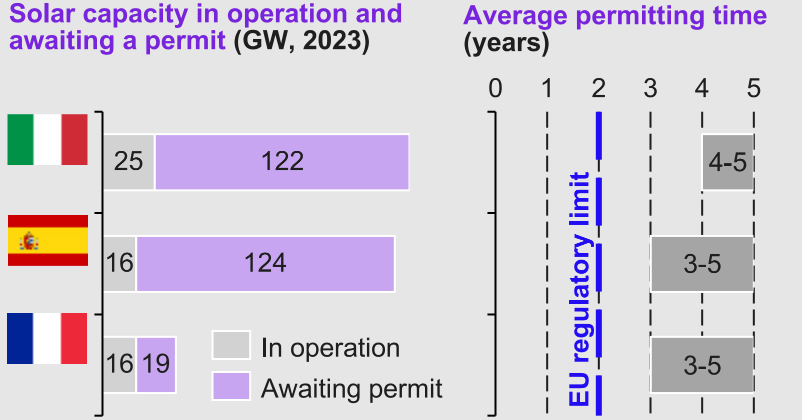
Sources: Reuters, 2021, China to stop subsidies for new solar power stations, onshore wind projects in 2021; Climate change news, 2022, China's ambitious rooftop solar pilot helps drive 'blistering' capacity growth; Xinyu Jia et al., 2020, Assessing the effectiveness of China's net-metering subsidies for household distributed photovoltaic systems; First Solar, 2022, 10-K SEC annual report; European Commission, 2023, Solar energy; European Commission, 2022, REPowerEU; Kearney Energy Transition Institute analysis

The EU is working on solving historical bottlenecks for utility-scale solar PV to unlock growth potential and develop supply chain independence

4.2 Policies country focus

Main historical bottlenecks

Permitting: Lengthy cycles with, in some countries like France, the ability to delay via legal recourse



Solar capacity in operation and awaiting a permit (GW, 2023)

Average permitting time (years)

Land: availability due to large surfaces for centralized farms and competition with other uses, land affordability due to ongoing speculation

Skills: availability of trained personnel and attractivity of sector to match the demand

European solar value chain: volumes and scale of projects challenging the small solar PV actors in Europe. Most of Europe's installed PVs modules have been imported.

EU efforts

←

Making permitting procedures shorter and simpler, through the adoption of a legislative proposal, a recommendation, and guidance alongside this communication. This is a review of the Renewable Energy Directive.

+

REPowerEU € 288 billion for the energy transition in grants (25%) and loans (75%)

EU solar energy strategy
Aims to bring 600 GW of solar by 2030.
Launched 3 initiatives:

←

European Solar Rooftops Initiative, introducing solar mandates on public, commercial, and residential buildings as these projects do not require any extra land use.[1]

←

EU Solar Skills Partnership: detail up- and re-skilling measures, foster cooperation between industry, social partners, training providers, and regional authorities, and unlock EU funding.

←

EU Solar PV Industry Alliance: Forum of stakeholders to relocate 20 GW of PV supply chain by 2025, facilitate suppliers – off-takers matchmaking and channeling funding from EU progams.[2]

[1] All new (2026) and existing (2027) public and commercial buildings; new residential ones from 2029 onward. Useful areas larger than 250m^2.

[2] E.g. InvestEU, the Innovation Fund, the Recovery and Resilience Fund and Cohesion Policies.

Sources: Solar Power Europe; Experts interviews; European Commission, 2023, Solar energy; European Commission, 2022, REPowerEU; IEA, 2023, World Energy Investment 2023; Kearney Energy Transition Institute analysis

Recent legislation in the US and the EU have been motivated by the need to boost local PV manufacturing to ensure competitiveness

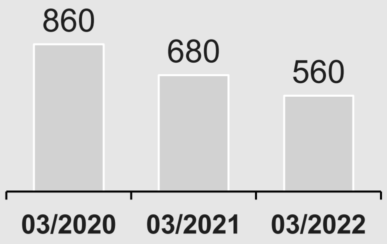
Uyghur Forced Labor Prevention Act

Took effect in June 2022

Blanket ban on all imports from China's Xinjiang province.

Several Chinese companies stopped exports to the US, accentuating the already falling PV imports from China.

US PV imports from China (USD million)



Inflation Reduction Act

Took effect in August 2022

USD 30 billion in production tax credits to accelerate domestic manufacturing of solar panels, wind turbines, batteries, and critical minerals processing.

→ IRA expected to boost US solar PV manufacturing with 10-year term tax credits

Critical Raw Materials Act

Announced on September 14, 2022

Aims to secure supply chain of raw materials by monitoring and mitigating disruption risks and enhancing circularity and sustainability.

It defines extraction, processing, and recycling mining objectives by 2030.

Underpinned by a new European Sovereignty Fund

Market ban for products made using forced labor

Announced on September 14, 2022

Regulation could come into force by the end of 2025.

Comprehensive approach to tackle forced labor taking place in the private economy as well as under state-imposed conditions.

→ EU following same approaches as US with a delay in time and scale

Sources: The White House, 2021, Statement by Press Secretary Jen Psaki on the Uyghur Forced Labor Prevention Act; US Department of State, 2022, Implementation of the Uyghur Forced Labor Prevention Act; The White House, 2023, Inflation Reduction Act Guidebook; European Commission, 2023, European Critical Raw Materials Act; European Parliament, 2023, Proposal for a ban on goods made using forced labor; Kearney analysis

The Inflation Reduction Act contains a USD 370 billion plan to boost renewable energy, with a focus on the solar ecosystem

The credits would begin to phase out by 30% in 2029 and then 35% in 2030 before ending completely in 2031.

4.2 Policies country focus

Inflation Reduction Act		Selected details	Eligibility criteria
Solar electricity generation	**Section 48** **Investment Tax Credit (ITC)**	• 30% tax credit of amount invested in new/upgraded factories to build specified renewable energy components: – Additional 10pp if domestic content requirements are satisfied – Additional percentage for small-scale projects	• Workers need to be paid the equivalent of union wages with apprentices hired for the construction and for 5 years after the project is commissioned. • Applies to both business and residential projects, including projects installed in 2022
	Section 45 **Production Tax Credit (PTC)**	• 1.5 cents per kWh for electricity produced from solar energy • New (restored) solar PTC could be more valuable than the ITC for larger-scale, more efficient PV generation projects	• Same criteria for workers from section 48 ITC
Solar energy manufacturing incentives	**Section 48C** **Energy Credit**	• USD 10 billion in tax credits for clean energy manufacturing projects • 30% tax credit for solar electricity production facilities	• Same criteria for workers from section 48 ITC
	Section 45X **Advanced Manufacturing Production Credit**	**Focus on next slide**	
Credit monetization	**Credit monetization**	• Transferability: eligible taxpayers can transfer eligible credits to unrelated taxpayers for cash. • Direct pay: If the taxpayer, taking into account the deemed tax payment for the credits, had "overpaid" their taxes they could elect a cash refund from the IRS.	• Transferability regime is not available for tax-exempts; the credits cannot be transferred a second time; larger for smaller project developers • The credit carryback period is extended from one to three years for any credit eligible to be transferred.

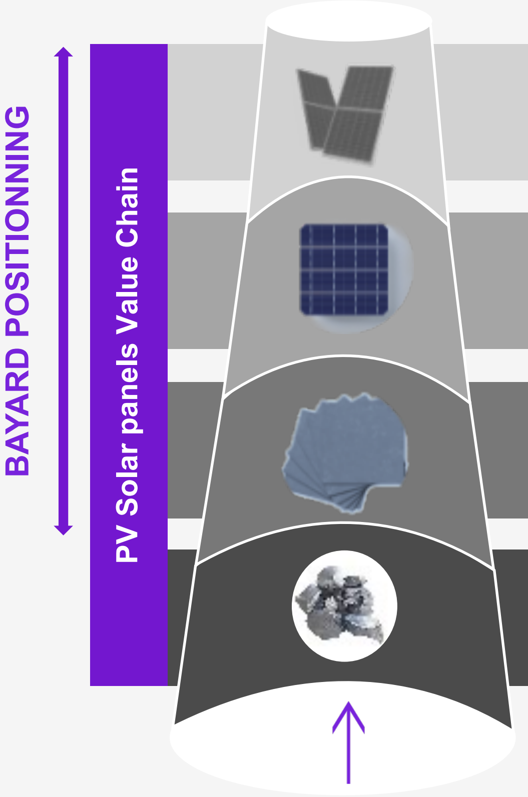
Sources: The White House, 2023, Inflation Reduction Act Guidebook; Kearney analysis

The US implemented massive tax credits to ramp solar manufacturing capacity by 2030

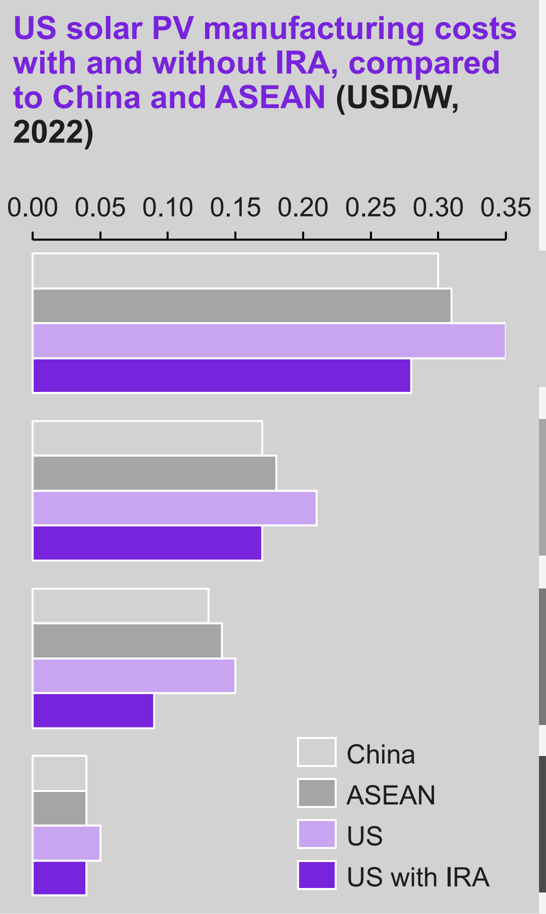
The new 45X credit for manufacturing solar cells, wafers, modules, etc., is a game-changer that will spur **domestic solar manufacturing** to a degree that may **affect worldwide solar PV manufacturers' competitiveness.**

4.2 Policies country focus

IRA tax credit schemes for PV manufacturers



Value chain	Credit amounts[1]	Condition
④ Module	7 ¢USD/Wp	Each component needs to be produced in the US and sold by a US manufacturer to an unrelated person
③ PV cells	4 ¢USD/Wp	
② Silicon wafers	12 USD/m^2	
① Solar grade polysilicon	3 USD /kg	
Total ①②③④	16 ¢USD/Wp	


US solar PV manufacturing costs with and without IRA, compared to China and ASEAN (USD/W, 2022)

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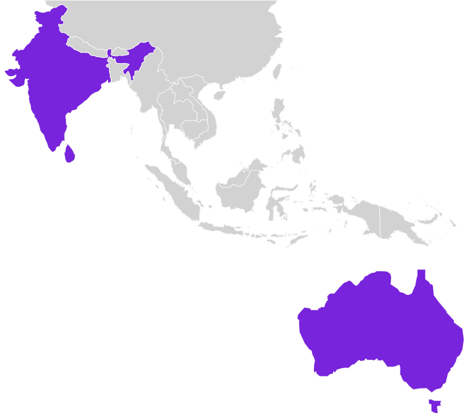
[1] The amount of the total credit is the sum of the amounts corresponding to each eligible component reproduced in the table below.

Sources: The White House, 2023, Inflation Reduction Act Guidebook; IEA, 2023, Renewables 2022; Kearney analysis

Australia still supports PV while limiting its impact on the grid, and India ramps up local content policies

Non-exhaustive



Australia

Category	Policies
Price-based mechanisms	
Feed-in tariff and net metering	**Feed-in tariff** and **net metering** conditions vary by state and by retailer. Support residential PV
Direct subsidies	A **direct rebate is applied** on the purchase cost of residential PV.
Quantity-based mechanisms	
Quotas with tradable certificates	**The LRET and SRES** create a green certificate trading system. They can be obtained by PV electricity producers and sold to entities who must have a certain amount to meet yearly quotas.[1,2]
Indirect instruments	
Grid access policies	The **Modern Manufacturing Strategy** allocates AUD 107 million to **supply chain resilience,** including semiconductors used in PV.
Market policies	In Victoria, settlement periods for self consumption were shortened to better incentivize technologies with fast responses to adapt to PV's variability.

India

Category	Policies
Price-based mechanisms	
Net metering	A **net metering system is** in place for installations up to 500 kW, and new projects must respect some local content requirements.
Quantity-based mechanisms	
Auctions and tenders	In March 2023, the government increased its **renewable energy auctions** to 50 GW annually, boosting demand for solar PV.
Indirect instruments	
Supply chain support/ mandates	The **Production Linked Incentive**, last updated in September 2022, provides cash incentives to local manufacturers to reduce dependency on foreign imports of solar modules. **Import duties** are imposed on solar modules (40%) and solar cells (25%) and **mandated** that all federal procurement be only of cells and modules produced domestically.

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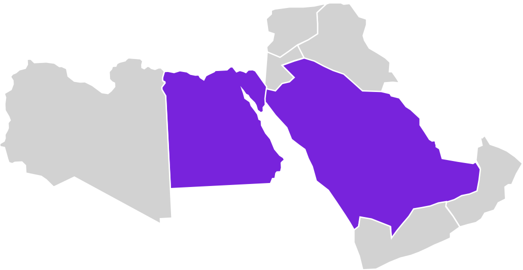
[1] Large-scale renewable energy target

[2] Small-scale renewable energy scheme

Sources: First Solar, 2022, 10-K SEC annual report; Indian Ministry of New and Renewable Energy, 2023, Government declares plan to add 50 GW of renewable energy capacity annually for next 5 years to achieve the target of 500 GW by 2030; PV magazine, 2022, India expands domestic content rules for open-access, net-metering PV projects; Australian Government DCCEEW, 2023, Renewable Energy Target Scheme; Renogy, 2021, Solar panel incentives and rebates in Australia; Australian Government CER, 2023, Renewable Energy Target – How the scheme works; IEA PVPS, 2022, Trends in Photovoltaic Applications; Australian Government DISR, 2020, Make it Happen: The Australian Government's Modern Manufacturing Strategy; Kearney Energy Transition Institute analysis.

Saudi Arabia aims to become a PV powerhouse in the Middle East while Egypt offers strong policy support to the solar sector

Non-exhaustive



4.2 Policies country focus

Kingdom of Saudi Arabia

Category	Policies
Price-based mechanisms	
Net metering	While net metering has been decreasing at a global level, **KSA** implemented **net metering** incentives in 2019 for projects <2 MW.
Quantity-based mechanisms	
Non-binding targets	The **Solar Energy Plan targets** 27.5 GW of solar installed capacity by 2030, from less than 0.5 GW in 2022.
Indirect instruments	
Regulatory adjustments	The **Private Sector Participation Law** allows developers to sell directly to consumers to facilitate PV development and boosted self consumption by increasing the limit to 2 MW.
Supply chain support	The country's **Vision 2030** targets a domestic **PV supply chain** to reach self-sufficiency, and eventually to become a net solar PV exporter.

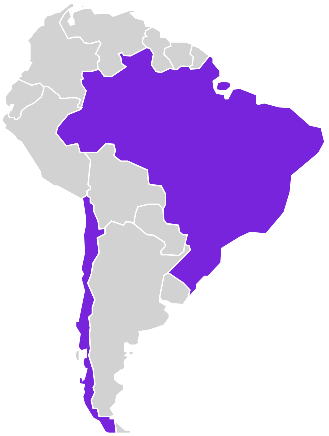
Egypt

Category	Policies
Price-based mechanisms	
Net metering	Amended 2022 bill outlines that the total capacity generated from solar net-metering projects (past and future) may not exceed 1,000 MW. Projects <10MW are **exempted from integration fee**
Feed-in tariffs	A **feed-in tariff** has been in place since 2014 and has been successful in attracting solar investments
Quantity-based mechanisms	
Non-binding targets	Integrated Sustainable Energy Strategy, installing additional renewable energy to reach electric power contribution target of 42% by 2035 with solar PV accounting for 21%
Indirect instruments	
Regulatory adjustments	Private investors entering into direct PPAs with (large) consumers and being granted access to the grid.

Sources: IEA PVPS, 2022, Trends in Photovoltaic Applications; PV magazine, 2023, Saudi Arabia's solar market; Zaid et al. 2020, Current status and future perspectives for localizing the solar photovoltaic industry in the Kingdom of Saudi Arabia; Hahasmart Solar, 2017, Saudi Arabia approves net metering framework for systems up to 2MW; IEA, 2017, UNFCCC, Kearney Energy Transition Institute analysis

Brazil innovates to encourage distributed PV and continue its quick growth, while Chile works on protecting its grid

Non-exhaustive



4.2 Policies country focus

Brazil

Category	Policies
Price-based mechanisms	
Net metering	**Net metering** incentives have been in place for several years, which boosted the distributed PV sector. In 2022, an update of the system increased confidence by guaranteeing net metering tariffs until 2045 for installations under 5 MW.
Quantity-based mechanisms	
Tenders and auctions	**Tenders** are used to secure electricity supply and favor PV technology.
Indirect instruments	
Grid access and market policies	To support grid improvements to cope with grid strain due to PV variability, a **grid fee** is imposed on prosumers from 2023, which will slightly increase the cost of solar PV.
Regulatory adjustments	Regulation was adjusted to favor self consumption by modifying the net metering scheme and allow for **self-consumption from owned distant sites**.

Chile

Category	Policies
Price-based mechanisms	
Net metering	**Chile** is one of the emerging PV markets to have implemented **net metering** in recent years.
Quantity-based mechanisms	
Tenders and auctions	**Tenders** are used to secure electricity supply and favor PV technology.
Non-binding targets	The country aims for **70% of renewables by 2050.**
Indirect instruments	
Grid access and market policies	A law was introduced in 2022 to **reduce energy curtailment** by incentivizing electricity storage to inject electricity to the grid, thus decreasing curtailment risk and ultimately favoring solar PV in the country.

Sources: IEA PVPS, 2022, Trends in Photovoltaic Application; EIA, 2019, Brazil's net metering policy leads to growth in solar distributed generation: PV magazine, 2022, Brazil introduces new rules for distributed generation, net metering; PV magazine, 2022, Chile enacts law on energy storage, electromobility; IEA, 2023, Renewable Energy Market Update; Bloomberg, 2015, Chile Sets Clean Energy Target of 70% of Generation by 2050; CMS, 2020, Expert Guide for renewable energy law and regulation in Chile; Kearney Energy Transition Institute analysis

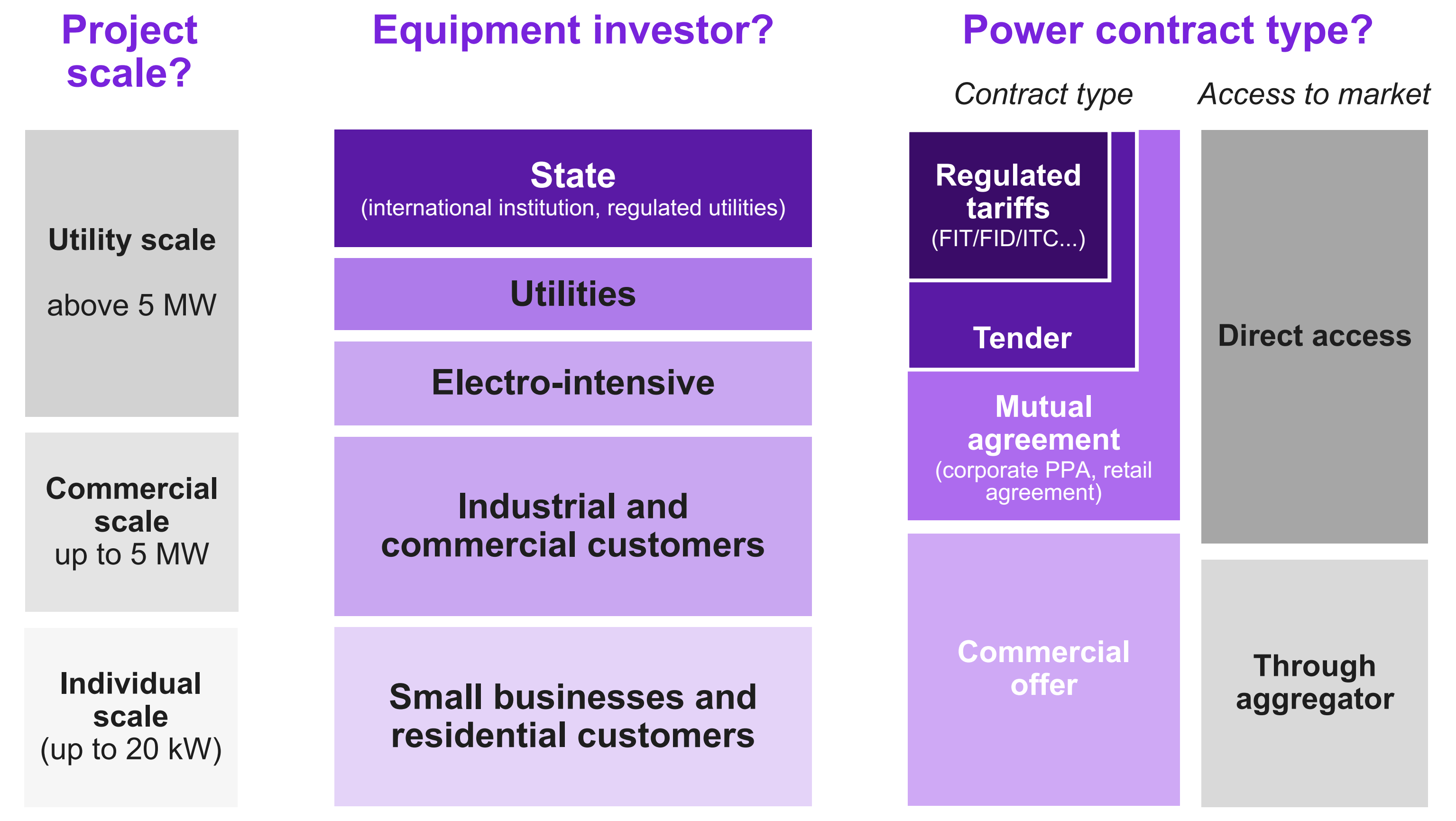
Solar PV offers a wide range of energy solutions combining project scales, investors, and power contract types

Solar PV offers flexible combinations of project scale, investors, and contracting types, which need to be properly tailored to optimize the power solutions for customers.

4.3 Financing schemes

Schematic framework of solar PV projects

Combination of scale, type of investors, and power contracts



Project scale?

Utility scale

above 5 MW

Commercial scale

up to 5 MW

Individual scale

(up to 20 kW)

Equipment investor?

State

(international institution, regulated utilities)

Utilities

Electro-intensive

Industrial and commercial customers

Small businesses and residential customers

Power contract type?

Contract type

Regulated tariffs

(FIT/FID/ITC...)

Tender

Mutual agreement

(corporate PPA, retail agreement)

Commercial offer

Access to market

Direct access

Through aggregator

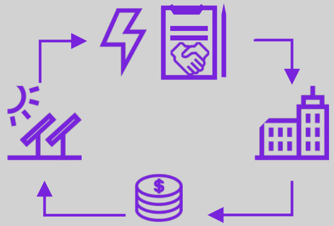
Source: Kearney analysis

PV business models are adapting to the transformation of the power system; they are based on the competition of PV with other generation sources

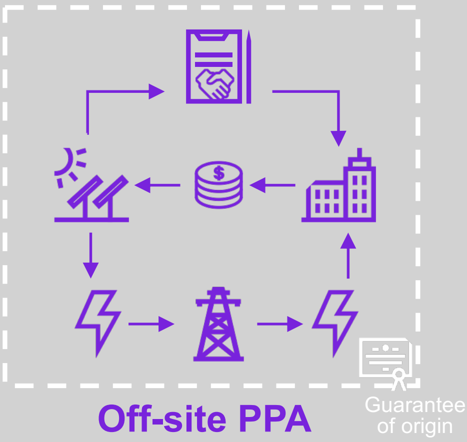
Direct sale of PV electricity **is growing** as developers and project owners take advantage of higher electricity prices to **avoid the constraints of tenders or** as **an alternative to support mechanisms that will be phasing out.**

Power purchase agreement (PPA)

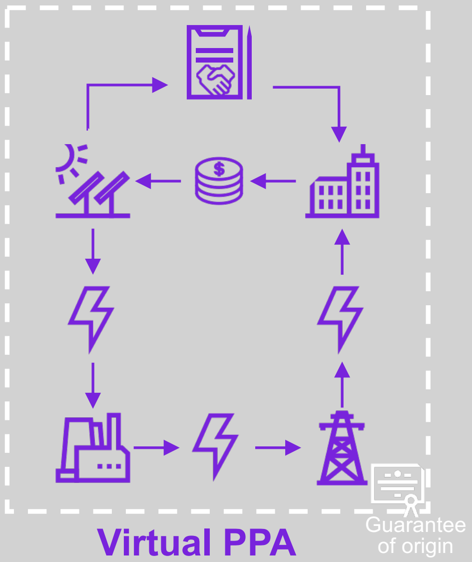
PPAs are contracts between electricity producers and buyers (off-takers) ensuring the transaction electricity volumes under a defined price and period of time.



On-site PPA



Off-site PPA



Virtual PPA

Physical PPA

Also called direct PPA, this is a direct exchange between the electricity producer and its customer. The generation can be:

– Located on the premises of the consumption site (on-site PPA)

– Located remotely with the electricity injected to the grid (off-site PPA) and the off-taker receives a guarantee of origin to ensure the source of the electricity bought

Virtual PPA

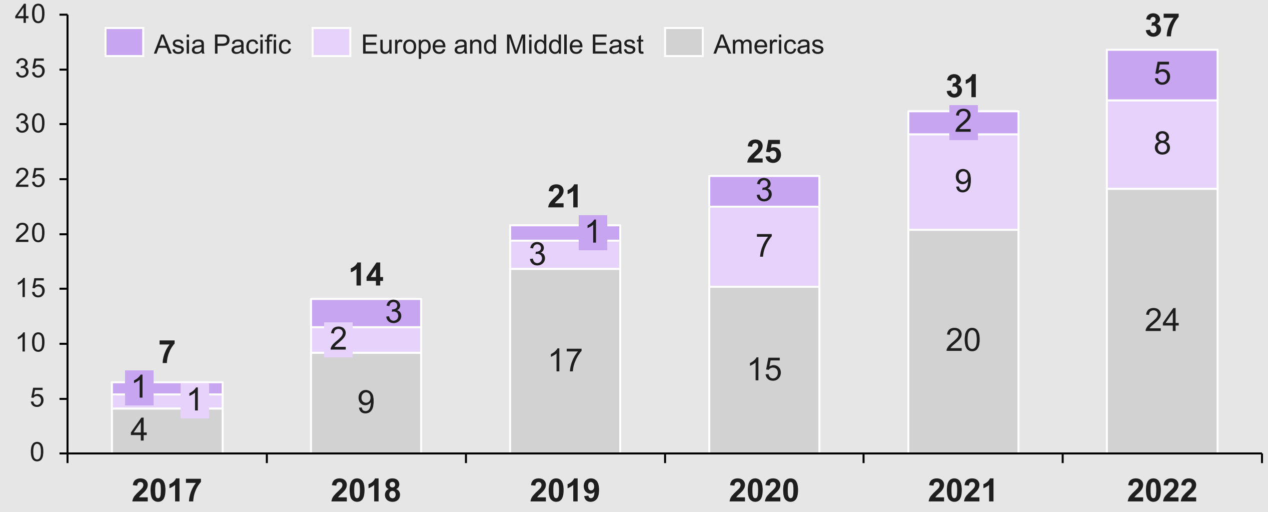
Also called financial PPA, these are agreements without physical delivery of electricity and are defined as a financial transaction between parties.

These agreements are usually defined as contracts for difference (CFD), where a price is agreed—a strike price. If the selling market price is lower than agreed, the producer pays the profit to the off-taker. If the market price is above the negotiated price, the off-taker pays the producer the difference.

Sources: IEA, Snapshot of Global PV Markets 2023; Kearney Energy Transition Institute analysis

Worldwide, corporate buyers have signed PPAs for 148 GW of renewables since 2008; solar is the preferred technology among top corporate buyers

Global corporate PPA volumes
Annual volume (GW), by region



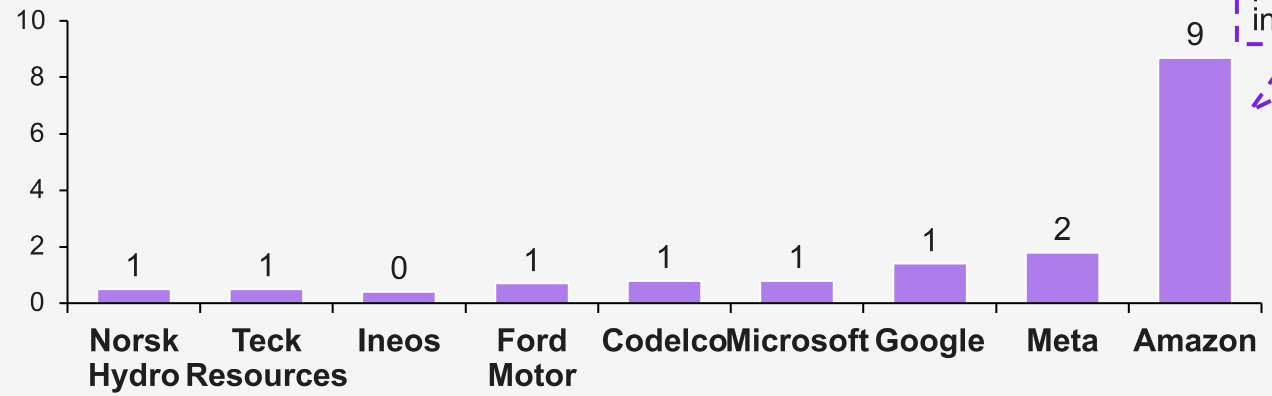
US corporations are driving **PPA expansion,** followed by Brazil, Australia, Spain, and Sweden.

In the US, **virtual PPAs** have been gaining momentum and **represented 82**% of signed PPAs **in 2019.**

The number of organizations having pledged **net-zero and operating with clean energy continues to grow**, driving **PPA growth** with it. This type of market-driven procurement is expected to contribute **to one-fifth of solar PV and wind capacity expansion** in 2023–2024.

4.3 Financing schemes

Top corporate buyers of solar electricity in 2022
GW_{DC}, excluding onsite PPAs



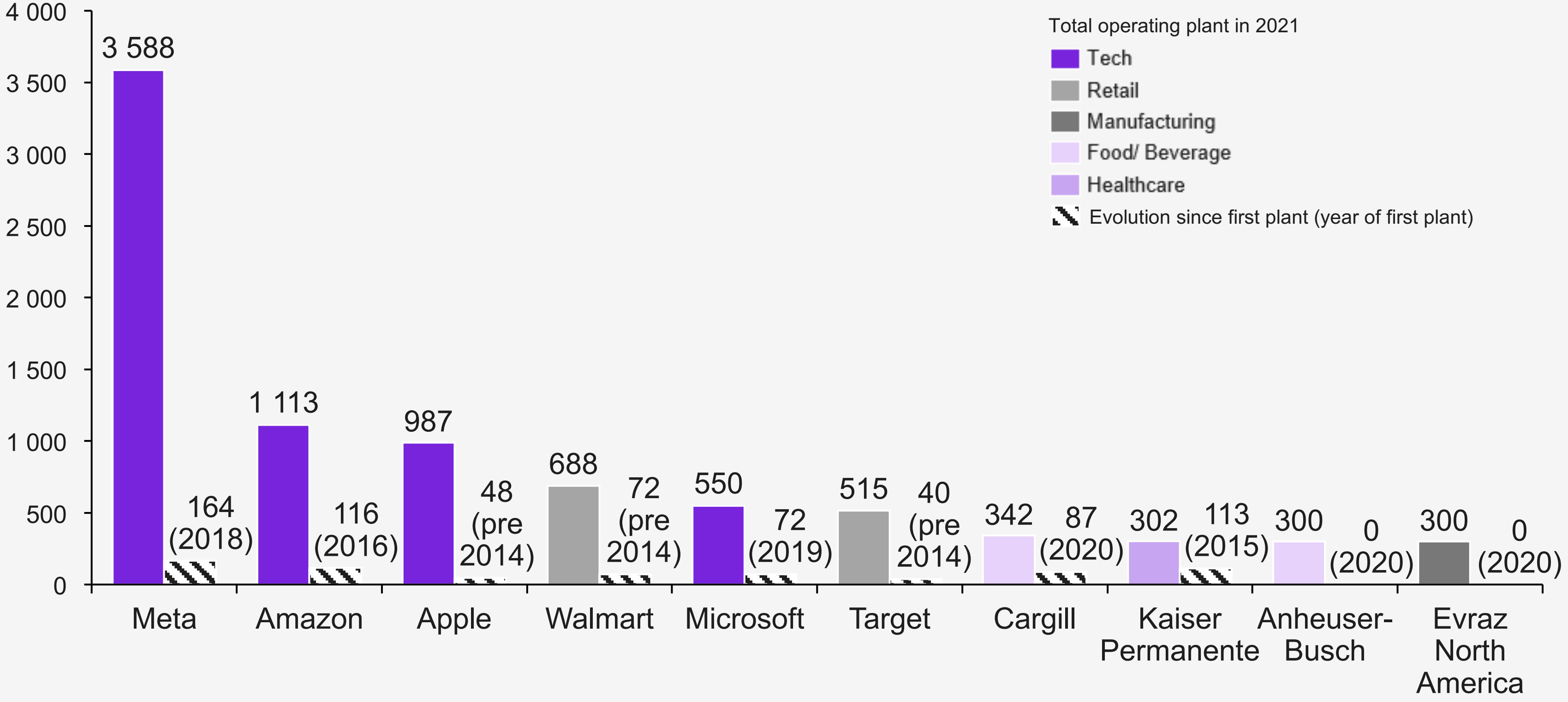
Amazon is the seventh largest clean energy portfolio globally, including utilities.

Sources: BNEF, Corporations brush aside energy crisis, buy record clean power, 2023; IEA, Renewable Energy Market Update – June 2023; Kearney Energy Transition Institute analysis

Private companies invest in solar plants to produce a part of their energy

- Companies often have **large spaces and roofs** available in their buildings and factories. Solar panels can be installed in those spaces to produce electricity locally and reduce energy bills.
- This specific type of usage is called **commercial** (or **industrial**) PV and represents a significant share of the overall PV installation. In 2022, commercial PV plants represented **19% of operating PV capacity**.
- Major corporations have been doing this for more than a decade now.

US top 10 largest cumulative corporate installed PV plant capacity in 2021 (MW)[1]



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[1] This list includes on-site and off-site installed capacity.

Sources: IEA, 2022, Renewables 2020: Solar PV; SEIA, 2022, Solar means business report; Kearney Energy Transition Institute analysis

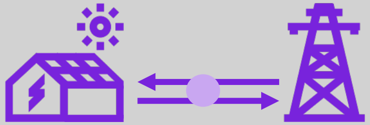
Other solar PV business models defined to reduce grid dependency, while others are exclusively defined for off-grid systems

Non-exhaustive

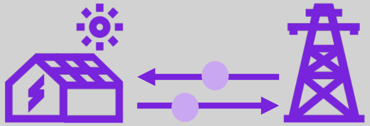
Self-consumption

Corresponds to those electricity consumers that can produce totally or partially their electricity needs. These schemes minimize the need for transmission of power across long distances by allowing the exchange of electricity between the consumer and the grid.

- **Net-metering:** the consumer gains credits when injecting excess electricity in the grid. It consumes electricity from the grid when needed. In practice, the consumer's bill is based on the difference in **quantity** between injected and withdrawn electricity.
- **Net-billing:** a compensation mechanism that remunerates prosumers based on the market value of electricity consumed or injected to the grid. The consumer's bill is calculated by the difference between **price** of the injected and the withdrawn electricity.



Net-metering

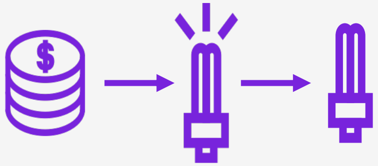


Net-billing

Off-grid

Supplies electricity through standalone products and services. Their business models have evolved ranging from service-based models providing electricity as a service to lease-to-own and cash sales to individuals. The models for these stand-alone systems include:

- **PAYGo:** the most common business model as it allows customers to **pay for systems in installments**, facilitating access to consumers. The global value of products sold via this model in S2-2022 is USD 280 million. This model is usually combined with cash only.
- **Cash only:** corresponds to products **sold** to the consumer through a **single transaction**. Cash only transactions dragged USD 86 million in S2-2022.



PAYGo

Cash only

Sources: GOGLA, Global Off-grid Solar Market report semi-annual sales and impact data, 2022; Kearney Energy Transition Institute analysis

Investment in solar PV has the fastest growth rate among all renewables

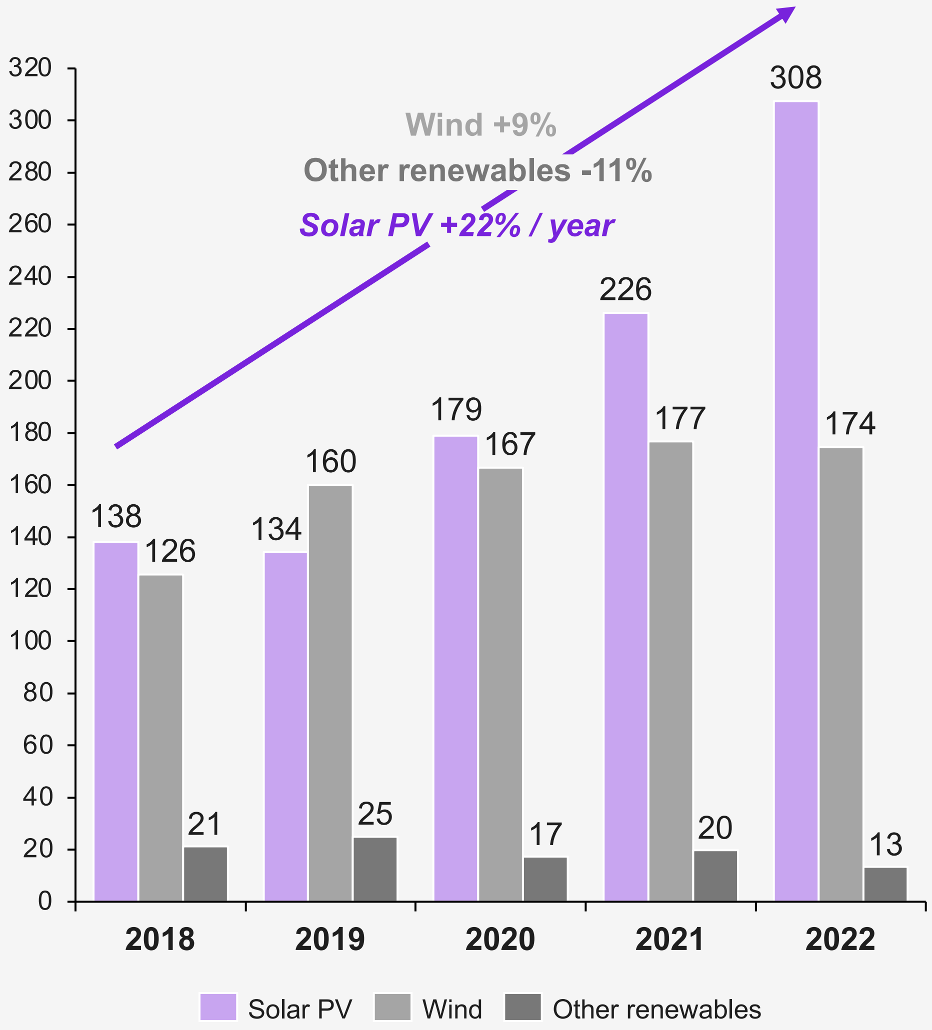
Solar PV represents more than 60% of investments for renewables power and fuels.

In 2023, the investment dedicated to Solar PV is expected to reach USD 380 billion

4.4 Investments in solar PV

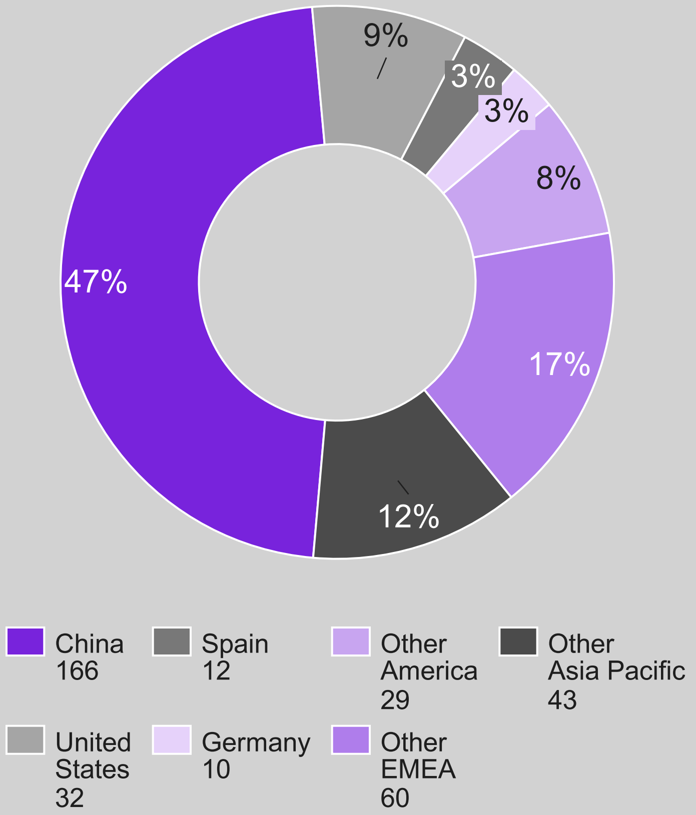
Investments in solar PV compared to other renewables

2022 USD billion, global



Share of investments in solar PV by country in 2022

2022 USD billion and (%), global



Note: Other renewables include biofuels, biomass and waste, small hydro, geothermal, ocean, and CSP.
Sources: Bloomberg NEF, "Energy Transition Investment Trends 2023"; BNEF, 2023, Renewable Energy Investment Hits Record-Breaking USD 358 billion in 1H 2023; Kearney Energy Transition Institute analysis

5. Composition and evolution of solar PV LCOE

Composition and evolution of solar PV LCOE

Solar PV costs have been declining globally, and in the past decade, the levelized cost of electricity (**LCOE**) **costs—**corresponding to installation and electricity production phases—**have declined by 89%** for utility-scale at a yearly rate of 16.5%.[1] In 2022, the LCOE ranged between **0.52 and 0.21 USD/kWh**, with the **lowest in China at 0.034 USD/kWh**. The **major driver** of LCOE decline **is module prices,** which have **dropped by 45%** between 2010 and 2022.

Total installed costs reached 848 USD/kW in 2022, almost five times cheaper than in 2010. Large price **variations exist** among countries, **ranging from 600 to 1,600 USD/kW** due to disparities in **soft costs—**mostly related to financing costs, development costs, and its associated labor.

Module costs also vary greatly depending on the **location of the production and final use**, ranging **from 220 to 490 USD/kW**. Although **module costs** have dropped significantly, reaching **0.3 USD/W**, further reduction will be driven by **technological innovation and productivity improvements along the value chain**. The application and the installation size influence the balance of system (BOS) and soft costs making **residential PV almost four times the cost of utility scale**. Factors such as the inverter costs and the cost of capital also have an influence on LCOE.

5.0 Summary

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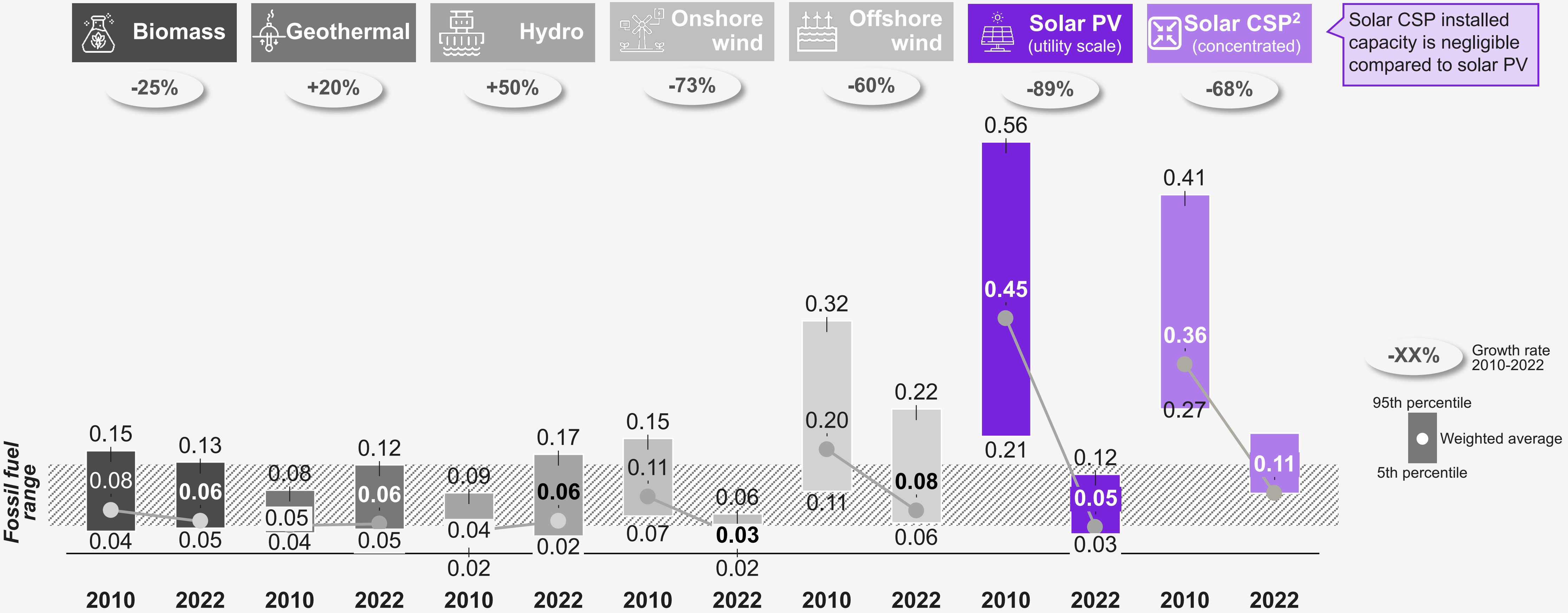
[1] LCOE is levelized cost of electricity; outliers not considered in max/min but included in weighted averages. According to the IEA, “The LCOE combines into a single metric all the cost elements directly associated with a given power technology, including construction, financing, fuel, maintenance, and costs associated with a carbon price. It does not include network integration or other indirect costs.” (IEA, WEO 2023)

As the technology matures and capacity increases, the cost of solar PV will continue to decline and become one of the most competitive power generation technologies

Global LCOE by renewable energy source[1]

2022 USD/kWh



Solar CSP installed capacity is negligible compared to solar PV

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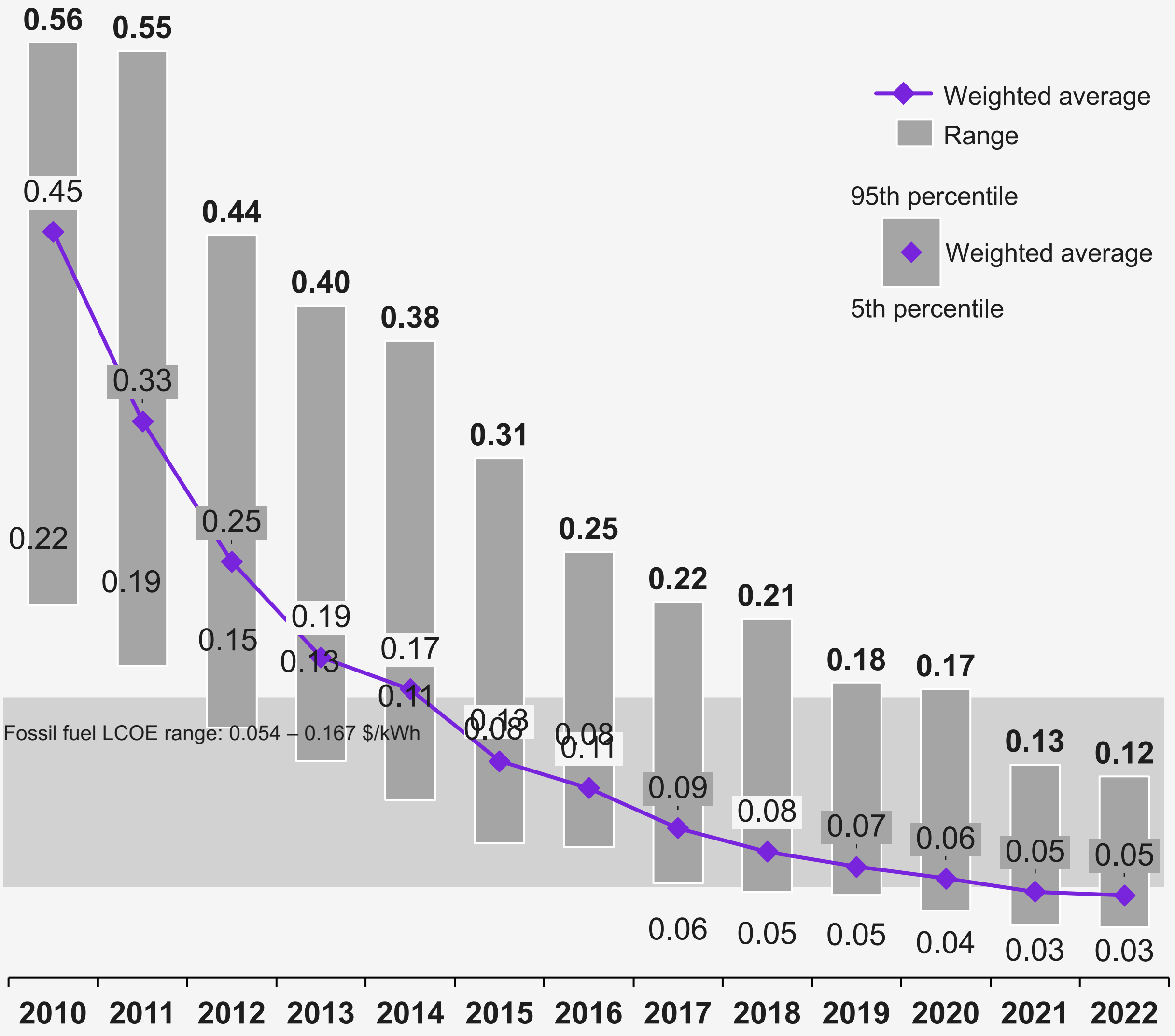
[1] LCOE is levelized cost of electricity; outliers not considered in max/min but included in weighted averages. [2] Because of insufficient data, CSP values are given for 2021.

Sources: IRENA, 2023, Renewable Power Generation Costs in 2022; Kearney analysis

Solar PV’s LCOE is on average below the entire range of fossil fuel LCOE for the first time

Global LCOE evolution for utility-scale solar PV

2022 USD/kWh



Sources: IRENA, 2023, Renewable Power Generation Costs in 2022; Kearney Energy Transition Institute analysis

- **Solar PV’s LCOE has been declining on average by 16.5% every year between 2011 and 2022**, and by 4% from 2021 to 2022.
- With this strong decline the average **solar PV LCOE is now below the entire range of fossil fuel LCOE**.
- **A decrease is seen in all main markets worldwide**, from an average of -10% per year from 2010 to 2022 in the US to -17% in Australia to -19% per year in Spain.

5.1 Levelized cost of electricity

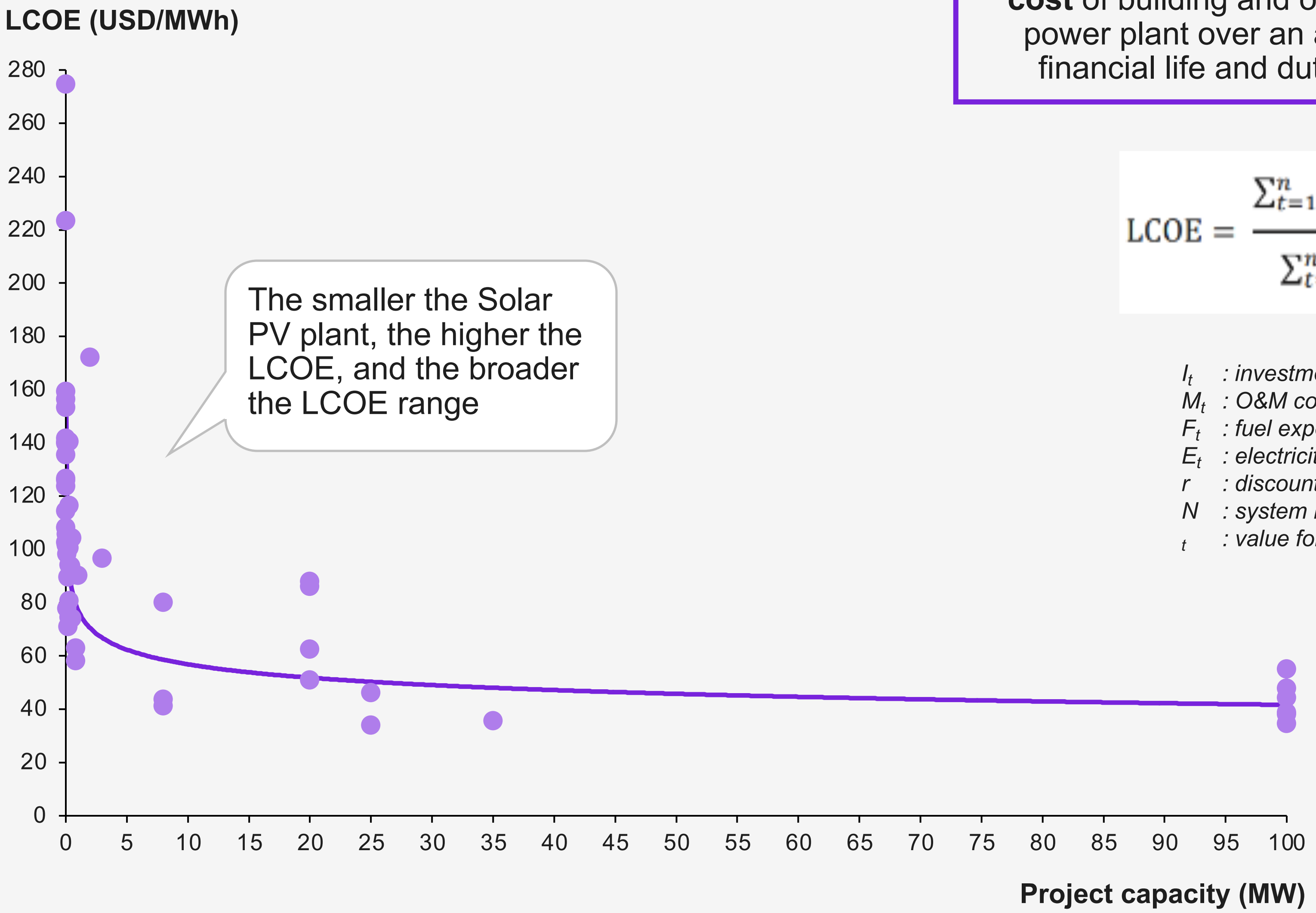
Several factors including solar PV plant scale and local irradiation intensity, affect the solar PV LCOE

Differences between solar PV LCOE values decrease as project size increases.

5.1 Levelized cost of electricity

Distribution of solar PV LCOE by project size

USD/MWh, MW



The smaller the Solar PV plant, the higher the LCOE, and the broader the LCOE range

Sources: IEA, Levelised cost of electricity calculator, 2020; Kearney Energy Transition Institute analysis

The levelized cost of electricity (LCOE) is the **per-kilowatt-hour cost** of building and operating a power plant over an assumed financial life and duty cycle.

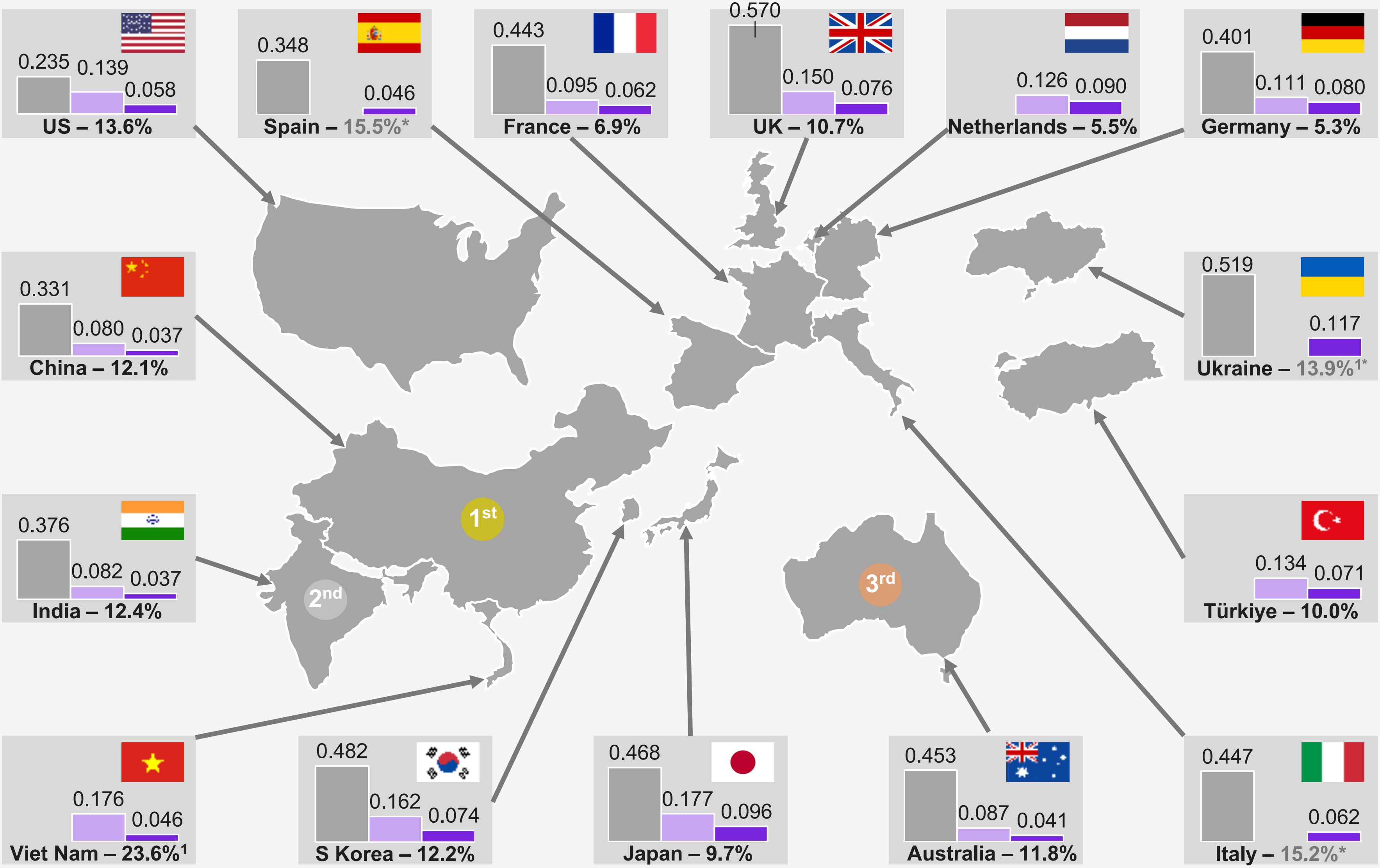
$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t : *investment costs*
M_t : *O&M costs*
F_t : *fuel expenditure = 0*
E_t : *electricity generation*
r : *discount rate*
N : *system lifespan*
$_t$: *value for year t*

Solar PV's LCOE has decreased quickly across the globe with China being among the lowest LCOEs, followed by India and Australia

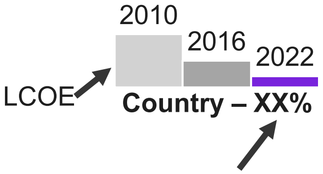
Utility-scale solar PV LCOE in 2021 and evolution since 2011, selected countries

2021USD/kWh, 2011/2016/2022



1st Ranking lowest to highest LCOE in 2021

▢ 2010
▨ 2016
■ 2022



Negative CAGR of LCOE from 2016 to 2022

XX%*: evolution from 2010 to 2022 because insufficient data

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* See box on the left.

[1] Deep purple boxes are data from 2021 (because of insufficient 2022 data).

Sources: IRENA, 2023, Renewable Power Generation Costs in 2022 Kearney Energy Transition Institute analysis

The LCOE regroups most factors affecting electricity generation costs in a single number

The LCOE allows for the combination of all direct costs associated with a power technology into a single metric. However, **LCOE does not include network integration or other indirect costs**. The value-adjusted LCOE (VALCOE) provides information about costs and the value provided to the system.[1]

Drivers of the levelized cost of electricity for solar PV

Categories		LCOE drivers	Cost description
Total installed cost Value per kW, measuring how much it costs to produce one kW of solar PV capacity before the beginning of electricity generation.	**Module costs**	**Module**	Solar photovoltaic module, includes raw materials, manufacturing, manufacturer's margin, shipping, seller's margin.
	Balance of system/ hard costs All hardware costs apart from the PV module	**Inverter**	Hardware that transforms the module's direct current into alternating current. It depends on the size of the inverter and the power plant's configuration compared to the modules.[2]
		Racking and mounting	Structure holding the modules together. The cost varies mainly between fixed-tilt and tracking systems, the latter being more expensive.
		Other BOS hardware:	
		– Grid connection	Includes all medium voltage components needed to connect to the grid.
		– Cabling/wiring	All DC components and AC low-voltage components.
		– Safety and security	Fences, cameras, and all other equipment needed to protect the facility.
		– Monitoring and control	Includes, among others, meteorological and data systems' equipment.
	Soft costs All other costs necessary before the beginning of electricity generation	**Development/EPC[3]/ installation**	Labor incurred during EPC and installation and other costs linked to installation/ EPC/development: access roads, cable trenches, construction supervision, transport.
		Other soft costs:	
		– Margin	The gross profit margin of contractors, mainly the EPC and developer.
		– Financing costs	Incurred to obtain the financing until the beginning of power generation.
		– System design	Designs, surveys, and preparation of documentation.
		– Permitting	Permits and environmental regulations.
		– Incentive application	Resources to apply for incentives and prove compliance to benefit requirements.
		– Customer acquisition	Resources used to gain the project, by winning a call for tender, for example.
Other LCOE drivers Costs associated to the electricity production phase of the power plant		**Capacity factor**	Ratio between generated power and theoretical maximum output.
		WACC	Debt and equity needed to finance the initial investment.
		All-in operation and maintenance	All operating expenses from the moment the solar plant starts producing electricity.
		Decommissioning[4]	Power plant dismantle and material recycling once it has ended its operation.

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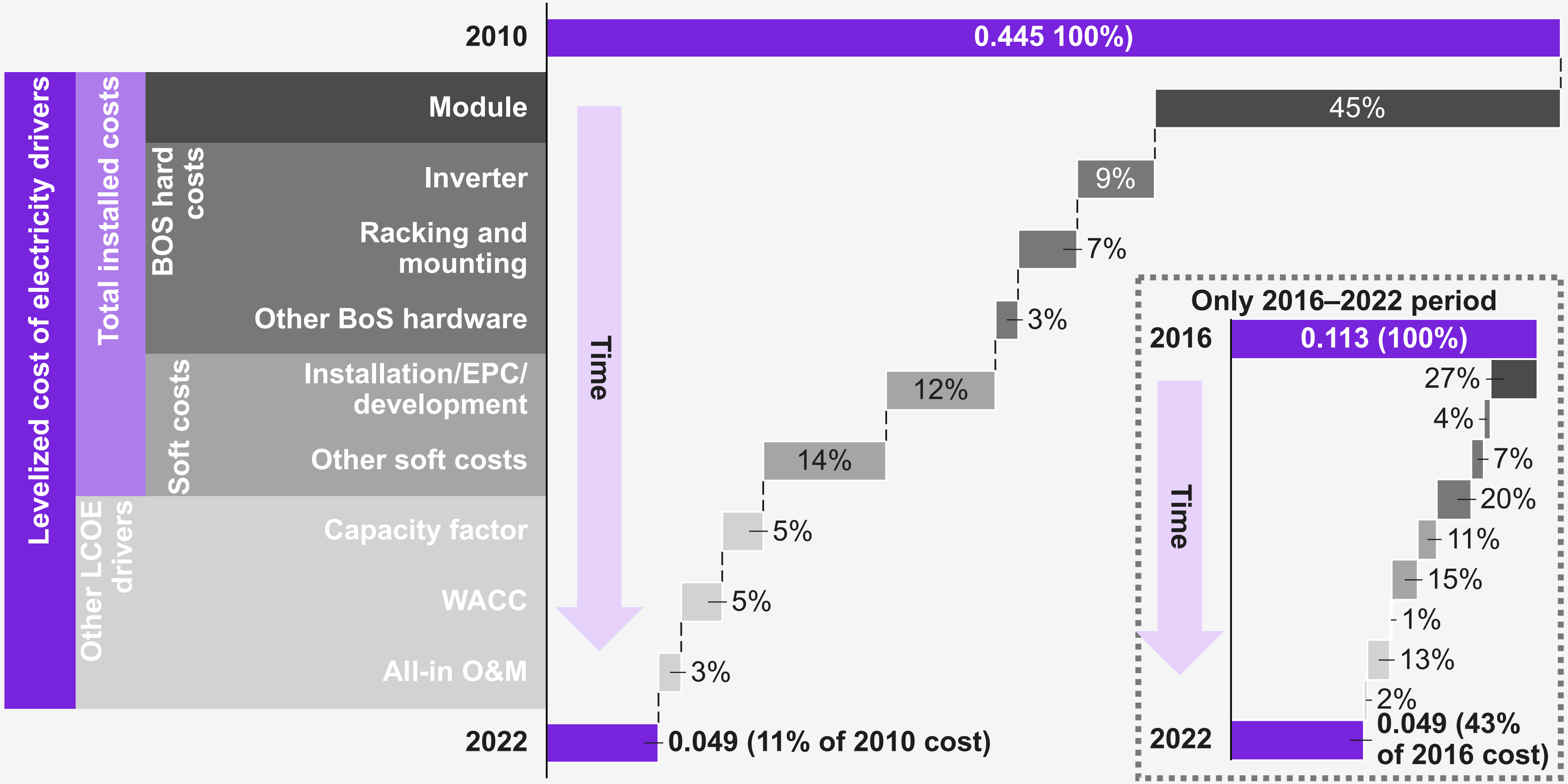
[1] See the IEA's World Energy Outlook 2022.
[2] See the inverter loading ratio slide for more detail on how it affects the LCOE. Note: inverter is sometimes not included in BOS.
[3] EPC is engineering, procurement, construction
[4] Decommissioning cost should be included in the LCOE in jurisdictions where it is borne by the energy producer.
Sources: Lawrence Berkeley National Laboratory, accessed July 2023, Energy I-SPARK ; IRENA, 2023, Renewable Power Generation Costs in 2022; IEA, 2022, WEO2022; Kearney Energy Transition Institute analysis

LCOE's drop over the past decade was mostly driven by decreasing module costs

Drivers of the decline of LCOE of utility-scale solar PV

2022 USD/kWh, share of decrease (%), global, 2010–2022



The decline of solar PV's LCOE is remarkable, notably due to the strong decrease in costs along the entire value chain, from modules to financing.

Module costs have decreased the most. This increases the share of LCOE made up of other costs such as BOS costs and soft costs.

Other drivers contributed significantly to LCOE's decrease since 2010. In total, they explain 11.5% of the decrease, more than the decrease explained by all BOS hardware excluding inverters.

Looking only since 2016, the share of each component in the decrease in LCOE varies. The decrease in WACC and BOS was especially important.

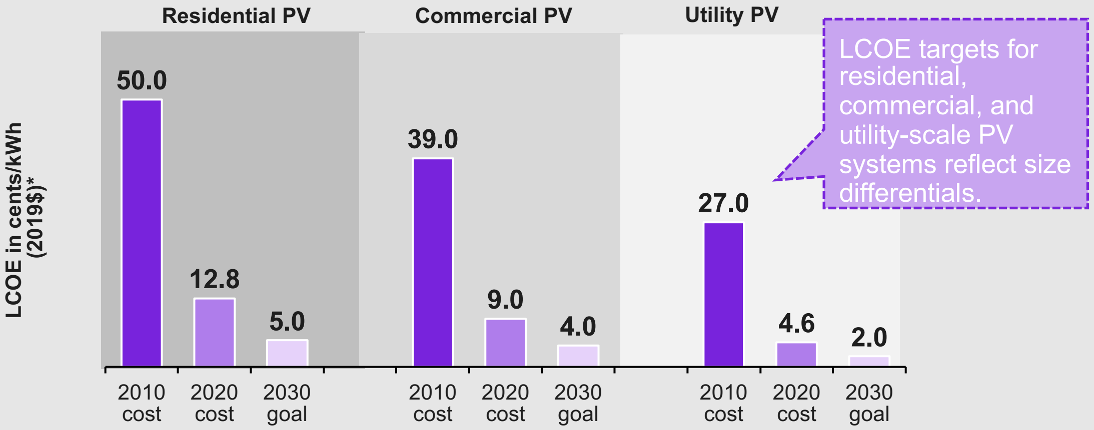
Sources: IRENA, 2023, Renewable Power Generation Costs in 2022; Kearney Energy Transition Institute analysis

Some countries, such as the US, have defined strategies to accompany the reduction in solar cost to accelerate solar deployment

The benchmark LCOE targets are for a location with medium solar resource. Hence, areas with high irradiation have lower LCOE, while those with less irradiation have higher LCOE.

5.1 Levelized cost of electricity

Cost reduction initiative progress and goals



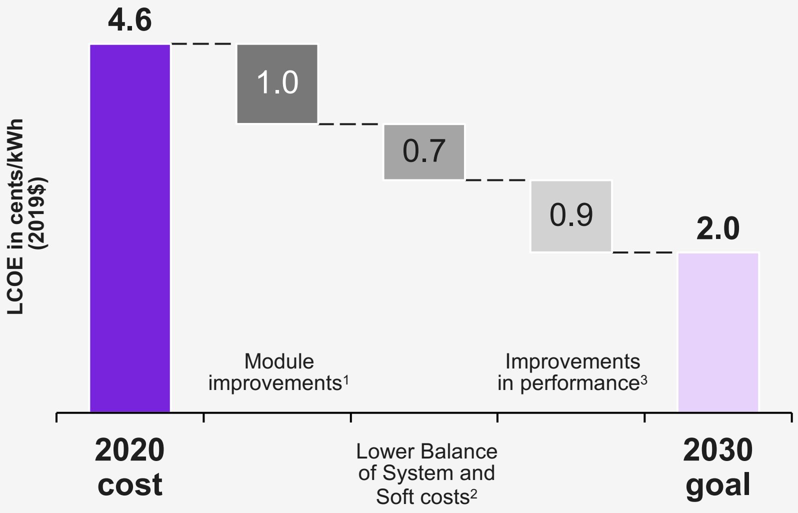
LCOE targets for residential, commercial, and utility-scale PV systems reflect size differentials.

****LCOE progress and targets are calculated based on average US climate and without the Investment Tax Credit or state/local incentives.**

- In 2011, the Solar Energy Technologies Office (SETO) of the US Department of Energy (DOE) launched the SunShot Initiative to lower the cost of solar-generated electricity by 75% to enable utility-scale solar costing approximately 1 USD/W or 0.06 USD/kWh by 2020, which was achieved three years ahead of schedule.
- In 2020, large utility-scale systems became one of the least expensive forms of new electricity generation.
- SETO is now working toward a levelized cost of 0.02 USD/kWh for utility-scale solar photovoltaics, 0.04 USD/kWh for commercial PV systems, and 0.05 USD/kWh for residential rooftop PV systems.

Pathway to 2030 cost target (utility scale)

- Key levers to decrease costs include module conversion efficiency, module cost, balance-of-system cost, initial operating cost, operating cost escalation, initial annual energy yield, and degradation rate.
- Falling module costs is projected to be the largest driver for the decrease in LCOE. However, a trade-off between allowable module cost and module efficiency has to be achieved to hit cost targets.



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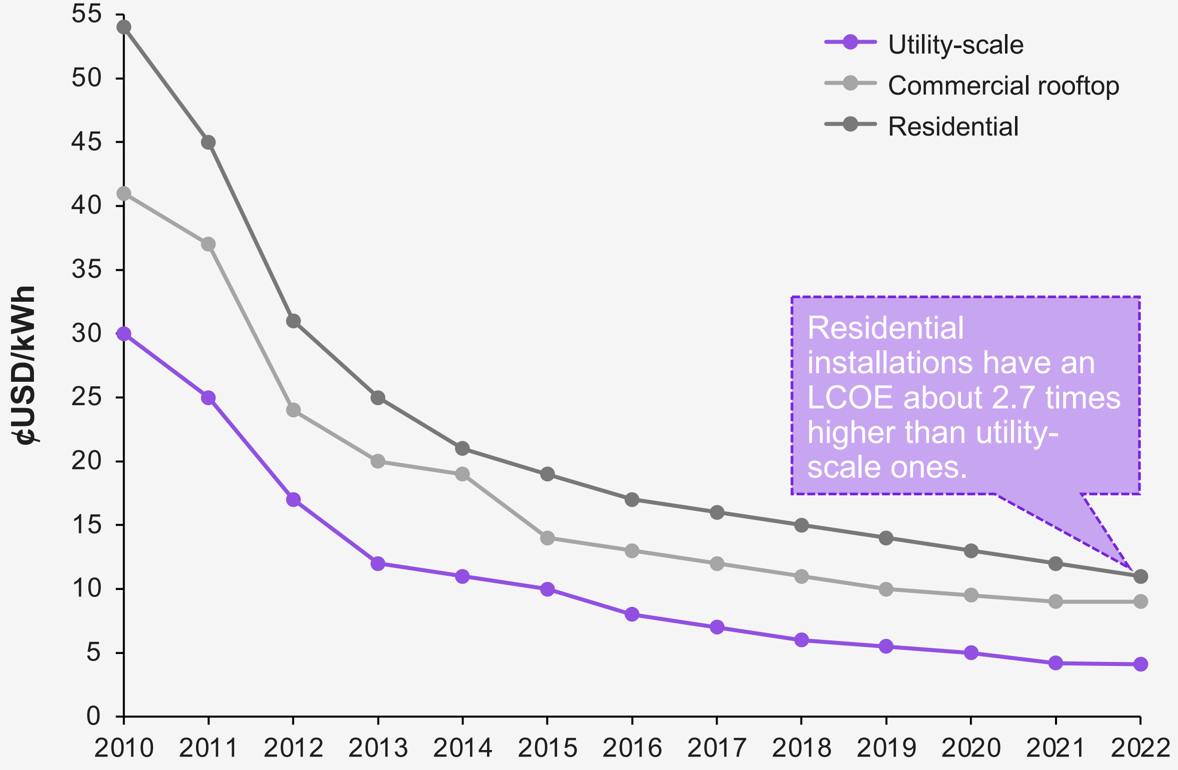
[1] \$0.41 to \$0.17/W; efficiency from 19.5% to 25%
[2] \$0.60 to \$0.30/W
[3] Lower O&M, reduced degradation, and higher energy yield

Sources: US DOE PV, US DOE 2030 PV goals; Kearney Energy Transition Institute analysis

The scale of PV power plants has a significant impact on LCOE

Solar PV LCOE modeling

2021 USD, USA



Residential installations have an LCOE about 2.7 times higher than utility-scale ones.

Overview of some input parameters for LCOE modeling

(2022 figures)

	Residential	Commercial	Utility-scale
Installed cost ($/$W_{DC}$)	2.55	1.63	0.87
Levelized O&M expenses ($/$kW_{DC}$x year)	29	18	16
Annual degradation	1.0	0.7	0.7
Equity discount rate (%)	10.2	6.1	5.1
Analysis period	25	30	30
Initial energy yield (kWh/kW_{DC})	1,491	1,398	1,694
Real LCOE (¢USD/kWh)	**11.1**	**8.7**	**4.1**

Type of systems

– Residential: 7.9 kW_{DC} rooftop
– Commercial rooftop: 200 kW_{DC}
– Utility-scale: 100 MW_{DC} one-axis tracking

Notes: This benchmark is performed for the minimum sustainable price (MSP), which consists in modeling the lowest price at which suppliers can remain financially solvent in the long term. This removes the short-term impact of market and policy events on price to serve long-term analysis and projections. The LCOE benchmark excludes financing costs for residential customers.
Sources: NREL, US solar photovoltaic system and energy storage cost benchmarks, with minimum sustainable price analysis: Q& 2022, 2022; Kearney Energy Transition Institute analysis

The real cost of a solar PV installation is better reflected by its VALCOE than its simple LCOE

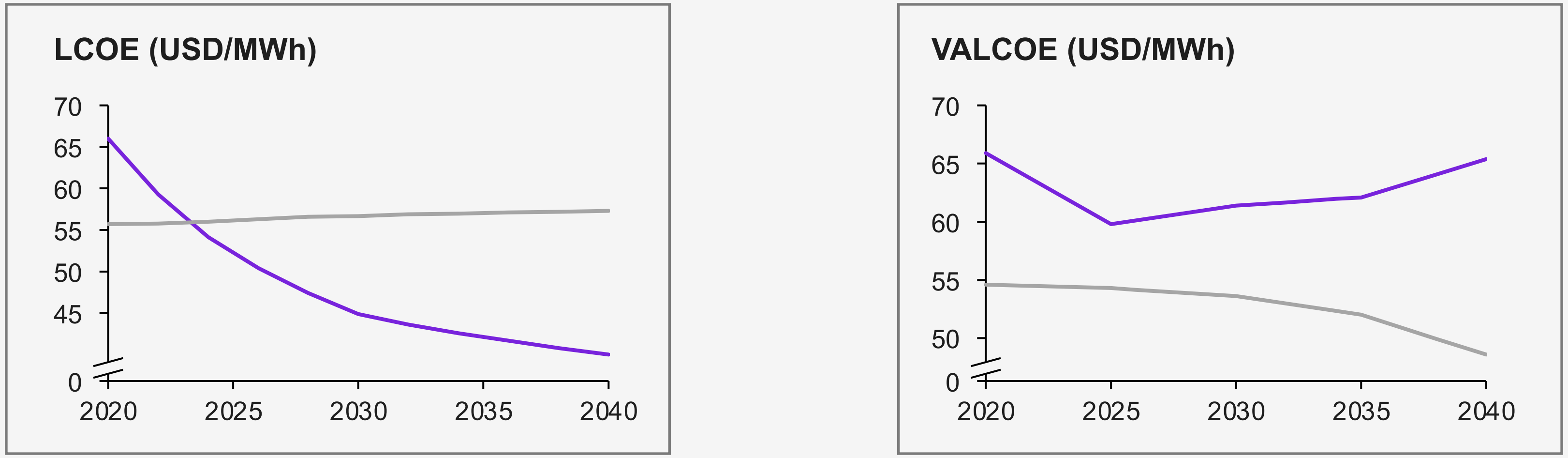
VALCOE provides a more complete metric of competitiveness for power generation technologies, thus representing an estimate of the full system costs of a technology

5.1 Levelized cost of electricity

Rationale for the use of VALCOE / LCOE for the comparison of energy production costs

- the **levelized cost of electricity (LCOE)**, provides a stand alone estimate of a power production technology. It includes overnight capital costs; capacity factor; cost of fuel inputs; operation and maintenance.
- “*The LCOE does not reflect the differing value propositions of technologies. It lacks representation of value or indirect costs to the system, and it is particularly poor for comparing technologies that operate differently (e.g., variable renewables and dispatchable technologies).*”
- **The value-adjusted levelized cost of electricity (VALCOE)** incorporates information on both costs and the value provided to the system. The VALCOE builds on the foundation of the average LCOE by technology, adding three elements of value: energy, capacity, and flexibility”.
- “*The VALCOE enables comparisons that takes account of both cost and value to be made between variable renewables and dispatchable thermal technologies.*”

Estimates of levelized cost of electricity LCOE and value-adjusted LCOE (VALCOE) for solar PV and coal-fired power plants in India

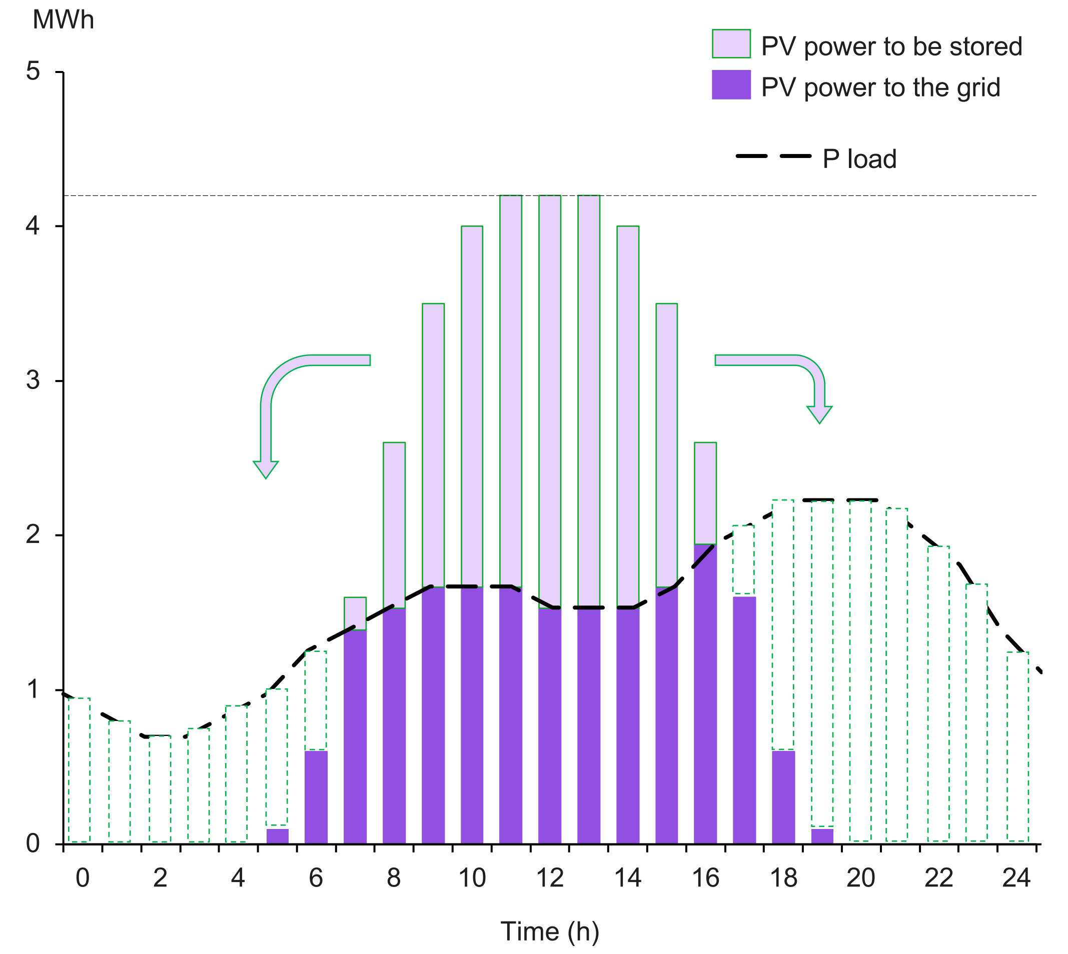


Sources: IEA, Projected-Costs-of-Generating-Electricity-2020; IEA, 2019, Levelised cost of value-adjusted LCOE (VALCOE) for solar PV and coal-fired power plants in India in the new policies scenario, 2020-2040
US DOE 2022 Grid Energy Storage Technology Cost and Performance Assessment 2022 (link); Kearney Energy Transition institute

Kearney XX/ID

When hybridized with Li-ion batteries, solar PV VALCOE could triple its LCOE

Example of a high estimate of VALCOE for a solar PV + Li-ion installation



To match the power demand profile, the solar PV plant must be completed with an electricity storage device (e.g., Li-ion battery).

In this example, the 4.2 MW_{DC} generates 37,4 MWh during the day, of which 18.3 MWh must be stored then released to satisfy the demand from roughly 5:00 p.m. to 7:00 a.m.

- Characteristics of the battery: ~18 MWh capacity, with a max power rating of 3 MW; LCOS ~180 USD/MWh
- The LCOE of the solar PV ~70 USD/MWh

The VALCOE of such installation is ~250USD/MWh; more than three times the LCOE of the standalone solar plant.

5.1 Levelized cost of electricity

Source: IEA, Projected-Costs-of-Generating-Electricity-2020 (link); US DOE 2022 Grid Energy Storage Technology Cost and Performance Assessment 2022 (link); Kearney Energy Transition institute

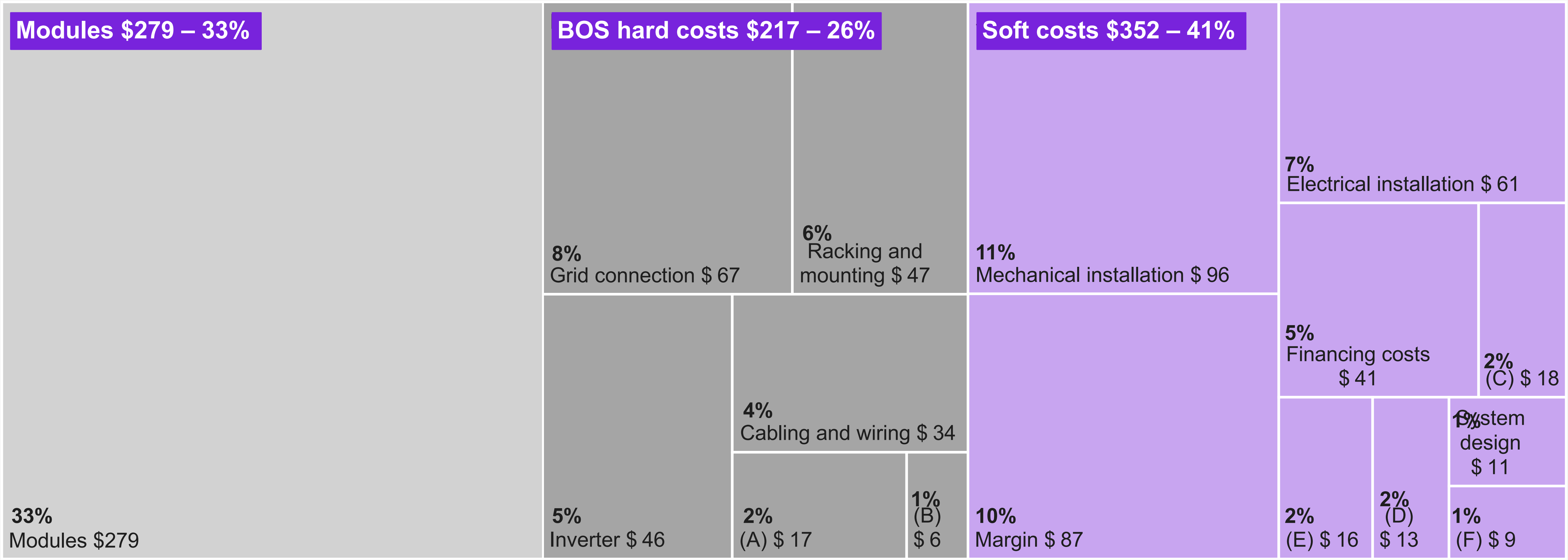
The average total installed cost of one kW of solar PV is of $848 and can be broken down in a multitude of components[1]

Total installed cost: $848/kW[2]

Global utility-scale solar PV total installed cost breakdown, average[1]

2022 USD/kW, share of total (%), 2022

XX% percentage of total installed cost



(A) Safety and security (B) Monitoring and control (C) Permitting (D) Inspection (E) Incentive application (F) Customer acquisition

[1] This is an average of the 36 countries in the IRENA dataset (representing 93% of additional capacity in 2022), weighted by capacity added in 2022.

[2] The total installed cost is the sum of all costs that are incurred by the developer until the beginning of electricity generation while LCOE is a metric for the competitiveness of PV within the energy marketplace, which incorporates many PV metrics—including upfront installation costs.

Sources: IRENA, 2023, Renewable Power Generation Costs in 2022; IRENA, accessed July 2023, Data and Statistics; IEA PVPS, 2023, Snapshot of Global PV Markets; Kearney Energy Transition Institute analysis

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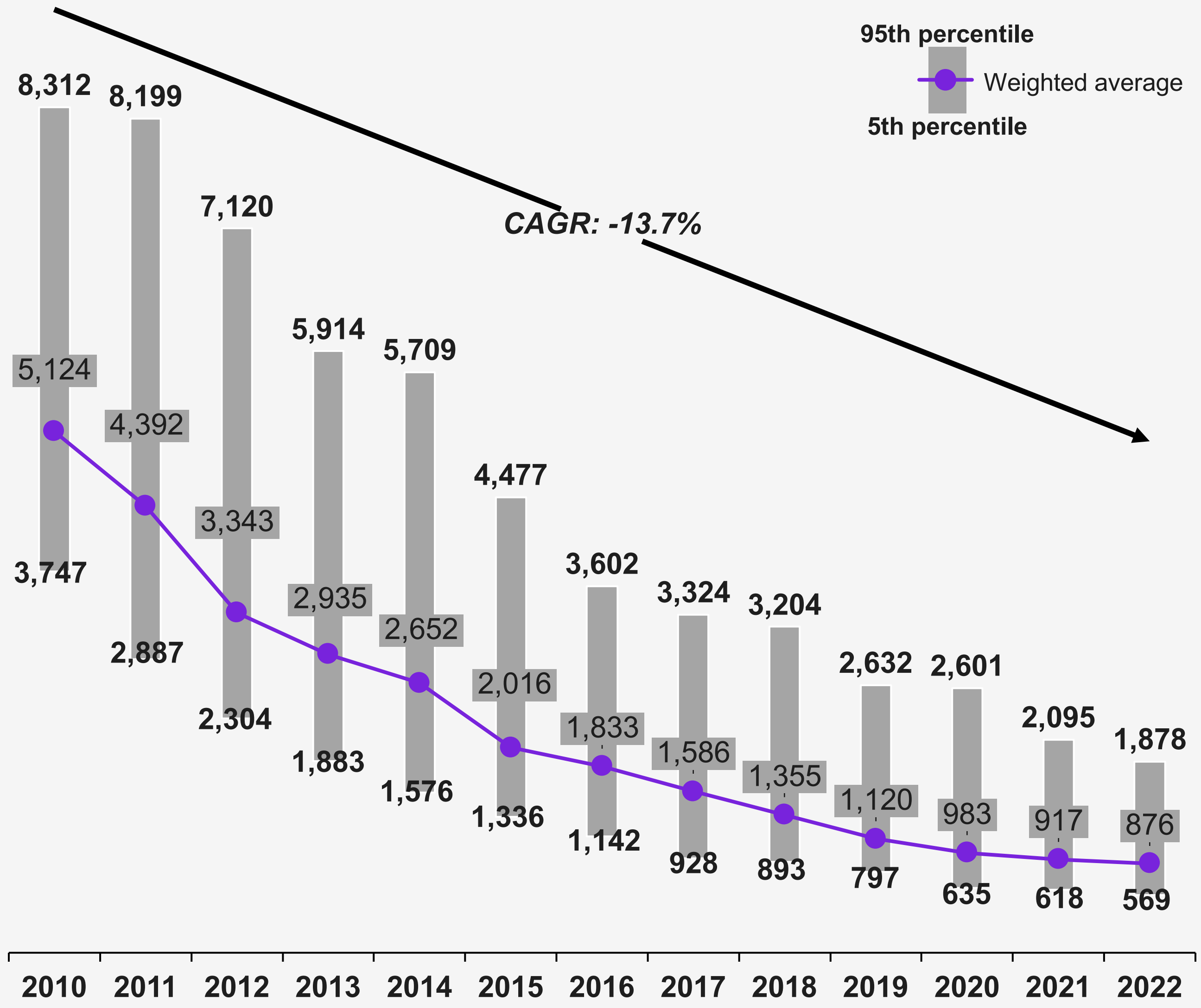
The total installed cost of solar PV has been divided by nearly five in the past 10 years

Total installed cost evolution for utility-scale PV
2022 USD/kW, 2010–2022, global



Sources: IRENA, 2023, Renewable Power Generation Costs in 2022; IEA PVPS, 2023, Snapshot of Global PV Markets; Kearney Energy Transition Institute analysis

Total installed cost

The total installed cost is the sum of all costs that are incurred by the developer until the beginning of electricity generation.

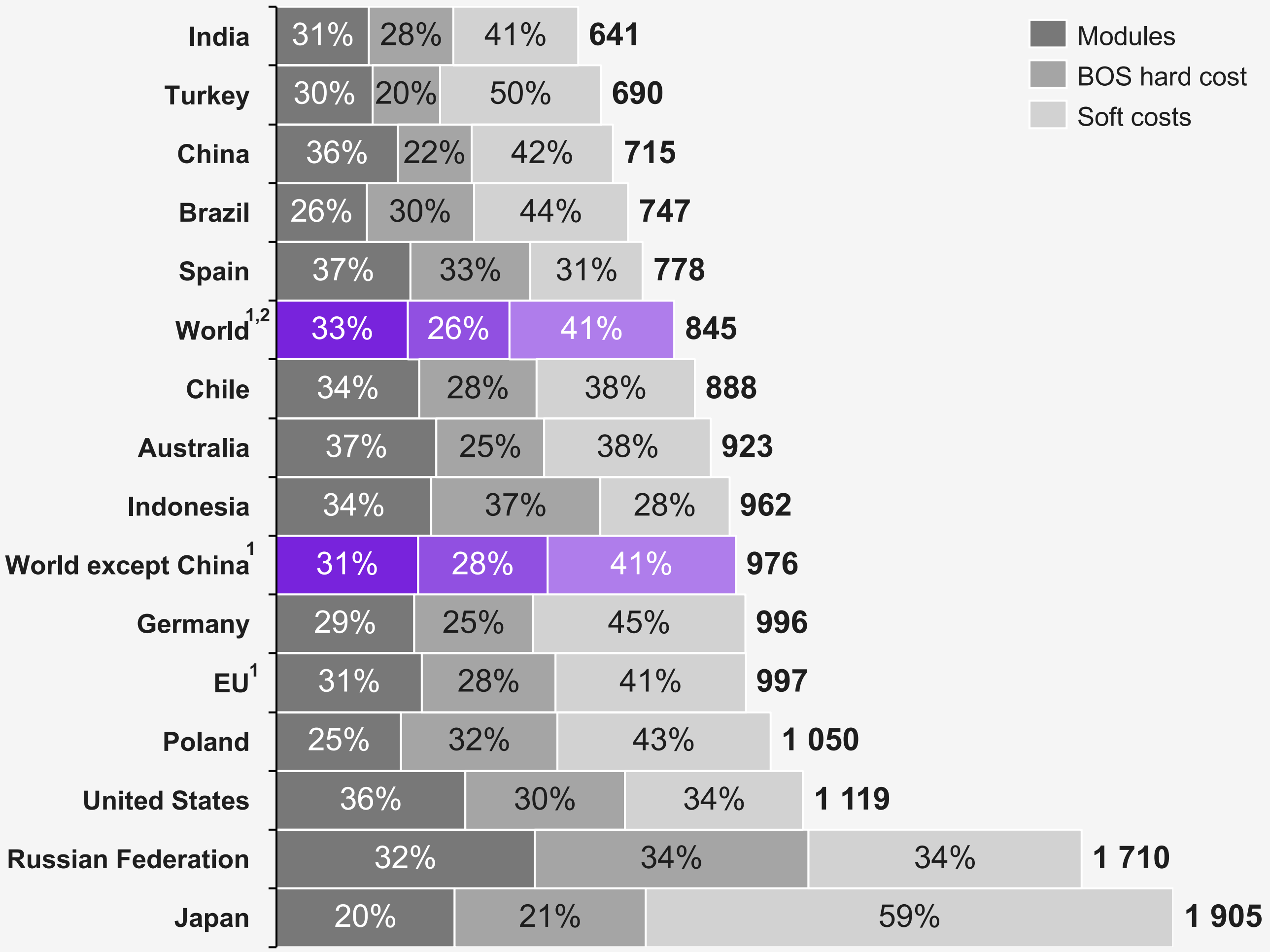
Total installed cost has been decreasing by 13.7% on average each year from 2010 to 2022, thanks to decreases in price for all cost drivers.

5.2 Total installed cost

The total installed cost of one kW capacity of solar PV varies by country, with India having among the lowest cost

Utility-scale solar PV breakdown of total installed cost

2022 USD/kW, 2022, selected countries



Large variations in total installed cost

Behind the current average total installed cost of around 850 USD/kW, **there are important variations by country**. India has the lowest cost among the reported countries, at 641 USD/kW, followed by Turkey and China.

At the higher end of installed costs, Japan and Russia are above 1,700 USD/kW and several other countries above 1,000 USD/kW, including the US.

Variations also exist in the distribution of the cost categories. Excluding Japan and Russia, which are outliers, modules make up 20–37% of total costs, hard costs 20–37%, and soft costs 29–59%.

[1] World, world without China, and EU are averages of the 36 countries in the IRENA dataset (representing 93% of additional capacity in 2022), weighted by capacity added in 2021.

[2] The value obtained here is slightly different from slide 92 due to rounding.

Note: the world average in the chart in the previous slide is different from the one in this chart as the former includes all countries representing the remaining 7% of additions not included in the latter.

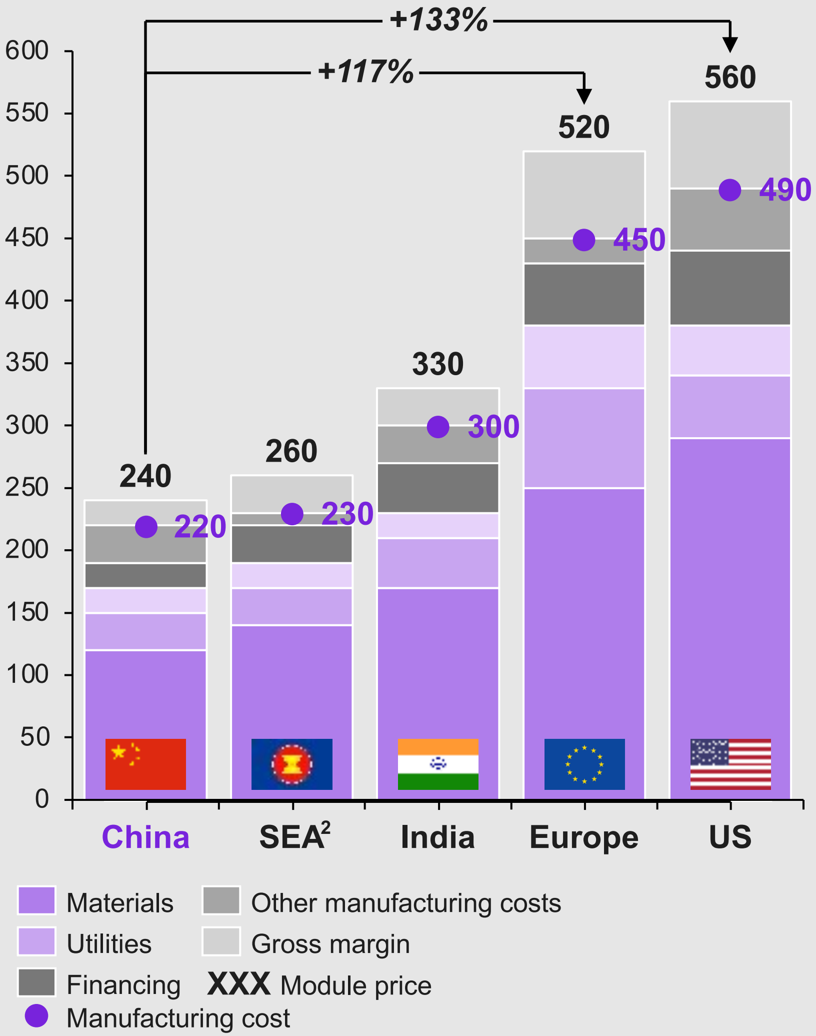
Sources: IRENA, 2023, Renewable Power Generation Costs in 2022; IEA PVPS, 2023, Snapshot of Global PV Markets; Kearney Energy Transition Institute analysis

Chinese PV module suppliers possess structural competitive advantages: access to raw materials and cheap energy and labor, economies of scale, in an integrated ecosystem

5.3 Module costs

Price breakdown for domestically produced and consumed modules[1]

2021 USD/kW, 2022



China is cheaper due to key structural advantages

1. **Access to strategic raw materials**
   - **Materials are the main cost component**
   - Key materials: silicon, silver, glass, aluminum
   - **More than 80% of PV silicon is produced in China**, so although they are traded as commodities, the freight cost is lower in China.
2. **Significant scale effect**
   - **High production capacities** in China, usually above 10 GW for mature technologies (c-Si) and above 5GW for less mature ones (ex: TOPCon)
   - **Shorter lead times to commission PV component plants** from polysilicon to modules, allowing for a fast solar PV capacity ramp-up
3. **Access to cheap electricity**
   - Chinese module companies benefit from **lower electricity costs than most other countries**.
4. **Increasingly integrated solar PV value chain**
   - Chinese players benefit from **end-to-end integrated value chains** from polysilicon to modules, with internal manufacturing capacities for EVA and glass.[3]
5. **Lower labor costs**
   - China has **lower labor costs** than the developed countries.

---

[1] This is the cost of modules domestically produced and consumed, so it does not necessarily reflect the price of all modules consumed in one country. For example, Europe and the US import most of the modules they use from cheaper suppliers than their domestic production. Utilities such as natural gas, electricity, and water are overhead costs that fluctuate with the quantity of materials being produced.

[2] Southeast Asia

[3] EVA is a material used to encapsulate PV cells in a module.

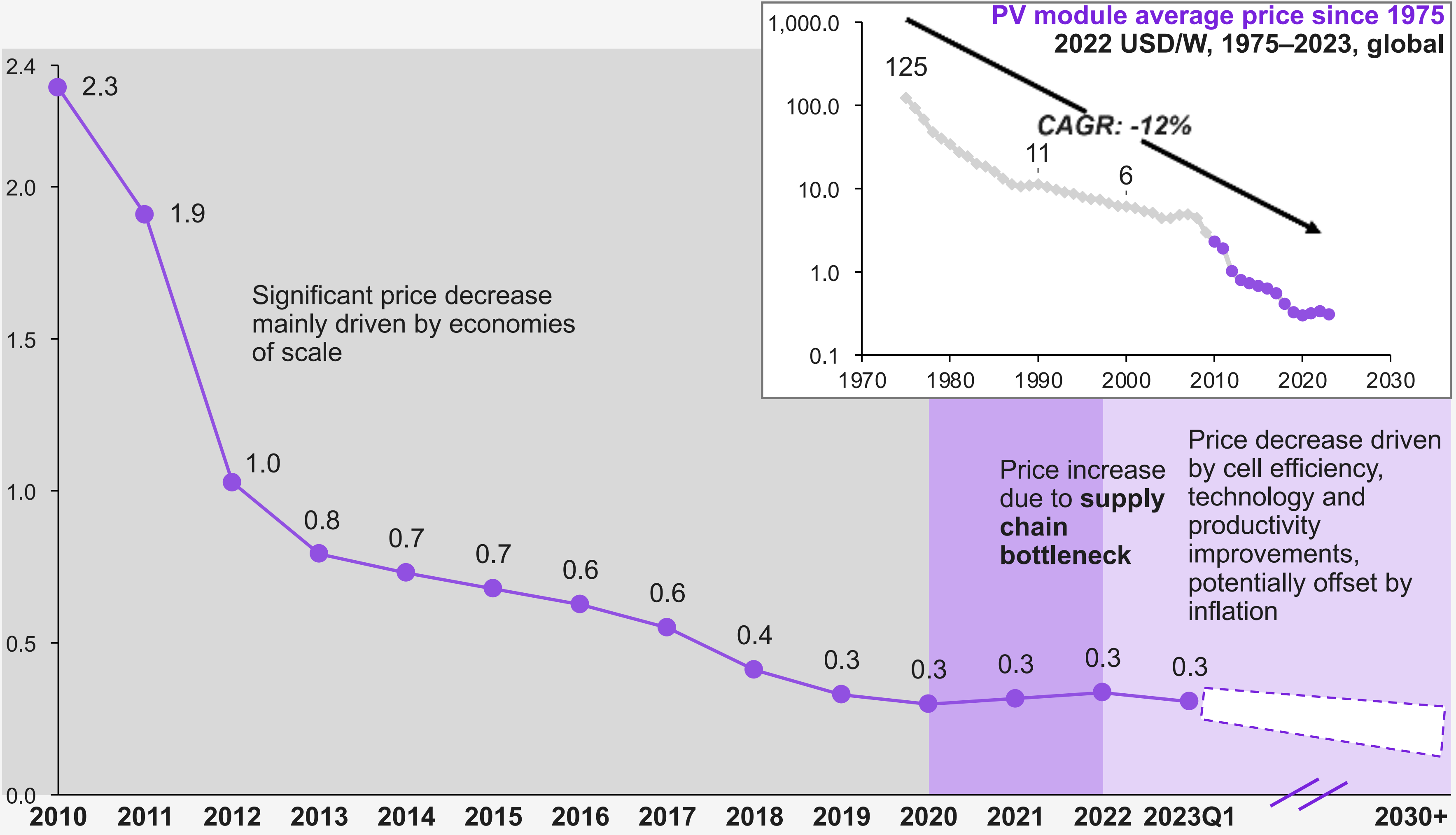
Sources: NREL, 2023, Spring 2023 Solar Industry Update; Kearney; Wood Mackenzie, 2022, Fully domestic manufactured module consumed locally; Bernreuter Research, 2023, Polysilicon price trend; IEA, 2022, Special Report on Solar PV Global Supply Chains; Kearney Energy Transition Institute analysis

Kearney XX/ID

After significant reduction over the last decades due to economies of scale, further variations in module prices will be mainly driven by technology and productivity improvements

Global average price of solar PV modules

2022 USD/W, 2010–2022



Significant price decrease mainly driven by economies of scale

Price increase due to **supply chain bottleneck**

Price decrease driven by cell efficiency, technology and productivity improvements, potentially offset by inflation

PV module average price since 1975

2022 USD/W, 1975–2023, global

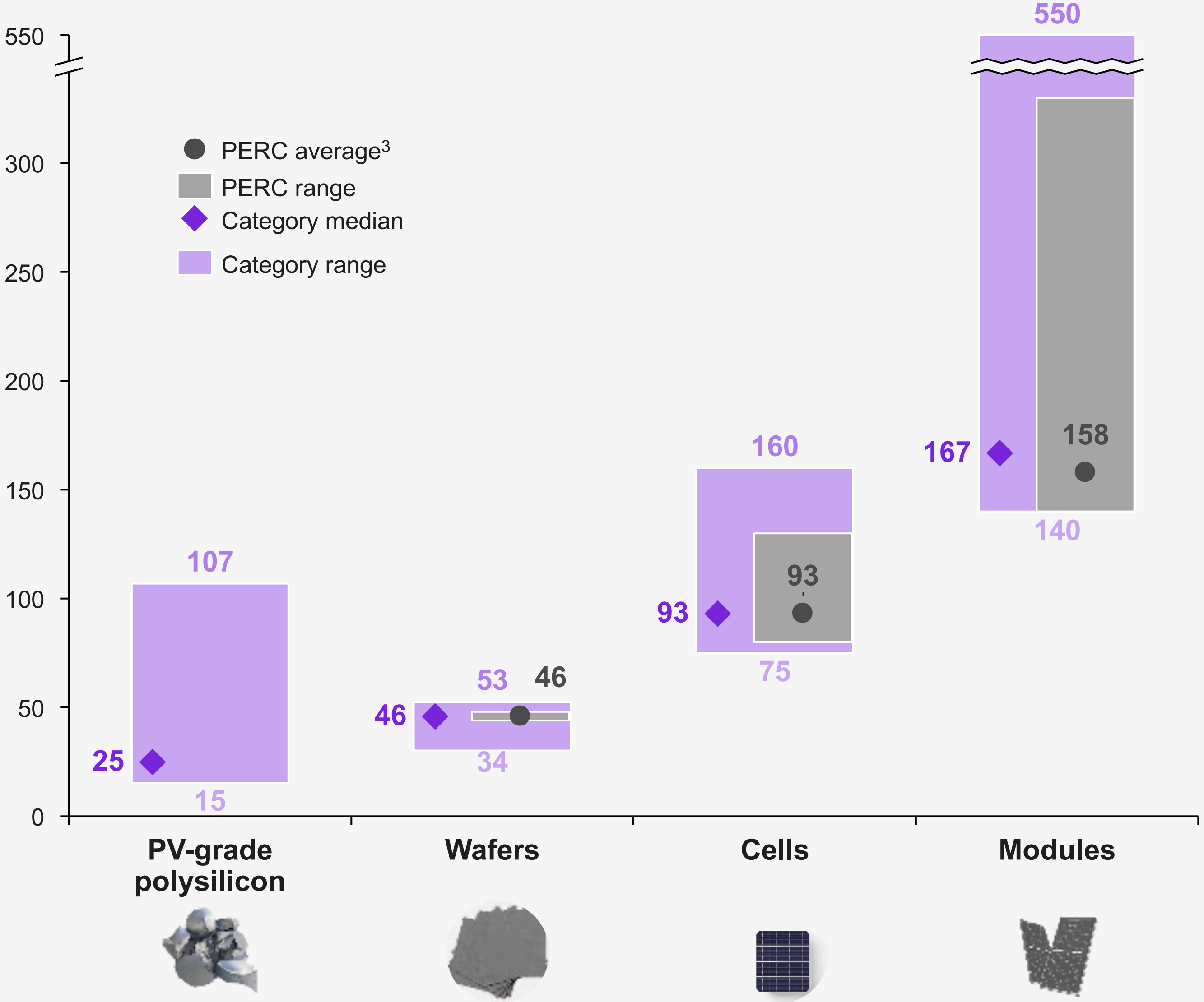
The era of massive economies of scale is over, as these have already been captured. Efficiency will drive prices down but will be offset at least partly by inflation, especially in freight and electricity prices.

Note: Data from Our World in Data until 2016, and from IRENA from 2017 to 2023. The data from Our World in Data was converted from 2021 USD to 2022 USD using US bureau of labor statistics.
Sources: Our World in Data, accessed July 2023, Solar (photovoltaic) panel prices; US Bureau of labor statistics, accessed August 2023, CPI inflation calculator; IRENA, 2023, Renewable power generation costs in 2022; Kearney Energy Transition Institute analysis

Module prices depend on the cost of components upstream in the supply chain

Global sales prices along the value chain, aggregated data and zoom on PERC[1] technology

2023 USD/kW, 2023, global[2]



Component costs define the price along the value chain.

PERC is the most common cell technology in 2022 with a 57% market share. **PERC modules are on average slightly cheaper than the median.**

Polysilicon prices per kW vary greatly depending on the amount of waste produced when cutting wafers out of polysilicon ingots.

The total range of prices for modules is considerable, from 140 USD/kW to 550 USD/kW. This is partly explained by the high variability further down the supply chain.

---

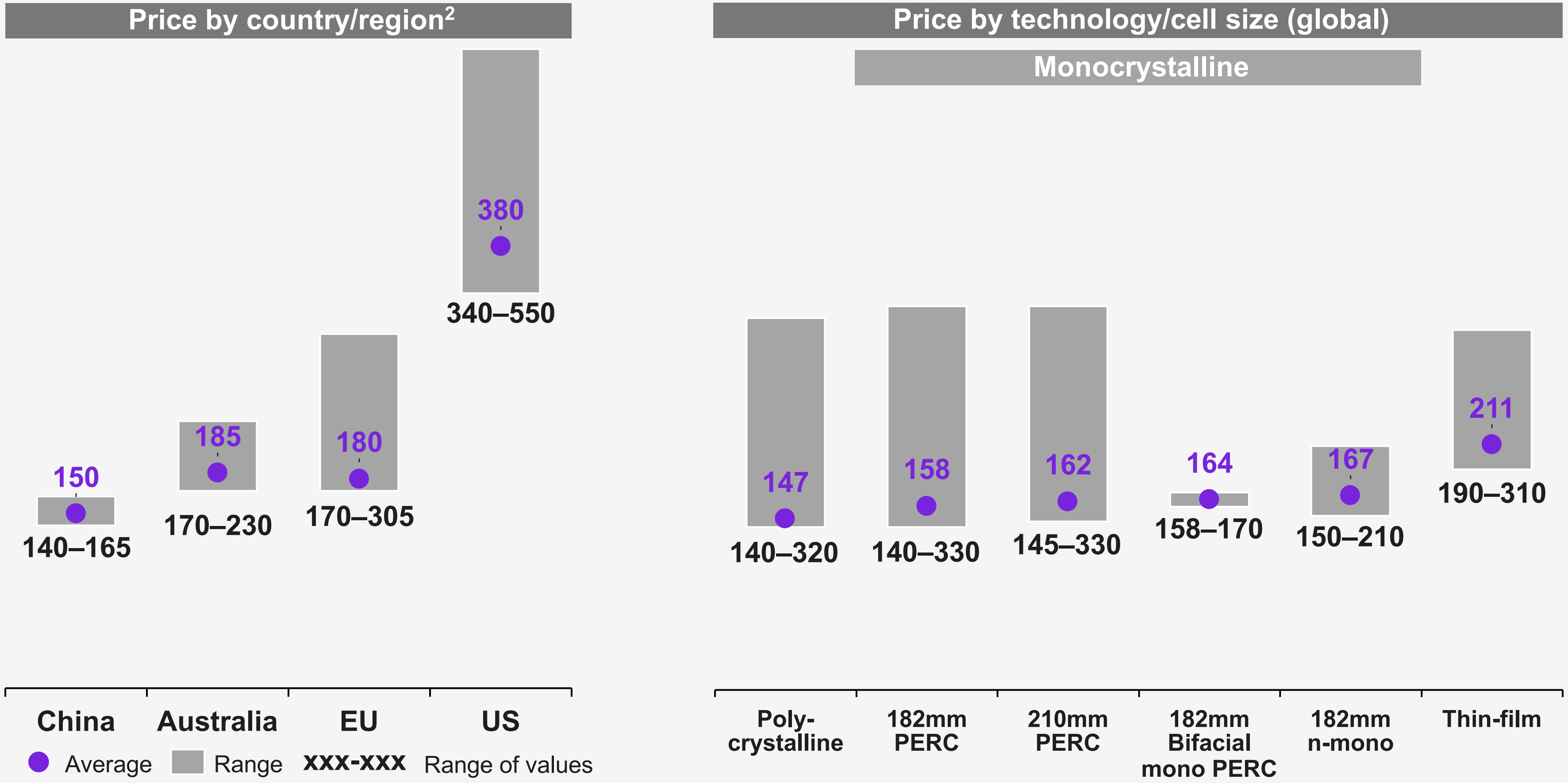
[1] PERC is passivated emitter rear contact; [2] The data is from July 19, 2023; [3] The technology considered here is for a 182mm monocrystalline mono-facial wafer/cell/module.

Sources:; IEA, 2022, Special Report on Solar PV Global Supply Chains; Bernreuter Research, 2023, Polysilicon price trend; Pvinsights, 2023, Spot prices; Energy Trend, 2023, PV spot price; InfoLink, 2023, Spot price; PV lighthouse, 2023, Wafer calculator; Kearney Energy Transition Institute analysis

Module prices vary by place of manufacturing, type of technology, and size of cells

Module price by country and by technology/cell size

2023 USD/kW, 2023[1]



Sources of price variation

Module prices vary considerably depending on the country where they are bought, with average costs for 182/210mm monocrystalline PERC two and a half times higher in the US compared to China. These variations have many sources, from local electricity prices to trade restrictions.

Module prices also vary by technology, with thin-film 44% more expensive per kW than polycrystalline modules.

There is also some variation depending on the size of the cell, but it is smaller: there is a 2.5% price difference per kW between 182mm PERC and 210mm PERC.

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[1] The data is from July 19, 2023. More common technologies had more data available which can explain why they have wider ranges.

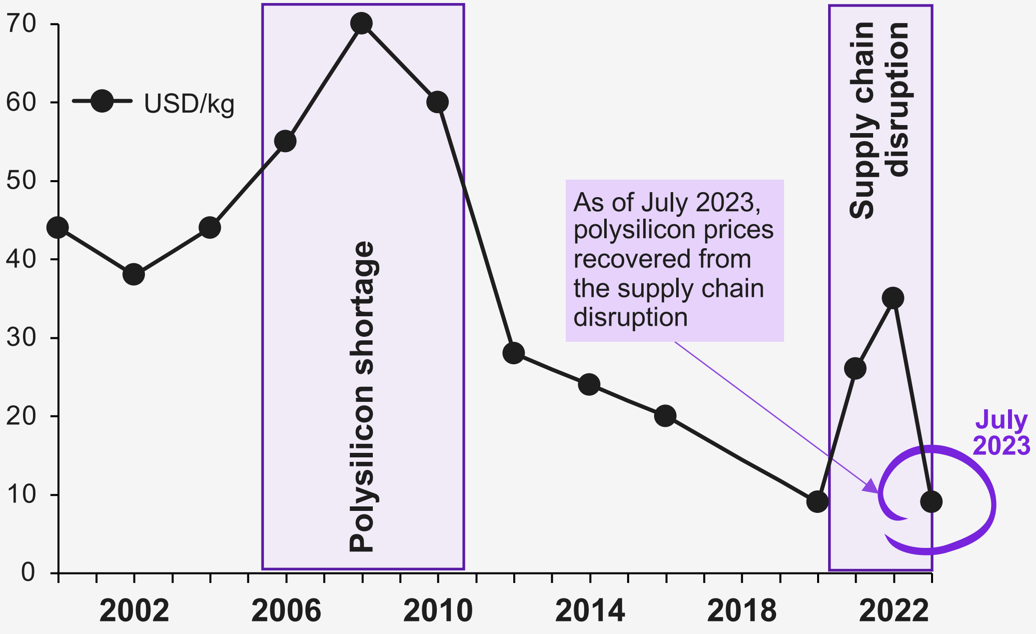
[2] Prices for 182-210mm monocrystalline PERC modules.

Sources: IEA, 2022, Special Report on Solar PV Global Supply Chains; Bernreuter Research, 2023, Polysilicon price trend; Pvinsights, 2023, Spot prices; Energy Trend, 2023, PV spot price; InfoLink, 2023, Spot price; PV lighthouse, 2023, Wafer calculator; Kearney Energy Transition Institute analysis

After increasing significantly in 2021–2022 due to Chinese supply chain disruptions, polysilicon prices returned to their previous minimum

Polysilicon yearly average prices

USD/kg, 2000–2023, global[1]



Polysilicon represents over half of solar module raw material costs.

Factors affecting polysilicon prices

↘ Downward pressure	↗ Upward pressure
- Additional manufacturing capacities - Module efficiency increase - Manufacturing costs decrease	- Delays in manufacturing additions - Electricity prices and inflation increase in China - Stricter controls on forced labor - Stricter CO_2 emissions requirements for PV production

Causes behind the recent price fall

During 2010–2015, massive **capacity growth in China pushed many competitors out** of the market.

Then, the **COVID-19 pandemic disrupted Chinese supply chains**, leading to price increases in 2021.

During S1 2023 polysilicon's **high prices and strong PV demand forecasts spurred massive capacity expansions** by leading manufacturers and brought new players to the market, lowering prices to 9 USD/kg.

As a result, plans for new production capacity have been halted, and even leading manufacturers have limited shipments.

However, over the long run, **non-Chinese producers are expected to increase their capacities,** which will lower polysilicon prices.

5.3 Module costs

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[1] The global value is calculated by weighting between Chinese and non-Chinese polysilicon prices according to their market share. For example, the latest value has 95% Chinese ($8.21) and 5% other ($21.30). Prices are reported before tax. There is no value for 2018.

Sources: Bernreuter Research, 2023, Polysilicon price trend; Kearney Energy Transition Institute analysis

Solar PV balance of system costs and soft costs vary greatly by application and installation size

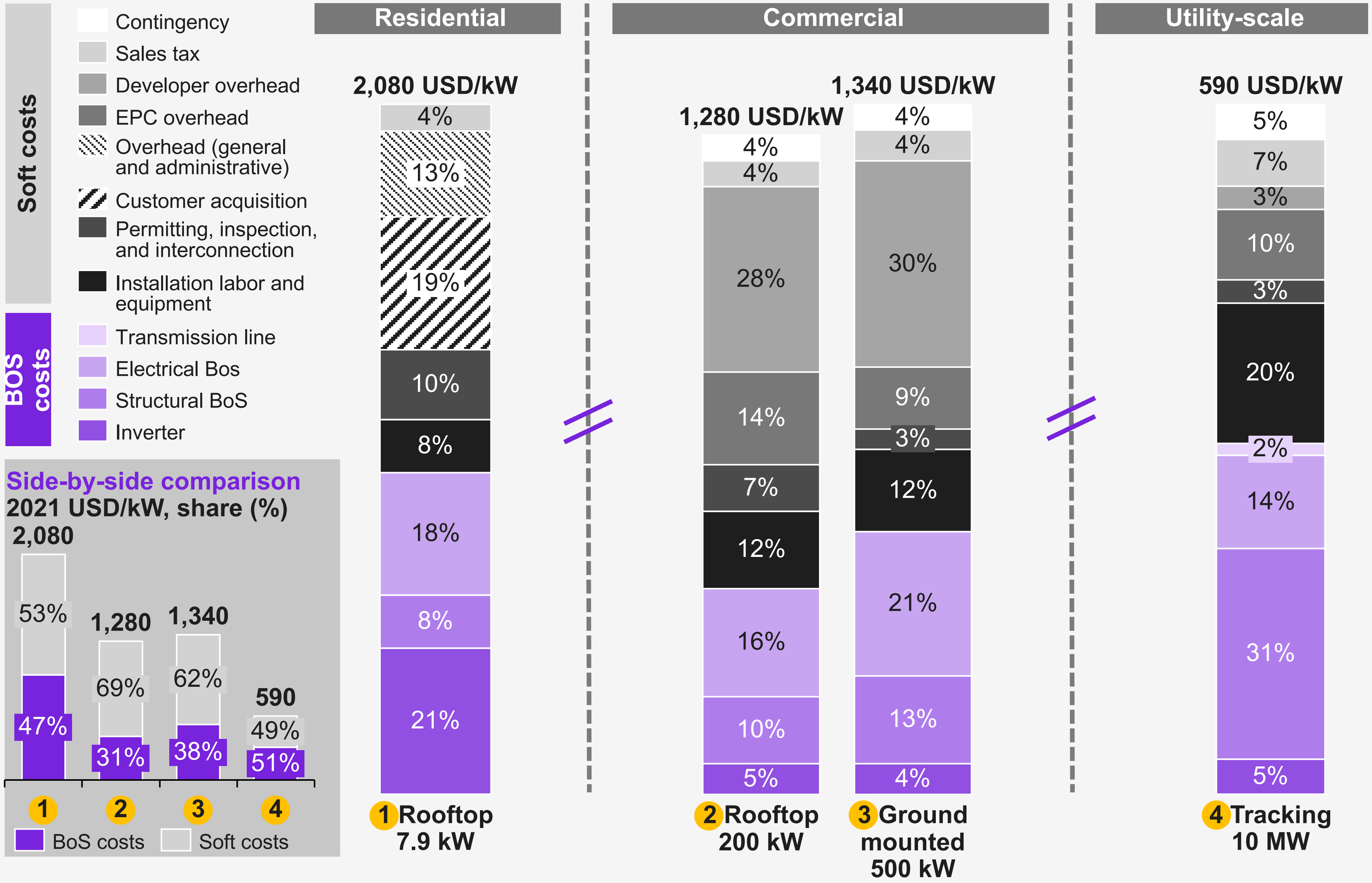
Residential and commercial PV soft costs are high due to greater customer acquisition and overhead costs.

For utility-scale, economies of scale decrease soft costs more than hard costs.

5.4 Other components costs

Balance of system costs and soft costs by application in the US

2021 USD/kW, Q1 2022



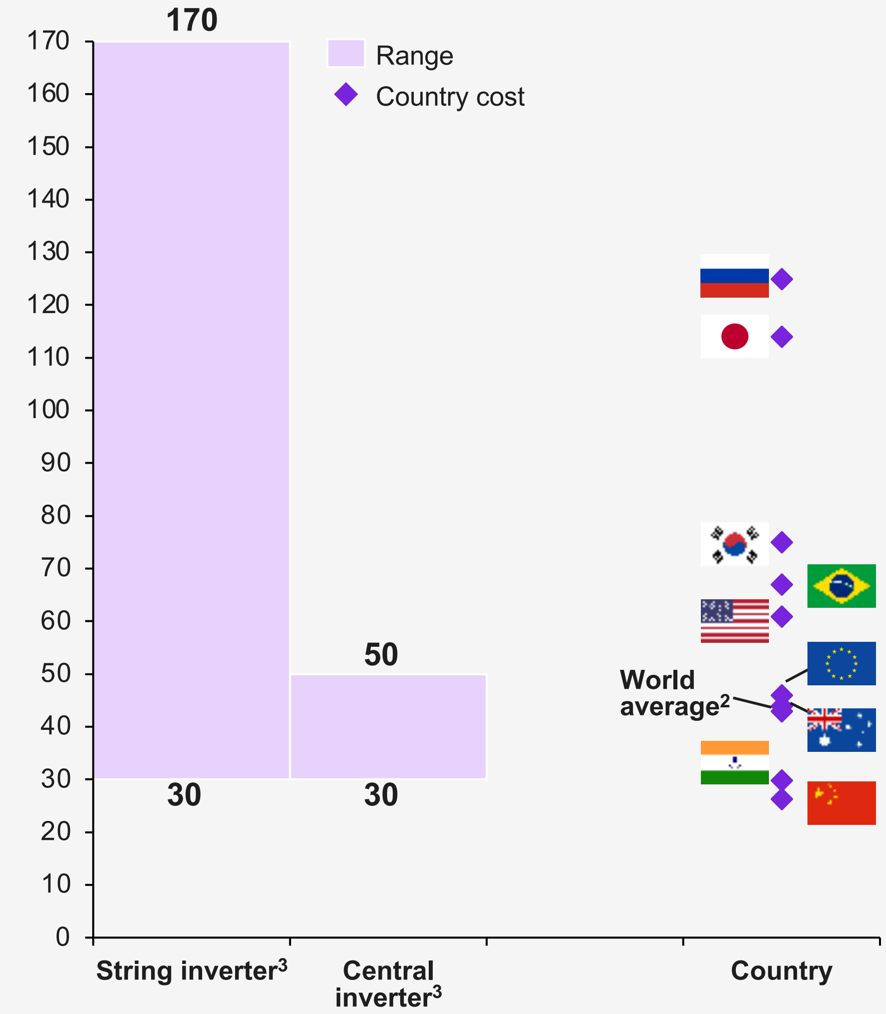
Sources: NREL, 2022, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks; Kearney Energy Transition Institute analysis

The inverter affects the LCOE through its own cost and by setting the maximum output of the PV system (1/2)

The inverter is a bottleneck because of its limited output.

A balance has to be found between a smaller and cheaper inverter with more curtailment and a larger and more expensive inverter with less curtailment.

Inverter cost by type and by country
USD/kWh, 2020–2021, global[1]



5.4 Other components costs

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[1] The ranges by inverter technology are from 2020 while the values by country are for 2021.
[2] The world average is an average of the 36 countries in the IRENA dataset (representing 93% of additional capacity in 2021), weighted by capacity added in 2021.
[3] Solar panels are linked together through wiring that connects to inverters. String inverters are smaller inverters allowing a modular architecture of the PV plant and granular energy optimization; central inverters are larger inverters used in a centralized architecture of the power plan; these have higher nominal power per unit and allow high-level energy optimization only.
Sources: IRENA, 2022, Renewable Power Generation Costs in 2021; IEA PVPS, Data Model for PV Systems, 2020; Fraunhofer ISE, 2023, Photovoltaics report; IEA, 2022, Special Report on Solar PV Global Supply Chains; Kearney Energy Transition Institute analysis

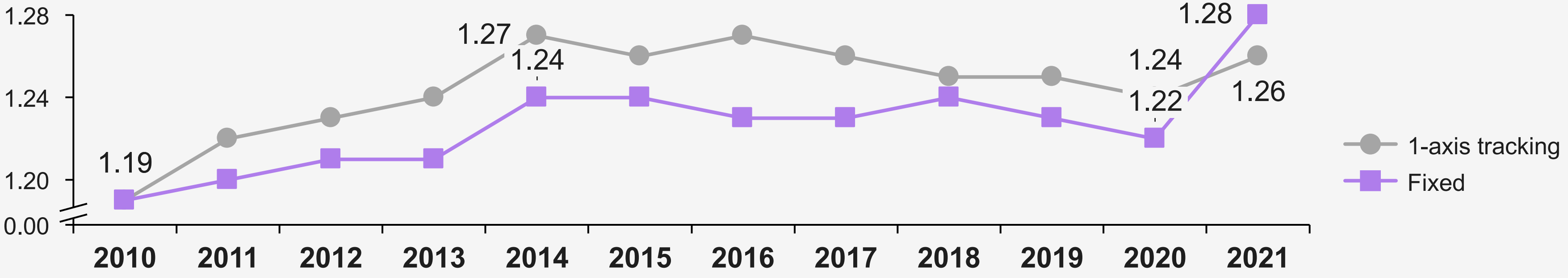
The inverter affects the LCOE through its own cost and by setting the maximum output of the PV system (2/2)

The inverter affects the LCOE in two ways

- **First, the inverter alone makes up over 5% of total installed costs** and represents 9% of the LCOE's fall between 2010 and 2022.
- The price depends on the size and type of the inverter. Most are string inverters (64% market share) or central inverters (34%). Some are micro-inverters (1.4%) but they are more expensive. (They are inverters connected to a single solar panel instead of the whole system.) **The manufacturing location and tariffs incurred at the final location** also affect prices and explain variations by country.
- **Second, the LCOE's denominator[1] is affected by the inverter load ratio (ILR):** the PV system's size over the inverter's size.[2]
- The system's maximum output is rarely reached. Larger inverters are costly so there is an optimal ILR which minimizes total system costs per kWh. Factors such as module and inverter prices, GHI[3], and whether it's a tracking or fixed-tilt system affect the costs.

Average inverter loading ratio by mounting type

ILR, 2021, global



5.4 Other components costs

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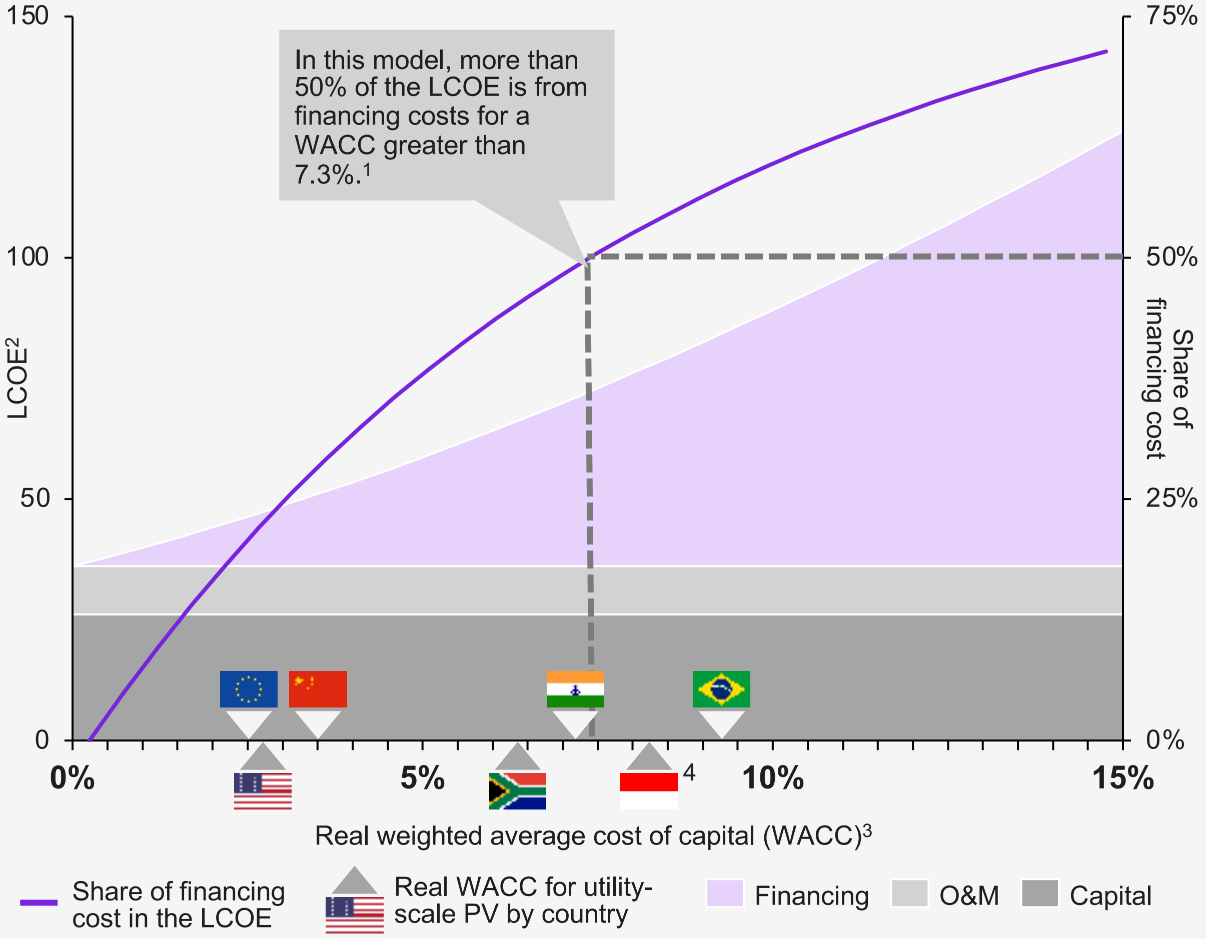
[1] The denominator of the LCOE is the amount of electricity produced.
[2] The system's size is in AC and the inverter's size is in DC.
[3] Global horizontal irradiance.

Sources: IRENA, 2022, Renewable Power Generation Costs in 2021; IEA PVPS, Data Model for PV Systems, 2020; Fraunhofer ISE, 2023, Photovoltaics report; IEA, 2022, Special Report on Solar PV Global Supply Chains; Kearney Energy Transition Institute analysis

As solar PV economics are dominated by the initial investment, cost of financing has a strong impact on the LCOE

Impact of cost of capital on solar PV LCOE[1]

USD/MWh (left, LCOE), % (right, financing share of LCOE), 2021, US



In this model, more than 50% of the LCOE is from financing costs for a WACC greater than 7.3%.[1]

With zero fuel costs, solar PV is a capital-driven industry. O&M costs are low (0.5%–1.5% of the initial investment annually).

PV project economics are highly sensitive to the cost of capital measured by the discount rate due to the investment structure of PV systems. Discount rates vary according to financing schemes (share of debt and equity, type of financing vehicles) and developers' credit rating.

Cost is also dependent on location as risks (regulatory, currency, political, off-taker…) can significantly vary from one location to another.

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[1] This model uses the IEA's assumption of a US-based utility-scale PV plant with 1,030$/kW cost of capital,10$/MW O&M, 1 year before production begins, and a productive life of 25 years. We vary the real WACC between 0 and 15%.

[2] Levelized cost of electricity: cost per MWh of building and operating a generating plant.

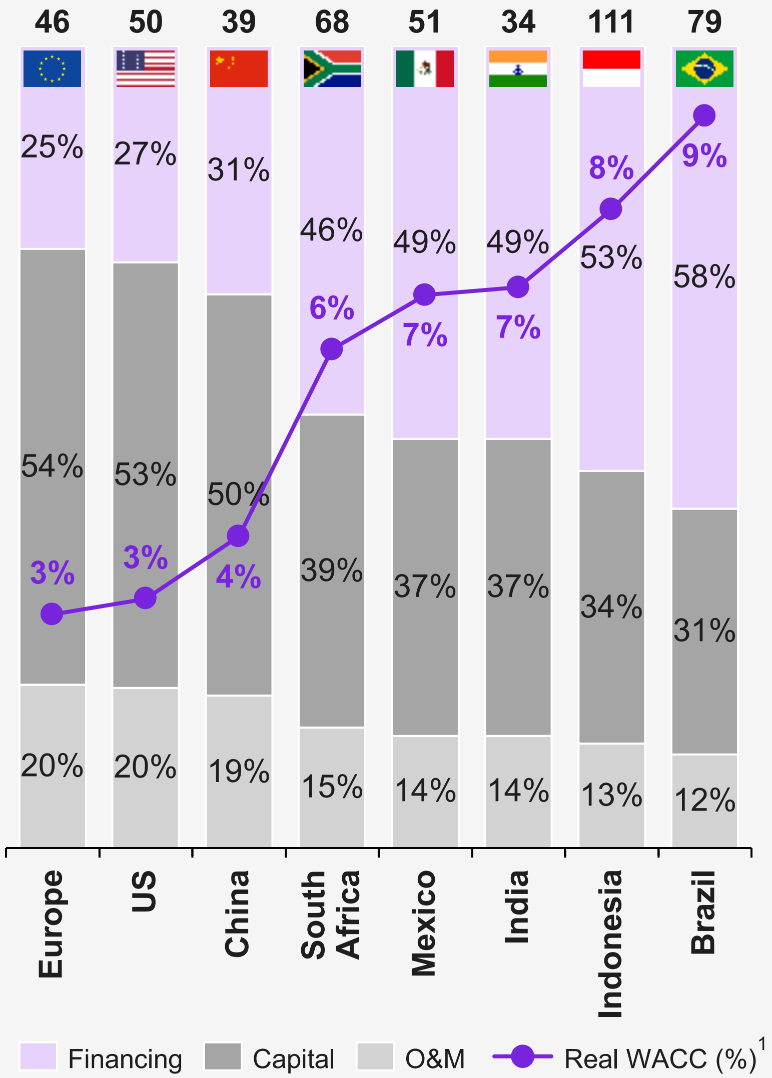
[3] WACC: weighted average of the different financing costs for a single project, in this case solar PV, real means adjusted for inflation

[4] Indonesia

Sources: IEA, 2023, Cost of Capital Observatory Dashboard; IEA, 2023, Cost of Capital Observatory Tools and Analysis; Kearney Energy Transition Institute analysis

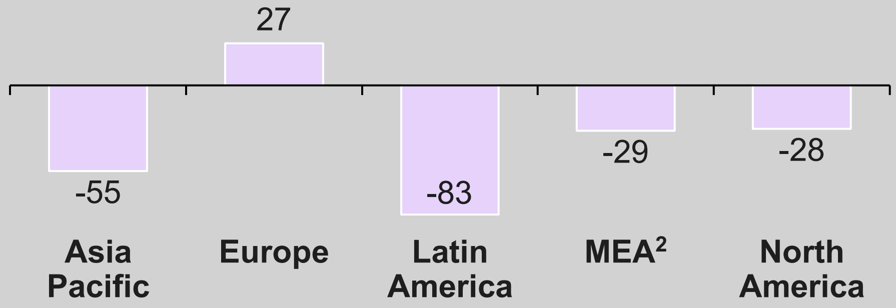
The importance of the cost of capital explains the differences in LCOE between countries

The share of financing in the LCOE for different costs of capital
USD/MW (LCOE), % (share of LCOE), % (WACC), 2022



- **Lower O&M and construction costs are usually more than offset by financing costs** in countries with higher costs of capital, which raises their LCOE.
- **Public-sector and institutional investors such as development banks have, therefore, an important role to play** in helping to reduce the cost of capital.
- **By 2025, the cost of capital for solar PV is expected to decrease in all regions facing high WACCs today**, helping them reduce their LCOE.
- **The small expected increase in Europe is mainly due to uncertainty on the extent of state support** for PV in the future, in light of its rising competitiveness.

Expected change in cost of capital by 2025 for solar PV
Basis points, 2019–2021 to 2025, by region



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[1] Real weighted average cost of capital, in %, real because adjusted for inflation
[2] MEA is Middle East and Africa.
Sources: IEA, 2023, Cost of Capital Observatory Tools and Analysis; IRENA, 2023, The cost of financing for renewable power; Kearney Energy Transition Institute analysis

6. Key players of the Solar PV value chain

Key players of the PV value chain

The solar PV ecosystem is well-established with **vertically integrated stakeholders**; **new entrants** still integrate at the different stages of the value chain through **horizontal diversification**.

Along the production **value chain, China holds the leading position**, concentrating most players in the **upstream part**, in particular for wafer manufacture. In contrast, demand of solar PV modules is spread across China, Europe, and North America. In 2021, **global production capacity of polysilicon and modules** reached **630 ktons and 391 GW** respectively. The largest factories are located in China, while Europe and the US have announced gigafactories in the coming years but still lack large manufacturing capacity.

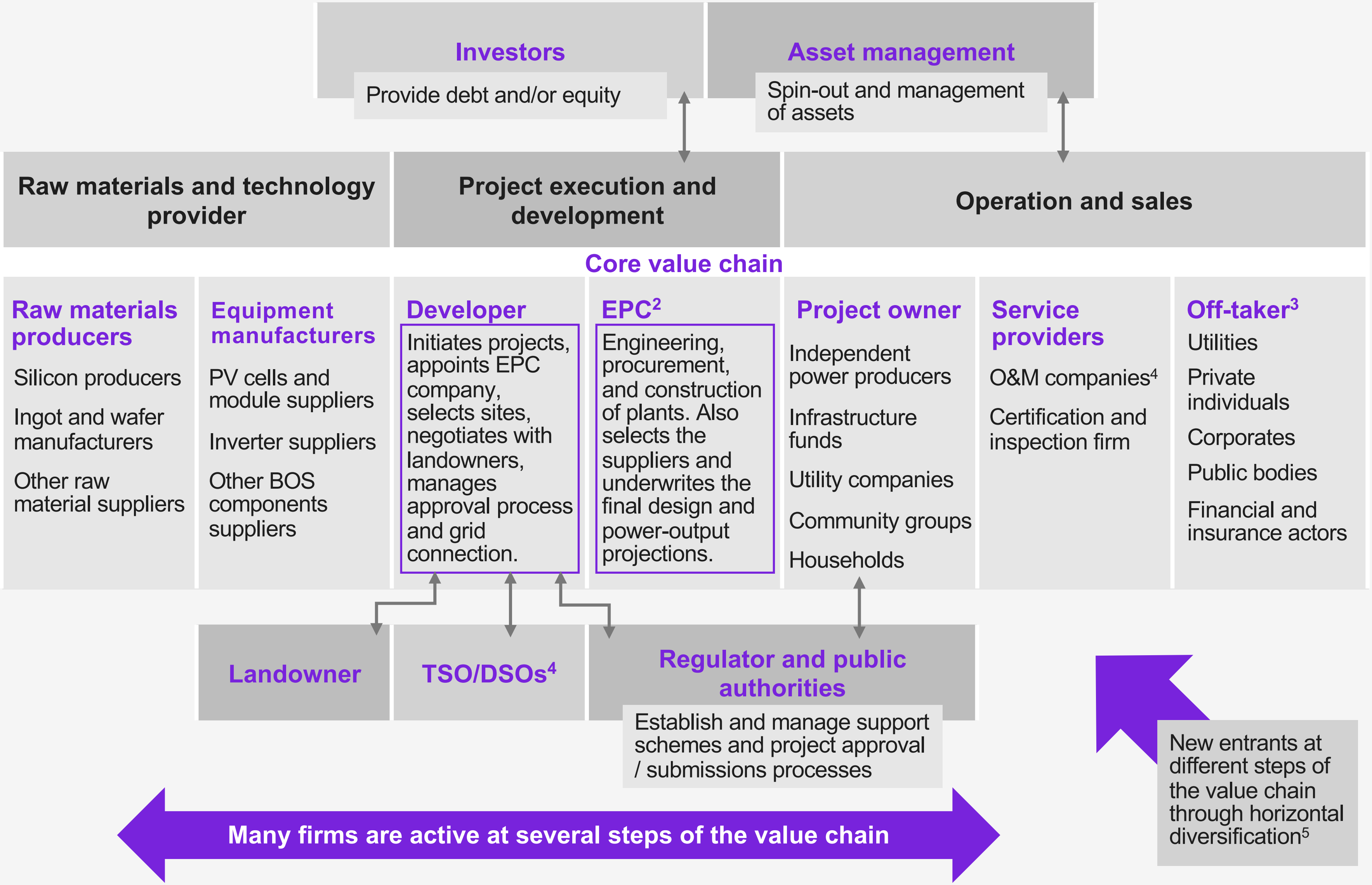
Risks affecting the value chain include future **lack of mining capacity** of raw materials and **long lead times for new production capacities**.

Developers and EPC contractors compete in a **global industry** that, unlike manufacturing, is not dominated by China. Oil and gas companies are driving the horizontal diversification of the sector through strategic investment and different levels of strategies announcements. In 2022, it is estimated that major **oil and gas** companies have invested around **USD 3.2 billion in solar PV**.

While the solar PV ecosystem is well-established with vertically integrated actors, there are still new entrants, especially through horizontal diversification

Illustrative

Solar PV ecosystem



Investors
Provide debt and/or equity

Asset management
Spin-out and management of assets

Raw materials and technology provider

Project execution and development

Operation and sales

Core value chain

Raw materials producers
- Silicon producers
- Ingot and wafer manufacturers
- Other raw material suppliers

Equipment manufacturers
- PV cells and module suppliers
- Inverter suppliers
- Other BOS components suppliers

Developer
Initiates projects, appoints EPC company, selects sites, negotiates with landowners, manages approval process and grid connection.

EPC[2]
Engineering, procurement, and construction of plants. Also selects the suppliers and underwrites the final design and power-output projections.

Project owner
- Independent power producers
- Infrastructure funds
- Utility companies
- Community groups
- Households

Service providers
- O&M companies[4]
- Certification and inspection firm

Off-taker[3]
- Utilities
- Private individuals
- Corporates
- Public bodies
- Financial and insurance actors

Landowner

TSO/DSOs[4]

Regulator and public authorities
Establish and manage support schemes and project approval / submissions processes

Many firms are active at several steps of the value chain

New entrants at different steps of the value chain through horizontal diversification[5]

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[1] Engineering, procurement, and construction
[2] Operations and maintenance
[3] Off-takers are the ones purchasing the electricity, often in bulk at a set price. They take on the risk of price fluctuations.
[4] TSO/DSOs: transmission system operator and distribution system operator
[5] An example of horizontal diversification is when oil and gas companies diversify by investing in solar PV electricity generation.
Sources: IEA, 2023, Energy Technology Perspectives; Kearney Energy Transition Institute analysis

6.1 Solar PV stakeholders

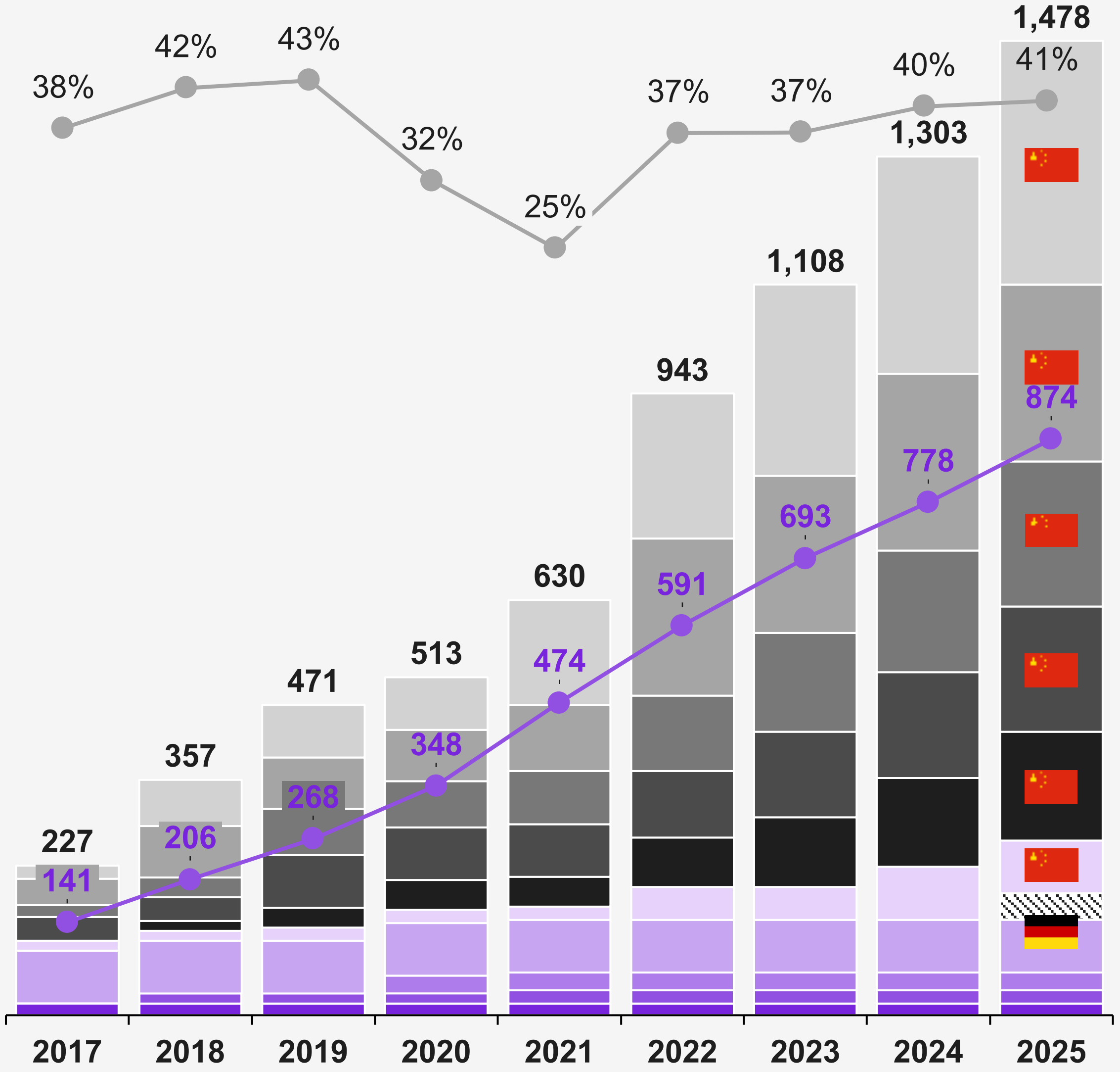
Polysilicon overcapacity anticipates increasing demand from solar industry growth

DRAFT

Predictive

Year-end capacities and demand for PV grade polysilicon

Thousand tons, 2017–2025, global



Estimated capacity shares in 2025		
Oversupply's share of production		
Demand		
Tongwei/Yongxiang	🇨🇳	26%
GCL-Poly	🇨🇳	19%
DAQO	🇨🇳	15%
Xinte	🇨🇳	13%
East Hope	🇨🇳	11%
Asia Silicon	🇨🇳	6%
Wacker[1]	🇩🇪	6%
OCI	🇰🇷	2%
Others		1%
Hemlock	🇺🇸	1%

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[1] Wacker announced a plan for increasing its capacity by 50% with a new factory in Norway in 2025.

Sources: Jefferies estimates; New York Times; PV Magazine; Kearney analysis

Polysilicon supply trends

Polysilicon represents more than half of solar module raw material costs. Polysilicon is obtained by purifying quartz and used to produce wafers.

There is an **overcapacity for polysilicon production**, which did not prevent stock shortages due to supply chain disruptions from the COVID-19 pandemic.

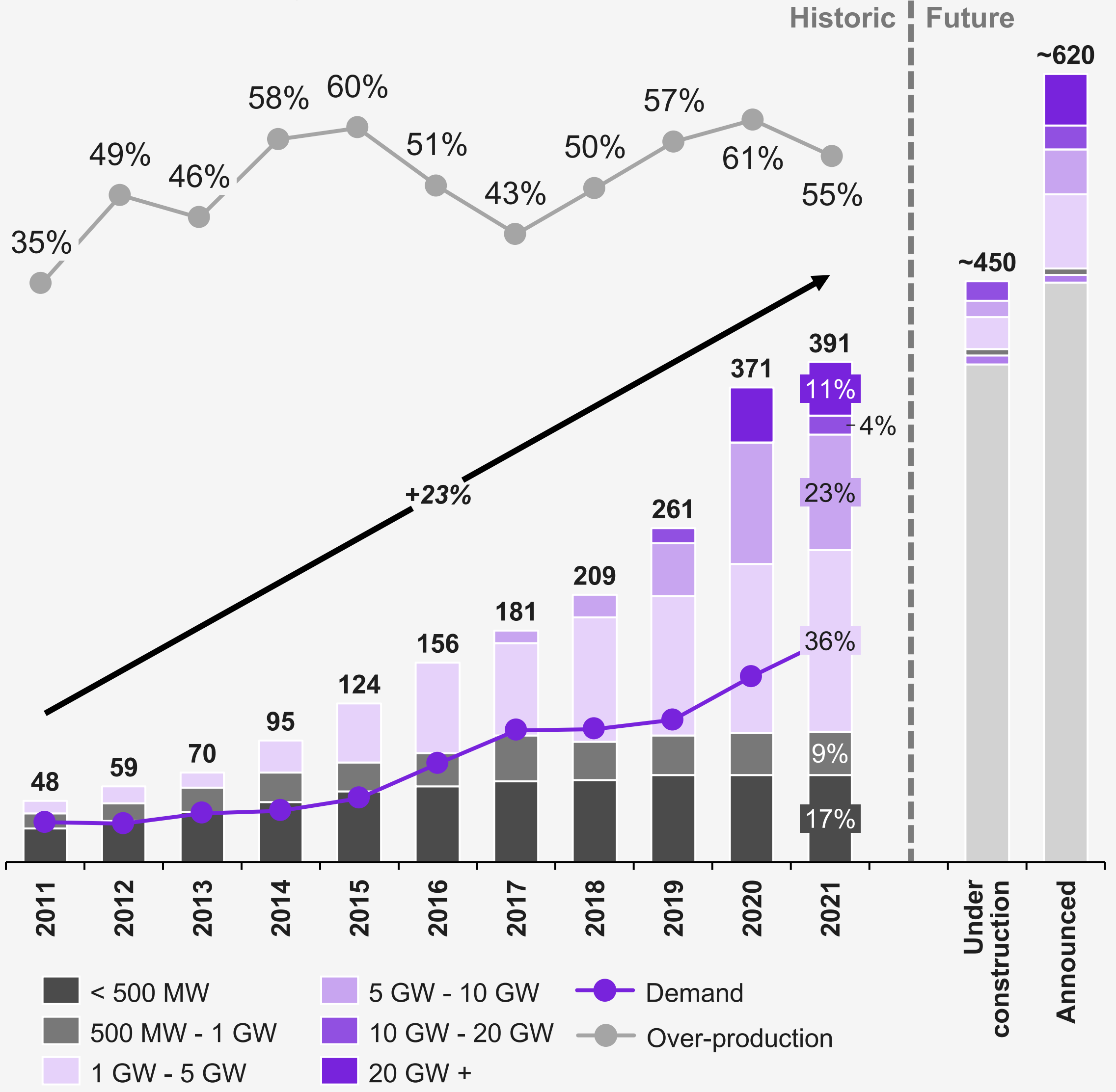
During 2010 to 2015, China increased its production capacities twice as fast as the rest of the world.

Producers of polysilicon are planning to increase significantly their capacities to keep with demand from the solar industry.

In polysilicon production it is frequent to see vertical integration from downstream players in the value chain.

Module production capacity has grown by 23% each year since 2011, pushed by larger manufacturing plants

Investment in solar PV manufacturing production has grown **four-fold** between 2018 and 2022, reaching around **USD 24 billion** in 2022.



Worldwide module manufacturing capacity by plant size

GW, 2011–2021, global

Modules

In 2021, **three-quarters of existing plants had a capacity above 1 GW**, close to 40% above 5 GW, and 14% above 20 GW.

Around 70% of the plants under construction or announced are 1–20 GW in size, and nearly 20% announced capacities are above 20 GW.

Out of the existing plants, the largest ones are in China. This is also the case for plants under construction and announced plants.

As with polysilicon production, there is a significant overcapacity as **the industry anticipates a strong growth in demand** driven by the global push in solar PV installations.

Module manufacturing employs the most people across the worldwide PV supply chain: Estimated workforce of 270k in 2019.

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[1] Demand is estimated as the capacity additions in that year.

Sources: IEA PVPS, 2023, Snapshot of Global PV Markets; IEA, 2023, Energy Technology Perspectives 2023; Kearney; BNEF; Fraunhofer ISE; Kearney analysis

The solar PV value chain is concentrated in China while demand is spread between markets

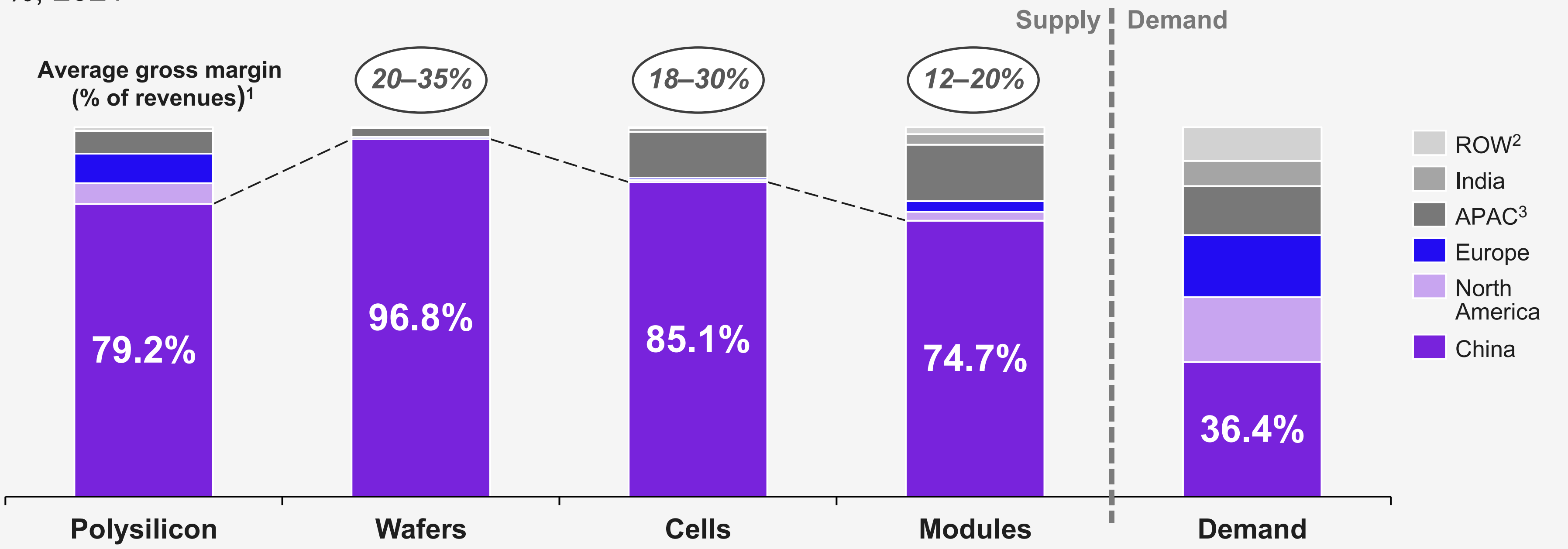
The supply chain is concentrated in China, especially at the wafer stage.

Solar PV employment is also concentrated in China, more so than for most other renewable energies.

6.2 PV value chain

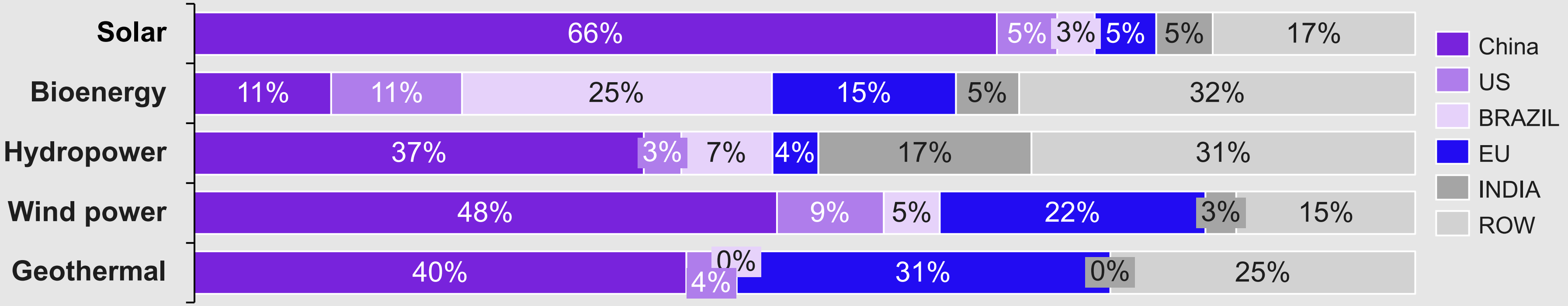
Global solar manufacturing capacity across the value chain by country and region

%, 2021



Employment (direct and indirect) in renewable energy by country/region

%, 2020-2021, by country/region[4]



[1] Average gross margin for industry players at each step of the PV supply chain

[2] ROW is rest of the world.

[3] APAC is Asia Pacific (except China).

[4] Solar includes Solar PV, CSP and Solar heating and cooling while Bioenergy incudes Liquid biofuels, Solid biomass and Biogas

Sources: IEA, 2023, Special report on Solar PV Global Supply Chains; IRENA and ILO, 2022, Renewable Energy and Jobs – Annual Review 2022; Kearney Energy Transition Institute analysis

At company level, the PV value chain is less concentrated than other clean technology industries

The PV supply chain is more concentrated upstream than downstream.

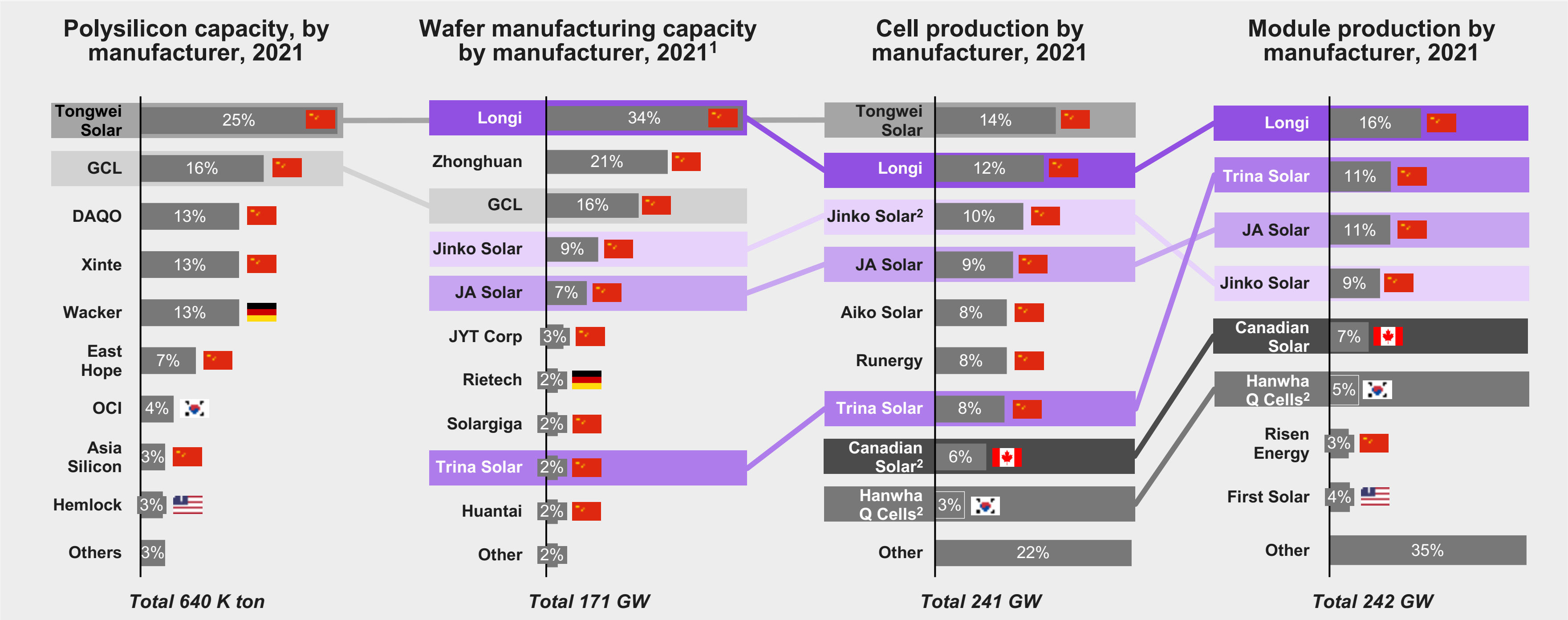
There are several large vertically integrated players.

Module manufacturing is less concentrated than other clean technology industries.

6.2 PV value chain

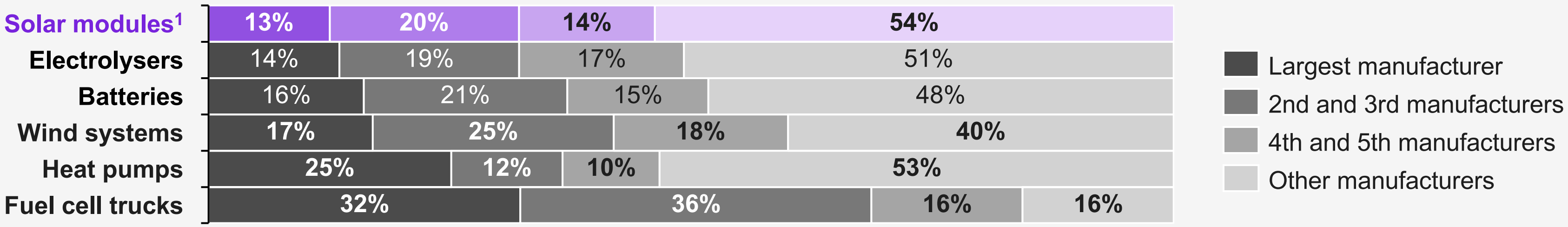
Main players across the PV supply chain

Share of capacity, 2021, global



Concentration of manufacturing capacity by clean technology industry

%, 2021, global



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[1] Total production capacity for 2021 is the same as for 2020.
[2] Assumed full capacity utilization
[3] Values are different from those in the above graph because the latter is production, not capacity.

Sources: IEA, 2023, Energy Technology Perspectives 2023; BNEF; IEA PVPS; Jefferies estimates; US Department of Energy; companies' websites; annual reports; desktop research (press); Kearney Energy Transition Institute analysis

The production capacity of most Chinese plants ranges between 5 and 10 GW per year, while gigafactories are still the exception in Europe

Non-exhaustive

Illustrative

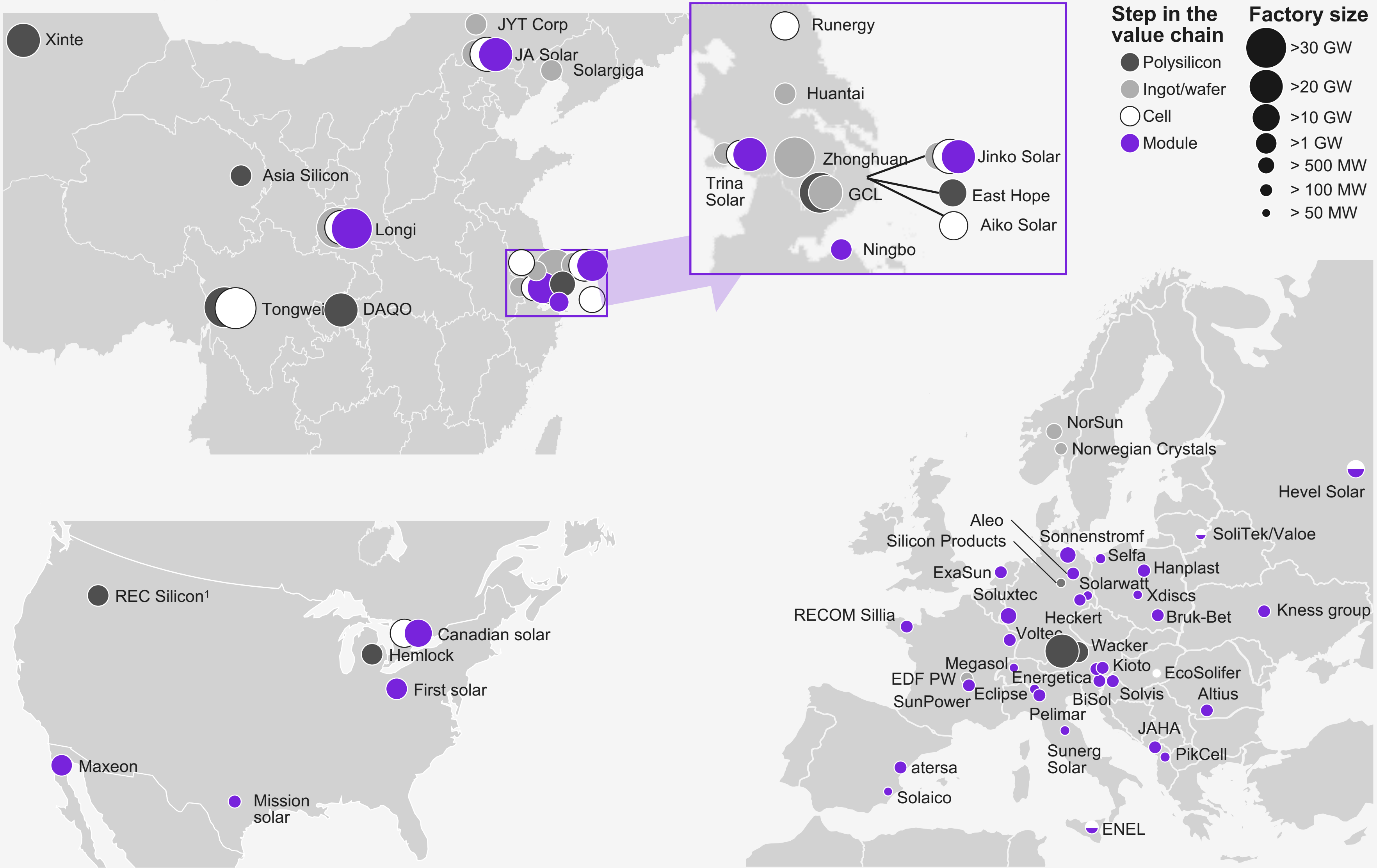
China manufactures at large-scale with many companies producing more than 10 GW in each step of the value chain, while Europe and North America have few companies above 10 GW.

Numbers are rapidly evolving for these regions.

6.2 PV value chain

Manufacturers across the PV value chain in China, North America, and Europe[1,2]

GW, 2021, by region



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[1] For China, the capacities are given per company, and the circle is located at their headquarter. Only the largest Chinese companies are shown (top 5 to top 9 depending on the step in the value chain). For China's polysilicon and wafers, values show capacity. For China's cells and modules, values show actual production in one year (2021).

[2] Headquarters or main manufacturing locations of the manufacturers. There are several smaller actors with capacities under 1 GW.

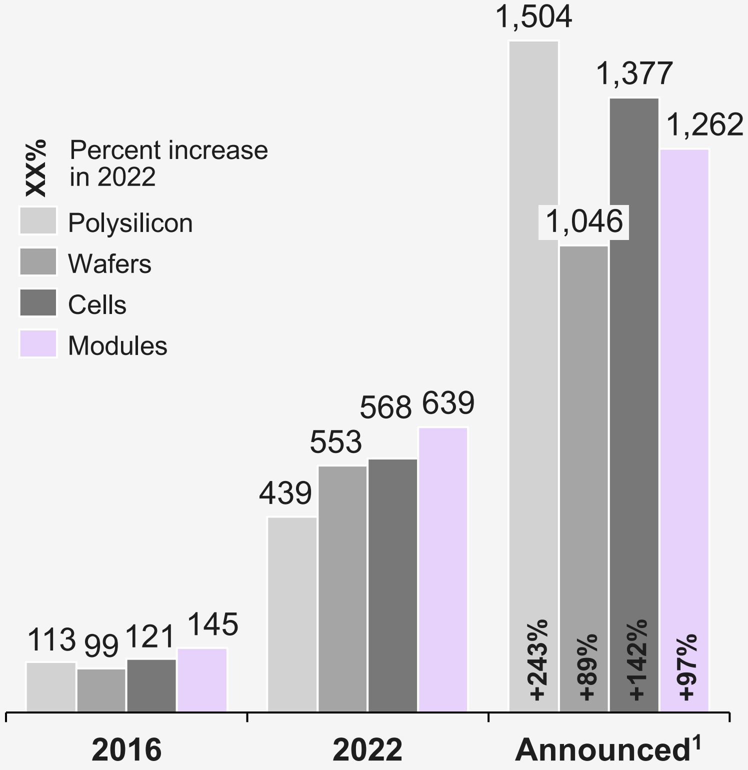
[3] REC Silicon is Norway based but its polysilicon manufacturing capacity is based in the US.

Sources: company websites, Kearney Energy Transition Institute analysis

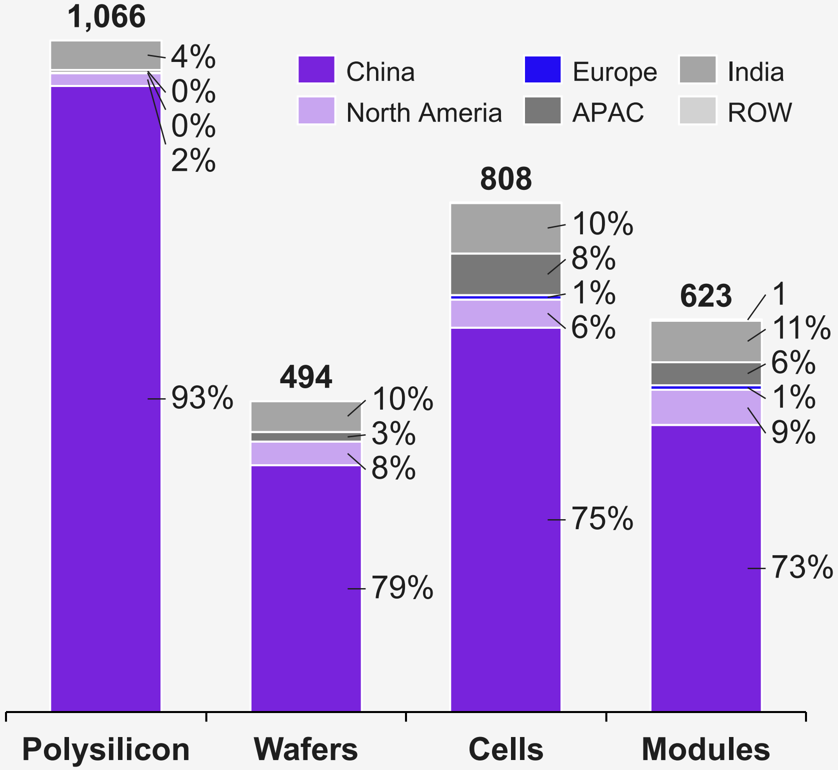
Global solar PV manufacturing capacity is set to grow for all components, with China leading the capacity growth

Announced manufacturing capacity growth by component

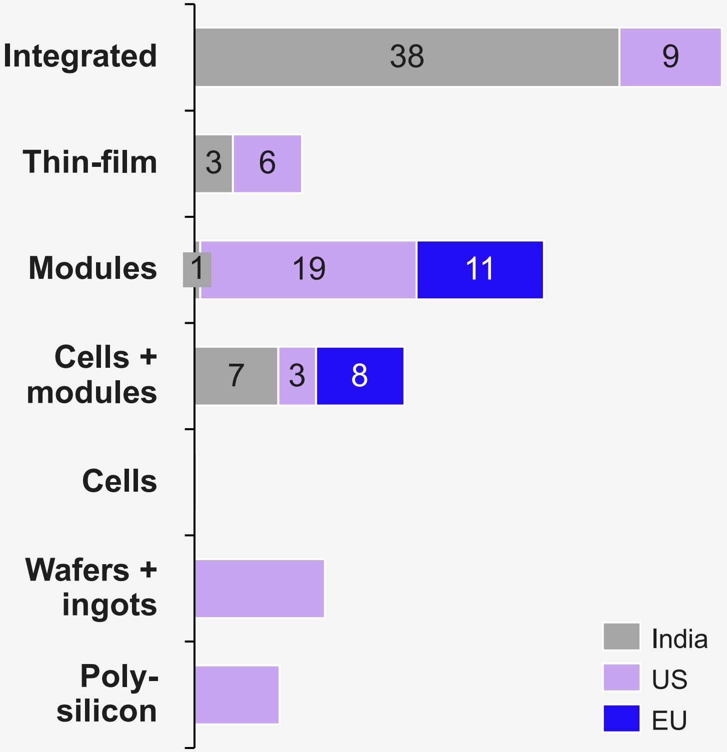
Recorded and announced manufacturing growth by component (GW, global)



Announced capacity additions by country and component (GW, 2021–2027, by country/region)[2,3]



Announced solar PV manufacturing capacity by component (GW, 2022–2023, by country)



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[1] Current capacity plus announced capacity additions

[2] Calculated using projected shares by countries in components and projected manufacturing capacity by component, with projections based on IEA and announced projects until 2027. There is a lack of data for the ROW category, with for example 1.5 GW module capacity in Brazil that is unaccounted for.

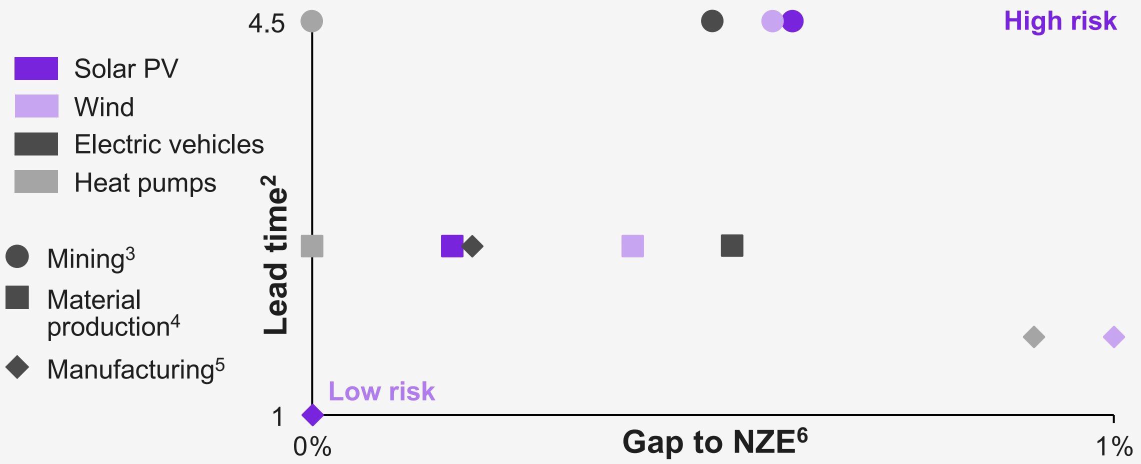
[3] See slide 111 to compare to their current shares of manufacturing capacity.

Sources: IEA, 2023, Renewable Energy Market Update June 2023; IEA, 2023, Renewables 2022; IEA, 2023, Solar PV manufacturing capacity according to announced projects and in the Net Zero Scenario, 2015-2030; PV Magazine, 2022, 'Made in Brazil' Solar; Kearney Energy Transition Institute analysis

The solar PV value chain faces two main risks, due to low mining capacity and regulatory uncertainty

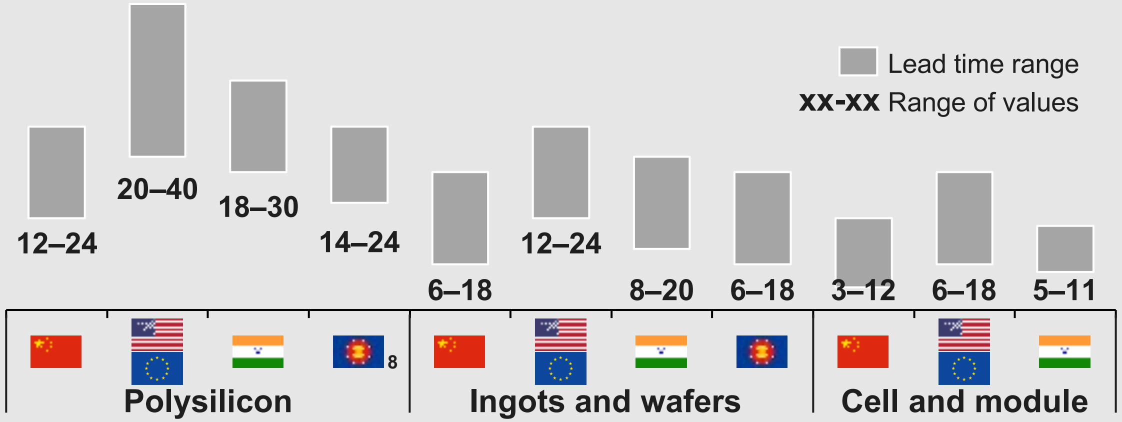
Risk level by clean energy transition technology

Lead time (years), gap (%), 2010–2022[1]



Lead times for solar PV investments by segment[7]

Months, 2018–2022, by country/region



Mining and lead time risk

While there is more than enough manufacturing capacity for modules, solar PV's development is facing the **risk of a future lack of capacity in mining for raw materials** and to a lesser extent in silicon production.

Long lead times will make it harder to close the gap between announced investments and what's needed in the NZE scenario, especially in the US and EU.

Manufacturing capacity is already on track with the NZE scenario for PV cells and modules.

Regulatory risk

Solar PV is vulnerable to trade sanctions as demand is spread around the world, while capacity is concentrated in China.

The rise in policies requiring local content in new PV projects could also increase costs by shifting capacity away from the cheapest locations.

---

[1] Lead time calculated on data sample from 2010 to 2022. [2] Time from project initiation to production. Mining values are from feasibility to production. [3] Mining includes copper, cobalt, lithium, and nickel. [4] Material production includes the production of bulk materials, critical materials, and polysilicon. [5] Manufacturing includes everything from solar cells to modules for PV. [6] The gap between planned investment and needs in the IEA Net Zero Scenario in 2030. [7] Here, time between announcement of the project and commissioning. [8] ASEAN Flag

Sources: IEA, 2023, Special report on Solar PV Global Supply Chains; IEA, 2023, Energy Technology Perspectives 2023; Kearney Energy Transition Institute analysis

Developers and EPC contractors compete in a global industry that, unlike manufacturing, is not dominated by China

Non-exhaustive

Selected developers and EPCs for utility-scale PV[1]

Developers

Company		Capacity (GW)	Area of activity					
SPIC	🇨🇳	35	■	■		■		
ENEL	🇮🇹	9.9	■		■	■	■	■
Recurrent Energy[1]	🇨🇦	9	■	■	■	■	■	■
Lightsource BP	🇬🇧	8.4	■		■	■	■	■
GCL New Energy	🇨🇳	7.3		■	■			
EDF Renewables	🇫🇷	6.8	■	■	■	■	■	■
ENGIE	🇫🇷	5.3	■		■	■	■	■
Adani GE	🇮🇳	4.6				■		

EPC contractors

Company		Capacity (GW)	Area of activity					
Sterling & Wilson	🇮🇳	15			■	■	■	■
Quanta	🇺🇸	12			■	■		
Tata Power	🇮🇳	11.5				■		
SOLV Energy	🇺🇸	10			■			
McCarthy Building	🇺🇸	9.5			■			
PowerChina	🇨🇳	9		■	■	■	■	■
Swinerton RE	🇺🇸	7			■			
Prodiel	🇪🇸	6	■		■		■	

■ Europe
■ China
■ North America
■ Asia/Oceania (excluding China)
■ South America
■ MEA[2]

Global players

Developer activities are global. Most top companies are active in foreign markets as well. EPC firms have global activities too, but to a lesser extent.

Unlike in technology supply, largely dominated by Asian manufacturers, the largest solar developers and EPC also include North American, European, and other Asian companies.

Developers face solar PV's largest challenges

They initiate the project, select the EPC contractor, and among other things oversee **land access and grid connection, both of which are proving to be the biggest bottlenecks for the industry.**

EPC market concentration varies by country

EPC markets go from very concentrated like in Spain to very fragmented like in Germany where the 10 largest EPCs control only a fifth of the market.

EPCs' responsibility for design and construction leads many of them to also take on O&M activities.

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[1] Part of Canadian solar. [2] Middle East and Africa

Note: Chinese companies are under-represented on the EPC list because of data unavailability. Some of the developers may also act as EPC for some of their projects. The data comes from these companies' websites; S&P Global, and thus the method to count capacity may vary. It represents the capacity of completed projects.

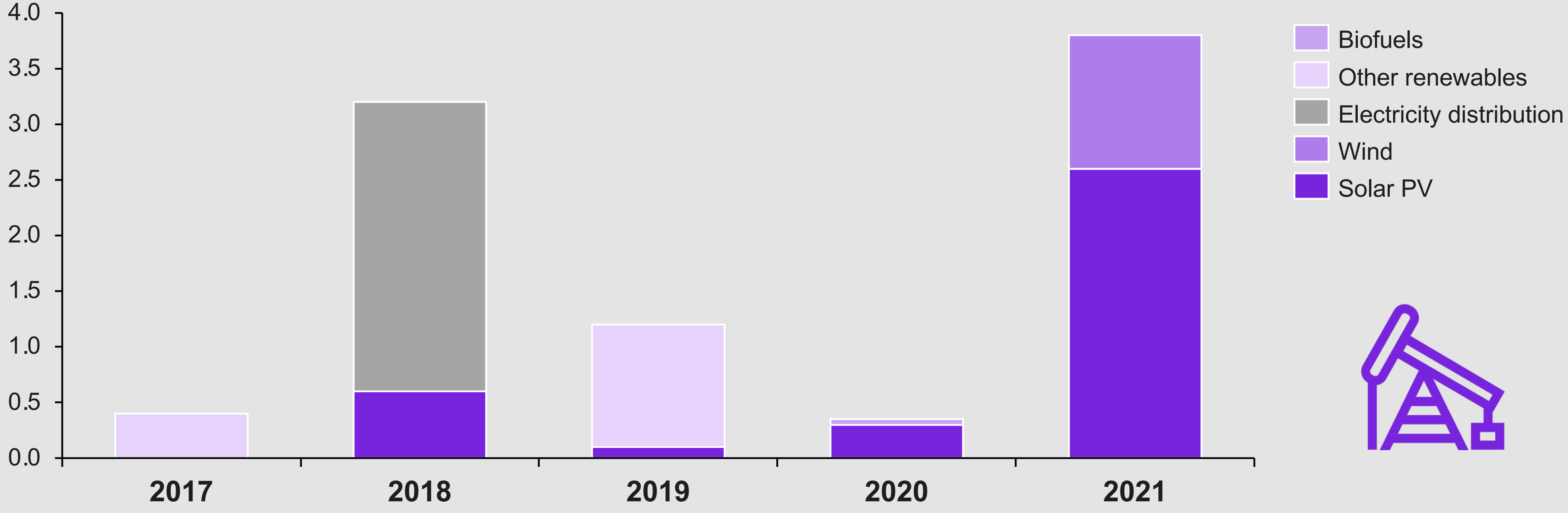
Sources: company websites; Kearney Energy Transition Institute analysis

Oil and gas companies are driving the horizontal diversification of the sector through strategic investment and different levels of strategies announcements

In 2022, it is estimated that major oil and gas companies invested **USD 3.2 billion on solar PV**, corresponding to less than **1% of their capex.**

M&A spending by selected oil and gas companies on clean energy technologies[1]

Billion 2021USD, 2017–2021



Investment diversification strategies by selected oil companies and NOCs

Solar PV and wind generation²

	ADNOC	BP	CNOOOC	CNPC	Eni	Saudi Aramco	Shell	Sinopec	Total Energies
Strategic investments	■	■			■	■	■	■	■
Strategy with limited evidence			■	■					

---

[1] Includes the majors, ADNOC, CNPC, CNOOC, Equinor, Gazprom, Kuwait Petroleum Corporation, Lukoil, Petrobras, Repsol, Rostneft, Saudi Aramco, Sinopec, and Sonatrach. Other renewables includes combined deals for solar, wind, and hydro.

[2] Strategic investments means growth supported by strategic investments (M&A), project FIDs, and/or spending on commercial-scale activities; strategy with limited evidence means announced strategy but little evidence of investment capacity or no announced strategy but minimal investments.

Sources: IEA, World Energy Investment 2022; Kearney Energy Transition Institute analysis

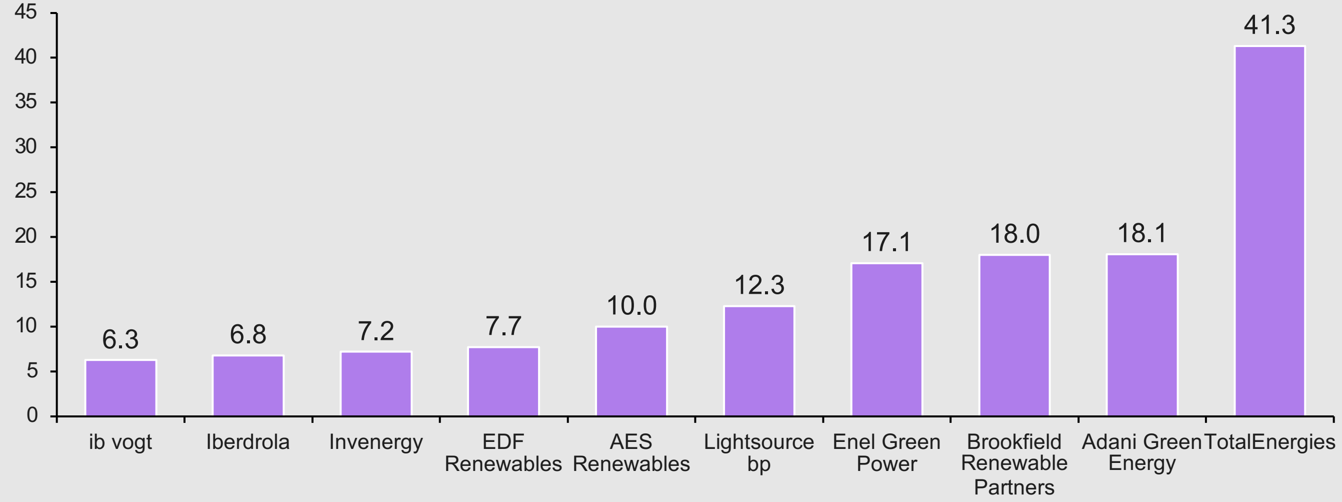
Solar PV developers have different strategies to expand their portfolio for their net zero emissions commitment by 2050

Top 10 leading developers accounted for about 145 GW of solar PV at different stages:
- 34% operational
- 20% under construction
- 46% in the pipelines (contracted)

6.4 Market stakeholders

Top utility scale global solar developers' market

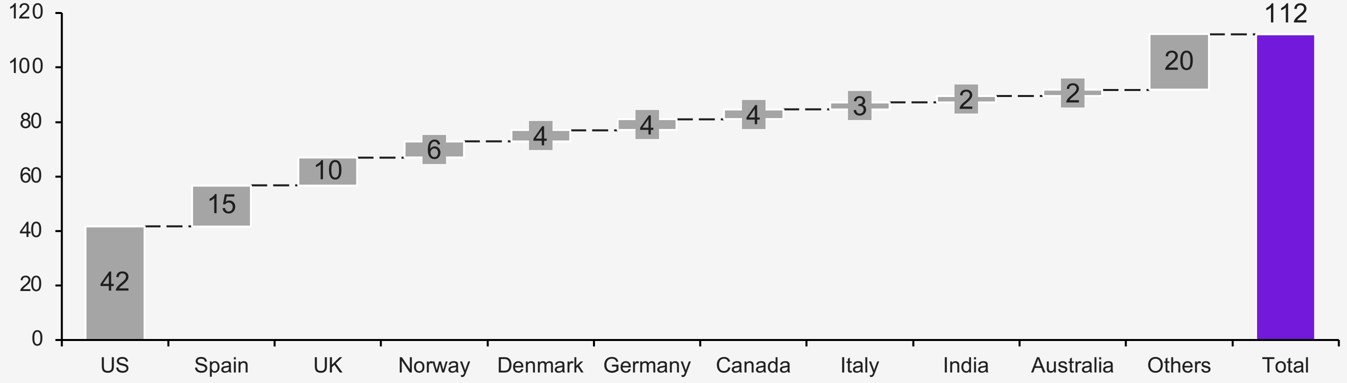
Total capacity, GW, 2023



TotalEnergies also has the largest portfolio of operational and awarded solar PV capacities.

Large-scale solar project acquisitions

By country, July 2022 to June 2023, GW



82% of project acquisition took place in the top 10 global markets.

Source: Mercom Capital Group, Leading global large-scale solar PV developers, 2023; Kearney Energy Transition Institute analysis

7. Environmental and social impacts

Environmental and social impacts

Because of silicon production, solar PV has a **higher carbon footprint** than other renewable energies, but it is still low when compared to carbon-emitting energies. Manufacturing represents a high share of panels life cycle emissions as these are highly linked to the power production mix used during manufacturing. Therefore, the location of the production is a key factor influencing overall emissions. However, PV has **limited water consumption**, and **its land footprint varies** depending on the type of installation.

Worldwide deployment of solar panels to produce electricity requires to properly manage solar panel end-of-life. IEA estimates that **solar panel waste** would represent between **60 and 80 million tons in 2050**. Due to the complexity of solar cell manufacturing, recycling solar panels needs to quickly progress. Recycling panels would benefit panel production, as retrieved material could directly be used again for new panels. Research has been done with regards to recycling panels since the 90s, and **theoretical panel recovery rate reached 95%** in 2016.

In 2022, solar PV industry was the energy industry that **employed the most people**, with **5 million jobs** distributed between O&M, manufacturing, sales, and construction. Most are employed in the construction of plants and in rooftop panel installation. Solar PV is also the energy industry with the **highest women representation** (40% vs. 22% in oil and gas).

Replacing fossil energies with solar PV panels contributes greatly to **avoiding greenhouse gas emissions**: around **2.1 Mt of CO_2eq for each GW installed**. The emissions reduction also contributes to air quality improvement that has a double benefit, it prevents health and respiratory diseases and reduces light obstruction from smog and dust.

Depending on the technology and location, solar PV panels have a different energy payback time. This payback time correspond to the time needed for a solar panel to produce the equivalent non-renewable energy required for its manufacturing. **Solar PV panels usually have an energy payback time of around 1 year.**

Finally, among all energies (renewable or not), solar PV has the **highest public support and acceptance**, reaching up to 77% support.

The country of production impacts the overall carbon footprint of the PV panel

LCA results highlights variable operation conditions to benefit from more or less GHG emissions abatement using solar PV electricity.

Please refer to Kearney Energy Institute's "Carbon emission assessment" factbook for a more detailed discussion on solar PV's carbon footprint.

7.1 PV environmental impact

Context and key factors

Solar PV energy can in general be considered as a low-carbon electricity source, and it is expected to represent ~37% of the world electricity mix in 2050.[1]

Several factors are to be monitored to estimate the environmental impacts of photovoltaic electricity, notably:

- The carbon emissions related to material manufacturing (silicon refining is energy intensive)
- The design of the panel to maximize its yield, lifetime and reduce its maintenance requirements
- The location which influences the irradiance thus the load factor and electricity production
- Recycling the materials

Material extraction & manufacture → **Installation** → **Operation and maintenance** → **Dismantling and disposal**

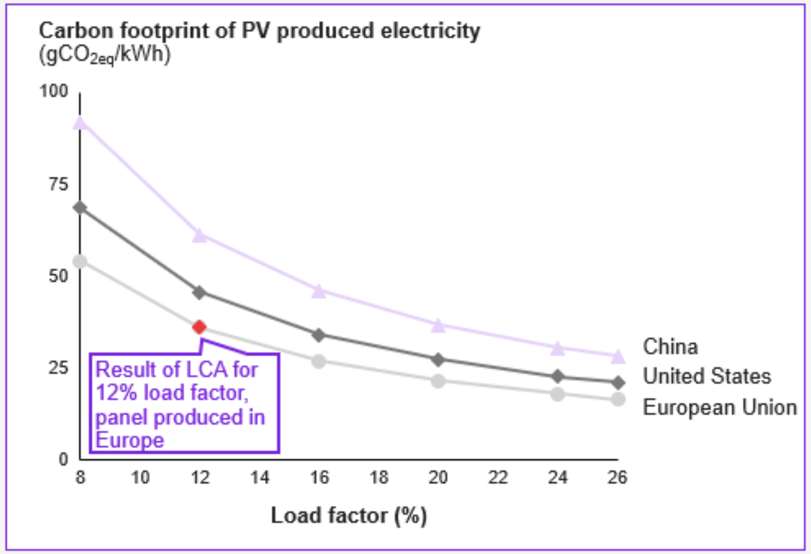
Key findings

Operating conditions unlocking the maximum decarbonization impact for solar electricity

Manufacturing represents 89% of emissions[2]; thus, the electricity carbon footprint is sensitive to materials' carbon footprint (e.g. energy used for transformation)

The panels' country of production impacts the final carbon footprint of produced electricity.

Panel location and load factor impact the yearly production and thus the carbon footprint of each produced kWh.



Carbon footprint of PV produced electricity (gCO_{2eq}/kWh)

Result of LCA for 12% load factor, panel produced in Europe

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[1] IEA NZE scenario. [2] This share corresponds to a 36.0 gCO2eq/kWh electricity mix.
Source: Kearney Energy Transition Institute analysis

More CO_2 is emitted in the life cycle of solar panels produced in China, followed by the United States and then the EU

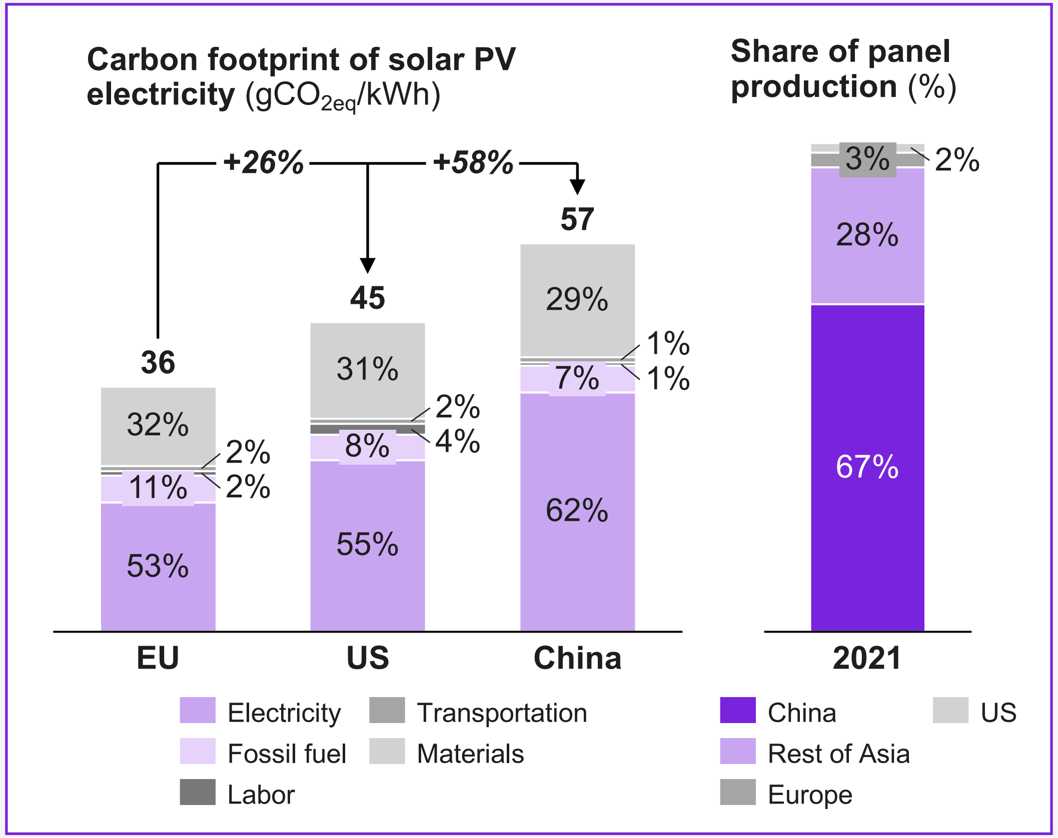
Around 70% of the crystalline solar panels are produced in China, even though it results in a higher carbon intensity embodied in the panel than in Europe or in the United States.

7.1 PV environmental impact

Carbon footprint of 1MW of solar PV

Manufacturing of the panel (module, frame) and of the balance of system (BOS) (cables, inverters, grid connection) represent **89% of life-cycle emissions**[1] for solar PV panels.

The energy requirements to purify and transform sand to solar grade silicon are high, thus depending on the energy/electricity mix of the country of production, the manufacturing strongly impacts the final carbon intensity of the electricity produced by the panels.



Carbon footprint of solar PV electricity (gCO_{2eq}/kWh)

Share of panel production (%)

In this figure, electricity and fossil fuels represent the direct energy input in the life cycle, excluding the energy used in the transportation process as it is separately shown. Labor and material are indirect energy inputs.

Carbon dioxide emissions embodied in solar power are determined by the carbon footprint of energy and non-energy inputs to the life cycle.
The EU has the lowest carbon footprint of power generation among the three regions (354 gCO_2/kWh), due to the high share of renewable power in its electricity mix as well as advanced generation technologies. The USA follow with a carbon footprint of power generation of 478 gCO_2/kWh, whereas China high share of coal power leads to a higher carbon footprint of electricity (673 gCO_2/kWh).

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[1] This share corresponds to a 36.0 gCO2eq/kWh electricity mix.

Sources: Liu & al., Differences in CO_2 emissions of solar PV production among technologies and regions: application to China, EU and USA, Fraunhofer ISE July 2021; Kearney Energy Transition Institute analysis

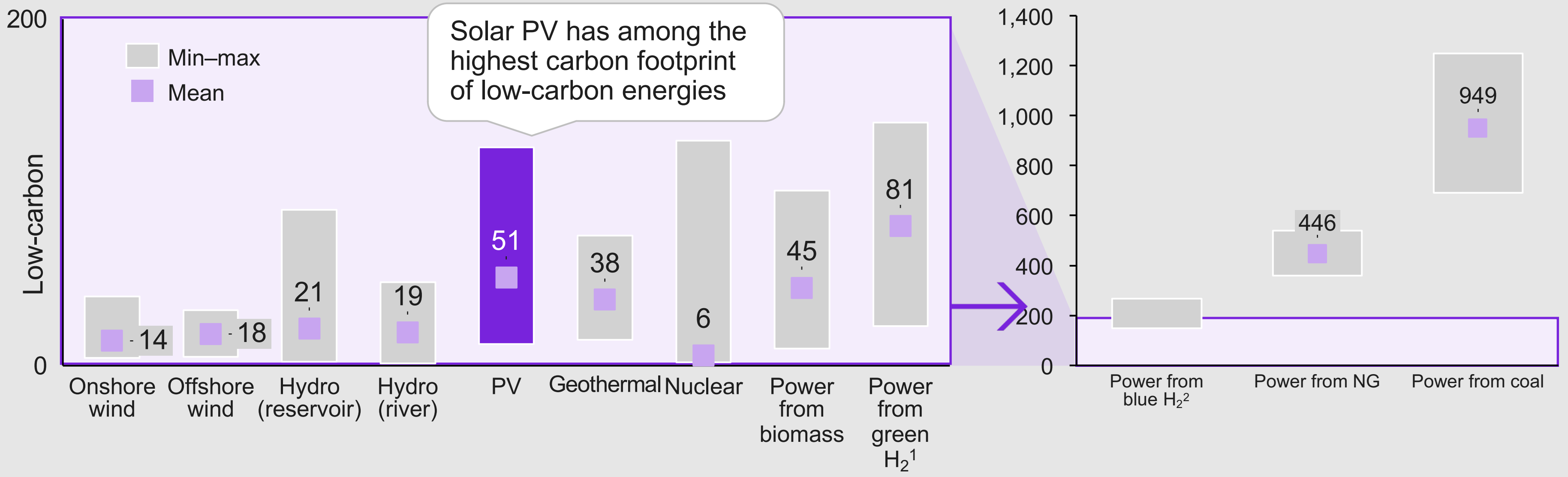
Solar PV is a promising technology to reach net-zero emissions, but it comes with a non-negligeable environmental cost

LCA results for various electricity sources show high variability in terms of related carbon footprint, which should be considered when assessing other value chains embodying energy inputs.

7.1 PV environmental impact

Life cycle assessment (LCA) carbon footprint

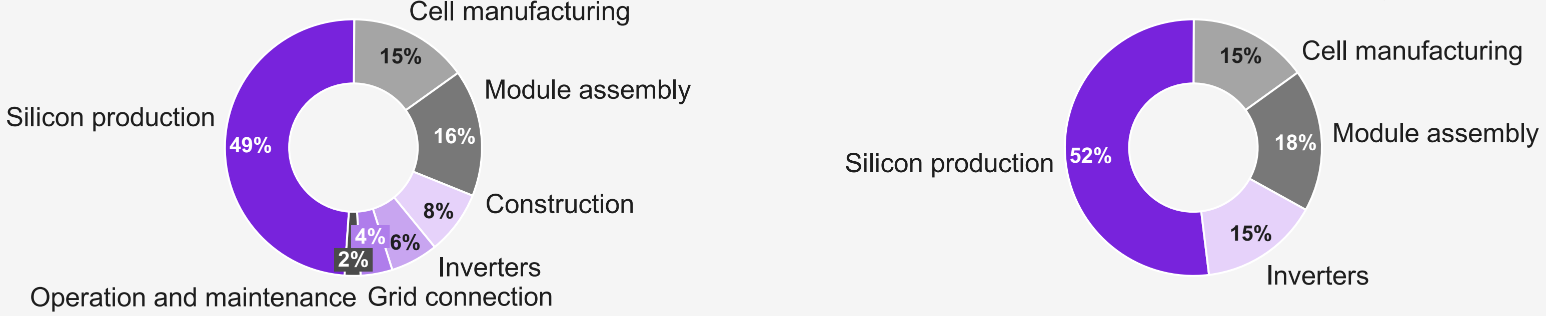
gCO$_2$eq/kWh



Solar PV has among the highest carbon footprint of low-carbon energies

Solar PV power plant GHG emissions

Share (%), polycrystalline PV ground mounted (left) and roof mounted (right)



Half of PV greenhouse gas emissions come from silicon production

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[1] Green hydrogen values based on electrolysis from wind electricity with an overall yield of the power to hydrogen to power value chain of 22.8%.

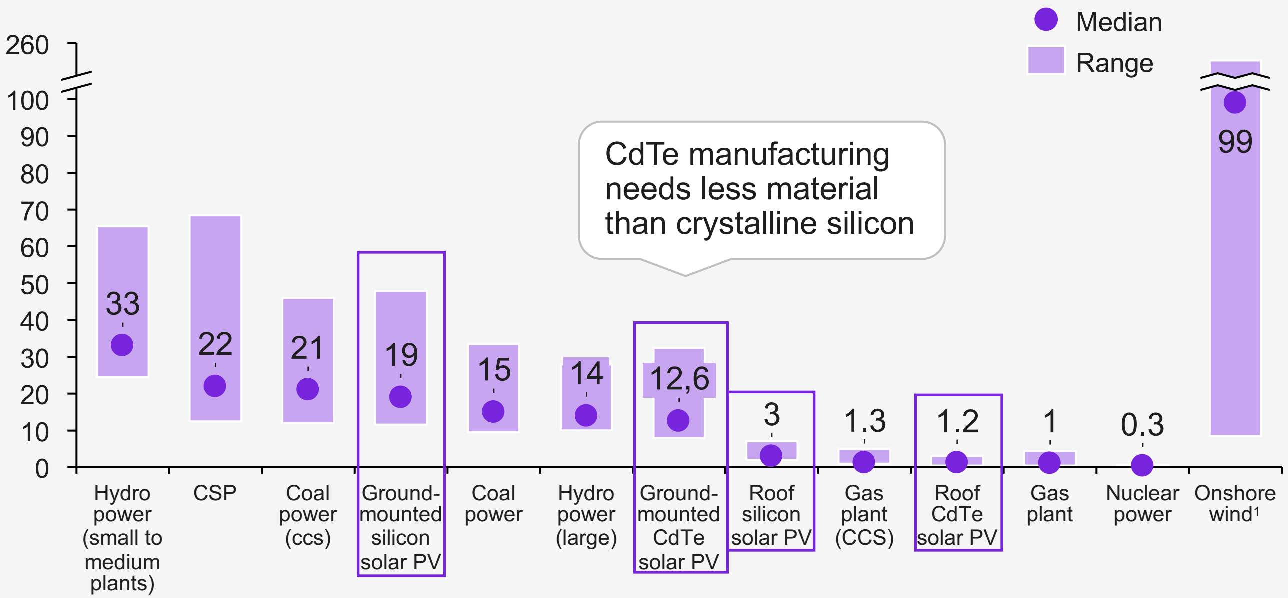
[2] Blue hydrogen values based on methane steam reforming with 93% carbon capture (with 0.2% fugitive methane emissions) with an overall yield of hydrogen to power value chain of 40.2%.

Sources: Ostfold, "Life cycle GHG emissions of renewable and nonrenewable electricity generation technologies," 2019; WNA Comparison of Life Cycle Greenhouse Gas Emissions of Various Electricity Generation Sources, 2011; Rendement de la chaine hydrogène Cas du « power-to-h2-to-power », Janvier 2020, ADEME, CertifHy Definition of Green Hydrogen, Blue Hydrogen GCCSI, Avril 2021; UNECE, 2022, Life Cycle Assessment of Electricity Generation Options; Kearney Energy Transition Institute analysis

Solar PV consumes water during operation and occupies land during most of its lifetime, but its footprint is less than other energies

Land use by energy source

(m²/kWh)

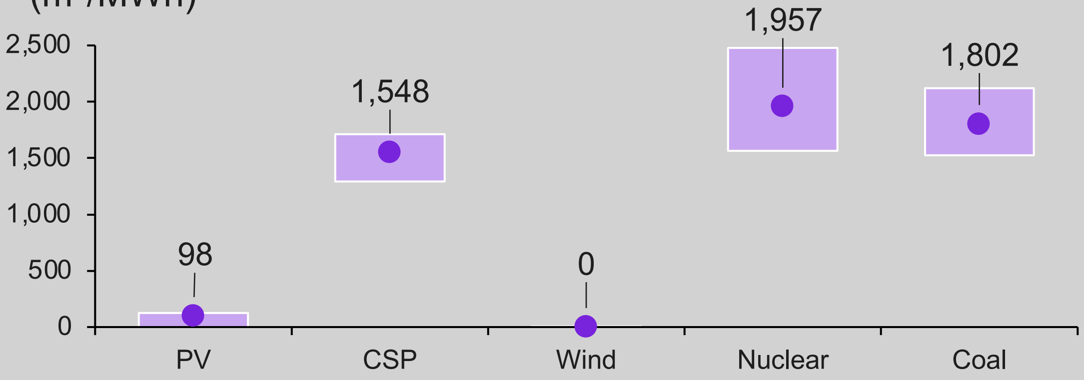


CdTe manufacturing needs less material than crystalline silicon

- It is often estimated that the **land occupied by PV plants is around 10 to 50 km² per GW**.
- However, to **effectively compare land use** with other energies, one must consider **land transformation, material extraction, facility construction and installation as well as land occupation**.
- As roof panel does not require new land; its land use is inferior.

Water consumption comparison

(m³/MWh)



- While operating, energy plants usually need **water to cool**, so that they **do not get damaged and can continue generating electricity**.
- Devices also need to **be cleaned and maintained**, requiring more water.
- Air-cooling is usually enough for solar panels to be cooled, and panels regularly need to be cleaned.

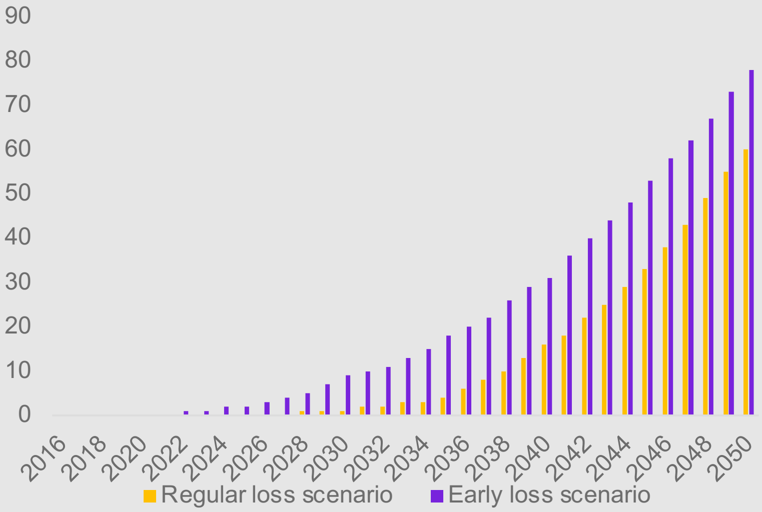
[1] The comparison takes into account the space required for a plant: a wind farm's land footprint can consider the space between turbines, which remains available for other activities such as agriculture or forestry.

Sources: SEIA; Ritchie, 2022, 'How does the land use of different electricity sources compare?'; UNECE, 2022, Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources; IEA, 2016, World Energy Outlook, 'Water-Energy Nexus'; Kearney Energy Transition Institute analysis

With the important increase of solar panels in the next years comes the increase of PV waste management

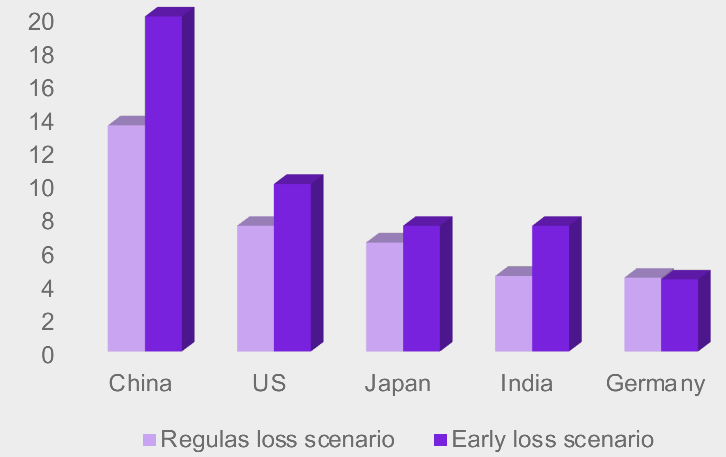
Estimated cumulative global PV panel waste for regular and early loss scenarios

Waste volume (million tons)



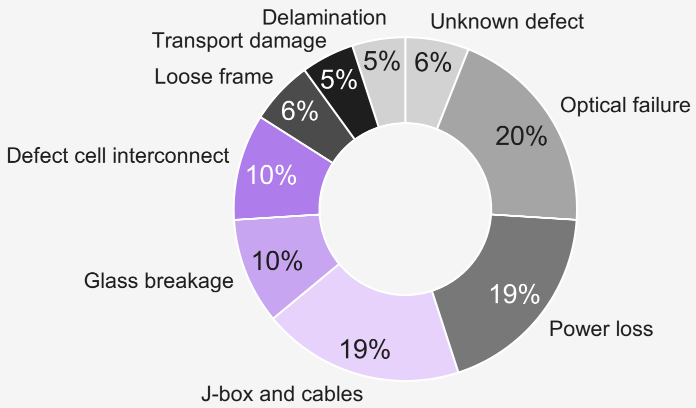
- By 2045, it is forecasted that the **cumulative PV waste capacity will surpass the operating PV capacity.**
- Increasing PV capacity installation also means increasing PV waste in the future. It is estimated that PV waste will represent between 60 and 80 million tons in 2050, depending on the scenario. **Regular loss scenario** assumes that all panels are operating for 30 years, while the **early loss scenario** takes into account all premature failures and replacements.

Cumulative waste volumes of top five countries for end-of-life PV panels in 2050



- Panel failures happen for different reasons, and sometimes these **cannot be prevented by the producer or the operator**.

Estimate share of failure origins



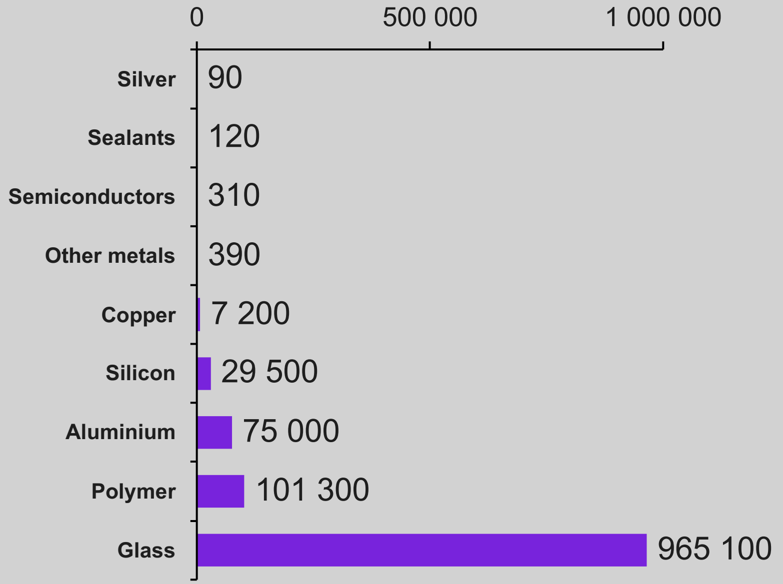
Sources: IEA PVPS, 2020, End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies; Kearney Energy Transition Institute analysis

7.2 PV recycling

With the important waste induced by solar PV, proper waste management needs to be simultaneously developed with PV deployment

End-of-life recovery potential under regular loss scenario to 2030

Material recovery weight (tons)

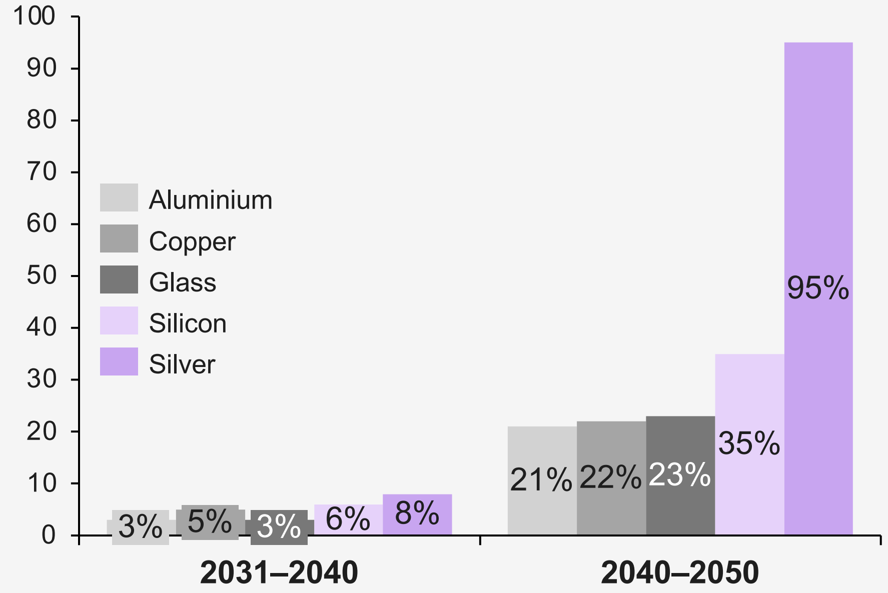


- Despite the additional cost, recycling solar panels **ensures PV sustainability in the long run** (cells and panels contain rare and valuable components as well as toxic materials).

- It is estimated that **recycling a panel could cost between USD 20 and USD 30 per panel**, while **burying** it might only **cost USD 1** (recycling processes are complex due to the multiple components of panel manufacturing and require additional space for storing waste).

Potential contribution of module recycling to solar PV material demand under net zero by 2050 scenario for selected materials

Share of PV raw material requirements (%)



- Retrieving materials by recycling panels could contribute to the **supply of raw materials** requirements to produce panels, instead of mining and manufacturing with new material.
- IRENA estimates that in 2050, recycled material from solar panels will be worth USD 15 billion in recoverable assets. **It is roughly equivalent to 2 billion new panels, or 630 GW additional capacity**.

7.2 PV recycling

Sources: IEA PVPS, 2020, End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies; Kearney Energy Transition Institute analysis

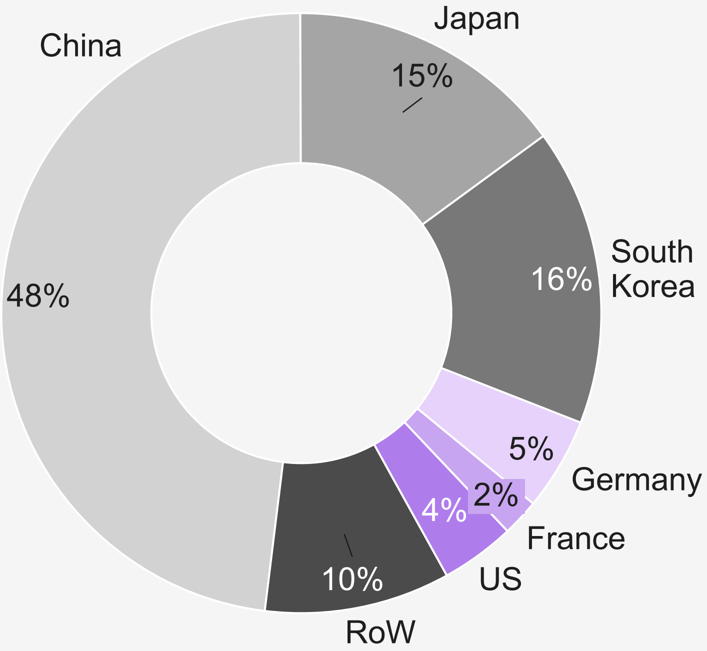
To face incoming waste, investments are made in R&D to maximize PV recycling

Recycling patents are mainly focused on recycling the ethylene-vinyl acetate (EVA) encapsulant, which envelopes the cells beneath the glass.

7.2 PV recycling

Cumulative number of PV recycling patents by country

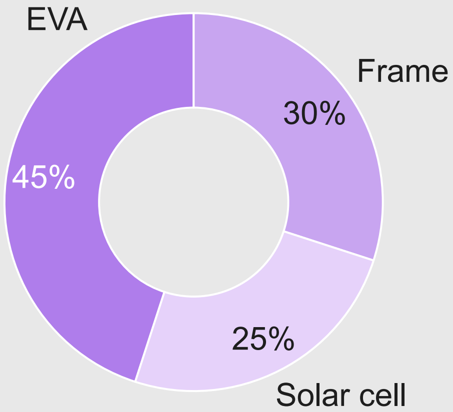
Share (%)



- In 2022, the PV recycling market accounted for about USD 200 million, and is expected to **reach USD 80 billion in 2050**. For this, investment and research are focused on recycling photovoltaic panels.
- From 1995 to 2016, **128 PV recycling patents were published** for c-Si solar panel recycling methods.

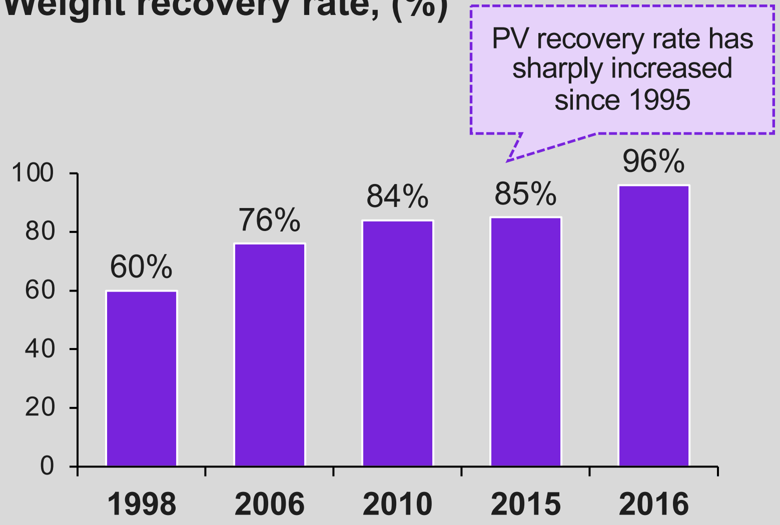
Recycling patents per PV part

Share (%), 2016



PV recycling evolution

Weight recovery rate, (%)



Sources: IEA PVPS, 2020, End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies; R. Deng and al., 2019, A techno-economic review of silicon photovoltaic module recycling, Renewable and Sustainable Energy Reviews 109; Kearney Energy Transition Institute analysis

Recycling panels requires a specific treatment to retrieve costly material from the solar cell

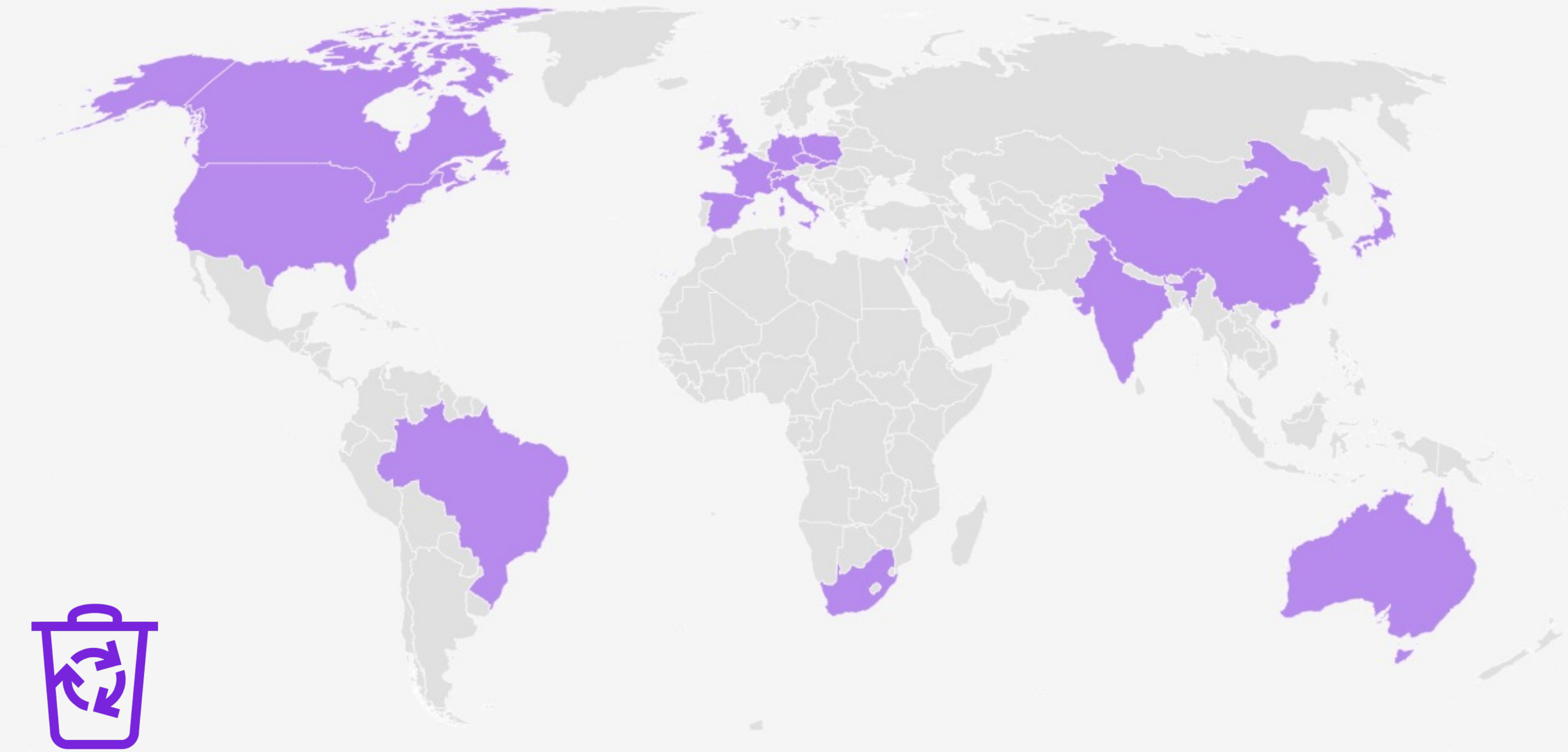
Non-exhaustive

Countries with the most solar panels installed are also the countries where specific PV recycling treatments are developed.

7.2 PV recycling

Countries with PV-only recycling companies

There are around 70 companies recycling exclusively solar panels



Due to the complexity of solar cell manufacturing, solar panels need a special method to recycle the solar cells. Most common recycling methods only recycle glass and metal, with most of the cell being buried.

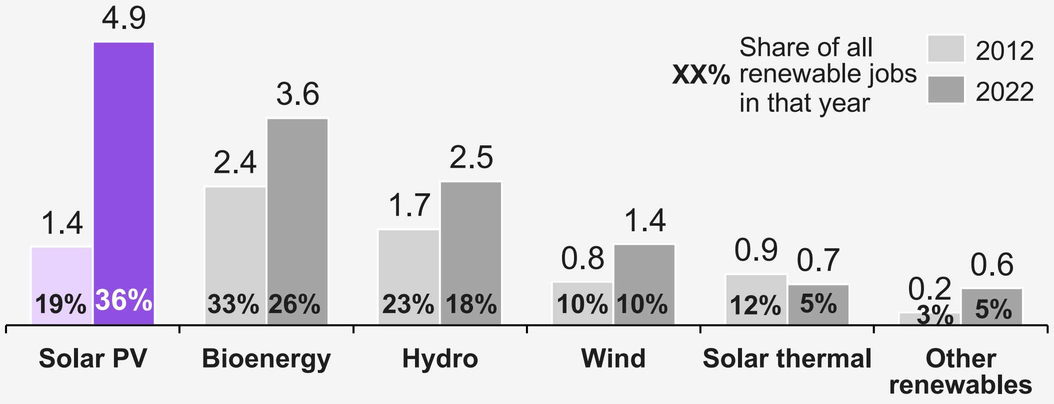
Sources: enf, 2023; Kearney Energy Transition Institute analysis

Solar PV is the largest employer among renewable power generation technologies, with most jobs being in construction and manufacturing

7.3 Social benefits

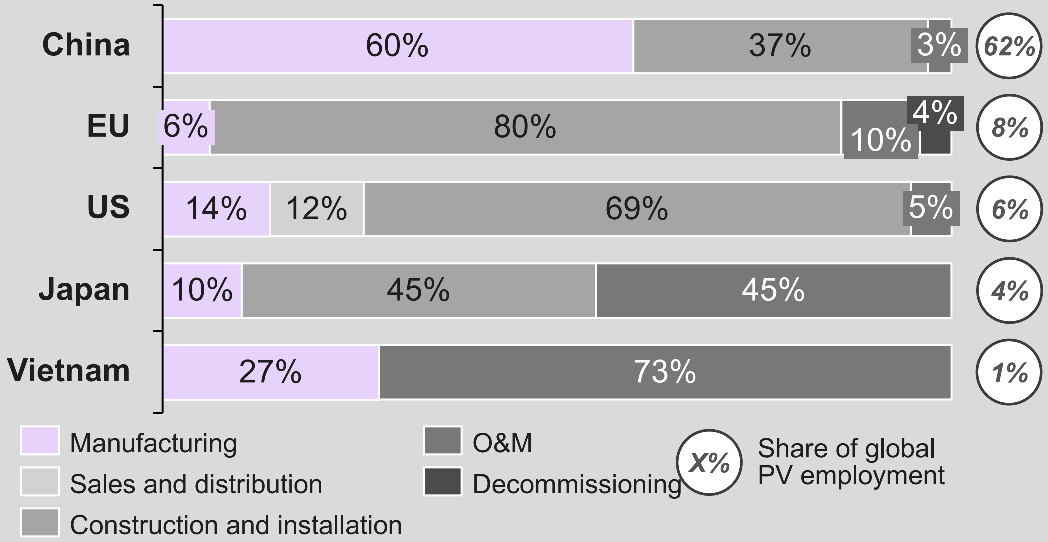
Employment in renewable energies by technology

Million employees, 2012–2022, global



Share of sectors in solar PV employment

Million employees, 2021, by country/region

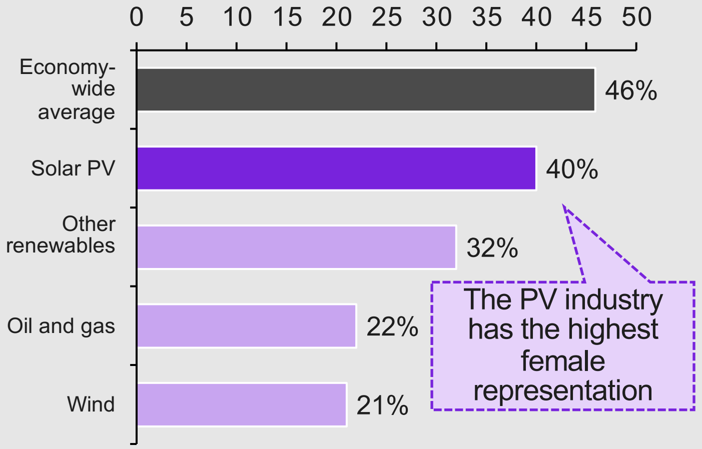


Solar PV employment

- **Solar PV employs more people than all other renewables.** Most are employed in the construction of plants and in rooftop panel installation.
- **The distribution between O&M, installation, manufacturing, and other jobs varies by country** depending on their local value chain.
- It is estimated that the solar PV industry could lead to the **creation of 1,300 jobs per gigawatt of panels installed**.

Female ratio for energy sources

Share of women (%), 2022



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[1] The weighted average of all renewables apart from solar PV. The weighted average of all renewables is 32%.

Sources: IEA, 2022, Special Report on Solar PV Global Supply Chains; IEA, 2022, World Energy Employment Report; IRENA and ILO, 2022, Renewable Energy and Jobs – Annual Review 2023; IRENA, 2022, Solar PV: A gender perspective; Kearney Energy Transition Institute analysis

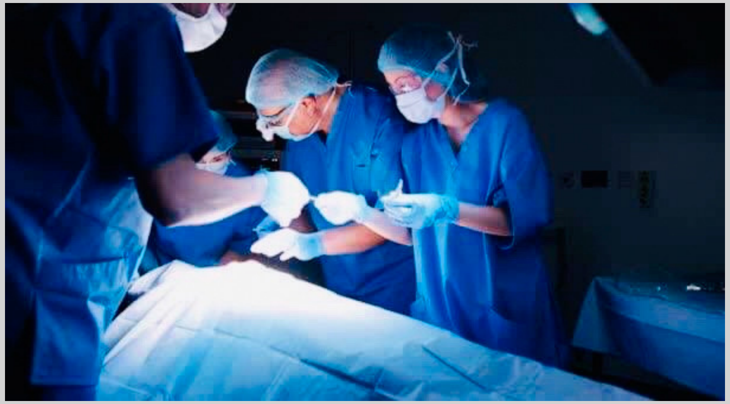
Health also benefits from solar panels

Air quality

Solar panels produce electricity without particles emissions when **replacing traditional fossil energy sources**.

This reduction directly leads to an improvement of air quality, which has significant health benefits. The **World Bank estimates that the cost of health damage due to air pollution is around USD 8.1 trillion a year** (about 6% of global GDP in 2022).

Improved air quality also means a clearer air with less dust: **less sunlight is absorbed by particles in suspension, increasing solar panel output**. In fact, air pollution diminishes PV efficiency up to 15–20%, and the energy loss cost associated is around USD 10 million annually.



Electricity access for care

With hundreds of millions of people still without access to electricity, solar PV offers **electricity access to remote areas or those without grid connection**. The World Bank estimates that in 2030, solar mini grids will power 380 million people.

But panels also give **power reliability and quality to facilities as hospitals and clinics**, so that lighting and refrigerating are no longer issues.

In 2020, about 1,000 health facilities were solar powered around the globe.

7.3 Social benefits

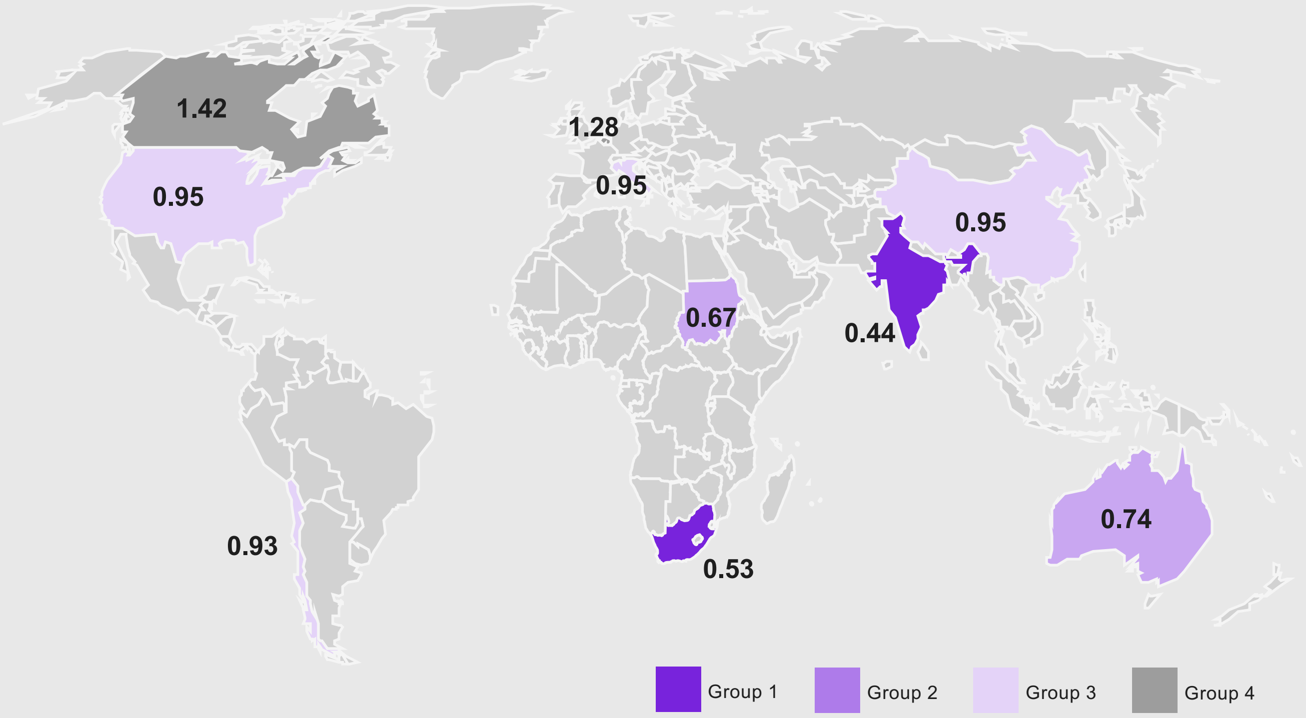
Sources: IEA, 2020, Sustainable recovery; The World Bank, 2022, “What You Need to Know About Climate Change and Air Pollution”; MIT News, 2018, “Air pollution can put a dent in solar power”; Fraunhofer ISE, 2023, Photovoltaics Report; World Bank, 2023, How solar can empower African youth; UN, 2020, Solar for Health: Five Ways Solar Power Can Make Universal Healthcare a Reality; Kearney Energy Transition Institute analysis

Solar panels rapidly recover their energy production needs

PV energy payback time

PV energy payback time (EPBT) refers to the time needed for a renewable energy to produce the equivalent non-renewable energy required for its manufacturing. **Solar panels usually have an EPBT around 1 year**: it takes about a year for solar panels to produce the equivalent non-renewable energy required for their manufacturing.
In case of solar panels, EPBT will depend on factors such as the **geographic location and irradiation on the panel, the technology used and the grid efficiency**.

Different EPBT worldwide[1]



EPBT by technology

Technology	EPBT (year)
Crystalline silicon	1.2
Cadmium telluride	0.9
Copper indium selenide	1.3

7.4 Environmental benefits

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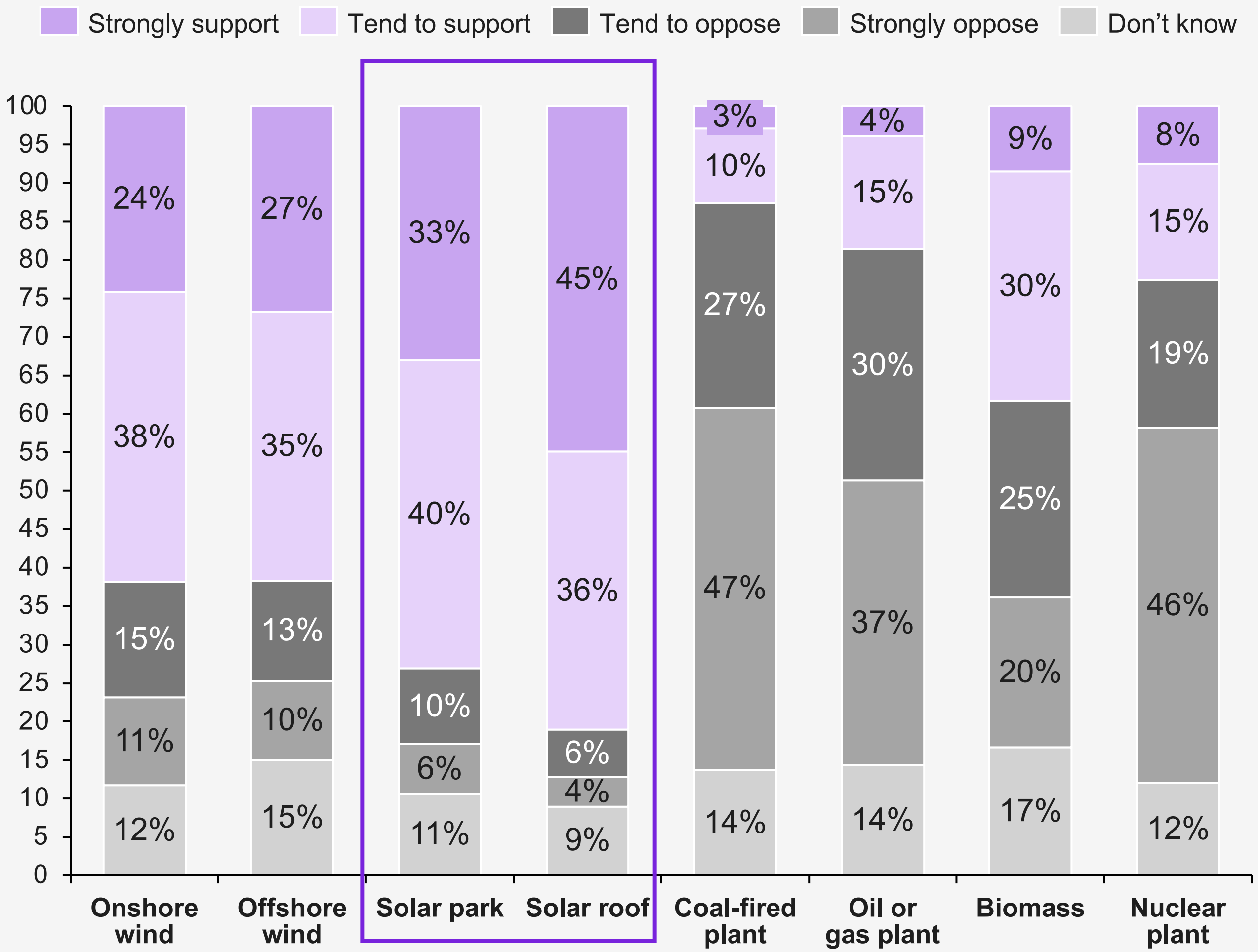
[1] The study was realized with a PERC cell module with 19.9% efficiency produced in China.
Sources: Photovoltaic report, Fraunhofer Institute for solar energy systems with support of PSE Projects GmbH, 2023; IEA-PVPS, 2021, Environmental life cycle assessment of electricity from PV systems; Kearney Energy Transition Institute analysis.

Among all energies, solar PV has the strongest public support

Public support for different energy plants[1]

Share of public opinion (%), 2021



Public perception includes:

- Support solar PV as a way to **reduce carbon emissions.**
- Attentive to **job creation** linked to the plant installation
- **Reduction of energy bill** with solar PV electricity
- Perceive **governments as not vocal enough and supportive** of this renewable energy.

7.5 Public support

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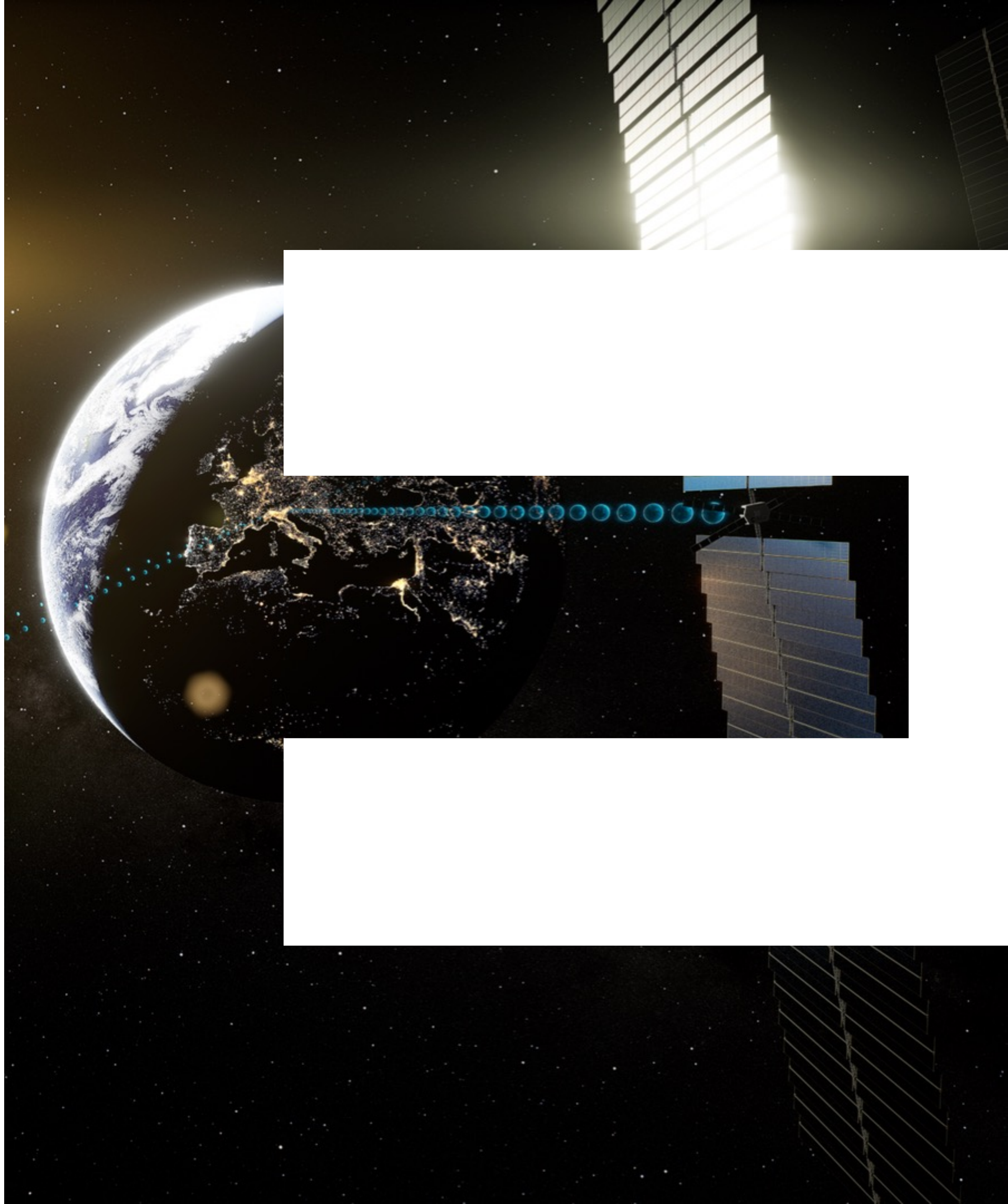
[1] This study was realized in autumn 2021 among 10 European countries (Bulgaria, Czech Republic, France, Germany, Greece, Italy, Poland, Romania, Spain, United Kingdom), questioning 10,547 people about their opinions on the construction of different energy plants near them.

Sources: European Climate Foundation and YouGov Plc., 2021; Kearney Energy Transition Institute analysis

8. Research, development, and innovation



Research, development, and innovation

Reducing solar PV costs and increasing performance are the main focus areas of R&D in materials and manufacturing spheres. Several new technological breakthroughs in materials (such as perovskites, organic electronics, etc.) seek to further **lower the costs while maintaining or even boosting the efficiency** of solar cells. Efforts have also been made to replace high-cost silver with low-cost copper paste without compromising the performance. Researchers are aiming to **improve reliability and increase lifetime** (to 50 years) through new materials and designs.

At the same time, **manufacturing technologies and processes are being improved**. Solar cells made from materials other than silicon have been printed on flexible substrates using 3D printers, which lowers manufacturing costs and increases end-use flexibility as they can be used where silicon-based panels can't.

Several start-ups and companies are developing commercial **solutions based on artificial intelligence, machine learning, construction automation, digitization, and robotics** to disrupt how solar power plants are designed, built, and operated. These solutions can **accelerate deployment of large-scale solar** by lowering costs and labor requirements.

Soiling is a major factor negatively affecting solar yields, especially in regions that are witnessing high growth in solar installation such as China and India. Recently, scientists have developed a **water-less soiling mitigation solution** that can be relevant for regions with water scarcity and high solar potential as water-based cleaning often accounts for 10% of the operation costs.

Innovative applications for solar PV such as transportation (air, marine, and road), buildings (building-integrated photovoltaic), space electricity generation, harnessing energy from rain, or night-time solar, are being explored. Some of these solutions have already proven to be environmentally and commercially better than the conventional fossil fuels-based alternatives (on a smaller scale). Developing and scaling these solutions can lead to solar playing an even more prominent role in meeting global decarbonization targets.

However, most of these initiatives are **not commercialized on a large-scale yet** and are still being trailed on a lab scale. Further, many of these novel approaches have challenges to overcome on costs, loss of efficiency, reliability in real-world conditions, and sustainability.

Key research, development, and innovation themes in solar PV

PV technology

R&D to fast-track commercialization for disruptive innovations in materials, manufacturing, longevity, performance, etc..

Design and build

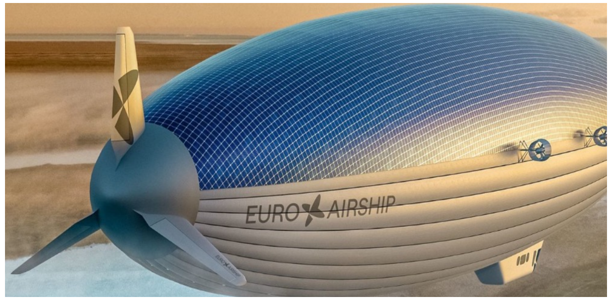
Novel technologies and solutions to accelerate deployment of large-scale solar

Operate

Lowering operating costs and increasing yields by addressing key challenges such as soiling

Applications

Futuristic and innovative end uses that can open up decarbonization pathways and add synergies to other carbon-neutral solutions



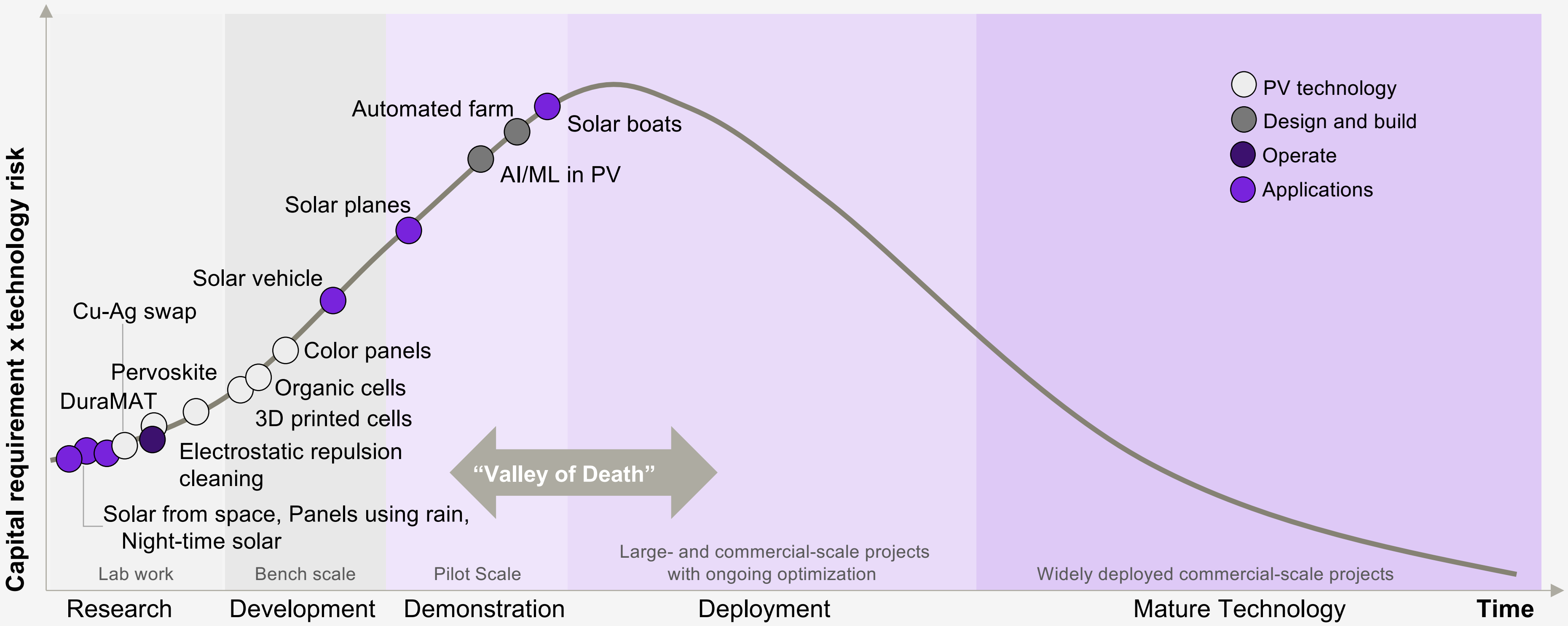
Source: Kearney Energy Transition Institute analysis

Most of the innovations are not commercial yet but are characterized by a promising future potential

TRL[1]	Description
1-3	Concept stage
4	Small/early prototype
5-6	Large/proven prototype
7-8	Demonstration
9-10	Early adoption
11	Mature

8.0 Summary

Solar PV research, development, and innovation themes mapped to maturity curve



Theme	TRL	
Colored panels	5-6	○
Organic cells	4	○
3D printed cells	4	○
Pervoskite cells	1-3	○
Cu-Ag swap	1-3	○

Theme	TRL	
DuraMAT	1-3	○
Automated farm	7-8	●
AI/ML in PV	5-6	●
Electrostatic repulsion cleaning	1-3	●

Theme	TRL	
Solar boats	7-8	●
Solar planes	5-6	●
Solar vehicles	4	●
Solar from space	1-3	●
Panels using rain	1-3	●
Night-time solar	1-3	●

[1] TRL = technology readiness level, Scale borrowed from IEA (2020), Assessing technology readiness: The ETP Clean Energy Technology Guide

Sources: Kearney Energy Transition Institute analysis

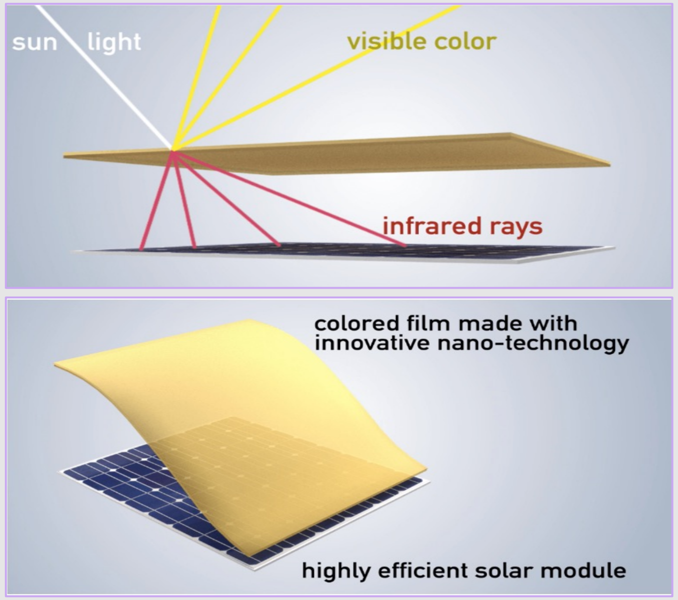
Colored PV panels can enable building-integrated photovoltaics market

Buildings are major energy consumers and greenhouse gas emitters. Building-integrated photovoltaics (BIPV) solutions aim to significantly reduce a building's carbon footprint.

8.1 PV technology

Colored PV panels

- Solar PV panels are generally **black** as it is the natural hue of silicon when manufactured. Panels also appear **blue** due to an applied anti-reflective coating to improve light absorption and generate electricity during manufacturing.
- **Different techniques** have been employed to obtain color panels such as anti-reflection coatings, colored and/or semi-transparent PV-active layers, special solar filters, colored polymeric encapsulant films, and modified front glass by printing, coating or alternative finishing.
- Demand for aesthetic PV systems is increasing rapidly in urban areas and portable devices where the harmonization of color with neighboring exterior elements is a high priority. However, considerable loss in **efficiency** (at times around 45%) and high **costs** are the main drawbacks.



Key application – building-integrated colored solar modules

Sources: COLOURED BIPV - Market, Research and Development (IEA PVPS, 2019), Fraunhofer Institute for Solar Energy Systems ISE; Kearney Energy Transition Institute analysis

- **Colored building-integrated photovoltaic (BIPV) modules** that replace roof or façade elements can be an attractive alternative to the traditional blue-black solar PV installations. A number of companies are beginning to produce colored solar panels.
- **MorphoColor®** technology, developed and patented by Fraunhofer Institute for Solar Energy Systems ISE, proposes to deliver ~90% of the yield of an ordinary module overcoming a key challenge. The MorphoColor® layer consists of a photonic structure in which an interference layer is combined with a geometrically structured substrate in such a way that a narrow-band reflection peak results, yielding maximum results. It reflects a small part of the color spectrum and allows the rest of the sunlight to pass through virtually unhindered.

Printable solar cells based on organic electronics offer lower-cost PV solutions

Solar cells made from materials other than silicon (such as perovskite) are especially amenable to be 3D printed on flexible substrates.

8.1 PV technology

Organic electronics

The design uses electrically conductive organic polymers and small molecules for light absorption, charge production, and transport to produce electricity from sunlight by the photovoltaic effect. These carbon-based electronic materials are soluble in a variety of liquids which makes them dissolvable into solutions. These solutions can then be printed, painted, or sprayed on to different surfaces while still being able to conduct electrical charges. Compared to conventional silicon solar cells, organic solar cells are thin, flexible, lightweight, and semi-transparent.

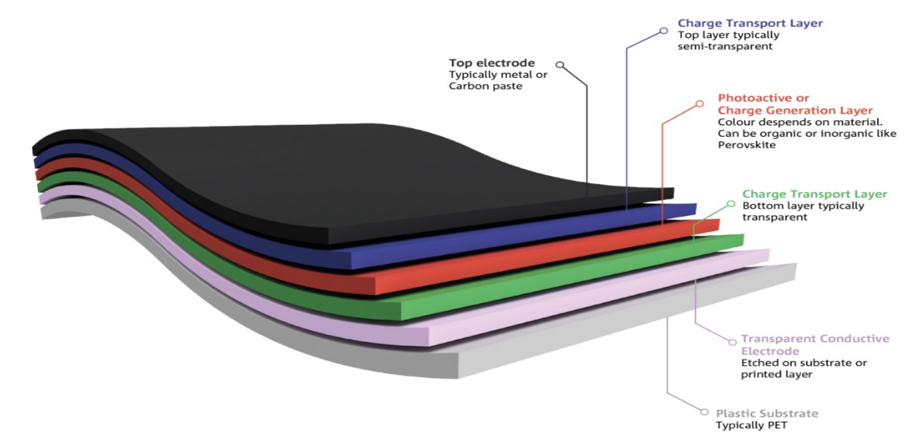
Development status

– In 2018, University of Newcastle (Australia) launched a commercial-scale pilot of printed solar, partnering with global logistics company CHEP, a Brambles subsidiary, to install a 200 m² rooftop array of printed solar. The team also completed the installation of a public interactive lighting in Sydney.

– Recently, it produced the highest-ever performance of solar paint cells at 2.5 to 3 percent. The cells can already produce output at lower light levels than existing solar-based silicon cells with installation costs approximately one-tenth of installing a silicon solar system.

– Backed with government support, CSIRO (Commonwealth Scientific and Industrial Research Organisation) is working with Victorian Organic Solar Cell (VICOSC) consortium to develop printed solar cells as well. A demonstrator canopy was installed in Melbourne zoo from 2016–2018.

Printed solar cell layers



3D printing (additive manufacturing) is utilized to print these solar cells. Efforts are being made to design solar-powered 3D printers for an increased symbiosis.

Pros

– Address applications where silicon solar panels cannot be used
– Rapidly manufactured and deployed and inexpensively replaced if damaged
– Potentially cost-effective for PV applications
– Remarkable customization and design flexibility

Cons

– Lower efficiencies (~1/3–1/10 of hard material) even though further improvements are being realized
– Susceptibility to photochemical degradation resulting in reduced longevity and durability (~2–3 years)
– Recyclability of the organic material (usually plastic)

Sources: University of Newcastle, CSIRO – Printed PV, press search; Kearney Energy Transition Institute analysis

Materials-based innovations such as perovskites and copper paste can drive solar PV costs down in the near future

To accelerate successful domestic commercialization of perovskite technologies in the US, National Renewable Energy Laboratory (NREL), University of Toledo, University of Washington and its Washington Clean Energy Testbeds, and the University of North Carolina Research Triangle together with leading domestic companies have formed **US Manufacturing of Advanced Perovskites (US-MAP) R&D consortium.**

8.1 PV technology

Perovskites advantage

Halide perovskites are a family of materials that have shown potential for high performance and low production costs in solar cells.

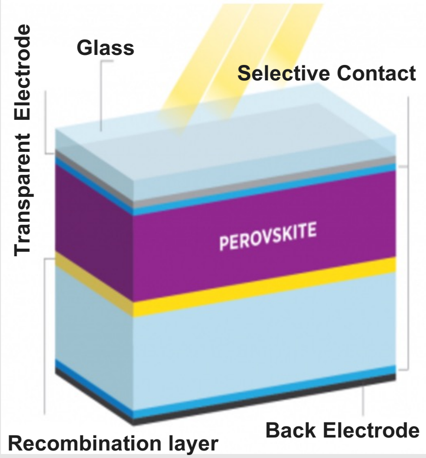
- Rapid improvements in efficiency, from ~3% in 2009 to over 25% today.
- Have been successfully integrated with established silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) solar technologies to deliver higher power with low-cost manufacturing compatibility.

Perovskites-silicon tandem solar cell

Perovskites can be tuned to respond to different length waves of the solar spectrum by changing the material composition, and a variety of formulations have demonstrated high performance. This flexibility allows perovskites to be combined with another, differently tuned absorber material to deliver more power from the same device.

Performance challenges

- Stability and durability
- Power conversion efficiency at scale
- Manufacturability at scale
- Validation, performance verification
- Bankability



Replacing silver with copper in PV solar cells

- **A solar cell includes a metal meshed pattern to collect and conduct the electricity generated from the silicon. This metal is silver, which is expensive and in high demand.** Others have attempted to replace the silver conductor with copper, which is far more abundant and less expensive, but their solutions have required introducing additional steps to the manufacturing processes and thus added expenses that offset the benefits of the copper paste.
- **CuBert™, a patented unique copper paste from Bert Thin Films LLC, has been trialed as a direct substitute for the silver paste in the manufacturing process.** CuBert™ is a direct plug-and-play replacement technology for the silver paste in the existing manufacturing process, so the cost benefits of the copper conductor could be fully and immediately realized by the manufacturers.
- **A total of USD 2 million in funding** has been secured and the source of funds includes a USD 1 million angel funding round, which was completed a few months after receiving a USD 1 million grant from the US Department of Energy Solar Energy Technologies Office.

Metal	**Copper**
Solids loading	**> 85%**
Viscosity	**<640,000 cP[1]**
Screen mesh	**300–400**
Wire diameter	**17.78–22.86 microns**
Emulsion thickness	**13–20 microns**

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[1] 0.5 rpm, Brookfield Ametek HBDV1M Cone and Plate Viscometer with CPA-52Z spindle

Sources: US DOE, US-MAP, Bert Thin Films LLC; Kearney Energy Transition Institute analysis

Durable Module Materials (DuraMAT) Consortium is exploring ideas that could extend solar module lifetime up to 50 years

Additional R&D efforts aimed at improving reliability and increasing lifetime are also under way, notably **through the introduction of air-stable and water-insensitive materials, light- or moisture-induced degradation mechanisms, and encapsulation.**

8.1 PV technology

Overview

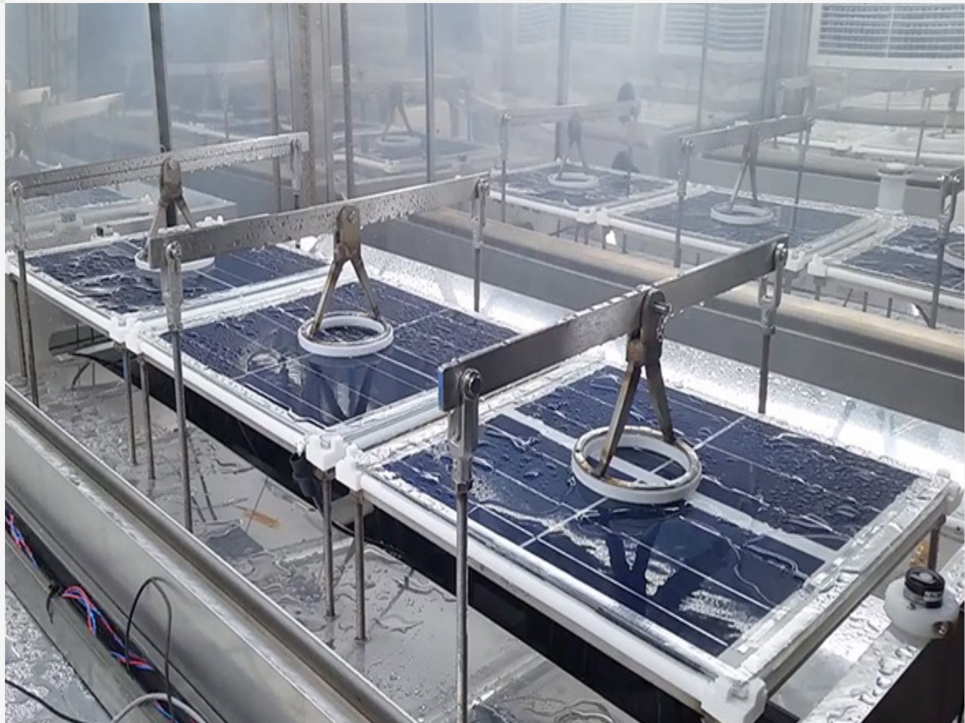
- Launched in November 2016, **DuraMAT** is a multi-laboratory consortium led by the National Renewable Energy Laboratory (NREL), with Sandia National Laboratories and Lawrence Berkeley National Laboratory as core research labs.
- Additional researchers from multiple universities, solar companies, other national laboratories, and an industry advisory board provide perspectives from across the solar energy community.
- Funded by the US Department of Energy's (DOE's) Solar Energy Technologies Office (SETO). Post awarding USD 30 million in high-impact projects from 2016–2021, DuraMAT was awarded an additional USD 36 million by SETO for six more years of funding starting in 2021.

Results and projects (indicative)

- Demonstration of an accelerated testing method capable of identifying material damages and design field failures that are not captured by existing standardized steady-state or sequential tests
- Accumulated 1,000+ hours of photothermal, thermal, and water soak exposure for combinations of encapsulant and backsheet materials. Evaluate additional materials for layers to mitigate hail damage.
- Explore the use of industrial femtosecond lasers to weld glass/glass modules together to form a strong, hermetic seal and to enable polymer-free, 50-year module designs that are easily recycled.[1]

Focus areas

- **Central data resource:** Collect and disseminate module reliability data and derive new insights.
- **Multi-scale, multi-physics model:** Develop modeling tools to rapidly scale accelerated testing results and assess the impacts and degradation modes of new materials and designs.
- **Disruptive acceleration science:** Understanding PV materials, modules, and systems performance outdoors based on relatively aggressive experimental conditions.
- **Fielded module forensics:** Quantify and characterize module failure modes.
- **Module materials solutions:** Design, develop, de-risk innovative materials and module architectures to address PV reliability issues.



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[1] An infrared laser with a wavelength of 1053 nm

Sources: DuraMAT, DuraMAT Annual Report 2022, "Aging gracefully" (NREL), Kearney Energy Transition Institute analysis

Artificial intelligence, construction automation, digitization, and robotics can transform the way solar power plants are built and accelerate their deployment

Productivity gains by incorporating these innovative technological solutions into solar power plant construction and operation will vary depending on the specific EPC and project location.

8.2 Design and build

Automated construction solutions

- These solutions combine a digital twin of the project site, advanced supply chain and inventory management systems, onsite wireless digital command center, field-deployed automated assembly line, and specialized installation rovers to allow for automated, 24/7 construction.
- Can increase installation productivity by a factor of 2x over traditional methods and lowers overall project costs, enabling the exponential growth of utility-scale solar PV.

Terabase	Sarcos
– Founded in 2019 and based in California (US). It's "Terafab" is the world's first automated, digital field factory for PV module and tracker assembly (launched in May 2023). – Its Woodland (CA) facility is manufacturing the first gigawatt of Terafab assembly lines with 10 GW capacity per year.	– Based in Utah (US), Sarcos Technology and Robotics Corporation received USD 1.9 million from the US DOE to develop robotics system to deliver, detect, lift, and place PV modules in the field. – The robotic solar field construction solution is expected in 2024.

Sources: DOE Agrivoltaic market study (2022), press search, Kearney Energy Transition Institute analysis

Artificial intelligence (AI) and machine learning

- The conventional methods employed currently for various functions related to design, forecasting, control, and maintenance deliver relatively inaccurate results. Using artificial intelligence to perform these tasks can achieve a higher degree of accuracy and precision. This capability keeps improving with the increasing computational power, tools, and data generation.

Designing
- ☐ Parameter identification
- ☐ PV sizing

Control
- ☐ Grid connected
- ☐ Standalone

Maintenance
- ☐ Optimize life
- ☐ Monitoring

Cybersecurity
- ☐ Active
- ☐ Passive

Forecasting
- ☐ Demand side
- ☐ Power output

Potential application case study: agrivoltaic

- Integration of artificial intelligence and machine learning for planning and operating phases of **agrivoltaic systems** can help accelerate deployment.
- The French companies Ombrea and RES are partnering to develop PV shade systems for agrivoltaics projects. For example, Ombrea has developed a system powered by AI to protect crops from extreme heat, drought, hail, and frost. The solar panel retracts in order to modulate light and shadow based on data collected through sensors on-site.

Soiling mitigation can help increase solar yields, but methods are dependent on local conditions

PV systems should be operated as close as possible to the optimal cleaning schedule, in order to maximize the electrical performance and, at the same time, minimize the costs.

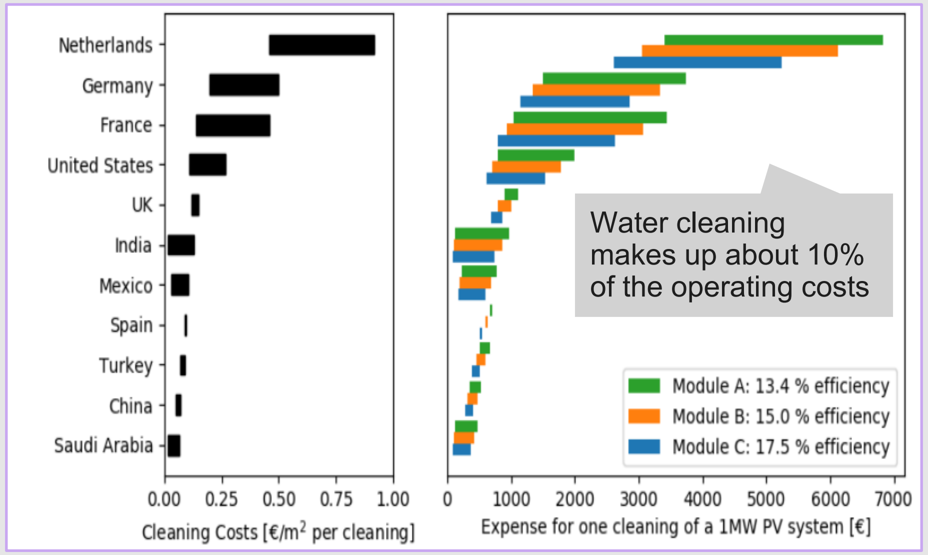
8.3 Operate

Impact of soiling

Soiling of PV systems from dust and snow, and resulting loss of energy yield, is the single most influential factor impacting system yield after irradiance.

- Dust accumulation can reduce the output of photovoltaic panels by as much as 30% in one month and it has been estimated that for a 1% reduction in power the loss registered could reach USD 200,000 in annual revenue for a 150 MW solar installation.
- Estimates indicate that in 2018 soiling caused the loss of at least 3% to 4% of the annual PV electricity output which corresponds to a loss of EUR 3–5 billion.
- High-insolation regions, such as China or India, are leading PV growth but are more exposed to soiling.

Cleaning costs combine labor and material



Water cleaning makes up about 10% of the operating costs

Sources: Soiling Losses – Impact on the Performance of Photovoltaic Power Plants (IEA-PVPS, 2022), MIT; Kearney Energy Transition Institute analysis

Soiling mitigation

- **Preventive mitigation** includes informed site assessment, adaptation, and planning, or improvements to minimize soiling such as:
  - **Anti-soling coating -** Hydrophobic based on fluoropolymers or hydrophobic functionalized silica with low surface energy hence repelling water/hydrophilic based on silicon dioxides or titanium dioxide with high surface energy hence attracting water,
  - **Module/plant designs -** vertically mounted, flipping monofacial modules upside down during non-sunshine hours, etc.
- **Corrective mitigation** includes cleaning solutions such as using dust brooms and water brushes, surface vibration, aerodynamic streamlining, autonomous robotic cleaning, stowing/inverting, sprinkling, high pressure water, dry scrubbing and cleaning, and electrodynamic cleaning system (EDS) which uses embedded electrodes in the panel.

Water-less cleaning techniques, such as one being developed at MIT, use electrostatic repulsion to cause dust particles to detach and virtually leap off the panel's surface, without the need for water or brushes. Unlike EDS (which suffer defects that allow moisture to seep in), only a simple electrode passes just above the solar panel's surface, imparting an electrical charge to the dust particles, which are then repelled by a charge applied to the panel itself.

Solar-powered boats can fulfill growing demand for eco-friendly and low-noise options suitable for tourism and leisure, particularly in protected areas

Solar-electric boats are more cost-effective in the long term even though the initial purchase price may be higher.

8.4 Applications

Suitability of solar-powered boats

- Higher flexibility in determining the shape and size of PV panels for boats (compared to other vehicle types where reduced area results in smaller engine power).
- Lower aerodynamic requirements due to the generally limited speed.
- Boats spend most of their useful life directly exposed to the sunlight.

Benefits compared to diesel ferries

Aditya results

Eco-benefits	Economics
– 1.7 million passengers ferried logging 100 km while avoiding: **165kl of diesel, 420 tonnes of CO_2, 1.2 tonnes of SO_2, 5.75 tonnes of NOx, 155 kg of particulates** – Low noise pollution and no diesel smell	– Total cost of ownership is **1/3** of the diesel ferry (INR 274.4 lakhs vs INR 914.7 lakhs) – The daily operating cost is **1/40** of a diesel ferry – Ferry achieved breakeven in 2019 (in less than **3 years**)

Other prominent areas for advancing solar energy-powered boats are **maritime drones and sporting boats.**

Solar boat projects

Navalt's Aditya is a ferry boat with a GRP (glass reinforced plastic) hull and an aluminum superstructure. Solar covers more than 80% of its energy needs and can be charged using electrical grid power.

Maturity	Small-scale commercialization
Dimensions	20m long x 7m wide
Capacity	75 passengers + 3 crew
Solar panel	20 kWp (poly-crystalline)
Battery	80 kWh (Li phosphate)
Motor	2 x 20 kW
Range	120 kms
Max speed	7 knots

Navalt has multiple offerings of solar-powered boats of varying capacity/designs. Examples of other commercialized tourist boats include **Aquawatt 715** (Central European lakes)**, SolarWaterWorld SunCat 46** (Germany), **Genesis Solar** (Galapagos Islands), **Solar Electric boats** (Soel Yacht, Netherlands), and **SeaZen** (French riviera).

Sources: Solar Impulse foundation, Navalt boats, Solar Energy-Powered Boats: State of the Art and Perspectives (Minak, 2023), press search; Kearney Energy Transition Institute analysis

Solar-powered airplanes have potential for high-altitude and long-endurance (HALE) missions

Other missions carrying passengers such as Solar Airship One are being developed by Euro Airship. Combining solar and hydrogen to power the airship, it aims to fly around the world for 20 days non-stop in 2026.

8.4 Applications

Solar impulse 1 and 2

As big as a Boeing 747 (wingspan 72m) but the weight of a car (2,300 kg)

- A manned solar-powered aircraft project, conceived in 2003 by André Borschbergand and Bertrand Piccard, which has resulted in two experimental planes – Solar Impulse 1 and Solar Impulse 2. Solar Impulse 2 recorded the **first ever travel around the world solar flight** in 2015–2016 through 17 stages/flights.
- **Monocrystalline silicon solar cells**, mainly on wings and some on horizontal stabilizers, generate electricity to propel the plane. The excess energy is utilized to recharge the lithium polymer batteries which are used during low sunlight.
- **Challenges:** Improving efficiency and costs, reducing weather dependence, managing long-distance flights (due to recharging requirement).

	Solar Impulse 1	Solar Impulse 2
First flight	26/06/2009	02/06/2014
Number of PV cells	11,628	17,248
PV cell area	200 m^2	270 m^2
Battery	4 X 21 kWh	4 X 41 kWh

Zephyr and other unmanned aerial vehicles

High-altitude pseudo-satellite that is powered exclusively by solar power

- **Initial attempts for solar-powered planes can be traced back to the 1970s but they were mostly pilotless.**
- **Airbus's unmanned High Altitude Platform Station (HAPS)**, Zephyr, can fly continuously for months at a time, at around 70,000 ft (stratosphere), above weather and conventional air traffic. It uses sunlight (through solar panels) to fly and recharge its batteries.
- With its ability to remain in the stratosphere for months at a time, Zephyr can bring new capabilities to both commercial and military customers. For example, it can provide direct-to-device connectivity with a reach of up to 250 terrestrial towers in difficult mountainous terrain, or high-quality imagery using the Airbus OPAZ earth observation payload.
- Other key current solar-powered unmanned aerial vehicle (UAV) projects include: **AtlantikSolar** – solar-powered 5m class UAV capable of performing flights up to 10 days, **EAV3** – developed by Korea Aerospace Research Institute (KARI), it's a solar-powered UAV built for high-altitude, long-endurance.

Sources: Solar impulse, Airbus Zephyr, Solar Airship One, press search; Kearney Energy Transition Institute analysis

Vehicle-integrated photovoltaic is an emerging technology in transportation that could complement battery electric vehicles

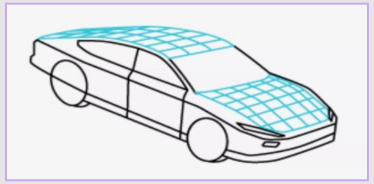
Solar PV integrated in the vehicle can extend the range (~70 km) and help drivers plugging in the vehicle around 3 times less often.

8.4 Applications

Photovoltaic vehicles integrate solar panels all over their upper body

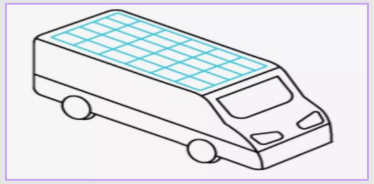
The operating system and propulsion mechanism of solar cars is very similar to those of electric cars.

Vehicles would be weather dependent



Light commercial vehicles have a larger solar surface

Alternative for traveling around urban areas while reducing operating costs



- The power generated by the solar panels is not sufficient to start an engine, but it can power all the inner electrical devices.
- PV cars provide an energy independency to drivers and help developing non-fossil fuel cars. Integrated solar panels also make car batteries last longer, reduce carbon emission, and alleviate grid stress.
- Vehicles with solar panels are still a developing technology, with significant challenges due to **high purchase costs and lower potential energy per unit of mass** compared to conventional vehicles.

Sources: Lightyear, press search; Kearney Energy Transition Institute analysis

Market status

Lightyear 0

- Long-range model from the Dutch manufacturer Lightyear
- Annual solar yield can add up to **11,000 km** in ideal weather conditions
- First units were delivered in end 2022
- Cost: **€250,000**

The assembly/delivery was suspended in 2023. The company will focus on **Lightyear 2,** the proposed short-range model which will be priced **under EUR 40,000.**

Some other solar vehicles include **Tesla Cybertruck, Toyota Prius PHEV Solar, and Lucid Motors's Air.**

Printed solar cells to power Tesla

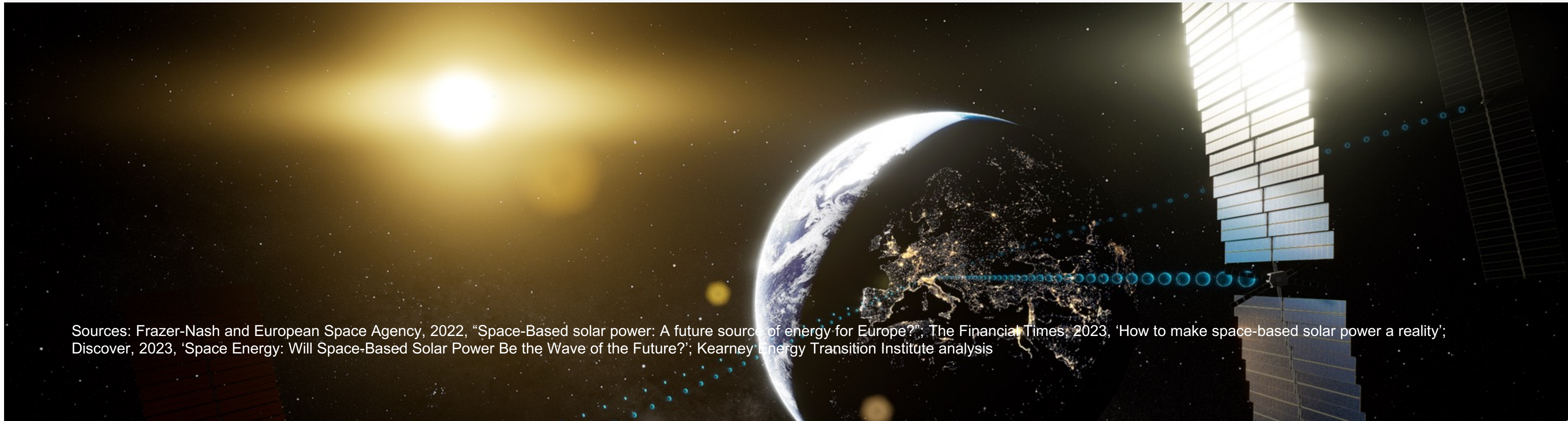
- **In 2022, the "Charge Around Australia"** project was launched to drive 15,000km of Australian coastline (in about 80 days) with a Tesla which was powered by printed organic photovoltaic (OPV) cells.
- Around 94km were covered every day powered by solar, and using PV cells allowed the journey to continue in stretches along the route where charging stations were unavailable.

Solar PV electricity generation from space could solve land use limitations and day–night variability issues (1/3)

Day-and-night production without land footprint.

Solar power in outer space

- **Space-based solar power** (SBSP) aims to produce electricity in outer space and bring it back to Earth.
- A satellite, equipped with large **solar panels or CSP,** is sent into space. The **satellite generates electricity** from the sun and **converts it into waves** (laser or microwave) **beamed in the direction of Earth**. On Earth, large platforms are designed to **retrieve the incoming waves, re-convert them into electricity,** and transmit into consumption areas.
- This PV innovation has the advantage of being independent from day-and-night cycles and can theoretically reach any part of the Earth.
- SBSP projects feasibility is still in question due to **research unpredictability, high deployment cost,** and **very low cost of Earth-based solar panels**. Moreover, satellite deployment will require specific method as projects will span across several kilometers.
- Additionally, concerns have been raised about potential hazardous microwaves beamed on Earth. Researchers affirm that **beams are similar to sunlight in terms of energy**.

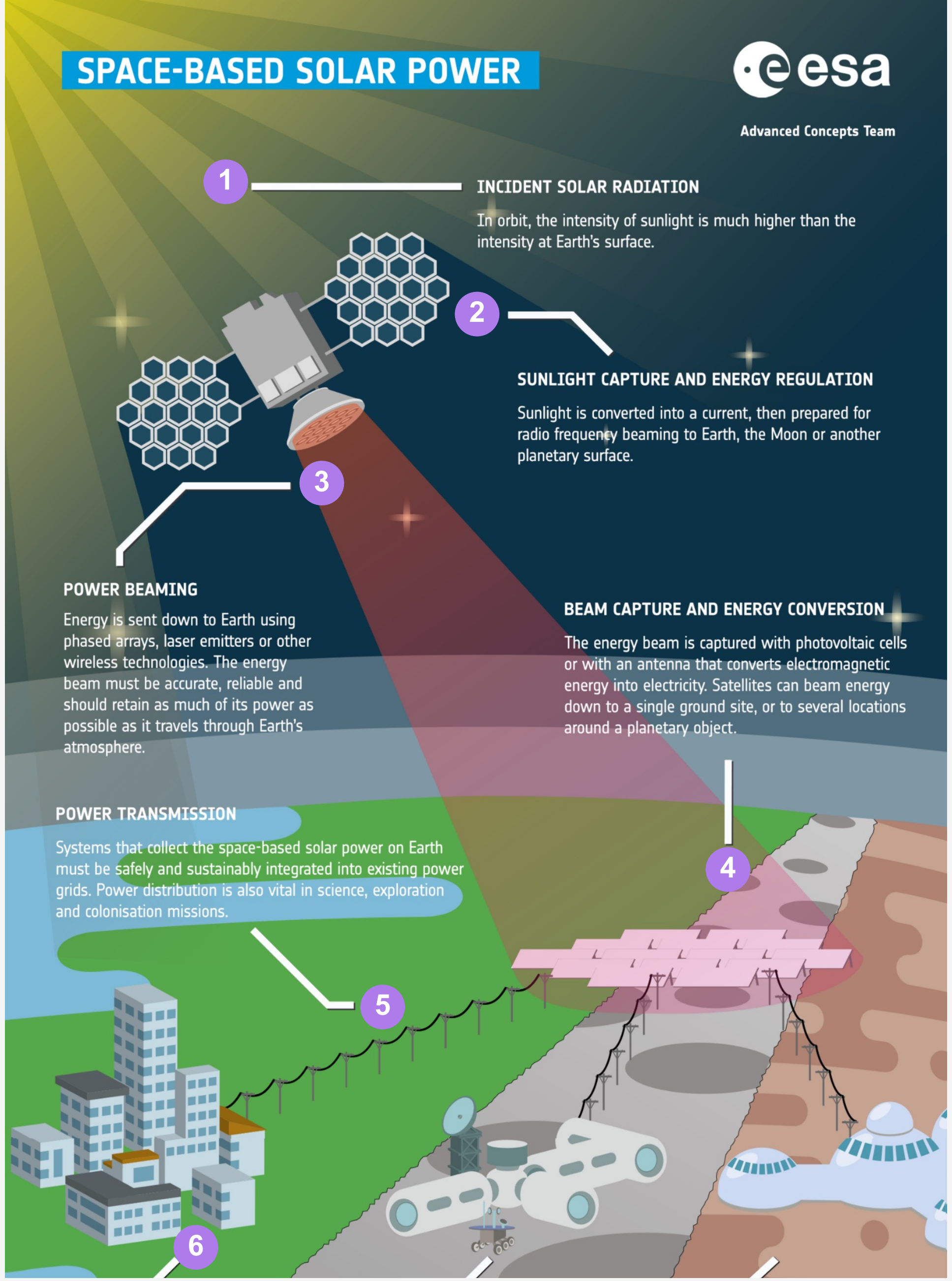


Sources: Frazer-Nash and European Space Agency, 2022, "Space-Based solar power: A future source of energy for Europe?"; The Financial Times, 2023, 'How to make space-based solar power a reality'; Discover, 2023, 'Space Energy: Will Space-Based Solar Power Be the Wave of the Future?'; Kearney Energy Transition Institute analysis

8.4 Applications

Spatial-based solar power principle (2/3)

● Applications



INCIDENT SOLAR RADIATION

In orbit, the intensity of sunlight is much higher than the intensity at Earth's surface.

SUNLIGHT CAPTURE AND ENERGY REGULATION

Sunlight is converted into a current, then prepared for radio frequency beaming to Earth, the Moon or another planetary surface.

POWER BEAMING

Energy is sent down to Earth using phased arrays, laser emitters or other wireless technologies. The energy beam must be accurate, reliable and should retain as much of its power as possible as it travels through Earth's atmosphere.

BEAM CAPTURE AND ENERGY CONVERSION

The energy beam is captured with photovoltaic cells or with an antenna that converts electromagnetic energy into electricity. Satellites can beam energy down to a single ground site, or to several locations around a planetary object.

POWER TRANSMISSION

Systems that collect the space-based solar power on Earth must be safely and sustainably integrated into existing power grids. Power distribution is also vital in science, exploration and colonisation missions.

1 **Incident solar radiation**

In orbit, **the intensity of sunlight is much higher that the intensity at Earth's surface.**

2 **Sunlight capture and energy regulation**

Sunlight is converted into a current, then prepared for radio frequency beaming to Earth, the moon or another planetary source.

3 **Power beaming**

Energy is sent down to Earth using phased arrays, laser emitters or other wireless technologies. The energy beam must be accurate, reliable and should retain as much of its power as possible as it travels through Earth's atmosphere.

4 **Beam capture and energy conversion**

The energy beam is captured with photovoltaic cells or with an antenna that converts electromagnetic energy into electricity. Satellites can beam energy down to a single ground site, or to several locations around a planetary object.

5 **Power transmission**

Systems that collect the space-based solar power on Earth must be safely and sustainably integrated into existing power grids. Power distribution is also vital in science, explorations and colonization missions.

6 **Energy utilization**

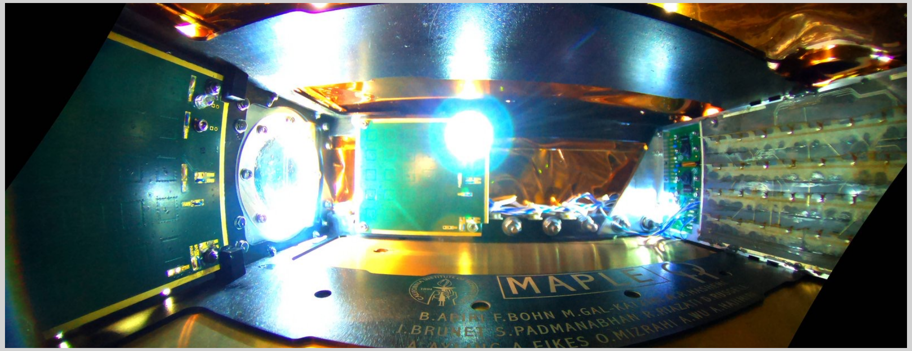
As well as having the potential to aid Europe's goal of becoming carbon neutral by 2050, **space-based solar power technologies could provide the flexibility and reliability required for science and exploration missions** where other power sources are limited, for example rover missions during the lunar night.

Sources: Frazer-Nash and European Space Agency, 2022, "Space-Based solar power: A future source of energy for Europe?"; The Financial Times, 2023, 'How to make space-based solar power a reality'; Discover, 2023, 'Space Energy: Will Space-Based Solar Power Be the Wave of the Future?'; Kearney Energy Transition Institute analysis

Several countries are investing in generating electricity from space, including numerous European countries, China, Japan, and South Korea, among others (3/3)

Caltech's breakthrough discovery

In 2023, a team from Caltech (California) was able to **transmit energy through space for the first time with the MAPLE Project: a satellite ~500 km** above beamed a microwave signal that was captured back on Earth.



ZhuRi to power China

China aims to deploy an **operational space-based solar power satellite at low Earth orbit in 2028, and at geostationary Earth orbit in 2030**, through its **ZhuRi project**.

Two initiatives, **Xidian University** and **Tiangong**, are conducting experiments to make wireless energy transmission from space to complete China's electricity generation.[1]

ESA to start SOLARIS project in 2025

ESA, through the SOLARIS project, estimates that SBSP could provide 800 TWh of electricity annually by 2050, at an affordable cost. Several companies are working for the SOLARIS project under ESA demand as Thales.

The UK government has also invested in SBSP, planning to include SBSP in its electricity mix as soon as 2035. The UK government chose EDF UK to conduct this work

8.4 Applications

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[1] The Chinese space station finished in 2022.

Sources: Frazer-Nash and European Space Agency, 2022, "Space-Based solar power: A future source of energy for Europe?"; Frazer-Nash, 2021, Space based solar power: de-risking the pathway to net zero The Financial Times, 2023, 'How to make space-based solar power a reality'; Discover, 2023, 'Space Energy: Will Space-Based Solar Power Be the Wave of the Future?'; Kearney Energy Transition Institute analysis

Research is ongoing to improve existing solar designs and give panels additional properties

Electricity from rain

- New panels can **generate electricity from rain energy, using the triboelectric effect**.
- The triboelectric effect is the effect behind **static electricity**: friction of materials can extract electrons, resulting in electric current.
- Those solar panels are built with high-efficiency **triboelectric nanogenerators (TENG)** arrays. When raining, **rain droplets will charge the panel surface due to friction**.
- Additional components will ensure the formation of usable electricity. This new technology reduces **day and weather influence** on solar panels.

Night-time solar panels

- PV electricity production is **limited by the presence of sunlight**, therefore solar panels can only function half of the day at most.
- To counter this limitation, research from Stanford University has developed **solar panels that can produce electricity during night-time**.
- Due to thermal loss, solar panels heat significatively during the day, and cool during night-time. These panels are equipped with a **thermoelectric generator,** a device conceived to **generate an electrical current from temperature variation**. However, power output in the night is just 0.04% of the power output of a regular solar cell during the daytime.

Sources: World Economic Forum, 2022, These solar panels can work at night, or get their power from rain; Liu and Al., 2018, Integrating a Silicon Solar Cell with a Triboelectric Nanogenerator via a Mutual Electrode for Harvesting Energy from Sunlight and Raindrops; Applied Physics Letter, 2022, Solar cells keeps working long after Sun sets; Kearney Energy Transition Institute analysis

9. Appendix and bibliography

Picture credit - Peschke, Kevin

Acronyms (1/2)

a-Si: Amorphous silicon
AC: Alternating current
APAC: Asia Pacific
ASEAN: Association of southeast Asian nations
AUD: Australian dollar
BIPV: Building-integrated photovoltaic
BOS: Balance of system
C&I: Commercial and industrial
c-Si: Crystalline silicon
CAGR: Compound annual growth rate
CdTe: Cadmium telluride
CIGS/CIS: Copper indium (gallium) selenide
CO_2: Carbon dioxide
CSP: Concentrated solar power
DC: Direct current
DSO: Distribution system operator
EPC: Engineering procurement construction
EU: European Union
EVA: Ethylene-vinyl acetate
FIT: Feed-in tariff
FIP: Feed-in premium
GHI: Global horizontal irradiance
GW: Gigawatt (one billion watts)
HJT: Heterojunction solar cell
IEA: International Energy Agency
ILO: International Labor Organization
ILR: Inverter load ratio
IRENA: International Renewable Energy Agency
kW: Kilowatt
kWh: Kilowatt hours
LCOE: Levelized cost of electricity
LRET: Large-scale renewable energy target
MEA: Middle East and Africa
MW: Megawatt
NREL: National Renewable Energy Laboratory
NZE: Net-zero emissions
O&M: Operations and maintenance
PERC: Passive emitter and rear cell
PPA: Power purchase agreement
PV: Photovoltaic
ROW: Rest of world
RPS: Renewable portfolio standard
R&D: Research and development
S Korea: South Korea
SEA: Southeast Asia
SRES: Small-scale renewable energy scheme
TOPCon: Tunnel oxide passivated contact
TSO: Transmission system operator
TW: Terawatt
TWh: Terawatt hour

Acronyms (2/2)

UK: United Kingdom
US: United States
USD: United States dollar
VALCOE: Value adjusted levelized cost of electricity
VIPV: Vehicle integrated photovoltaic
VRE: Variable renewable energy
W: Watt
WACC: Weighted average cost of capital

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Picture credits

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Slide 10: Photovoltaic principle (**link**)
Slide 11: Wafer-based solar panel breakdown (**link**); Thin film solar panel breakdown (**link**)
Slide 13: Wafer-based classification (**link**); wafer-based manufacturing process (**link**)
Slide 15: Thin-film classification (**link**); thin-film manufacturing process (**link**)
Slide 17: Perovskite cells (**link**); dye sensitized cells (**link**); quantum dot cells (**link**); organic cells (**link**)
Slide 21: Bandgap absorption (**link**); Tandem cell (**link**)
Slide 27: Schematic view of renewable energy generation and integration into the grid (**link**)
Slide 29: Utility-scale PV plant (**link**)
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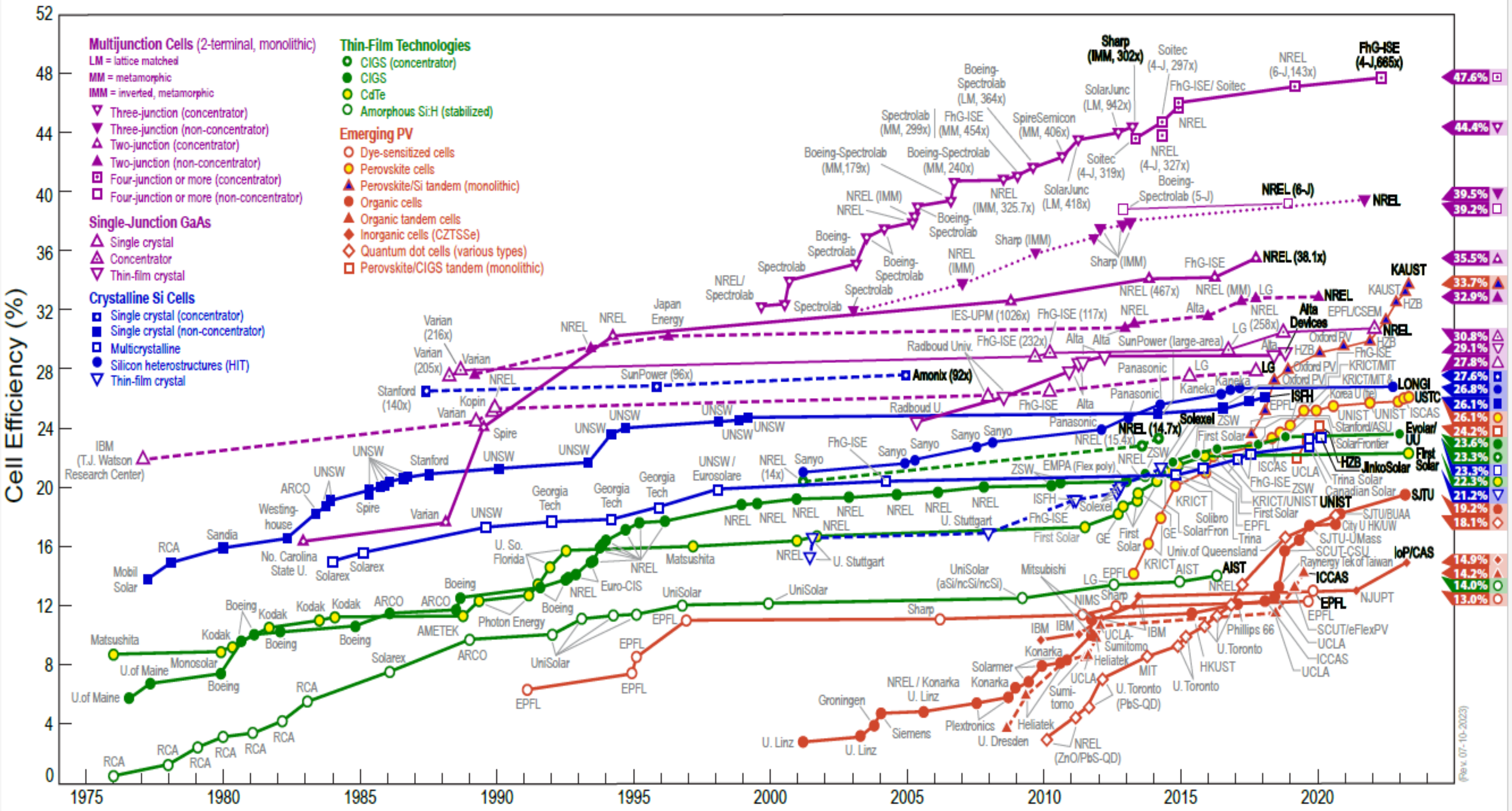
Slide 172: Quantum dot cells (**link**); organic cells (**link**)

Cell efficiency and factcards

Improving the efficiency of cell materials and the power density of PV modules are key research focus areas

Efficiencies have increased across all technologies over the past 50 years

Best research-cell efficiencies



- **Improving the efficiency of cells and modules will play an important role in making solar PV economically viable.** All other things being equal, improving efficiency would lower the cost per unit of energy ($ per watt-peak) by reducing the quantity of module and land/area needed to produce an equivalent quantity of energy^2. Obviously, the main trade-off is between gain in efficiency and additional costs.
- **Several technological approaches seek to boost solar cells' efficiency**: (i) improve surface passivation to reduce recombination loss; (ii) develop transparent electrode materials, which are more conductive and therefore reduce resistive losses; (iii) enhance engineering of optical and electronic materials to improve current collection; (iv) employ advanced-cell architecture.
- **R&D efforts are also essential to reduce efficiency losses in BOS components and modules.** At present, there is a gap between the efficiencies achieved by solar modules and those achieved by small-area cells.

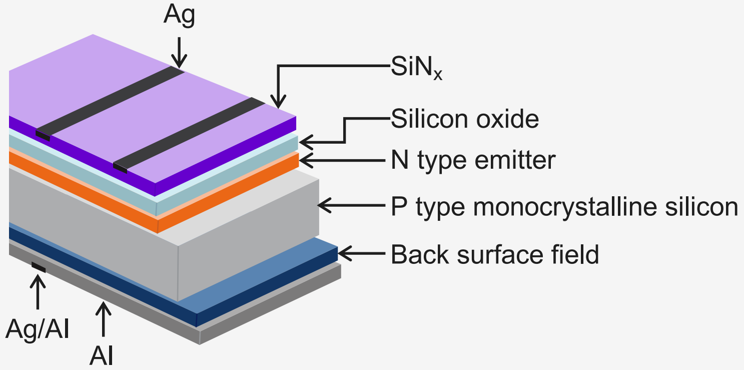
Note: Approximately half the world's solar cell efficiency records, which are tracked by the National Renewable Energy Laboratory (NREL), were supported by the US Department of Energy (DOE), mostly by its Solar Energy Technologies Office (SETO) PV research.
Sources: NREL cell efficiency; Kearney Energy Transition Institute analysis

Crystalline silicon solar cell uses a highly purified silicon crystal

FactCard: Crystalline silicon (c-Si)

There are two types of c-Si cells: **mono crystalline** and **multi crystalline**. Both are made from doped silicon semiconductor.

- Mono crystalline is produced from a single silicon crystal wafer with a 99.99…% (9N) purity[1]
- Multi crystalline is produced by melting several silicon crystals together, giving a purity of 99,99…% (7N or 8N)



Characteristics	Mono c-Si	Poly c-Si
Efficiency	~20%	~17%
Efficiency record	26.1%	23.3%
Lifespan	25–30 years	25–30 years
Thickness	~200 µm	~200 µm
Critical material	Silver	Silver
Maturity	Mature	Mature
Color	Black	Blue

PROS	Good efficiency
	Long lifespan
	Mature technology and easily improvable
	Abundant silicon resources on Earth
CONS	Thicker and heavier than other solar cells
	Not flexible nor customizable
	High life cycle GHG emissions
	Bad temperature tolerance

9.4 Appendix: cell efficiency and factcards

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[1] That means out of a billion atoms, only one is not silicon.

Sources: NREL, Best research-cell efficiencies [accessed June 2023]; NREL, Spring 2023, Solar Industry update; NREL, 2021, Photovoltaic (PV) Module Technologies: 2020 Benchmark Costs and Technology Evolution Framework Results; IEA, Solar PV, Bernreuter; Kearney Energy Transition Institute analysis

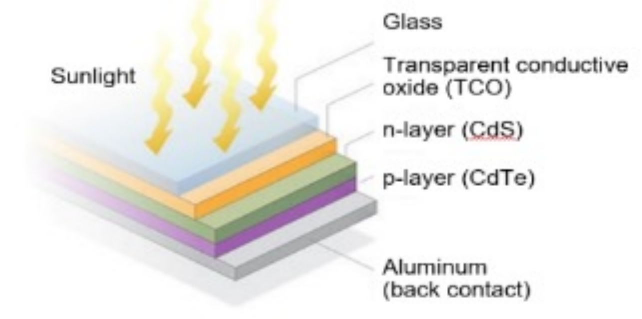
Cadmium telluride technology is the main technology sold among thin films cells

FactCard: Cadmium telluride (CdTe)

9.4 Appendix: cell efficiency and factcards

CdTe is the second most commonly used solar cell technology in the world after crystalline silicon. The principal layer is made of a crystal of cadmium and telluride, on which a layer of cadmium sulfide (CdS) is added.

CdTe cell layout



PROS	Ideal wavelength bandgap absorption Easy to manufacture Cheaper to produce than c-Si Convenient usage (flexible)
CONS	Less efficient than crystalline technology Cadmium is toxic Telluride is a rare material Less cost efficient than c-Si

Characteristics	Cd-Te
Efficiency	~17%
Efficiency record	22.1%
Lifespan	25-30 years
Thickness	~1 µm
Critical material	Telluride
Maturity	Mature
Color	Customizable

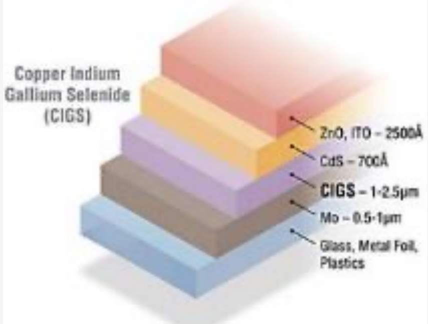
Sources: NREL; Kearney Energy Transition Institute analysis

CIGS is a promising TF technology that could one day replace CdTe

FactCard: Copper indium gallium selenide (CIGS)

9.4 Appendix: cell efficiency and factcards

CIGS technology is made of an absorbing layer made from copper, indium, gallium, and di-selenide. It is still a technology under deployment but has higher efficiency potential than CdTe.



PROS	Good temperature tolerance
	High efficiency among TF
	Lightweight and convenient usage
	Not toxic
CONS	High degradation potential
	Rare material needed (indium and gallium)
	Not competitive with CdTe
	Higher cost than c-Si

Characteristics	CiGS
Efficiency	~18%
Efficiency record	23.6%
Lifespan	25 years
Thickness	~1 μm
Critical material	Gallium–indium-selenide
Maturity	Deployment
Color	Customizable

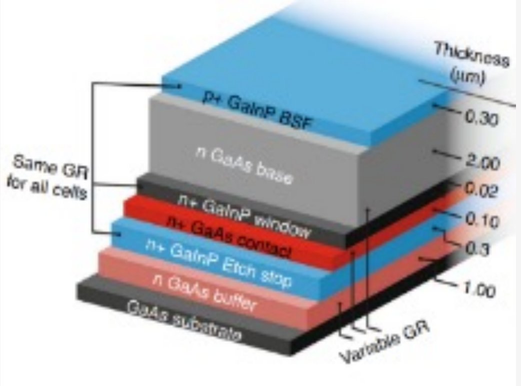
Sources: NREL; Kearney Energy Transition Institute analysis

Gallium arsenide compound is the most efficient, but is limited to spatial devices

FactCard: Gallium arsenide (GaAs)

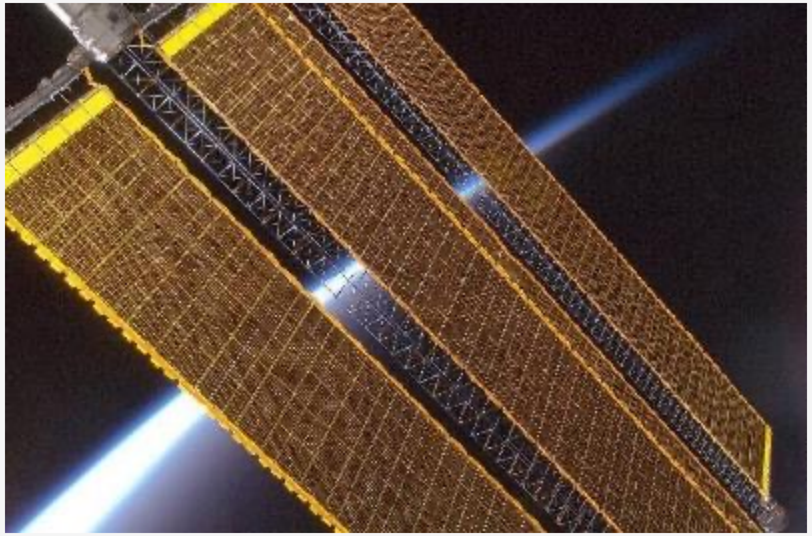
9.4 Appendix: cell efficiency and factcards

GaAs solar cells are the most efficient cells commercially produced, with efficiencies around 30%. This type of solar cell is very resistant to heat and radiation but is extremely expensive. Their usage is mainly limited to spatial purposes and has been used since the 1960s.



PROS	Best efficiency on the market
	High temperature tolerance
	Good radiation resistance
	Can be flexible
CONS	Very expensive
	GaAs ingots are smaller than silicon ones (~)
	Gallium is a rare material
	Arsenide is toxic

Characteristics	Cd-Te
Efficiency	~28%
Efficiency record	29.1%
Lifespan	25–30 years
Thickness	~1 µm
Critical material	Gallium
Maturity	Mature
Color	N/A

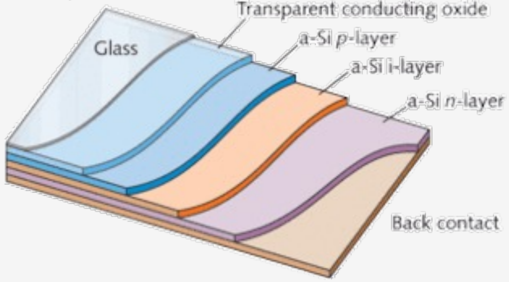


Sources: NREL, USGS, Wiley online library; Kearney Energy Transition Institute analysis

Amorphous silicon is a declining TF technology

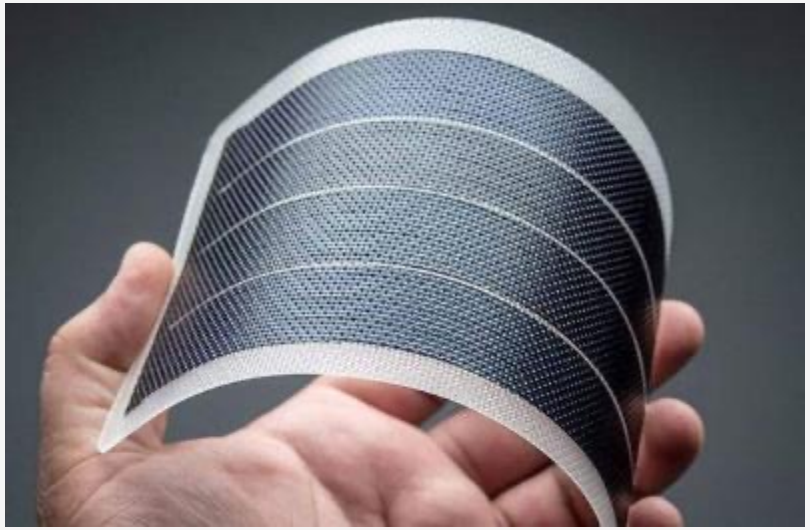
FactCard: Amorphous silicon (a-Si)

Amorphous silicon as we know it today is an old technology (1969) made of silicon deposited on a substrate (that can be flexible). This technology is easier and cheaper to manufacture than crystalline silicon but has a much lower efficiency. However, a-Si is disappearing with the rise of more performing TF technologies.



PROS	Cheap to produce
	Easy to manufacture
	Lightweight
	Convenient usage
CONS	Low efficiency
	Short lifespan
	Suffer from light-induced degradation
	Being replaced by emerging TF

Characteristics	a-Si
Efficiency	~7%
Efficiency record	14%
Lifespan	10–20 years
Thickness	~1 µm
Critical material	N/A
Maturity	Mature
Color	Customizable



9.4 Appendix: cell efficiency and factcards

Sources: NREL; Fraunhofer ISE; Kearney Energy Transition Institute analysis

Emerging solar cells are promising technologies to make solar panels more affordable (1/2)

Mini-FactCard: Perovskite – dye sensitized

Perovskite

These solar cells are made of perovskite, a family of materials with a lot of interesting properties. Combined with other technologies, it could reduce the cost of solar panels while increasing the conversion efficiency.

INFO	Efficiency record: 26.1%
	Highly tunable and high efficiency potential
PROS	Low manufacturing cost
	Does not require high purity
CONS	Toxic material
	Short lifespan

Dye sensitized

Dye-sensitized solar cells (DSSC) are made from semiconductors that are electrochemically dyed. The solar cell contains a liquid electrolyte inside, making its usage more challenging because of temperature concerns.

INFO	Efficiency record: 13%
	Versatile usage
PROS	Low manufacturing cost
	Works under low light conditions
CONS	Cannot work in extreme conditions
	Contains toxic volatile compounds

Sources: MIT, 2022, Explained: Why perovskites could take solar cells to new heights; Maalouf and al., 2023, A comprehensive review on life cycle assessment of commercial and emerging thin-film solar cell systems; Kearney Energy Transition Institute analysis

Emerging solar cells are promising technologies to make solar panels more affordable (2/2)

Mini-FactCard: Quantum dot - organic

9.4 Appendix: cell efficiency and factcards

Quantum dot

Quantum dots are used to replace the absorbing material (as silicon or CdTe). They are made from semiconducting particles and have a customizable absorption bandgap.

INFO	Efficiency record: 18.1%
	Different thermodynamical limits (up to 66%)
PROS	Highly tunable
	High efficiency potential
CONS	Toxic material (often made of lead or cadmium)
	Short lifespan

Organic

Organic solar cells rely on a polymer-based absorbent; semiconductor is carbon-based. The manufacture is cheap with abundant and nontoxic materials, and they have a very convenient usage.

INFO	Efficiency record: 19.2%
	Abundant resources
PROS	Low manufacturing cost
	Eco-friendly technology
CONS	Subject to air degradation
	Short lifespan

Sources: Quantum Dots Promise to Significantly Boost Solar Cell Efficiencies; Maalouf and al., 2023, A comprehensive review on life cycle assessment of commercial and emerging thin-film solar cell systems; Kearney Energy Transition Institute analysis