Sunny days

Solar Photovoltaic

A.T. Kearney Energy Transition Institute
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About the FactBook – Solar Photovoltaic

This FactBook seeks to summarize the status of the solar photovoltaic (PV) power industry and paths for development, analyzing the principal technological hurdles, likely areas of focus for Research and Development (R&D) efforts and the economics of PV systems.

About the A.T. Kearney Energy Transition Institute

The A.T. Kearney Energy Transition Institute is a nonprofit organization. It 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 economical 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.

Photovoltaic technologies harness energy from the sun and are categorized by the material used in the cell’s absorber

Solar is the most abundant renewable-energy resource in the world and has the potential to meet all global primary energy demand. Solar irradiance, the instantaneous amount of power provided by the sun at a given location and time, is of fundamental importance in the use of solar power. It is considered good to excellent between latitudes of 10° and 40°, South and North. Nevertheless, the solar resource is one of the most evenly distributed energy resources available on Earth.

Solar PV is one of the four main direct solar-energy technologies, the other three being concentrating solar power (CSP), solar thermal and solar fuels. Electricity is generated via the direct conversion of sunlight into electricity, in PV cells. Light shines onto a semiconductor (e.g. silicon), generating electron-hole pairs separated spatially by an internal electric field, which induces a voltage and a direct current when connected to a load. PV cells are interconnected to form PV modules with a power capacity of up to several hundred watts. PV modules can be further connected in series or in parallel to form arrays. These are combined with a set of additional components (e.g. inverter, support rack, switch…), known collectively as balance of system (BOS), to form PV systems.

PV technologies are categorized by the type of material used in the cell's absorber. Wafer-based crystalline silicon (c-Si) cells are the most common type of PV cells (with a market share of around 93%). This technology is the most mature and benefits from high conversion efficiency. Crystalline silicon is expected to continue to dominate the PV market in the near future, as most solar PV projects are based on crystalline silicon technology. Some thin-film technologies made from semi-conductors have also become commercial and account for roughly 7% of the market. However, thin-film technologies are less efficient than c-Si and their cost advantage has been eroded by a recent decline in c-Si prices. New thin-film PV technologies are being investigated in the hope of achieving ground-breaking reductions in module costs and enabling novel PV applications by virtue of properties such as transparency and versatility. Nevertheless, these technologies are still at the research stage. Concentrated PV (CPV), which uses mirrors or lenses to concentrate and focus solar radiation on high-efficiency cells, is an alternative to concentrating solar power (CSP), but requires better solar irradiance than other PV technologies and is, at present, far less common.

The electrical and mechanical devices that make up the BOS are critical components of solar-PV systems. While some BOS devices, such as inverters, are common to most PV systems, the presence of some components depends on the application (e.g. whether the system is off-grid or grid-connected, sun-tracking or not). Among other developments, solar tracking systems and plant-level controllers could be instrumental in exploiting the full potential of utility-scale PV systems.

The vast majority of installed PV-systems are connected to the power network, inducing challenges for grid management

Solar PV has various applications. Contrary to common belief, the vast majority (99%) of PV capacity is connected to the grid, either through small-scale rooftop or ground-mounted systems installed on residential or commercial properties, or through utility-scale PV farms (1 MW or more). The share of the latter has increased quickly since the late 2000s, largely because of development in China and the US But commercial PV systems (typically up to 1 MW) and residential PV (typically up to 20 kW) still account for more than half of grid-connected PV capacity – 39% and 19% of the total, respectively.

It is important to make a distinction between grid-connected PV capacity and off-grid systems (i.e. those not connected to a large, centralized grid). The latter (typically up to 5kW) account for around 1% of global PV capacity. While the development of grid-connected PV has far exceeded that of the off-grid market in recent years, growth in off-grid applications is now accelerating in several countries. There are high expectations for off-grid solar PV and, for instance, its use in supplying electricity to remote communities or powering isolated telecommunications facilities. Having been at the forefront of early PV deployment in the 1980s, off-grid systems could yet regain momentum and become instrumental in alleviating energy poverty.

PV technologies are constrained by the intermittent availability of solar energy. Indeed, solar is distinguished from other sources of energy by its imperfectly temporal predictability and deterministic variability. Its output is variable, imperfectly controllable and predictable, and subject to sudden changes – in the event of a passing cloud, for example. Therefore, the development of solar PV tends to increase flexibility needs in the forms of dispatchable power plants, energy storage or demand-side response. Flexibility needs and associated costs are, in general, increasing in line with growing solar PV penetration in the power mix. Nevertheless, solar output tends to be closely correlated with demand, especially in areas where peak demand occurs during the sunniest hours and where it can mitigate the need for expensive power plants to meet marginal demand (e.g. in the Middle East or in the Southwestern United States, where air-conditioning usage drives demand peaks). Finally, distributed solar PV, like other distributed generators, may require enhancements in the distribution system to improve grid stability and ensure power reliability, although the need for long-distance transmission lines is limited.

Solar PV has taken off in the past decade

Solar PV development, which began in the 1990s, has accelerated since the mid-2000s, with numerous countries introducing policies to support it. By the end of 2016 – another record-breaking year for the solar PV market – cumulative capacity had reached 291 GW. Initially driven predominantly by Europe and Japan, solar PV deployment has spread to other areas of the world. In recent years, there has been rapid development of PV systems in China and the US, for example. At the end of 2016, China (77.4 GW) led in terms of cumulative capacity, followed by Japan (41.6 GW), Germany (40.9 GW), US (32.9 GW) and Italy (19.2 GW). Together these five countries account for about 73% of the total global installed capacity.

Solar PV's contribution to the global generation mix remains marginal and it currently produces only 1.8% of global electricity (2016). This is largely explained by solar PV's low capacity factor. However, some countries have high penetration rates; PV supplies more than 7% of the electricity consumed in Greece, Italy, Germany and Honduras. Japan is just short of the 5% mark, while other majors like China and the US exhibit penetration rates of less than 2%.

Installed PV capacity is expected to rise from 175 GW in 2014 to 547 GW in 2021. Asia should be the principal engine of market growth (China, Japan and India being major contributors). The US market is expected to grow by 60 GW between 2014 and 2021, driven by utility-scale projects. By 2021, PV capacity in other regions (Middle East, South Africa, etc.) will witness rapid growth to 30 GW, which will be more than cumulative global PV capacity in 2009. Europe will lag behind in capacity additions, but may still witness solar PV making bigger contribution in its overall generation mix compared to other regions as they suffer curtailment and delays in grid-connection.

In the long run, solar PV is expected to play a crucial role in most visions of the energy future. Under the IEA's 2 °C Scenario, for example, solar PV would account for 9.4% of global electricity supply by 2050. To meet this target, all applications - i.e. utility-scale, distributed generation, and off-grid - will need to coexist and expand rapidly.

PV Energy Technology has experienced rapid and significant annual cost reductions as a result of falling module prices

PV is a capital-driven technology. Total PV investment costs typically range between $1.3 and $5.1 per watt, depending on project location, application, scale, and market conditions. Annual operating and maintenance costs account for only 0.5%-1.5% of the initial investment. Investment costs can be divided into two components: module costs and BOS costs.

Once accounting for the majority of PV costs, modules now account for a limited share of total investment costs (typically 20% and 36% for residential and utility-scale systems, respectively). This is largely because, over time, modules have experienced significant decreases in prices: costs have fallen on average by 22% for each doubling of cumulative production capacity. The prices of PV modules associated with various technologies have converged. Cost reductions are expected to be limited in the future, as manufacturers are already selling modules at no margin.

BOS costs typically account for 80% and 64% of investment costs for residential and utility-scale systems respectively, and vary significantly, depending on the labor costs and regulatory environment of each local market. Reducing balance of system (BOS) costs has become a priority to drive down overall PV system costs. The main ways of doing this include lowering the costs of hardware components, improving module efficiency and standardizing and modularizing PV systems. In some regions, market growth may also lead to reduced soft costs due to greater competition, lower customer acquisition costs and processes.

PV has experienced significant cost reductions as a result of falling module prices. Reflecting the strong decline in costs, variations in solar irradiance and the large number of manufacturers and technology in existence, solar PV generation costs vary significantly. This is reflected in the levelized cost of electricity, LCOE, which typically ranges from $60 to $400 per MWh. However, significant subsides have recently contributed to a price as low as $30 per MWh.

PV generation costs are still, on average, higher than those of conventional technologies. Generation costs are often compared to the prices paid by end-consumers of electricity to highlight the growing competitiveness of solar in some regions. Grid-parity is commonly used to design the tipping point at which the levelized cost of electricity (LCOE) from solar PV falls below the consumer price of electricity. However, as relevant as it may be for off-grid solar, grid-parity does not suffice is assessing PV’s competitiveness, since it does not take into account: transmission and distribution fees; the taxes that are usually included in final electricity prices; and the time at which the electricity was produced.

Despite a maturing industry and the development of innovative business models, the ecosystem of solar PV is largely shaped by public support policies

Government support policies remain crucial for solar PV deployment. Support instruments are usually categorized according to whether they mandate a certain minimum quantity (quantity-driven), or alter the prices to which investors are exposed (price-driven). These measures are highly variable between countries, but feed-in tariffs, tax incentives and renewable portfolio standards are generally the preferred choice of governments. Net energy metering is another support policy that has proved efficient in bolstering distributed solar PV in some regions, such as California, but is criticized for not being sustainable it the long run.

A number of new business models have emerged to overcome barriers to solar PV deployment. In addition to the role of public support, the outstanding dynamic and innovativeness of the solar PV ecosystem should be recognized. Among various business models, third-party ownership (leasing or purchasing-power agreement) have proved highly efficient in fostering the deployment of distributed solar PV by reducing upfront investment costs and revealing cost savings. At the same time, the entrance of new financing players, combined with the introduction of new investment vehicles, such as Yieldcos (dividend growth-oriented public companies), have lowered financing costs, a key success factor in any capital-driven technology.

The solar PV industrial landscape is highly competitive. The latter can be involved at various stages of the solar PV value chain, from the production of raw materials, such as feedstocks, ingots and wafers, to the operation and maintenance of solar panels. As an industry, solar PV is experiencing fierce competition, reflected in production overcapacity and numerous trade disputes in recent years. Despite the recent elimination of numerous companies as part of market rationalization, Asian companies now dominate the silicon value chain. China continues to be the dominant player in module production, accounting for around two-thirds of global production. European and North-American companies, meanwhile, remain strong in engineering, procurement, construction (EPC) and development activities.

Solar-powered water desalination has the potential to increase access to fresh water significantly in many arid locations. Desalination is an energy-intensive process, consuming 75 TWh of electricity per year (in 2012). Currently, less than 1% of the energy used for desalination globally comes from renewables because it remains substantially cheaper to use grid electricity generated from conventional fuels. However, recent studies indicate that solar PV desalination is more economic than other low-emissions alternatives (including nuclear energy) and, under certain conditions, can even compete with conventional desalination.

Solar PV-driven desalination integrated with water storage instead of electricity storage presents promising potential, especially in water-stressed regions, such as Middle East. Recent research results from Saudi Arabia indicate that water storage is more cost competitive than electricity storage because of high battery costs.

Solar PV is not facing significant environmental and social challenges, despite concerns over rare materials

The manufacture and installation of PV systems account for the bulk of greenhouse gas emissions from and the energy consumption of PV systems. Nevertheless, contrary to common belief, the energy payback of solar panels (the time it takes for a solar system to generate the same amount of energy that was used to manufacture it) is relatively short – typically less than two years with moderate solar irradiation of around 1,700 kWh/m2/yr.

With respect to lifecycle GHG emissions, median emissions range around 41 and 45 gram of CO2 equivalent per kWh (gCO2eq/kWh) for rooftop panels and utility plants, respectively, but can reach up to 180 gCO2eq/kWh. This level depends mainly on the material used in the cells, the manufacturing process, the power mix and recycling measures. For the purposes of comparison, median emissions range around 11 gCO2eq/kWh and 490 gCO2eq/kWh for onshore wind power and combined cycle gas turbines, respectively.

Recycling is crucial in ensuring the PV industry is sustainable, since it generates large amounts of electronic waste. It is predicted that 80%-96% of the rare materials used could be recycled. Since solar PV systems require relatively little land and almost no water, and as no greenhouse gas (GHG) or other pollutants are emitted during the producing life of PV plants, they are considered environmentally benign and are usually accepted by the public.

Research, development & demonstration (R,D&D) is focused on improving efficiency and minimizing the cost of materials used to produce cells

Reducing solar PV costs is the main focus of R,D&D. Several technological approaches seek to boost the efficiency of solar cells and BOS components. R&D efforts are also aiming to improve reliability and increase lifetime and to reduce material requirements through the development of thin-film technologies, and reuse and recycling. At the same time, manufacturing technologies and processes are being improved in order to reduce raw-material use, energy consumption and costs.

R&D is also increasingly exploring flexibility means, such as energy storage, and there is real momentum behind solar PV combined with battery systems. Despite the launch of commercial, energy-storage batteries in 2015 in the US, Australia and Germany, R&D is still actively trying to make the case for battery use. Battery makers' priorities are higher-durability chemistries and materials. In addition, improvements in power electronics and hardware technologies are making it possible for distributed PV to supply an increasing share of power, without impairing the reliability of electricity supply.

Solar PV experienced significant R&D investments in 2008-2014, with a 14% compound annual growth rate (CAGR) leading to a peak of $6 billion in 2014. Since then, R&D spending on solar has declined and amounted to $3.6 billion in 2016 (a negative 23% CAGR since 2014). Private funding accounted for $1.6 billion of the total, while public support remained similar to previous years, at around $2 billion. However, this still exceeded spending on the next two biggest renewable-energy sectors (biofuels and wind) combined.

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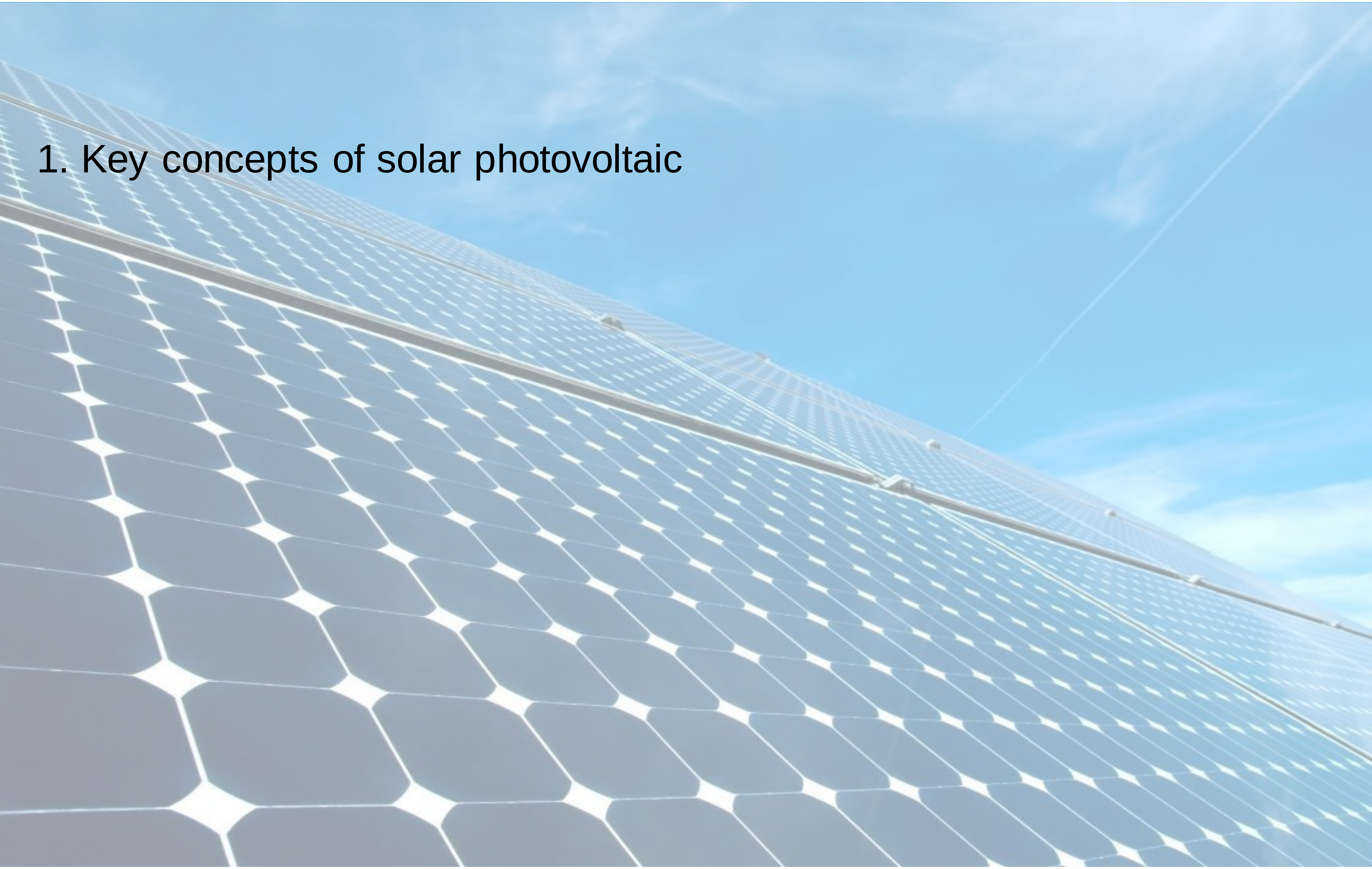
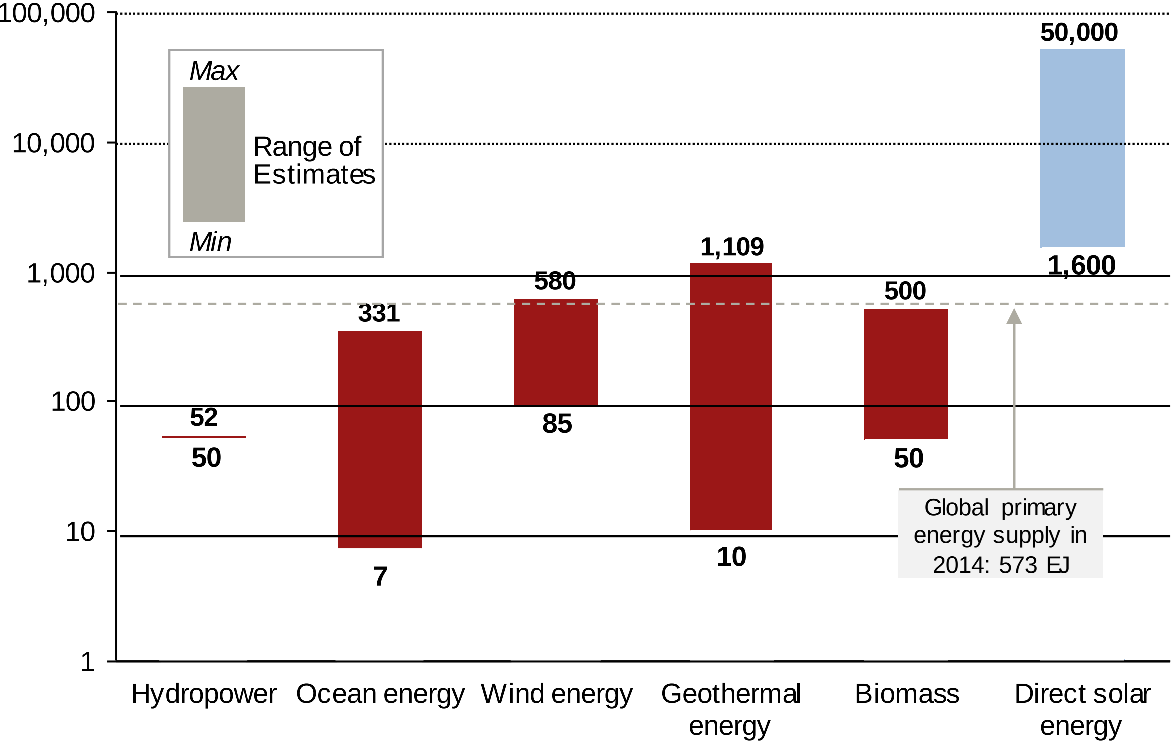


1. Key concepts of solar photovoltaic

Solar is the most abundant renewable-energy resource in the world and has the potential to meet all global primary energy demand.

Ranges of global technical potential of energy sources

Exajoule (10^{18} Joules) per year, log scale



- **The solar resource is larger than any other energy source available on Earth**. Estimates for solar energy's technical potential range roughly between three and 90 times the world's primary energy consumption in 2004[1]. This estimate takes into account the fraction of land that is of practical use and realistic conversion efficiency.
- **Solar energy is transported through sunlight[2]**. The instantaneous amount of power from sunlight available at a particular location and at the given time is measured by the solar ***irradiance*** (in watt per m^2). Solar ***insolation***, also known as solar ***irradiation***, is the resulting solar energy[3] received at a given location during a specific period of time, measured in watt-hours per m^2.
- **There are two main methods of capturing energy from the sun**: (i) heat: irradiative solar energy is easily transformed into heat through absorption by gases, liquids or solid materials; and (ii) photoreaction: solar radiation can be viewed as a flux of elementary particles that can promote photoreactions and generate a flow of electrons.

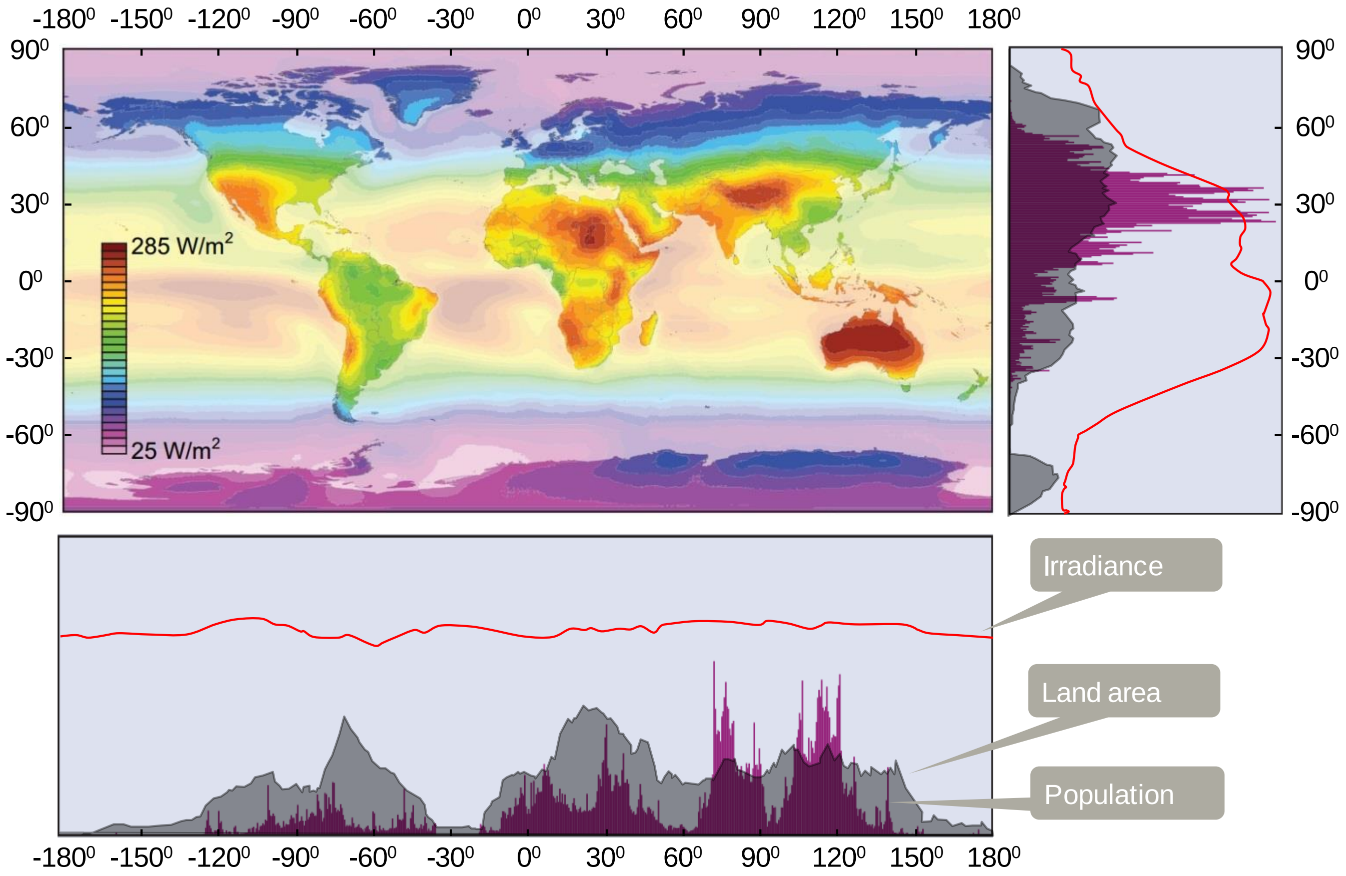
1. This number is on an indicative basis only; 2. Solar rays can be categorized in terms of the wavelengths that determine visible light, infrared and ultraviolet (respectively ~40%, 50% and 10% of radiated energy). During its transit through the atmosphere, sunlight interacts with air molecules (primarily water vapor, carbon dioxide, methane, nitrous oxide, and ozone) and portions of light are absorbed or reflected; 3. While part of sunlight arrives at a specific location without being scattered in the atmosphere, part of it is diffused. Solar PV can benefit from both parts.

Source: modified from IPCC (2011), "Special report on renewable energy"; IEA (2016), "Key World Energy Statistics"

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

Worldwide Distribution of the Solar Resource

W /m^2



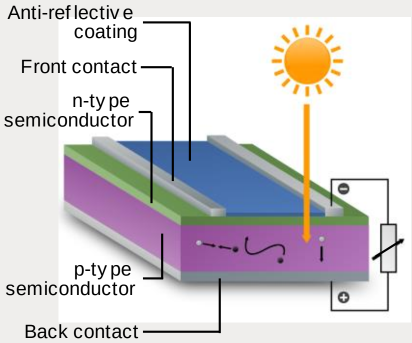
- **Solar irradiance is of fundamental importance in the use of solar energy.** It is considered good to excellent between 10° and 40°, South or North, although it can vary significantly at a given latitude.
- **The major causes of variation in solar intensity over time and across geographic location result from**: (i) the varying obliquity of incoming solar radiation across different latitudes; (ii) the Earth's revolution around the sun (seasonal variation); (iii) the Earth's rotation about its own axis (diurnal variation); and (iv) 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.

1. Graph courtesy of MIT (2015), "The Future of Solar Energy".

Source: MIT (2015), "The Future of Solar Energy"

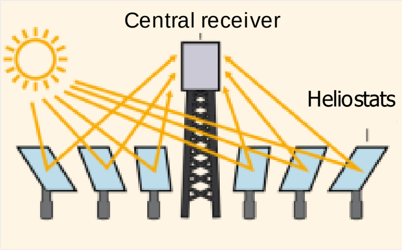
Solar photovoltaic (PV) is one of the four main direct solar energy technologies

Solar photovoltaic (PV)



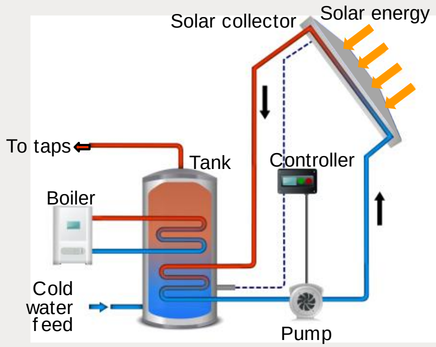
Electricity generation via direct conversion of sunlight to electricity by **photovoltaic cells** (conduction of electrons in semiconductors).

Concentrating Solar Power (CSP)



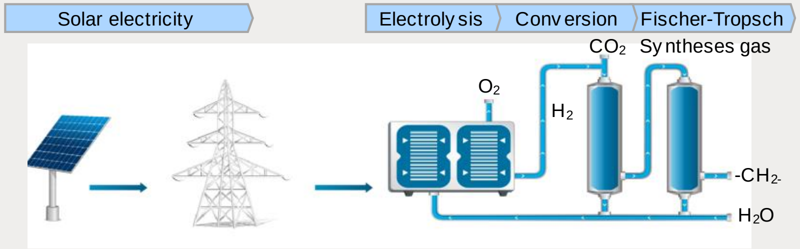
Electricity is generated by the **optical concentration** of solar energy, producing high-temperature fluids or materials to drive heat engines and electrical generators.

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



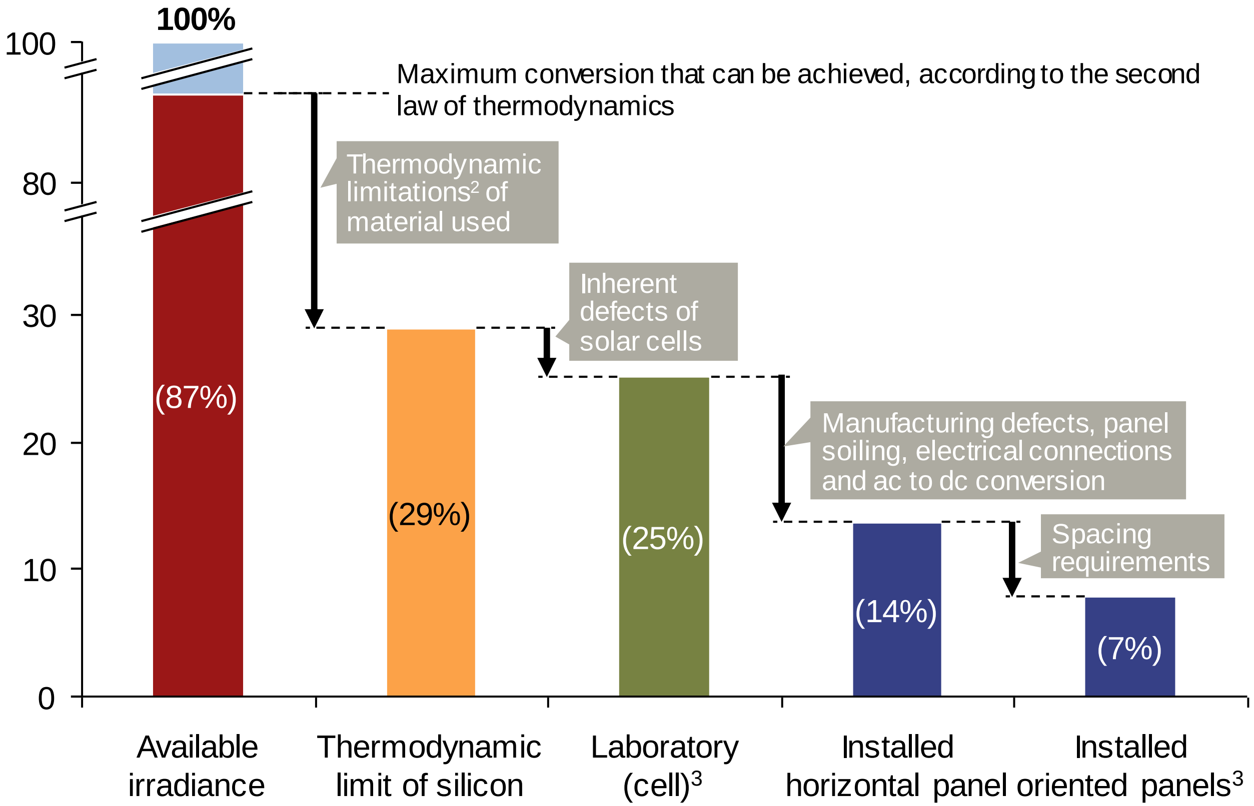
Solar Fuels processes are being designed to transform the radiative energy of the sun into chemical energy carriers such as hydrogen or synthetic hydrocarbons.

Note: Direct solar energy technologies exclude natural solar energy conversions, such as natural photosynthesis for biomass.
Source: IPCC (2011), "Special report on renewable energy"; IEA (2011), "Solar Energy Perspectives"; SolarFuel (accessed July 2015); A.T. Kearney Energy Transition Institute

Converting solar irradiance to useful electricity through PV systems engenders power losses

Power conversion losses for solar PV

Power density, W /m²



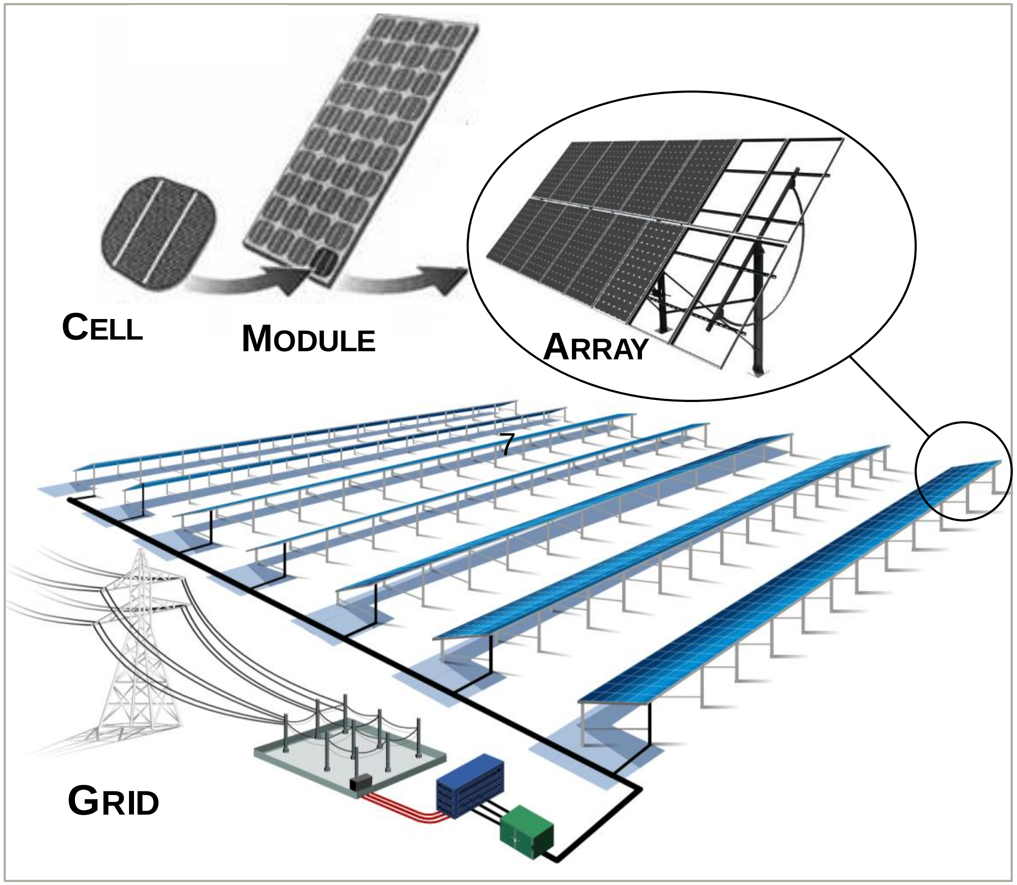
- **Converting solar Converting solar power into useful electrical or chemical energy results in power losses.** This explains discrepancies between theoretical efficiency, laboratory efficiency and real-world efficiency, and partly explains the wide range of efficiencies found in the literature.
- **Conversion efficiency varies significantly, depending on cell material and technology.** This is due to the thermodynamic limits of cell materials such as silicon, and to inherent defects in the cell. The efficiency of solar cells is currently limited to 46%, a world record established by Soitec-Fraunhofer ISE for a multi-junction concentrated PV cell (CPV)[4].
- **Finally, conversion efficiencies in installed systems are lower than cell efficiencies achieved in laboratories.** This discrepancy results from inherent cell defects, inactive areas, optical effects as well as manufacturing defects, panel soiling, poor electrical connections, conversion from direct current to alternating current (DC-to-AC) and spacing requirements[5].

1. Data are given for flat-panel single-crystalline silicon PV arrays at the average latitude of the contiguous US, and can vary by technology used and location; 2. Absorbing materials such as silicon only harness a fixed amount of energy from each photon above a critical threshold of energy; 3. Laboratory modules now have similar efficiencies to laboratory cells, despite inactive areas, optical effects and interconnection losses; 4. The most commonly used solar cells (multi-crystalline silicon) have recorded lab efficiencies of 20.8%. For more information on technologies and efficiencies, refer to slides 19 to 23; 5. Panels may have to be tilted to optimize their power production (depending on their latitude), requiring enough space between the panels so that they do not shade each other.

Source: MIT (2015), "The Future of Solar Energy"; Colthorpe (2014), "Soitec-Fraunhofer ISE multi-junction CPV cell hits world record 46% conversion efficiency"; Fraunhofer ISE (2012), "PV Module efficiency analysis and optimization"

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

Grid-connected PV systems: main components



- **The main components of solar PV systems are photovoltaic solar cells, modules and balance of system.**
- **Having a size of typically 15x15 cm², solar cells typically produce 4–5 watts under peak illumination**[1]. They are interconnected to form a PV module and increase their collective output. The power output of PV modules depends on the number and type of cells, and their total surface area. Typically, a module consists of 60-90 cells connected in a 1x1.5m panel, and generates a voltage of 30–48 volts and a power output of 260–320 watts. Modules can be further connected in series or in parallel to form arrays.
- **PV modules or arrays are then combined with application-dependent components known as balance of system (BOS) to form a PV system**. BOS encompasses both the structure (*e.g.* support rack) that supports the modules, 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…). Structural components vary, depending on whether the system is ground-mounted or installed on a rooftop, and whether it includes a system to follow the sun (tracking) or whether it is fixed[2]. Similarly, electrical components vary, depending on whether the solar panels are off-grid or grid-connected[3].

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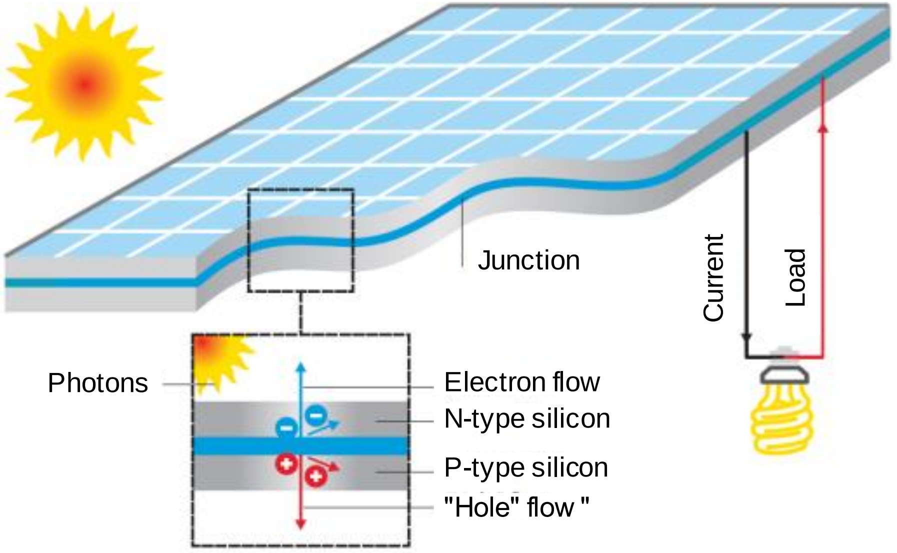
1. Standard test conditions of irradiance and temperature (solar irradiance of 1 kW/m², air mass 5 and a PV cell temperature of 25°C); 2. Typically on one axis for non- or low-concentrating systems, and two axes for high-concentrating systems; 3. For more information on BOS components, refer to slide 25 and 26.

Source: MIT (2015), "The Future of Solar Energy"; IPCC (2011), "Special report on renewable energy"; IEA (2011), "Solar Energ y Perspectives"

Photovoltaic solar technologies generate electricity by exploiting the photovoltaic effect

The photovoltaic effect



The conversion efficiency of a solar cell is defined as the ratio of the output power from the solar cell by unit area (W/cm^2) to the incident solar irradiance

- **Semiconductors** (somewhere between metals and insulators) **are critical components of solar cells.** The most common solar cells, known as p-n junction cells, are made of two semi-conductors: one is doped with electron-donating impurities (referred to as n-type because of the excess of negatively charged electrons) and the other is doped with an excess of holes donating impurities (referred to as p-type because of the excess of positively charged holes). When p-type and n-type are put in contact, electron-hole pairs are separated spatially by an internal electrical field at the interface.
- **When light shines onto some semiconductors, such as silicon (Si), electron-hole pairs are generated as a result of incoming photons.** The internal electrical field moves negative charges on one side of the interface, and positive charges on the other side, generating a voltage and direct current (DC) when connected to a load (known as the photovoltaic effect).
- **Two main processes can be used to manufacture solar cells**: wafer modification and additive deposition. The former[1] involves using a very pure, doped wafer of semiconductors, and the introduction of other dopants near its surface[2]. Charge carriers are generated within the wafer and extracted directly from its faces via electrical contacts. For the latter[3], a separate substrate[4] supports the active cell. Light-absorbing films and electrical contacts are formed in a layer-by-layer process on the substrate[5].

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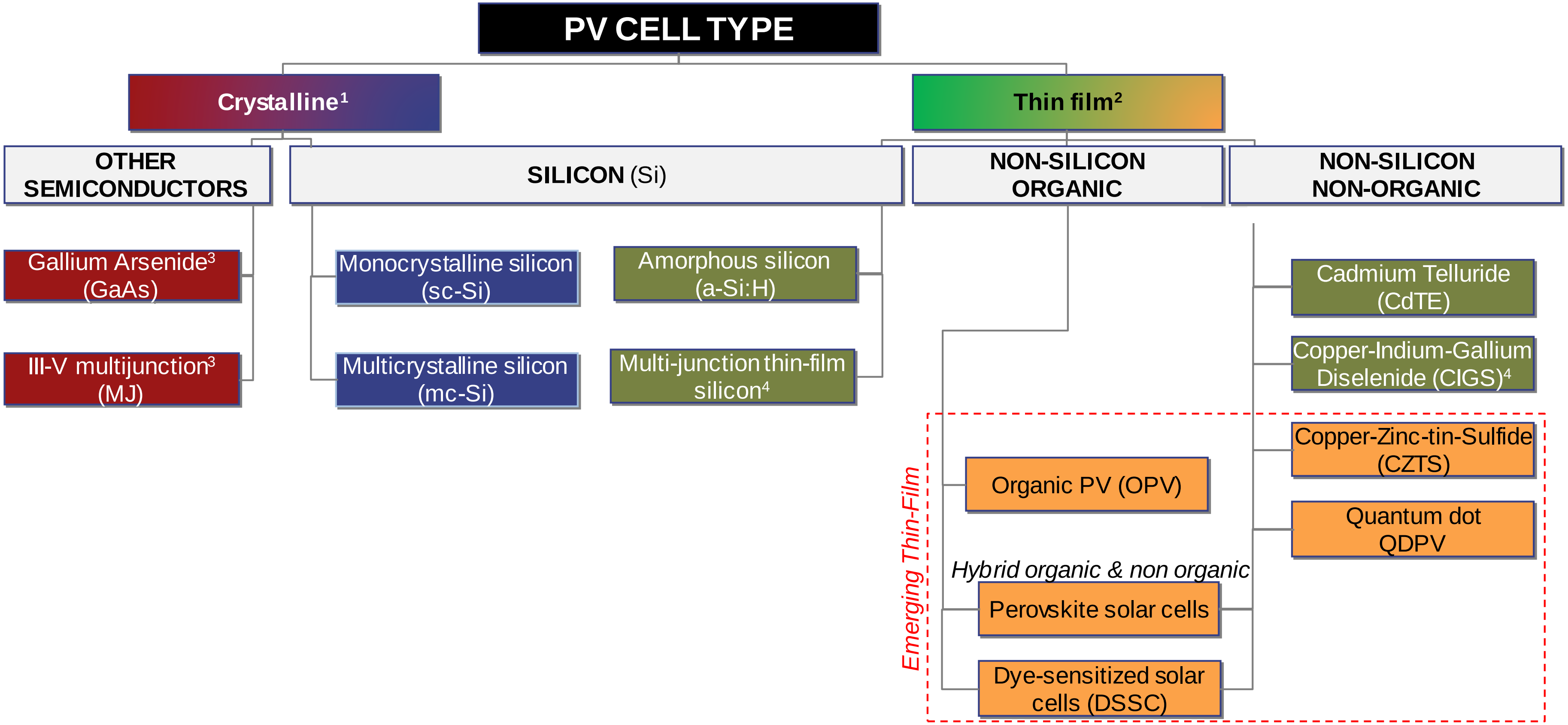
1. Typically used for crystalline silicon cells and III-V multijunction cells; 2. The wafer serves as both light absorber and substrate; 3. Used to make most thin-film solar cells; 4. Can be made of glass, plastic, or metal, and can be either rigid or flexible; 5. Using vapor- or solution-based deposition techniques, such as thermal evaporation, chemical vapor deposition, plasma-enhanced chemical-vapor deposition (PECVD), spray coating, or screen printing.

Source: IPCC (2011), "Special report on renewable energy"; IEA (2011), "Solar Energy Perspectives"; MIT (2015), "The Future of Solar Energy

There are several types of PV technology, varying by the type of material used in the cell's absorber

Classification of Solar PV cells



PV CELL TYPE

- **Crystalline**[1]
  - **OTHER SEMICONDUCTORS**
    - Gallium Arsenide[3] (GaAs)
    - III-V multijunction[3] (MJ)
  - **SILICON** (Si)
    - Monocrystalline silicon (sc-Si)
    - Multicrystalline silicon (mc-Si)
- **Thin film**[2]
  - **SILICON** (Si)
    - Amorphous silicon (a-Si:H)
    - Multi-junction thin-film silicon[4]
  - **NON-SILICON ORGANIC**
    - Organic PV (OPV)
    - Perovskite solar cells
    - Dye-sensitized solar cells (DSSC)
  - **NON-SILICON NON-ORGANIC**
    - Cadmium Telluride (CdTE)
    - Copper-Indium-Gallium Diselenide (CIGS)[4]
    - Copper-Zinc-tin-Sulfide (CZTS)
    - Quantum dot QDPV
    - Perovskite solar cells
    - Dye-sensitized solar cells (DSSC)

Hybrid organic & non organic

Emerging Thin-Film

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1. Crystalline silicon Gallium arsenide and III-V multijunction solar cells are sometimes classified into the same category, known as wafer-based cells. A wafer is a thin slice of semiconductor material, such as silicon crystals; 2. Thin-film cells consist of semiconducting films deposited onto a substrate; 3. These cells are typically used for concentrated PV applications; 4. For this type of cells, amorphous silicon cells are combined with other cells, based on nanocrystalline silicon (nc-Si) or amorphous silicon–germanium (a-SiGe); 4. Derive from copper indium diselenide cells (CIS) films, in which Gallium is partially substituted for Indium

Source: A.T. Kearney Energy Transition Institute; IPCC (2011), "Special report on renewable energy"; MIT (2015), "The Future of Solar Energy"

Solar-cell materials must be assessed in terms of efficiency, cost, maturity and material requirements

Main technical features of solar cell materials

Solar PV technologies

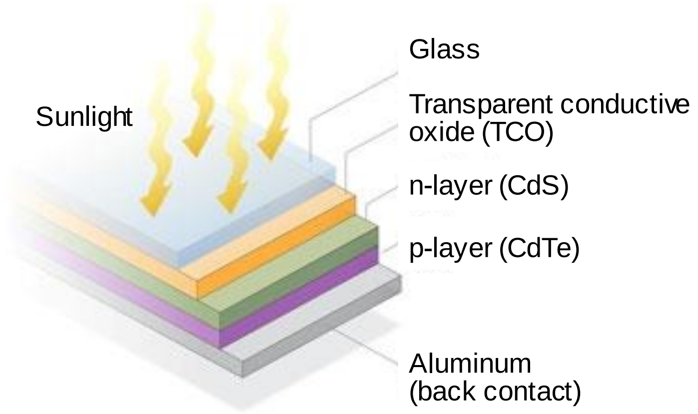
	Market share (2015)	Record cell efficiency	Record module efficiency	Typical commercial module efficiency[1]	Average module price[4]	Lifespan	Critical material used
Crystalline silicon	93%[2]	20.8% (multi-crystalline), 25.6% (mono crystalline)	18.5% - 22.4%	16%-21%	$0.65 - $1.6 /W	25-30 years[5]	Silver Silicon
Commercial thin film	7%	21.0 % (CdTe), 20.5 % (CIGS)	12.2% - 18.2%	8%-16%	0.6 $ /W	25 years	Rare elements (*e.g.* Tellurium, Gallium, Indium) & toxic elements (*e.g.* Cadmium)
Emerging thin-film[3]	<1%	20.1%		NA		Very short	No
Other high-efficiency	<1%	46.0% (high concentration multi-junction solar cells)	24.1% - 36.7%[6]	>30%[6]		NA	Rare elements: Gallium

Note: [1] Module efficiencies are increasing quickly, thanks to influential R&D programs; [2] Approximately 24% and 69% for single-crystalline and multi-crystalline modules, respectively; [3] Emerging thin films remain at the early R&D stage and technologies are improving at rapid rates (leading to fast increases in efficiency); [4] In Q4 2013, in the US the factory-gate price varied between $0.64 /W and $0.75 /W for standard (13.5%-15.5% efficiency) c-Si modules, and between $1.20 /W and $1.60 /W for higher-efficiency (19.6%–21.0% efficiency) c-Si modules; [5] Modules are usually guaranteed for a lifetime of 25 years at a minimum 80% of their rated output, and sometimes for 30 years at 70%; [6] For concentrator PV modules

Source: A.T. Kearney Energy Transition Institute; MIT (2015), "The Future of Solar Energy"; IEA (2014), "Technology Roadmap Solar Photovoltaic Energy"; Wesoff (2015), "First Solar Reaches 16.3% Efficiency in Production PV Modules"; NREL (2014), "US Residential Photovoltaic (PV) System Prices, Q4 2013", Fraunhofer Institute for Solar Energy Systems PHOTOVOLTAICS REPORT (November 2016)

Crystalline silicon is the main commercial, and the most efficient, technology today

FactCard: Crystalline silicon



Wafer-based crystalline silicon (c-Si) is the dominant solar-cells technology. It can be classified as single crystalline or multi-crystalline, which account for global market shares of 24% and 69%, respectively[2].

Cells are made of highly purified silicon (5 grams per watt), which accounts for at least a quarter of their costs.

A potential junction is created, and an anti-reflective coating and metal contacts are added.

The cells are then grouped into modules, resulting in a slight loss of efficiency.

Modules usually have transparent glass on the front, a weatherproof material on the back (often a think polymer) and a frame.

Key data

Efficiency:	**16-21%**	🟩
Module price (2014):	**$0.65-1.6 /Watt**	🟨
Lifespan:	**25-30 years**	🟩
Market share:	**93%**	🟩
Material issues:	**Silver**	⬜

Drawback 🟥 🟨 🟩 🟩 **Advantage**

Pros

- Higher efficiency than other technologies (15-21% for commercial modules)
- Most mature technology, benefits from semi-conductor industry
- Long lifespan – currently 25-30 years, could increase to 4 years
- High abundance of silicon in Earth's crust

Cons

- Efficiency decreases as temperature rises (-0.45% per °C)
- High manufacturing capital costs and constrained module form[1]
- Important wafer thickness
- Higher lifecycle GHG emissions than other technologies

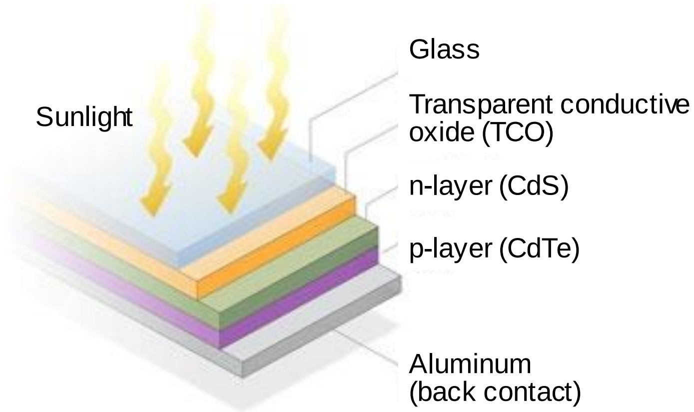
---

1. Silver used for contact metallization accounts for 5% of the cost and may have an impact on cost reduction in future. In addition, ability to absorb light is limited, and thick, rigid, costly and impurity-free wafers are required; 2. The use of thin (2–50 mm) c-Si membranes instead of wafers as a starting material is also being investigated.

Source: A.T. Kearney Energy Transition Institute; IPCC (2011), "Special report on renewable energy"; IEA (2011), "Solar Energy Perspectives"; US DoE Office of Energy Efficiency & Renewable Energy (Accessed June 2015), "Crystalline Silicon Photovoltaics Research"; Jean et al. (2015), "Pathways for solar photovoltaics

Some thin-film technologies made from semi-conductors have become commercial, but are less efficient than c-Si and are challenged by the decline in c-Si prices

FactCard: Commercial Thin-Film



Thin-film (TF) technologies include a range of absorber semi-conductor material systems[1]:

- Hydrogenated amorphous Silicon (a-Si:H)[2] and multi-junctions, (14% of TF market share), with limited efficiencies: from 8 to 13%;
- Cadmium Telluride (CdTe) thin-film solar cells (60% of TF market share) have the lowest production costs and efficiencies, of up to 21%;
- Copper-indium-(gallium)-(di)selenide (CIS-CIGS) (26% of TF market share) have achieved efficiency levels of up to 21.7% under laboratory conditions.

These active materials are deposited in thin films by additive fabrication processes on low-cost backings, such as glass, metal or plastic substrates.

Key data

Efficiency:	**8-16%**	🟥
Module price (2014):	**$0.6 /Watt peak**	🟩
Lifespan:	**25 years**	🟨
Market share:	**10%**	🟩
Material issues:	**Rare & toxic elements**	⬜

→

Drawback 🟥 🟨 🟩 🟩 **Advantage**

Pros

- Reduced use of materials
- The production of modules can be streamlined and automated
- Possibility of low manufacturing costs, so cheap when land-use constraints absent
- Lower life-cycle greenhouse gas emissions than c-Si2
- Flexible, available in many colors, shapes and sizes. Helps integration onto buildings

Cons

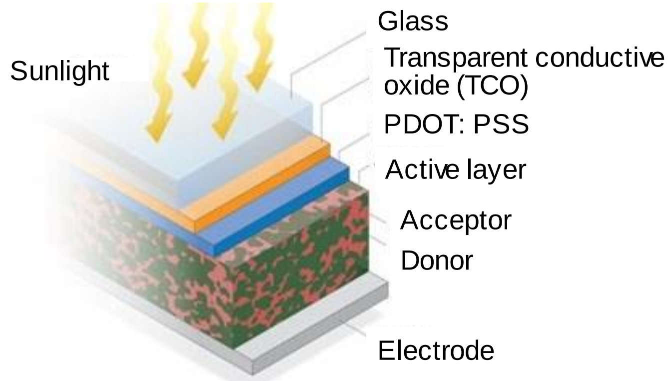
- Conversion efficiency is limited for commercial modules (8-16%)
- The toxicity of Cadmium and availability of Tellurium raise concerns for CdTe cells
- Scarcity of indium and Gallium could hinder large-scale deployment of CIGS technologies
- Sensitivity to external environment sometimes requires hermetic encapsulation

1. The picture represents a Cadmium Telluride (CdTe) solar cell. 2. a-Si:H cell can be combined with cells based on nanocrystalline silicon (nc-Si) or amorphous silicon-germanium (a-SiGe) alloys to form a multi-junction cell without lattice-matching requirements, increase efficiency and reduce light-induced degradation. For more information on greenhouse emissions, refer to slide 78.

Source: A.T. Kearney Energy Transition Institute; IPCC (2011), "Special report on renewable energy"; IEA (2011), "Solar Energy Perspectives"; Jean et al. (2015), "Pathways for solar photovoltaics"; Guha et al. (2013), "High efficiency multi-junction thin film silicon cells incorporating nanocrystalline silicon"; US DoE Office of Energy Efficiency & Renewable Energy (Accessed June 2015), "Cadmium Telluride";

New thin-film PV technologies are emerging to enable groundbreaking reductions in module costs and novel PV applications

FactCard: emerging Thin-Film



R&D efforts and device engineering led to the emergence of very low-cost thin-film PV technologies, such as (i) copper zinc tin sulfide[1], an earth-abundant alternative to CIGS, with efficiencies of up to 12.6%; or (ii) perovskite cells[2], one of the most promising, fastest-improving emerging hybrid thin-film technologies, with efficiencies of up to 21%.

In addition, emerging technologies include organic solar cells, either (i) full organic cells known as organic photovoltaics (OPV), which use small stacked organic molecules or Earth-abundant polymers to absorb light, with efficiencies of up to 11.1%; (ii) hybrid-organic dye-sensitized solar cells (DSSCs), among the most mature of nanomaterial-based technologies (record efficiency: 12%); or (iii) Colloidal quantum dot photovoltaics (QDPV)3 using quantum dots as absorbing photovoltaic materials, which have reached a record efficiency of 9.2%.

Key data

Efficiency:	**9-21%[4]**	🟧
Module price (2014):	***NA***	⬜
Lifespan:	**NA**	⬜
Market share:	**<1%**	🟥
Material issues:	**None**	🟩

Drawback 🟥 🟧 🟩 🟩 **Advantage**

Pros

- No requirement for rare / exotic materials
- Simple manufacturing methods
- Promises a more substantial module-price reduction than thin-film silicon
- Additional properties, such as transparency

Cons

- Shorter lifespan than competing technologies
- Stability issues for Perovskite, OPV, and DSSC cells
- High sensitivity to moisture and toxicity of lead for Perovskite cells
- Efficiency limits for OPV cells
- Low open-circuit voltages for DSSC, and QDPV

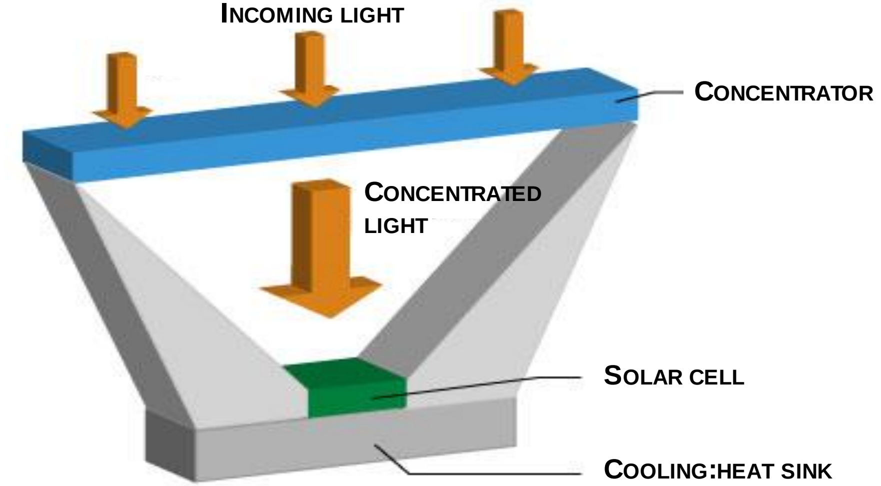
---

1. Also known as Cu2ZnSnS4; 2Perovskite materials are compounds with specific crystalline structures. The most widely investigated perovskite for solar cells is the hybrid organic-inorganic lead halide CH3NH3-Pb(I,Cl,Br)3; 2. The dye has a similar role to chlorophyll in plants, harvesting solar light and transferring the energy via electron transfer to a suitable material. Unlike the other technologies, DSSCs often use a liquid electrolyte to transport ions to a counter electrode, but efficient solid-state devices have also been demonstrated; 3. Also known as quantum dots (QDs); 4. Record lab efficiencies, vary between technologies

Source: A.T. Kearney Energy Transition Institute; Jean et al. (2015), "Pathways for solar photovoltaics"; Gratzel (2003), "Dye-sensitized solar cells"; US DoE Office of Energy Efficiency & Renewable Energy (Accessed June 2015), "Organic Photovoltaics Research";

Concentrated solar PV requires better solar irradiance than non-concentrated technologies and is far less common

Concentrated solar PV basics



Concentration ratio Elements	Low (2-10)	Medium (10-100)	High (>100)
Tracking	Not required	1 axis	Dual axis
Cooling	Not required	Passive	Active
PV Material	High Quality Si		Multi-junction cells

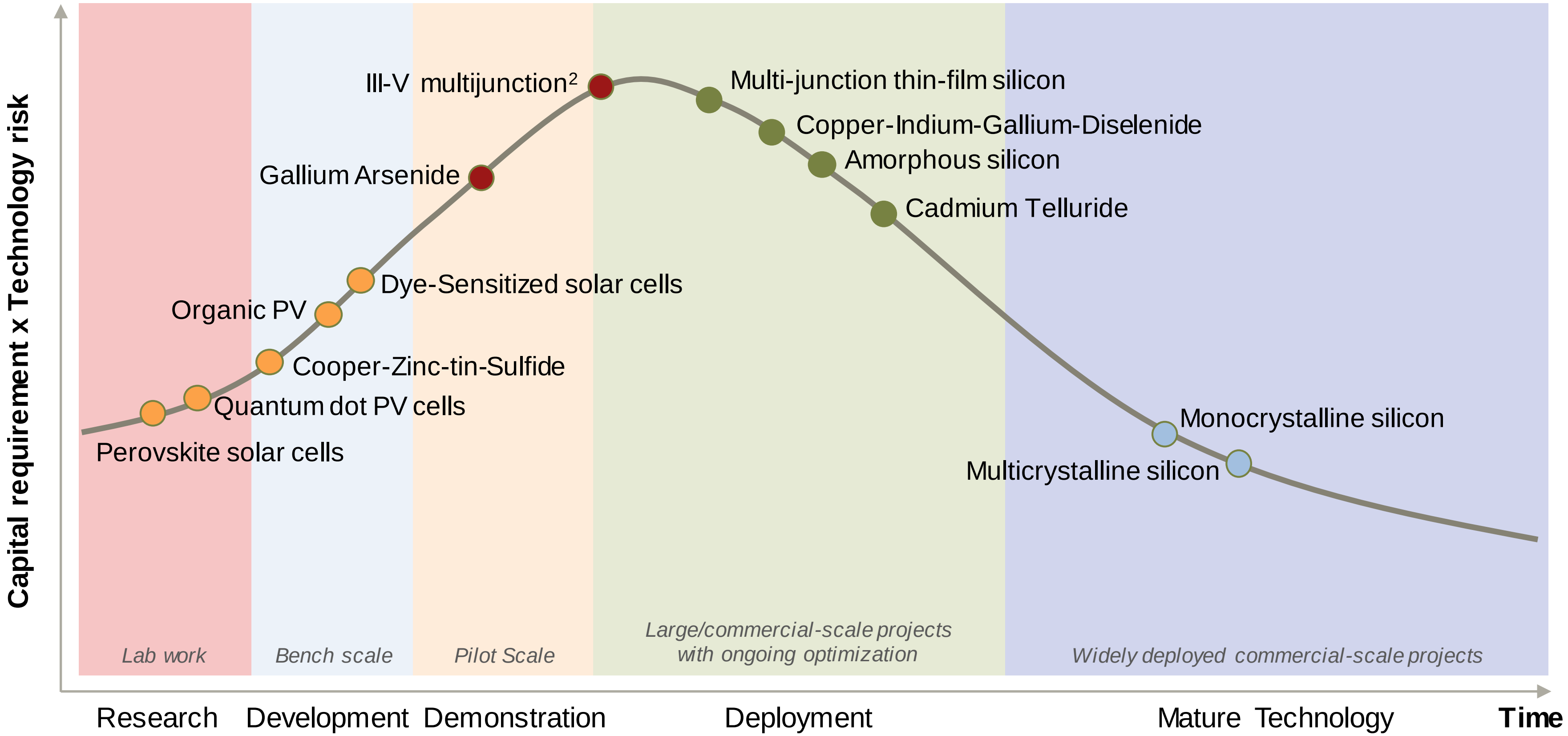
- **Concentrated PV (CPV) uses mirrors or lenses to concentrate and focus solar radiation on high-efficiency cells**. As in concentrating solar power, several concentrator technologies can be used, either linear or point-focus – mainly parabolic mirrors, Fresnel lenses, reflectors and luminescent concentrators.
- **High-efficiency cells are used to capture most of the solar light spectrum**. These cells, which can reach up to 46% efficiency, are composed of different materials in several layers[1]. The rationale is that the higher cost of these cells is outweighed by their higher efficiency.
- **Contrary to PV, CPV requires** (i) direct sunlight rather than scattered light, and is thus geographically limited (to high direct normal irradiance areas, space); (ii) sun-tracking systems (more or less accurate); (iii) cooling (active if a fluid is needed, passive if not). As with concentrating solar power (CSP), CPV is well suited for steam-based desalinization.
- **The CPV market remains negligible compared with those of conventional PV technologies.** CVP suffers from the perception among investors that it is not economically viable, resulting in important uncertainties regarding market development. Nevertheless, an increasing number of plants have been installed over the recent years[2] in China, the United States, South Africa, Italy, Australia, and Morocco. In 2015, cumulative installed capacity reached 360 MW, from 300 MW in 2013.

Note: [1] III-V multi-junction solar cells use multiple layers of semi-conductor material to absorb and convert more of the solar spectrum into electricity than a single-junction cell. They have reached efficiencies of up to 46%. III-V multi-junction solar cells have become a standard for High concentration PV; [2] Most of the projects were around 1MW, with several of them exceeding 20 MW, with more than 90% of the total being high concentration photovoltaic

Source: IPCC (2011), "Special report on renewable energy"; IEA (2011), "Solar Energy Perspectives"; Simon *et al.* (2015), "Current status of CPV technology"

PV cell technologies are at very different points of maturity

Technology maturity curve[1]



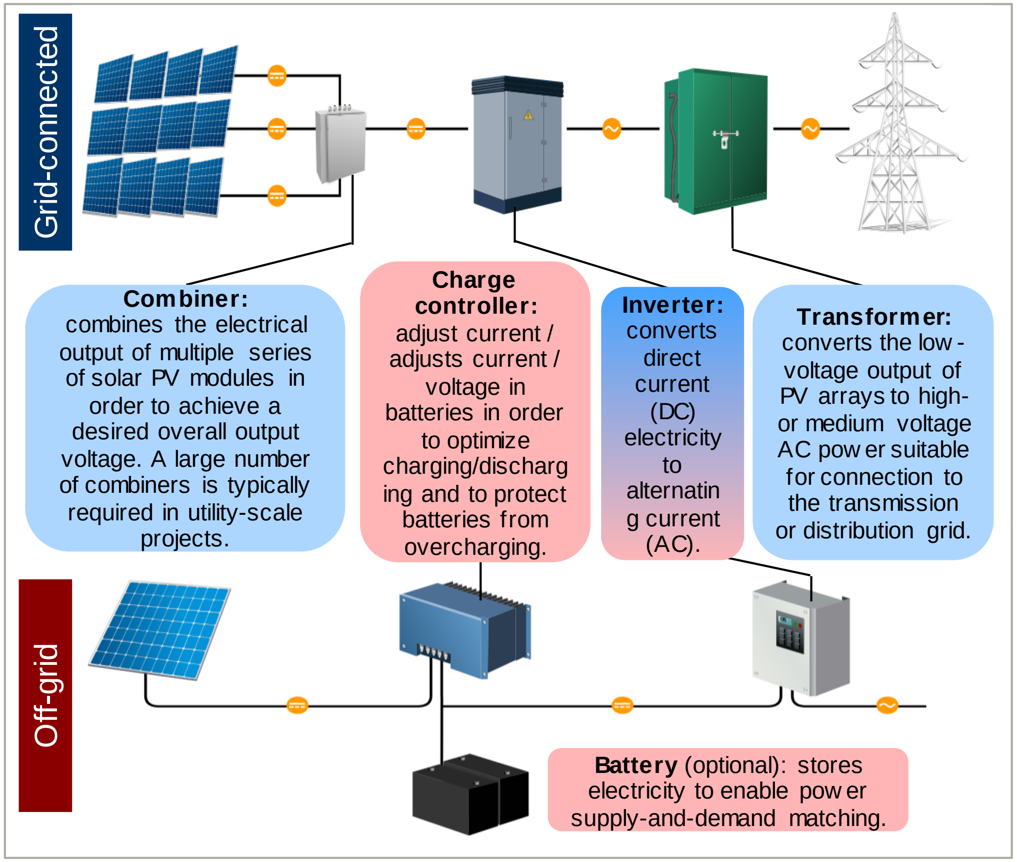
● Others high efficiency solar cells ● Commercial thin-film solar cells ● Emerging thin-film solar cells ● Crystalline silicon solar cells

1. As of April 2017, Investment valley of death refers to two critical stages: the early demonstration stage, in which capital required tends to outstrip the resources of a typical lab and where the high technology risk deters some private-sector investors; and the early deployment stage, in which high investment requirements and further risk taking are needed to push the project from demonstration to deployment; 2. II-V MJs are the leading technology for space and CPV applications due to their high resistance to radiation, low sensitivity to temperature, and high efficiency but are uncommon in conventional solar PV applications.

Source: A.T. Kearney Energy Transition Institute

Electrical devices are critical components of solar-PV systems

Main electrical components of PV systems



Grid-connected

Combiner: combines the electrical output of multiple series of solar PV modules in order to achieve a desired overall output voltage. A large number of combiners is typically required in utility-scale projects.

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

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

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

Off-grid

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

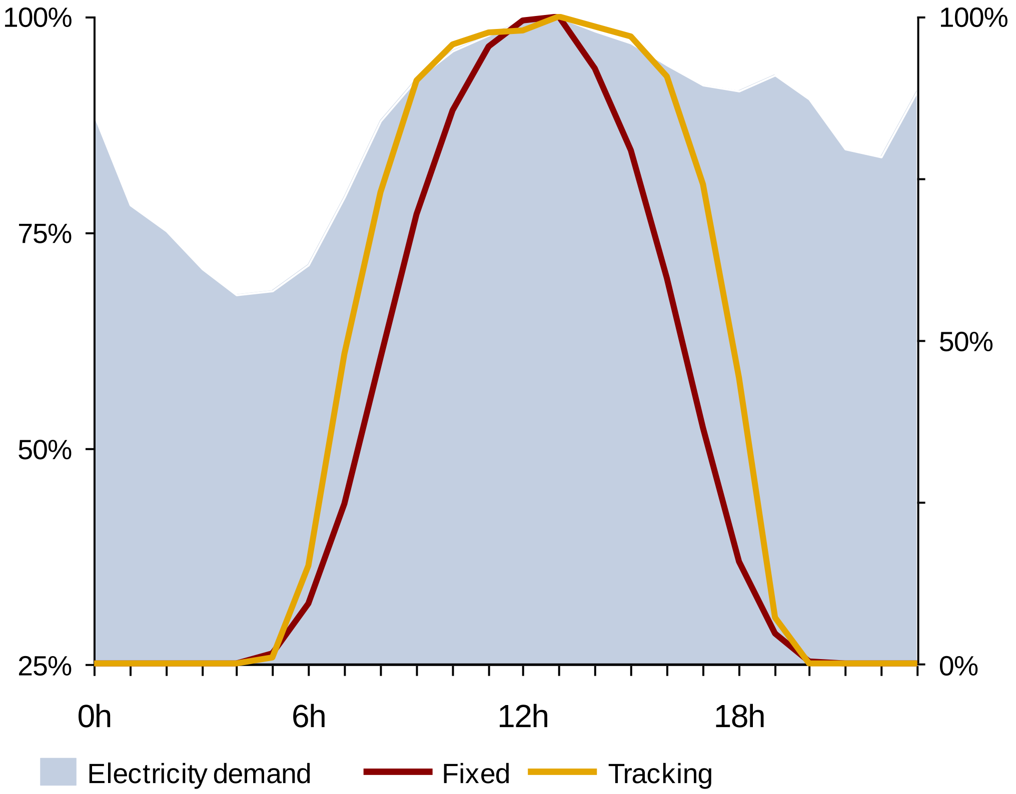
- **Electrical equipment is a critical component of solar PV balance-of-system (BOS).** Its purpose is to collect power from the PV modules and transfer it to the grid or to the point of use in a reliable and safe manner.
- **Many components are common to all PV systems**. Power-conditioning appliances such as inverters[1] convert direct-current electricity to alternative current in order to meet grid requirements[2]. Safety devices, such as safety disconnects, grounding equipment or surge protection, protect people and equipment from injury and damage. Finally, metering and instrumentation ensure the monitoring and control of power consumption and generation[3].
- **However, some electrical components may or may not be present, depending on whether the PV system is off-grid or grid-connected.** Off-grid, stand-alone systems are dependent on the electrical appliances to which they provide power[4] and typically include a battery and charge controller to store electricity. Grid-connected systems require equipment to safely transmit electricity to the grid and to comply with grid requirements. In addition to inverters, grid-connected systems typically incorporate combiners and transformers, and their precise make-up varies according to voltage (*i.e.* on the points of connection).

1. Inverters have generated a lot of attention as they can be a source of inefficiency and a major contributor to maintenance costs; 2. Most solar electric units produce direct current (DC) electricity but most electrical appliances and equipment run on alternating current electricity; 3. PV systems connected to the electricity grid need meters to keep track of the electricity fed into and withdrawn from the grid; 4. Some systems, such as single meters, can also measure the amount of excess electricity fed back into the grid.

Source: 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

Solar tracking systems and plant-level controllers could be instrumental in exploiting the full potential of utility-scale PV systems

Main electrical components of PV systems



- In addition to conventional BOS equipment, which enables safe power collection and transmission, **new components have been introduced to improve system efficiency and facilitate the integration of utility-scale plant output into the grid.**
- **Tracker systems are intended to make the solar panels follow the movement of the sun across the sky.** Being pointed directly at the sun all day increases the amount of power a solar panel can produce (by 20-30%). In addition, tracking is deemed to improve the correlation between solar power output and demand[2]. Due to the increase in upfront power costs arising from the addition of tracking systems, they are likely to be used mainly in utility-scale PV plants, in which they are considered a vital element in the plant maximizing its potential.
- **Plant-level controllers could also ease and improve the connection of utility-scale PV plants to the grid.** Controllers help coordinate the power output of individual generators, making them act as a single, virtual large-scale generator. It may also provide grid services or help power regulation through (i) dynamic voltage / power factor regulation at the point of interconnection; (ii) real power output curtailment of the plant when required[3]; (iii) ramping-rate controls[4]; (iv) frequency control or (v) start-up and shut-down control.

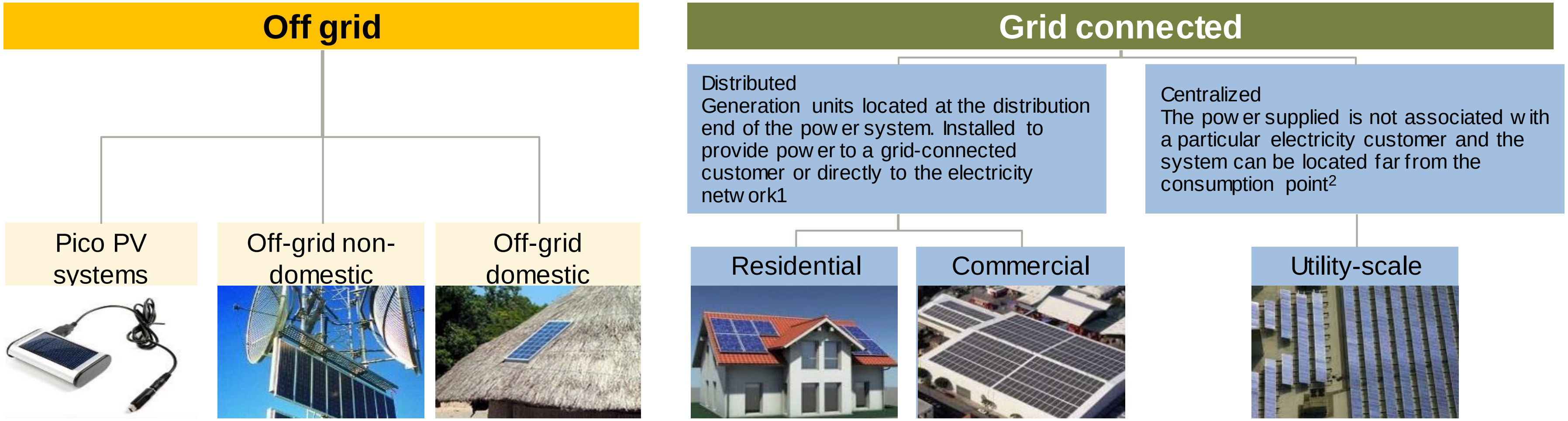
Note: [1] Based on tests in Marseille, France; [2] Trackers often suffer from the outdated perceptions that they are unreliable and require a lot of maintenance. However, recent innovations include simpler designs with fewer motors and self-calibration, obviating routine maintenance; [3] So that it does not exceed an operator-specified limit; [4] To ensure as far as is possible that plant output does not ramp up or down faster than a specified ramp-rate limit. Note that controllers cannot always accommodate rapid reductions in irradiance due to cloud cover.

Source: A.T. Kearney Energy Transition Institute based on RTE eco2mix, "Production d'électricité par filière" (accessed July 2015); NREL PvWatts accessed July 2015); First Solar (2013), "'Grid Friendly' Utility-Scale PV Plants"; Bellemare (2015), "Solar Tracking: A Key Technology for Unlocking the Full Potential of Utility-Scale PV"

2. Applications and grid integration

Solar PV has different applications with varying location, grid connection or power capacity requirements

PV applications and market segments



Off grid

Grid connected

Distributed
Generation units located at the distribution end of the power system. Installed to provide power to a grid-connected customer or directly to the electricity network[1]

Centralized
The power supplied is not associated with a particular electricity customer and the system can be located far from the consumption point[2]

	Pico PV systems	Off-grid non-domestic	Off-grid domestic	Residential	Commercial	Utility-scale
Typical location	N/A, typically stand-alone	Depends on applications	Typically on houses but also ground-mounted	Small Businesses Residential customers	Industrial & commercial customers Highly varied group depending on project size	State institutions Utilities Electro-intensive industries
Application	Lighting, phone, radio or small appliances[3]	Wide range of applications	Households and villages not connected to the electricity network[4]	Individual buildings/houses or electricity network	Buildings and electricity network	Electricity network
Size	Only a few watts	Varying sizes	Up to 5 kW	Up to 20 kW	20 kW < x < 5 MW	Starting at 5 MW, Up to 600 MW

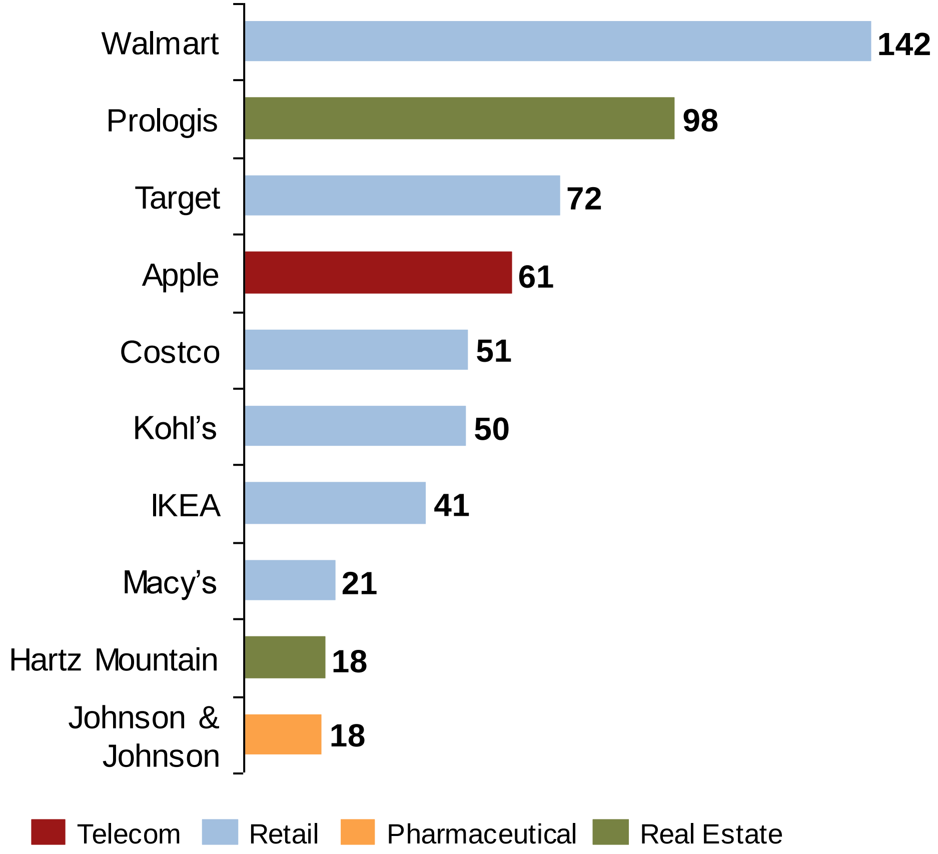
1. Typically connected to the distribution network but can also be connected to the transportation network in the case of commercial PV. 2. Typically connected to the transportation network; 3. Such as telecommunication, water pumping, vaccine refrigeration and navigational aids; 4. PV systems can also be hybrid, combining the advantages of PV and diesel generator in mini grids.

Source: A.T. Kearney Energy Transition Institute; IEA (2014), "Technology Road Map Solar Photovoltaic Energy"; IEA PVPS (2014), "Trends 2014 in Photovoltaics Applications

The modular nature of solar PV enables deployment at various scales and by many players

Top 10 US commercial solar users

Installed capacity in 2014 (MW)



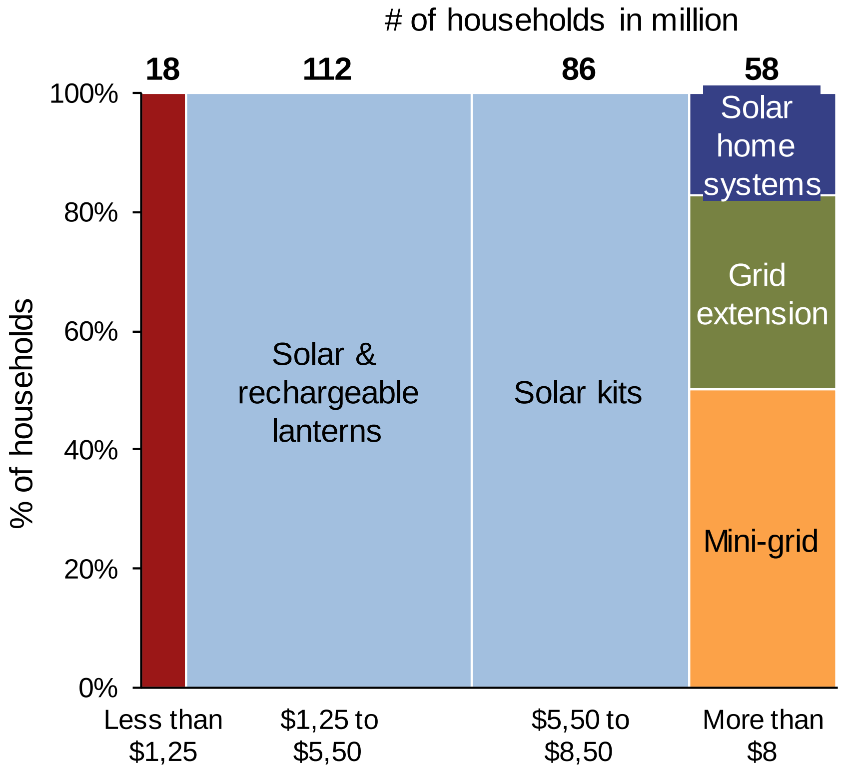
- **The modular nature of solar PV is yet deemed to be one of the main advantage of solar PV compared to most alternative fossil or renewable technologies**. Solar PV modules can be distributed in numerous locations such as rooftops on residential buildings, schools, hospitals or parking lots. Distributed PV is notably well fitted for installation on commercial buildings with important electricity needs and available floor space. Besides, commercial customers tend to be less reluctant vis-a-vis the upfront investment costs of solar PV than individual customers. Therefore, many large corporations have been installing solar panels on their rooftops to cut energy costs and hedge against potential electricity price increase[2]. After large companies and households, solar players are now turning to small- and medium-size corporations in a move to further accelerate the solar spread as illustrated by recent announcement from SolarCity.
- **Contrary to what is commonly believed, the vast majority of solar PV capacities are today connected to the electric grid[1],** either on the distribution end of the grid such as rooftop residential/commercial systems or through centralized, utility-scale solar PV plants.
- **Utility-scale power plants have grown in size and numbers over the past years.** They can be connected to the medium or low voltage distribution networks, but also to the high-voltage transmission grid, similarly to large conventional thermal power plants. As of 2016, the largest utility-scale solar PV plant in operation is in India (Tamil Nadu). Powered by more than 2.5 million solar modules, capacity is rated at 648 MW.

1. For more information on the share of grid-connected vs. off-grid capacities, refer to slide 38; 2. Utility price volatility can present a challenge to businesses' long-term budgets.
Source: A.T. Kearney Energy Transition Institute; Sunpower (2015), "FactSheet Solar Star Project"; SEIA (2015), "Solar Means business Top US Commercial Solar Users"; Douglas (2015), "SolarCity Aims to Power Nation's Smaller Businesses" (link)

Off-grid solar PV is expected to be instrumental in alleviating energy poverty

Theoretically addressable market for "Lighting plus" according to IFC[1]

Total: 274m households



- **Access to modern energy services such as electricity or cooking facility is crucial** to human well being and countries' development. And yet, the IEA estimates that over 1.3bn and 2.6bn people lack of electricity access and clean cooking, respectively. Energy poverty[2] is especially affecting Sub-Saharan Africa and developing Asia, which accounts for 96% of these people, and more specifically impacting rural areas (86% of population without access to electricity).
- **Solar resources are good to excellent in most regions where people live in energy poverty**. In addition, since energy poverty is mostly affecting rural area, it is likely to favor off-grid or micro-grid solutions and to line up with distributed off-grid systems: PV will indeed be in competition with expensive diesel generator or long-to-develop, capital intensive grid extension.
- **Therefore, off-grid solar PV could be instrumental in alleviating energy poverty**. According to a study from the IFC[1], the theoretically addressable market for off-grid PV is enormous and could contribute to its development. French oil major Total for instance introduced *Awango*, a solar lighting and phone charging solutions in 2011 and sold 5 millions units as of 2015.

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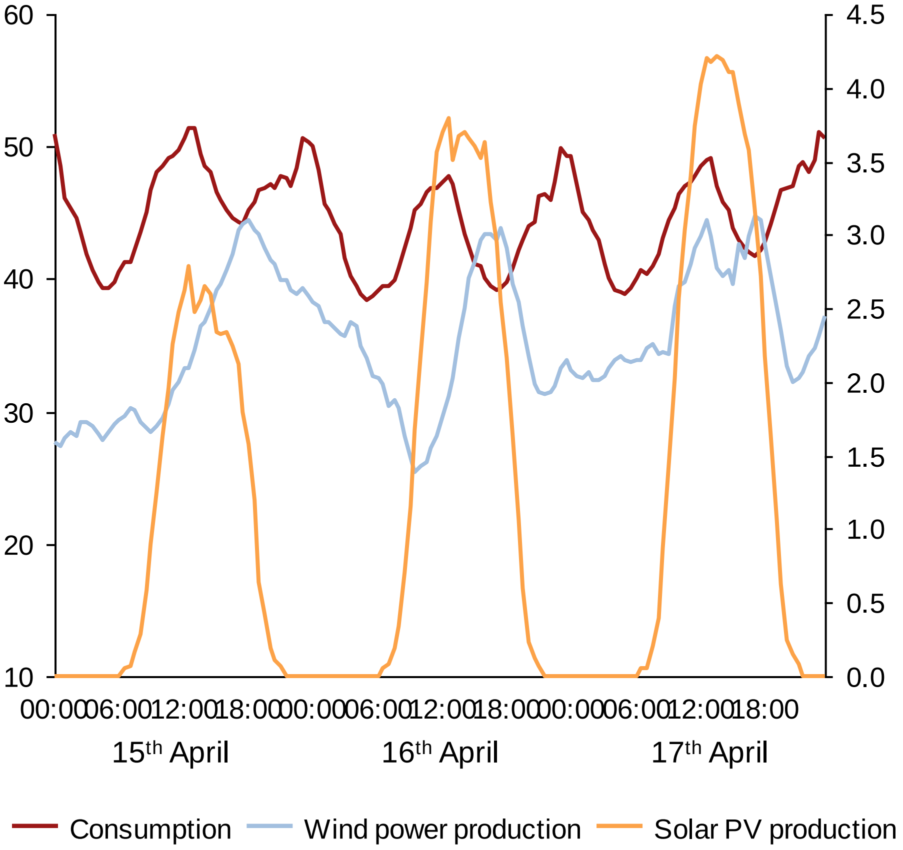
1. Graph credit International Finance Corporation – IFC (2012), "From gap to opportunity, Business Models for scaling up energy access"; 2. Energy poverty include the lack of access to electricity, commercial energy, clean cooking facilities and mechanical power. It should be distinguished from fuel poverty that refers to the inability to afford adequate energy services.

Source: A.T. Kearney Energy Transition Institute; World Bank online database on population (link); World Bank (2015), "Sustainable Energy for All: Global Tracking Framework"; IEA (2011), "Energy for all: financing access for he poor"; Total (2015), "Photovoltaic Solar Energy in Non-OECD Countries"

Solar PV is distinguished from other sources of energy by its imperfectly temporal predictability and deterministic variability

Wind & Solar Generation vs. Demand

Demand (left), Generation (right), Gigawatt (GW) - French Grid



- **Solar is an intermittent source of energy**: Its output is variable daily, seasonally and yearly[1], imperfectly controllable and predictable, and subject to sudden changes in the event of a passing cloud or atmospheric turbidity. Therefore, solar PV penetration tend to increase flexibility needs. The latter are often divided into three groups, depending on timescale: (i) grid stability that refers mainly to frequency and voltage control to comply with the grid's technical limits over a period of seconds; (ii) grid balancing that refers to load changes over minutes or days that must be balanced; and (iii) grid adequacy, which refers to capacity needed to meet peak demand even under the most extreme conditions in the long term (months to years).
- **Nevertheless, unlike wind, solar has a clear day/night production pattern and is more predictable. In addition, solar output tends to be well correlated with demand**, especially in areas where peak demand occurs during the sunniest hours and where it can mitigate the need for expensive power plants to meet marginal demand (*e.g.* in the Middle East or in the Southwestern United States, where the peak of demand is driven by air conditioning).

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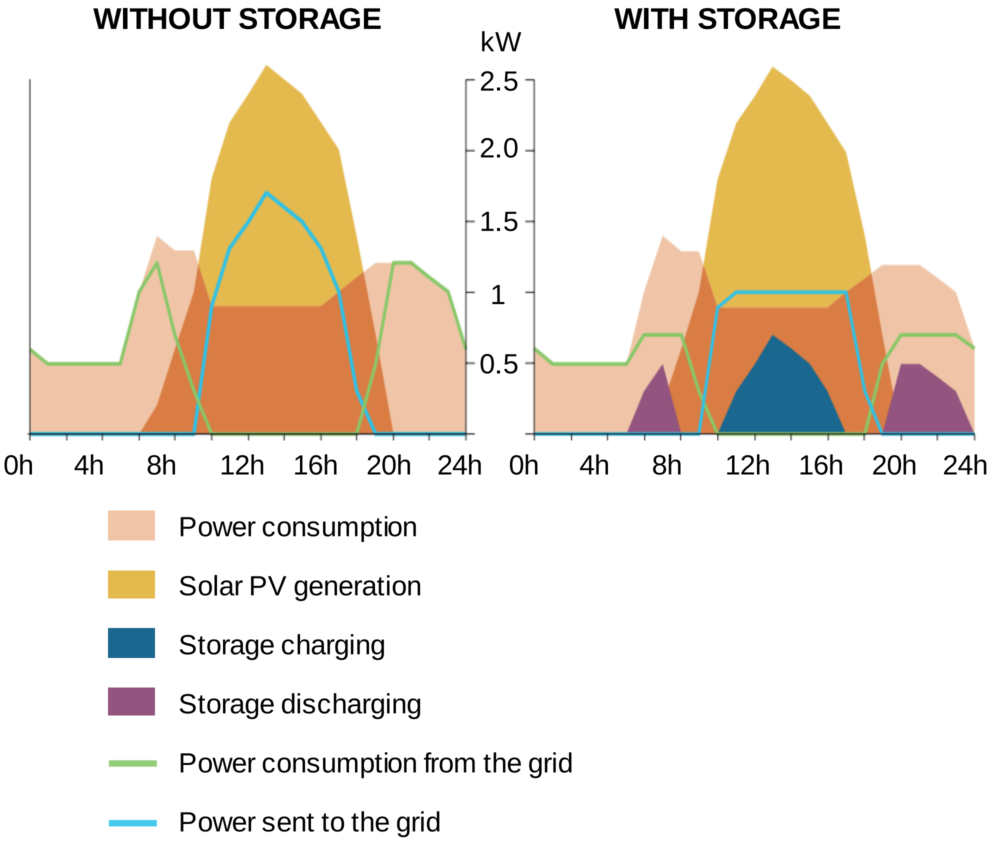
1. Seasonal and annual variations are more extreme at higher latitudes, making it more difficult to balance supply and demand.

Source: A.T. Kearney Energy Transition Institute based on RTE eco2mix, "Production d'électricité par filière" data (accessed April 2017)

There is a growing interest for the development of combined solar PV and batteries storage solutions

Increasing self-consumption of rooftop PV with electricity storage



- **Solar PV makes power demand-supply matching more difficult**[1]. Being variable, solar PV increases the need for flexibility within the system, but does not itself contribute significantly to flexibility. Flexibility management can be optimized by fine-tuning market regulations or improving solar forecasting, but additional flexibility will be needed in the form of demand-side participation, better connections between markets, greater flexibility in base-load power supply or electricity storage.
- **Many storage technologies have been developed in recent decades**[1] such as pumped-hydro storage or flywheel. These technologies are not in direct competition with one other. They are constrained by their design limitations to meet specific storage applications requirements. Due to the relative predictability of solar PV daily patterns, and to the development of distributed PV generation with limited power and energy storage requirements, batteries seem very fitted for PV.
- **Batteries deployment accompanies solar development**, notably in the US, in Australia and in Germany. In addition to the recent launch of Tesla lithium-ion solutions, both for residential (13.5 kWh *Powerwall*) and utility-scale (100 kWh *Powerpack*)[2], many other manufacturers are offering batteries solutions for PV customers such as LG, Panasonic, GE, Samsung, Schneider Electric, or Daimler. Batteries cells are thought to exhibit common features with PV cells, notably their modularity and associated learning rate.

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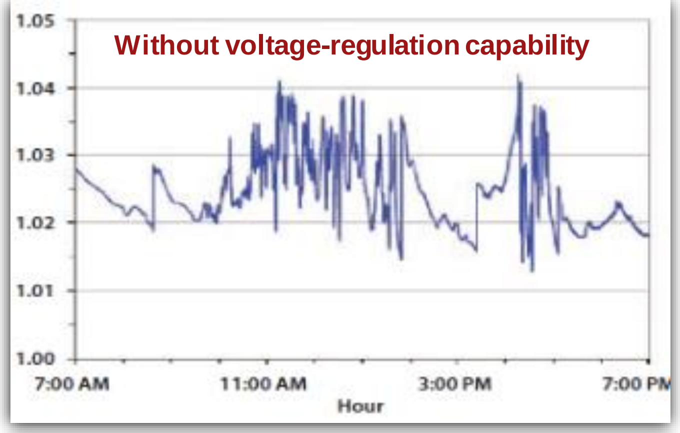
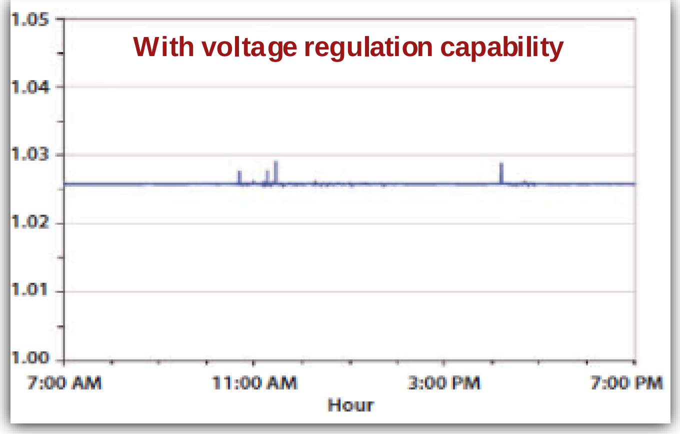
1. For more information on electricity storage and intermittency challenging, refer to A.T. Kearney Energy Transition Institute Electricity Storage FactBook (link); 2. For more information on Tesla, refer to Tesla website

Source: IEA (2014), "Technology Roadmap Solar Photovoltaic Energy"; IPCC (2011), "Special report on renewable energy"; IEA (2011), "Solar Energy Perspectives

Distributed solar PV requires distribution-system enhancements to improve grid stability and ensure reliable power flows

Voltage at the Point of Interconnection of a Solar PV System with the grid

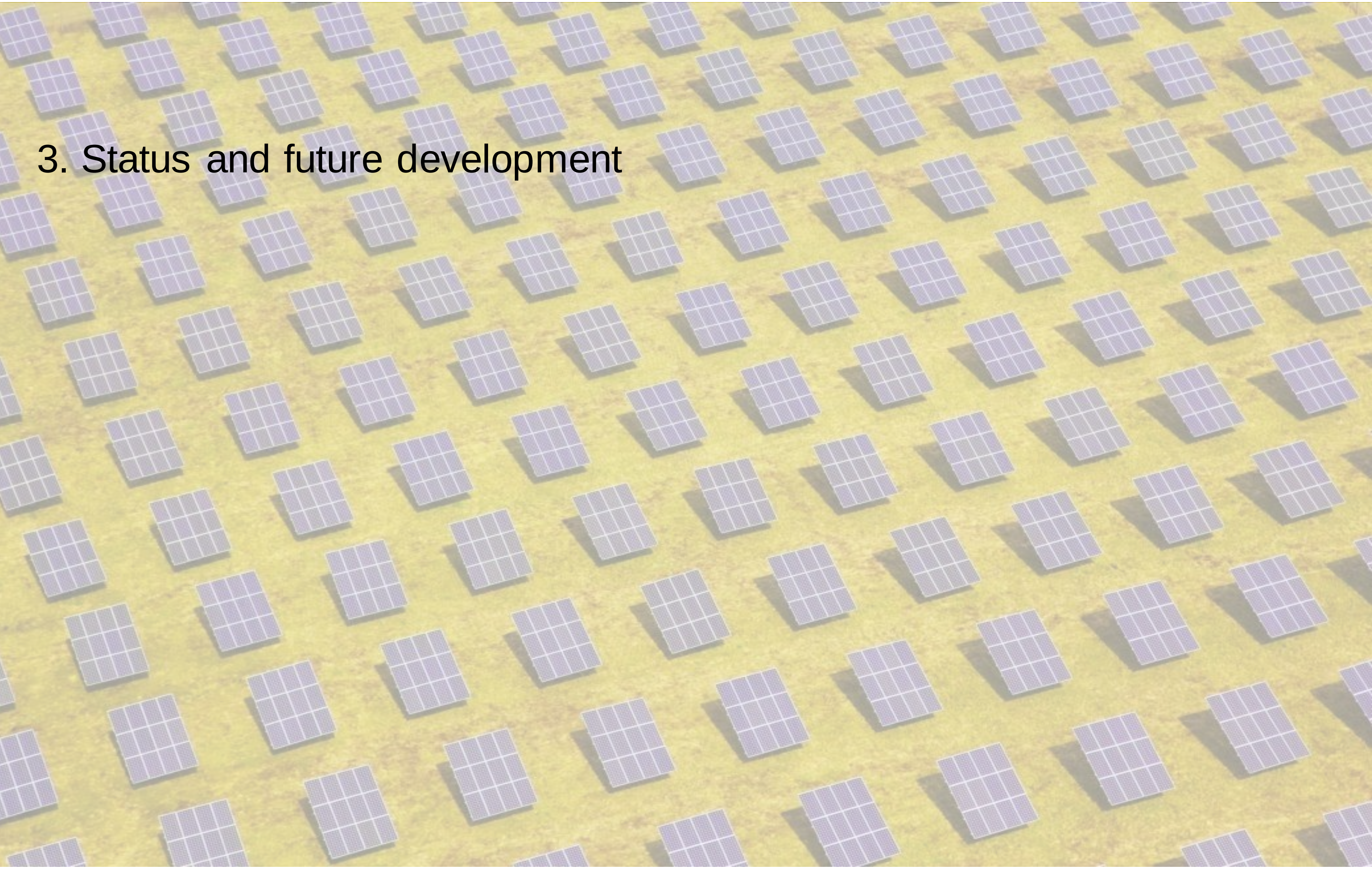




- **If the penetration of distributed generation (DG) grows, DG cannot continue to be regarded simply as a reduction in load**. The 'fit & forget'[1] approach that drove the creation of today's distribution system will no longer apply. Distributed generation can have an adverse impact on an electricity-supply system and requires:
  - Power quality (voltage and frequency control);
  - System reliability (fault detection);
  - Safety (islanding operation).
- **Voltage regulation:** distributed generation can complicate the regulation of voltage along distribution feeders. Advanced power electronics could help distributed generation units play an active role in voltage regulation (*e.g.* power-conditioning modules within units).
- **Islanded operations**: system operators may require distributed generation units to be disconnected during system outages, preventing distributed generation from providing reliability benefits. Distributed monitoring and control overcome this hurdle (only possible for mid-sized distributed generation or micro-grids for cost reasons).
- **Management system**: distributed generation can disrupt the operation of system-protection schemes by making it harder to detect a fault and to coordinate protection devices. New sensors, communication equipment and management systems could help reduce costs.

1. The fit and forget approach means that distributed generations are built on the basis of present technologies where centralized control is applied to transmission systems and passive control to distribution systems.

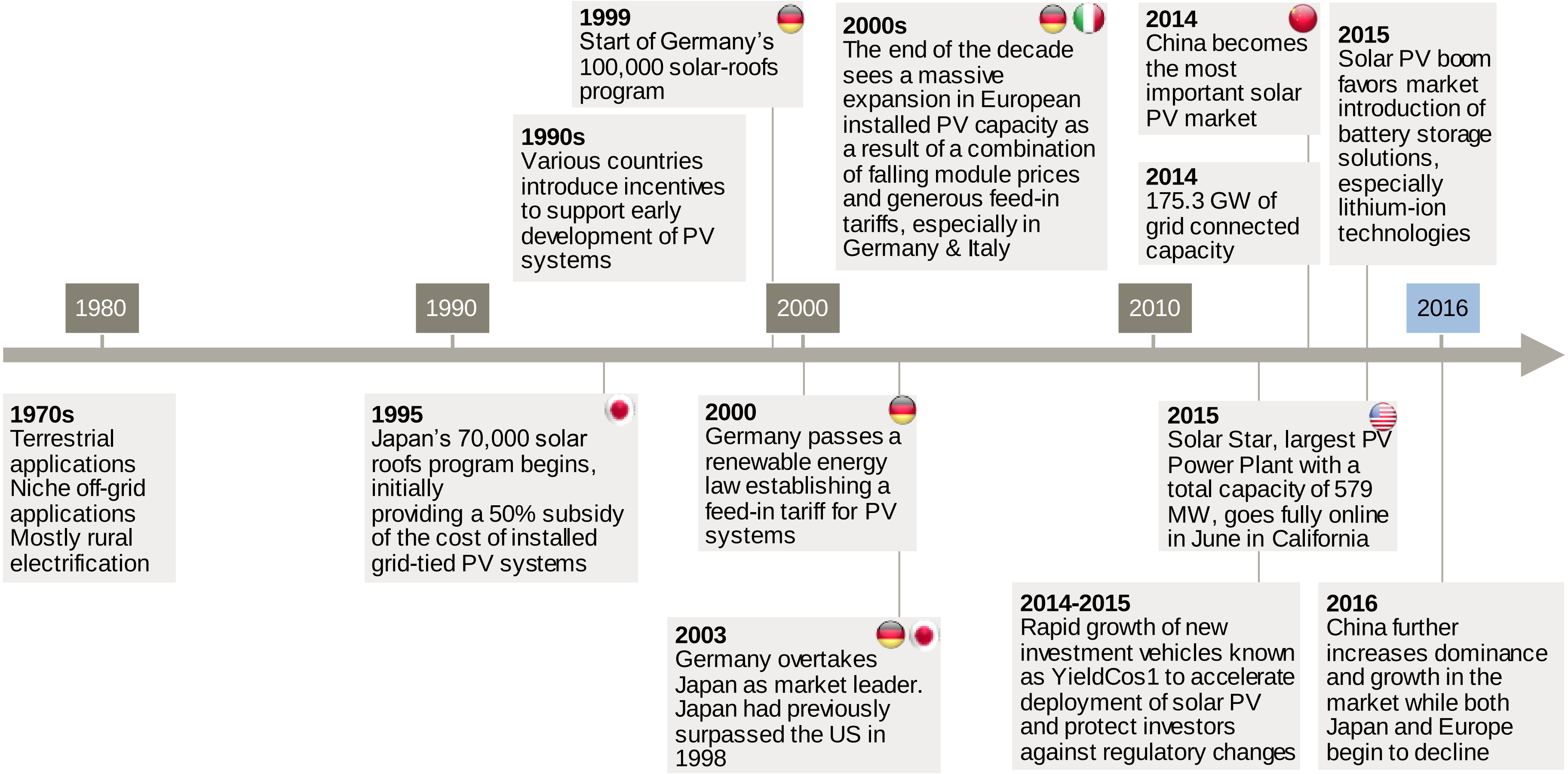
Source: MIT (2011), "The Future of Electric Grid"



3. Status and future development

Solar PV development started in the 1990s

Solar PV development timeline



1970s
Terrestrial applications
Niche off-grid applications
Mostly rural electrification

1990s
Various countries introduce incentives to support early development of PV systems

1995
Japan's 70,000 solar roofs program begins, initially providing a 50% subsidy of the cost of installed grid-tied PV systems

1999
Start of Germany's 100,000 solar-roofs program

2000
Germany passes a renewable energy law establishing a feed-in tariff for PV systems

2000s
The end of the decade sees a massive expansion in European installed PV capacity as a result of a combination of falling module prices and generous feed-in tariffs, especially in Germany & Italy

2003
Germany overtakes Japan as market leader. Japan had previously surpassed the US in 1998

2014
China becomes the most important solar PV market

2014
175.3 GW of grid connected capacity

2014-2015
Rapid growth of new investment vehicles known as YieldCos1 to accelerate deployment of solar PV and protect investors against regulatory changes

2015
Solar Star, largest PV Power Plant with a total capacity of 579 MW, goes fully online in June in California

2015
Solar PV boom favors market introduction of battery storage solutions, especially lithium-ion technologies

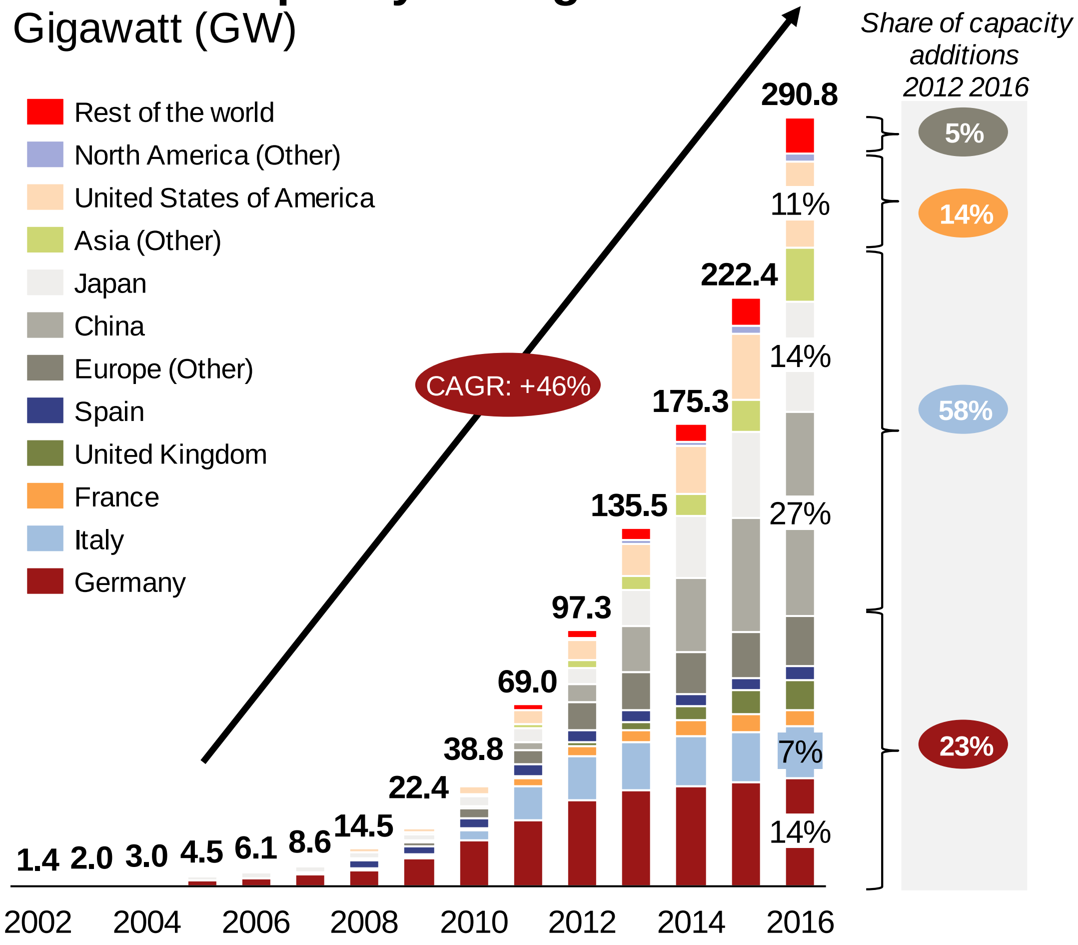
2016
China further increases dominance and growth in the market while both Japan and Europe begin to decline

Note: [1] For more information on YieldCos, refer to slide 64.
Source: A.T. Kearney Energy Transition Institute; IEA (2012), "Renewable Energy, Medium-term market report"; IEA (2012), "A Snapshot of Global PV 1992-2016"

PV capacity has grown at an average annual rate of 46% over the past decade, with China replacing Europe as the major growth driver

Installed capacity BY region

Gigawatt (GW)



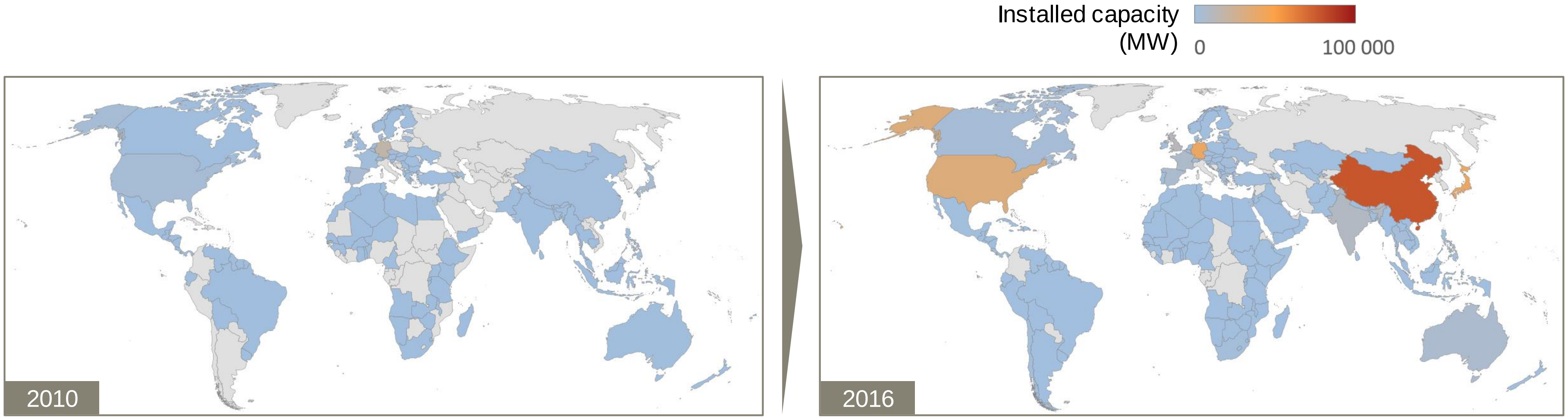
- **PV has been the fastest-growing renewable technology since the 2000s**, with an average annual growth rate of around 30% over the past four years, compared with 16% in the case of onshore wind.
- **Recent years have seen a rapid development of solar PV in Asia**, particularly in China and Japan. In 2013 and 2014 China made the world's largest capacity additions, with more than 10 GW each year, confirming its role as a leader in renewable technologies. After China, Japan and the US made the second- and third-largest capacity additions, with 9.6 GW and 6.2 GW, respectively.
- **Conversely, capacity additions in Europe in 2016 were down by 65% from 2012.** Germany has long been the main market for solar PV and accounts for ~14% of installed capacity but is lagging behind in capacity additions. Growth is flattening out because of reductions in feed-in tariffs, regulatory changes and the political will to reduce the cost of renewables borne by electricity consumers.
- **At the end of 2016, total capacity amounted to around 291 GW**. China (77.4 GW), Japan (41.6 GW), Germany (40.9 GW), the US (32.9 GW) and Italy (19.2 GW) are the largest countries in terms of installed capacity. Together, these five countries account for about 73% of total global installed capacity.

Source: IRENA (Accessed April 2017), "Data and Statistics"; IEA PVPS (2016), "Trends 2016 in Photovoltaic Applications"

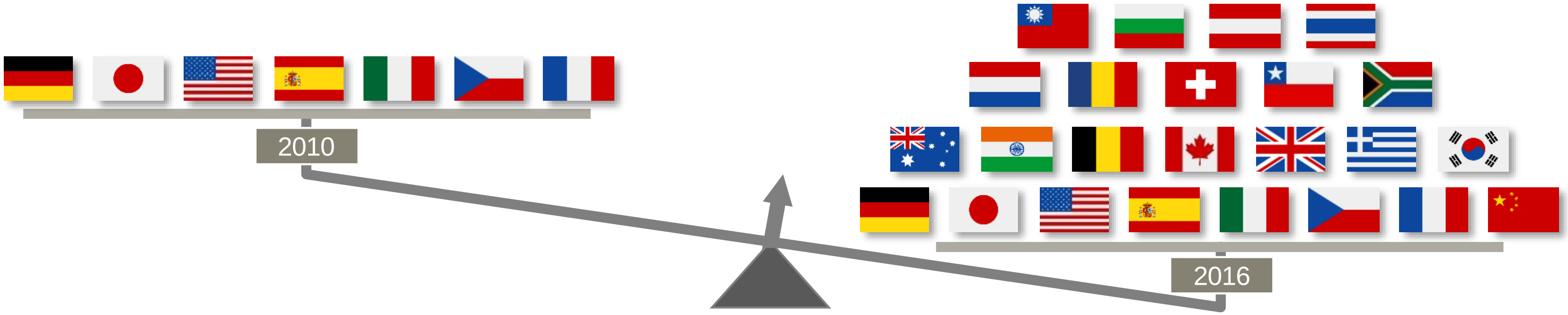
Solar PV deployment is spreading worldwide

Cumulated installed capacity

Gigawatt (GW), 2010, 2016



Countries with more than 1 GW cumulated installed capacity only

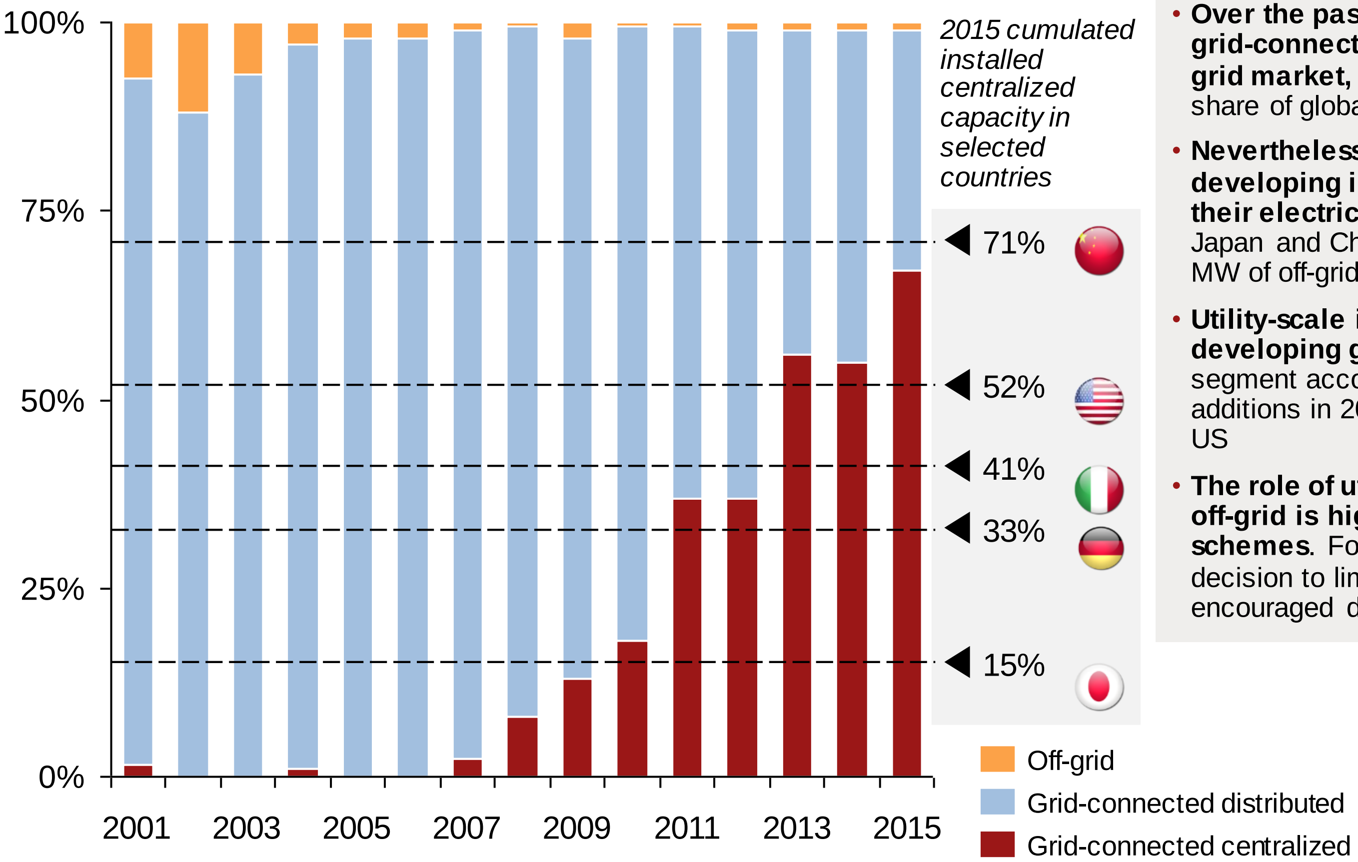


Source: IRENA (Accessed June 2017), "Data and Statistics"; IEA PVPS (2016), "Trends 2016 in Photovoltaic Applications"; A.T. Kearney Energy Transition Institute

The vast majority of PV capacity is connected to the grid, with utility-scale systems playing a growing role

Annual PV capacity addition by type

Share (%)



- **Over the past decade, rapid deployment of grid-connected PV systems outshone the off-grid market, which** accounts for an embryonic share of global installed capacity.
- **Nevertheless, off-grid applications are developing in countries with constraints in their electricity grids[1].** For instance, Australia, Japan and China[2] installed 25 MW, 2 MW and 20 MW of off-grid systems in 2015, respectively.
- **Utility-scale is playing an increasing role in developing grid-connected systems.** This segment accounted for almost 66% of capacity additions in 2015, mainly driven by China[2] and the US
- **The role of utility-scale, distributed solar and off-grid is highly dependent on local support schemes**. For instance, in Europe, recent decision to limit support for utility-scale PV have encouraged deployment of decentralized PV[3].

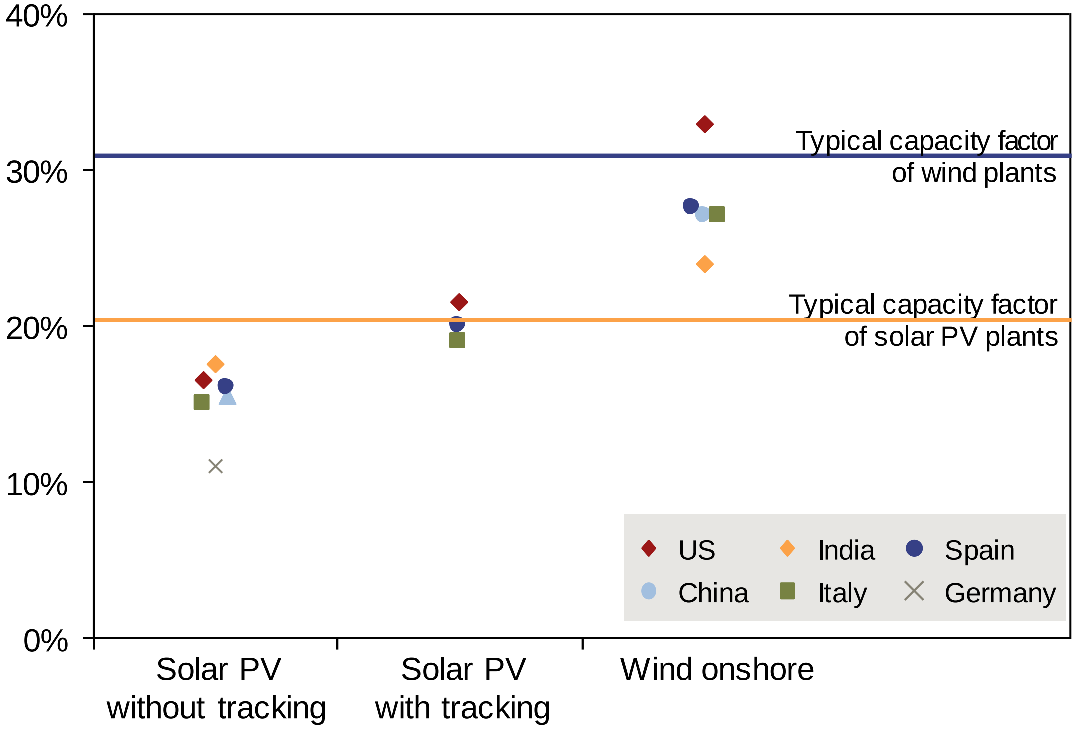
1. Such as remote areas or islands. In some countries, off-grid PV systems are connected with back-up supply, such as diesel generators or chemical batteries: 2. The share of distributed generation in China should be analyzed with caution since systems of up to 6 MW can be categorized as distributed; 3. This decision can be explained by a combination of concerns, such as land-use, grid connection issues, and the limited competitiveness of centralized PV with the wholesale electricity market..

Source: IEA (2014), "Technology Roadmap Solar Photovoltaic Energy"; IEA-PVPS (2016), "Trends 2016 in Photovoltaic Applications"

Capacity factor varies from a technology to another and depends on local conditions

Average capacity factors (CF) for selected Countries and technologies

Capacity factor in %



- **Capacity factors have a crucial impact on the competitiveness of generation technologies.** Capacity factor is a measure (expressed as a percent) of how often and how efficiently an electric generator operates over a specific period of time, using a ratio of the actual output to the maximum possible output over that time period. Capacity factors for renewable energy are hence highly technology- and site-specific[1].
- **In the case of solar PV, capacity factors are highly dependent on actual insolation**, **shading losses** (e.g. due to soiling or snow coverage), **module efficiency losses** (*e.g.* in electrical components, due to tracking inaccuracy or age-related degradation).
- **Solar PV capacity factors, which tend to be around** 20%, are generally lower than those of **other technologies**: 22% for solar thermal and 31% for wind. The capacity factor for a natural gas combined cycle typically reaches around 44%, but can technically reach 90%.

$$CF = \frac{\text{Actual AC output (kWh/y)}}{\text{DC peak power rating}\left(\text{kW}_\text{p}\right)\text{ x 8,766 (h/y)}}$$

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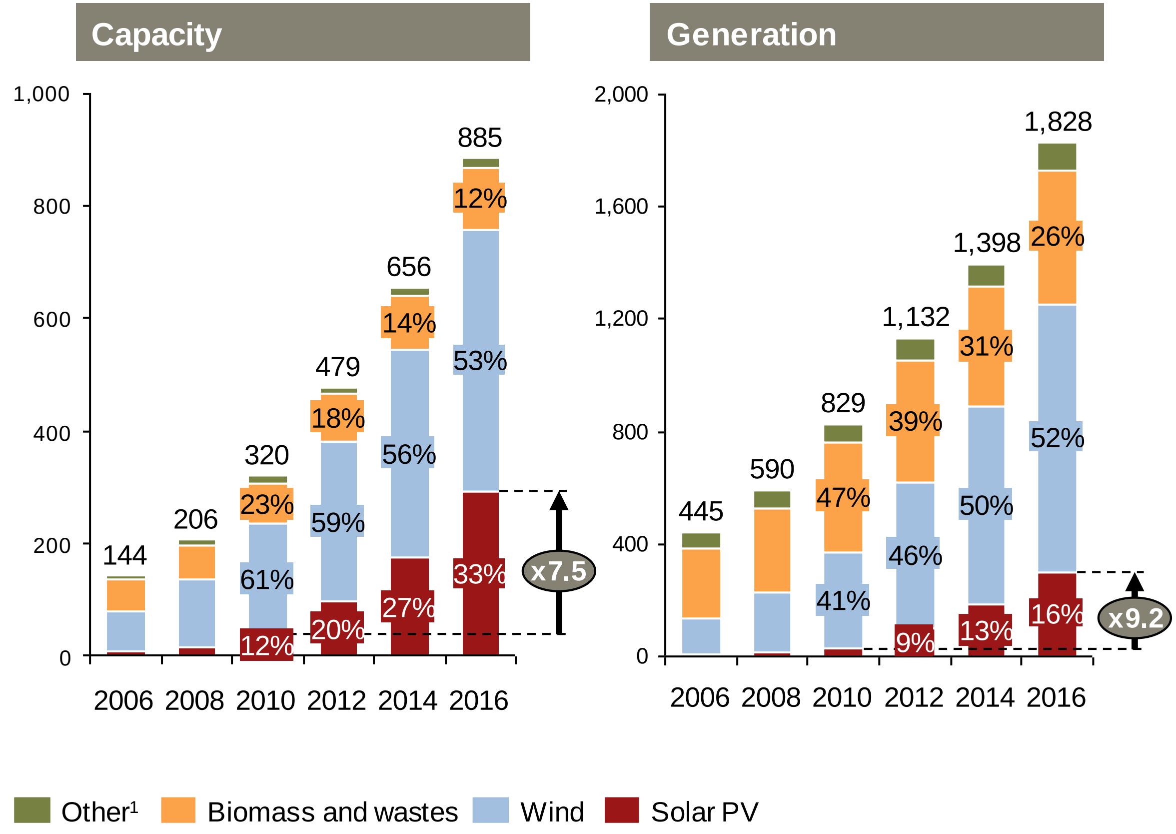
1. Capacity factor is sometimes referred as load factor. However, capacity factor is usually used only on an annual basis, whereas load factor can refer to any defined time period. More importantly, capacity factor is the ratio of power actually produced to rated power output, whereas load factor refers to the reference power capacity over the considered period; 2. This is not the case of DC peak power rating (in Wp), which reflects the efficiency of solar modules under given standard test conditions: 1000W/m2 irradiance, 250C and air mass 1,5 (AM 1,5) spectrum.

Source: MIT (2015), "The Future of Solar Energy"; BNEF (2015), "H1 2015 EMEA LCOE Outlook"; WEC (2013), "World Energy Perspective« ; EIA (2015), "Electric Power Monthly"

Solar PV's share of the generation mix is growing faster than the contributions of other renewables

Renewable Power installed capacity and generation, excluding hydropower

Capacity (GW), Generation (TWh)



- **With regards to installed capacity, solar PV is lagging behind hydro and wind. In 2015, installed solar capacity amounted to** 222 GW, compared with 1,209 GW for hydro and 430 GW for wind. However, thanks to the recent boom in capacity additions, solar PV is catching up with renewable alternatives, recently overtaking biomass and waste as the third-largest renewable technology by installed capacity.
- **Solar PV electricity generation has grown faster than installed capacity** (increasing by a factor of 9.2 between 2010 and 2016, compared with 7.5 in the case of capacity). The is because the average capacity factor has increased as a result of the deployment of solar PV in sunnier countries, and as a result of improvements in the orientation of modules and system performance factors.
- **Nevertheless, the contribution of PV to the generation mix remains significantly lower than its share of installed capacity**. Although a similar discrepancy also applies to wind, PV is characterized by lower capacity factors, typically ranging from 10% to 25%, depending on technologies and locations.

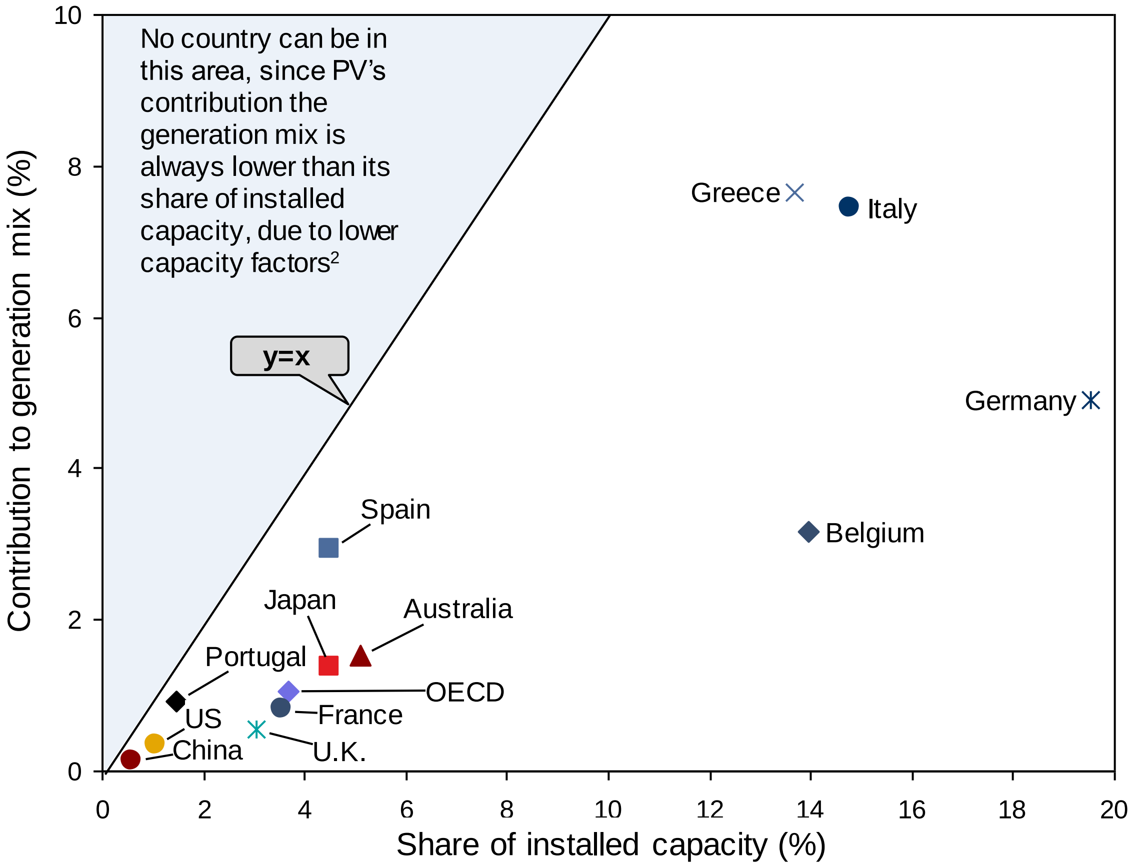
---

1. Includes geothermal and CSP; 2. Such as temperature, module mismatch, varying irradiance, dirt, line resistance and conversion losses in inverters. Some PV plants can reach yearly average performance ratios of 80-90%.

Source: A.T. Kearney Energy Transition Institute analysis based on IRENA (accessed April 2017), "Data and Statistics"; IEA (accessed 2017), "Power Generation" (link); IEA (2017), "Energy Technology Perspective"; IEA (2015), "Renewable Energy Medium Term Market Report"

Solar PV's share of the power generation mix varies by country, according to installed capacity and solar irradiance

Solar PV: contribution to generation mix vs. share of installed power capacity, 2013[1]



- **The penetration of solar PV in national power markets is highly variable** and is not correlated to market size. For instance, China is the largest country in terms of installed capacity, but ranks poorly in terms of PV penetration (estimated 1.6% in 2016).
- **In 2016, the global PV penetration rate was 1.8% (% of world electricity demand met by PV)** with Greece (7.4%), Italy (7.3%), Germany (7.0%) and Japan (4.9%) achieving penetration rates significantly above the average.
- Some small countries have attained even higher PV penetration rates. **Honduras leads the world, with 12.5% penetration rate** achieved in a short span highlighting the speed at which PV can be deployed. Meanwhile, several islands and countries with low energy demand have also achieved penetration rates of 4-12%.
- In Germany, solar PV accounted for 18% of total power capacity (2012) and can generate up to 50% of instantaneous power demand on some days, and around 13% of electricity during peak periods. Nevertheless, because it has lesser solar resources than Italy, Germany lags behind in power generation.

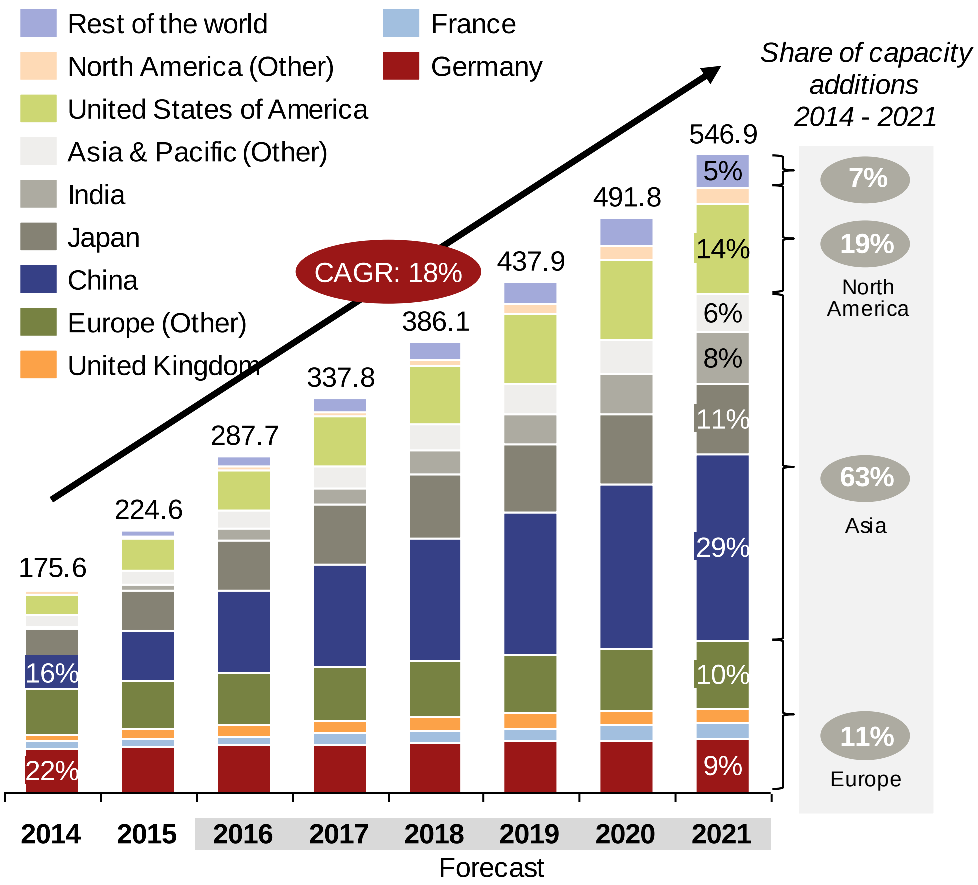
1. Data for China are given in 2012; 2. For more information, refer to slide 39

Source: IEA (2015), "World Energy Outlook"; IEA-PVPS (2013), "Trend 2013 in Photovoltaic Applications"; EIA (accessed July 2015), "International Energy Statistics", IRENA (accessed July 2015), "Renewable Power Capacity Statistics 2000-2014", IEA-PVPS Snapshot of Global PV 2016, IEA-PVPS Trends in PV Applications 2016

Solar PV will continue to spread

Projected mid-term Cumulative PV Capacity

GW[1]



- **PV should maintain strong growth to 2021**, expanding by 18% a year over the period, according to the IEA latest Medium-Term Renewable Energy Market Report. The IEA's projections have been revised up several times, reflecting improving economics and accelerated deployment in a number of countries.

- **PV deployment will continue to spread to more countries.**
  - **Asia-Oceania:** China will see the strongest growth, adding more than 18 GW per year[2]. Economic incentives[3] are expected to boost Japan's capacity to 60 GW by 2021. India should also play a leading role, with capacity surpassing 40 GW in 2021. The Australian market should also take off, as rooftop solar PV becomes competitive with grid electricity.
  - **Americas**: the US market is expected to grow by 60 GW between 2014 and 2021, driven by utility-scale projects[4], and the growing attractiveness of rooftop systems. Mexico, Canada, Brazil and Chile[5] are also attractive markets.
  - **Europe**: despite a slow-down in capacity growth, Europe remains an important market for solar PV, driven by the long-established markets of Germany, Italy and Spain, as well as by emerging markets, such as the United Kingdom, Turkey or eastern Europe.
  - **Other:** PV capacity in other countries should reach 30 GW by 2021 – more than total world capacity at the end of 2009, with important programs in the Middle East and South Africa

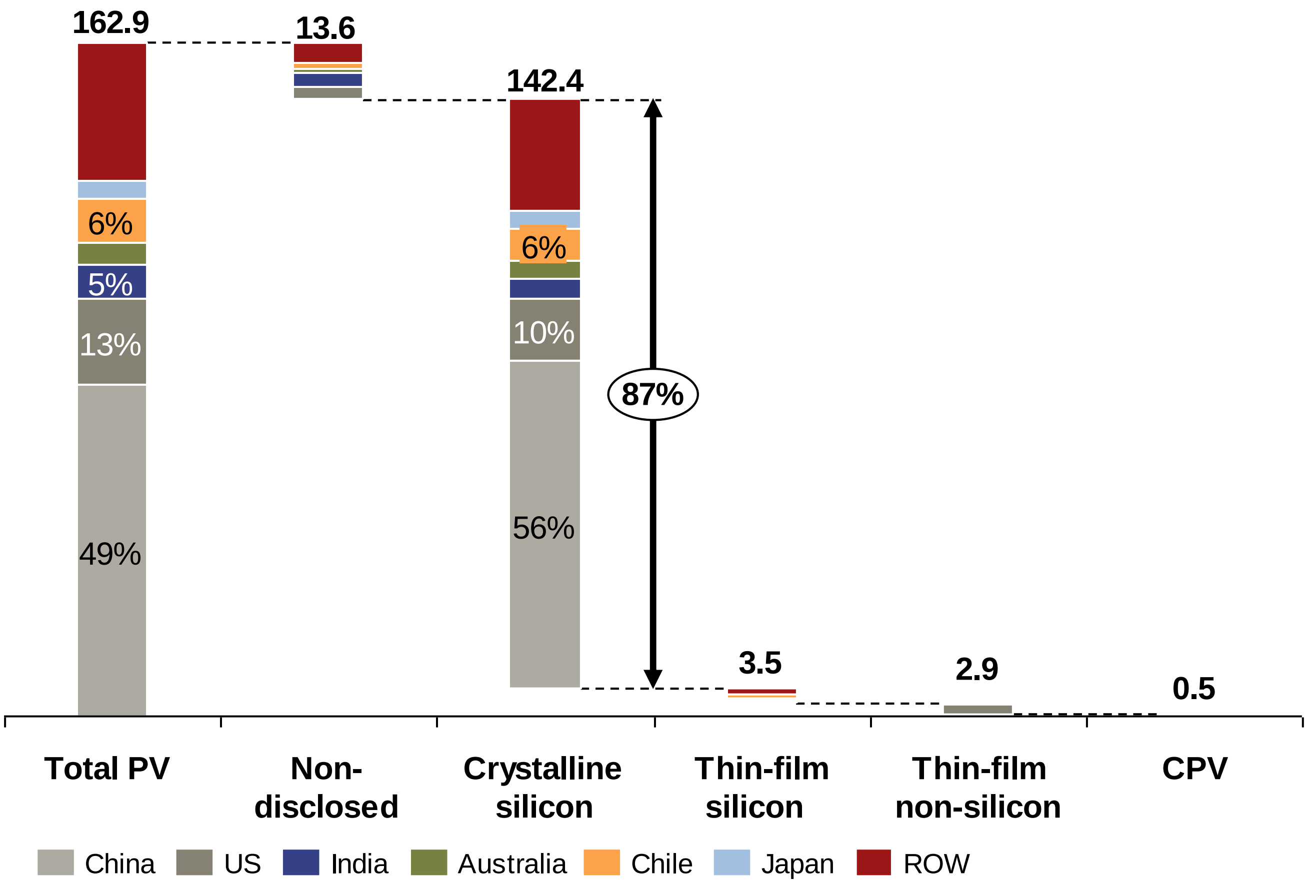
1. 2014 data are from IRENA (2015) and forecast data are from the IEA (2016); 2. Driven in particular by relatively low investment costs. Development of commercial scale PV is nevertheless constrained by difficult access to financing; 3. Also grid congestions limit PV deployment; 4. Despite a planned reduction in the ITC, from 30% to 10%, in 2016; 5. Large pipeline of utility-scale plants; 6. According to the IEA, this rate could be even higher under favorable conditions

Source: IEA (2011), "Solar Energy Perspectives"; IEA (2016), "Renewable Energy, Medium-term market report"

Most solar PV projects are still based on crystalline silicon technology

Projects under construction, announced and Permitted

Gigawatt (GW)



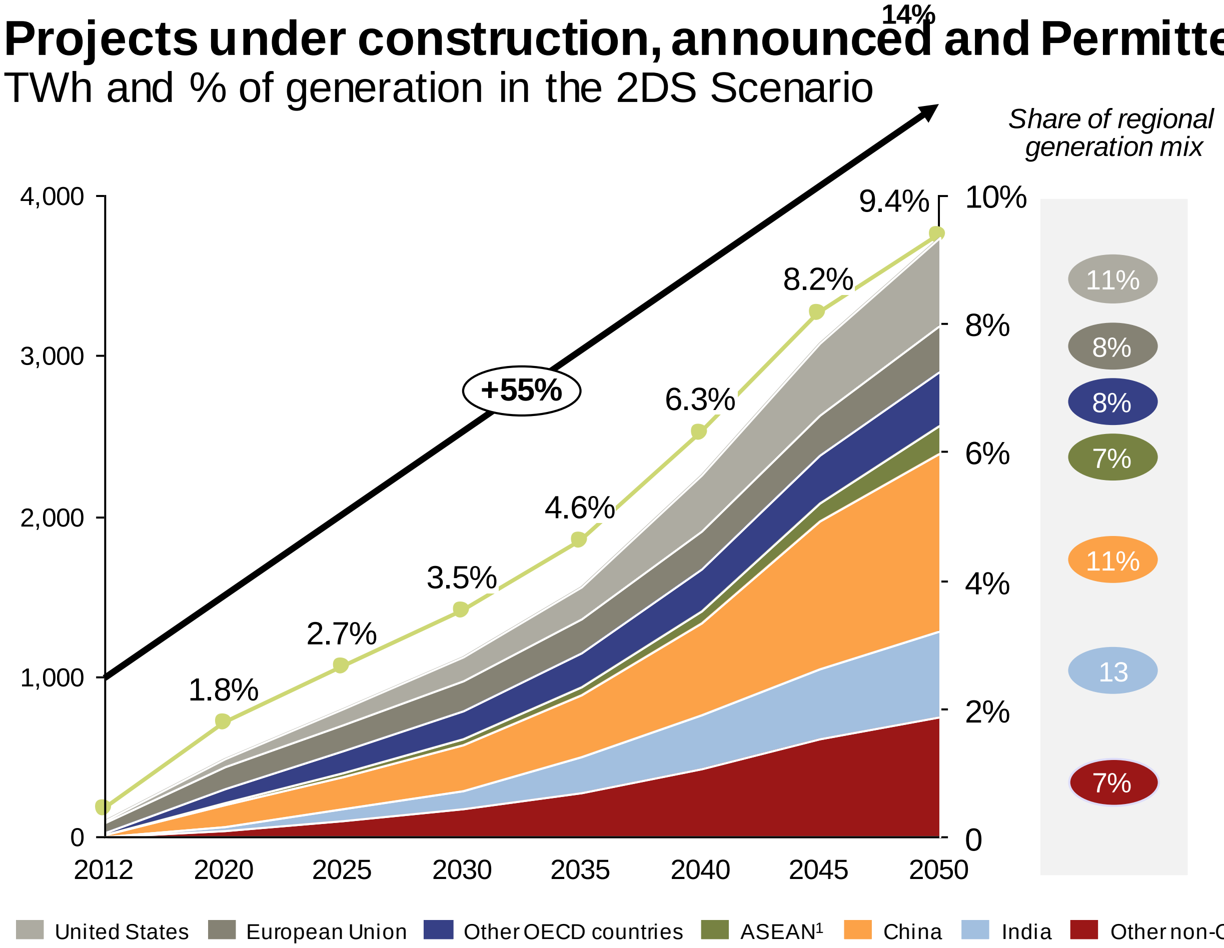
- **Overall, 162.9 GW of PV projects are announced, planned, permitted, or under construction.** These additions to capacity, if commissioned, would result in almost a doubling of current cumulated global capacity (175.3 GW).
- **Of projects announced or under construction, 87% will deploy crystalline silicon PV cells.** 95% of projects announced or under construction that have disclosed their technology will deploy crystalline silicon PV cells. This is even higher than two years ago, when these shares were 74% and 91%, respectively.
- **The US is also especially active in novel PV technologies**, accounting for 86% of non-silicon thin-film projects. China, meanwhile, accounts for 75% of CPV projects.

Source: Bloomberg New Energy Finance (accessed July 2015), "Renewable Energy Projects"

Solar PV is expected to play a crucial role in most long-term energy scenarios

Projects under construction, announced and Permitted

TWh and % of generation in the 2DS Scenario



- **Most long-term scenarios foresee solar PV as a crucial source of low-carbon energy.** Solar PV would, for instance, need to account for 9.4% of global electricity supply by 2050 in order to meet the IEA's 2°C Scenario[2] (2DS, compared with 0.1% in 2010. To that end, capacity would need to increase to 3,743 GW. BNEF also forecasts a boom in solar installation worldwide, with PV accounting for 26% of generation capacity by 2040, with 3,695 GW.
- **All applications** – *i.e.* utility-scale, distributed generation and off-grid – **will have to coexist and expand rapidly** for PV's share of global generation to meet IEA and BNEF targets. Both envision an equal role for distributed generation and utility-scale systems[3].
- **Asia is at the forefront of PV development.** China is expected to overtake Europe as the largest producer of PV electricity in the early 2020s and to account for more than 30% of PV power generation in 2050..

1. ASEAN includes Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam; 2. And up to 16% in the high-RES ETP 2015 Scenario; 3. According to BNEF, the real solar revolution will be rooftops, driven by high residential and commercial power prices, and the availability of residential storage in some countries. In addition, the IEA indicates as possible break-down of PV capacity addition: over 50% from utility scale, 32% from commercial and 15% from residential.

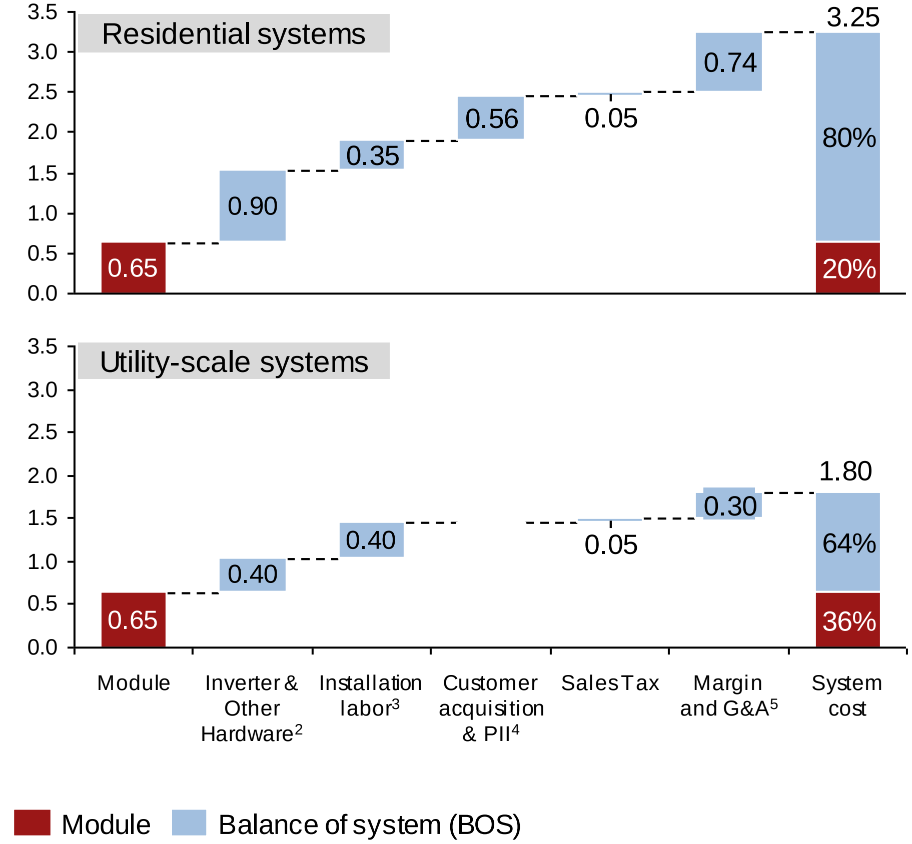
Source: IEA (2014), "Technology Roadmap Solar Photovoltaic Energy"; IEA (2015), "World Energy Outlook 2015"; Bloomberg New Energy Finance (2015), "New Energy Outlook 2015"

4. Economics and ecosystem

Investment requirements are highly sensitive to system scale and application

Estimated System cost breakdown in the US[1]

$ /Wp



- **The capital cost of a PV system is made up of two main components: PV module and balance of system (BOS).** PV module costs comprise raw materials, cell processing and manufacturing, and module assembly. For a long time, modules accounted for the largest share of PV-system costs. But, as a result of recent declines in module costs and prices, BOS has become the main cost driver (64%-80%), especially in small-scale residential systems.
- **Nevertheless, BOS costs vary widely, according to PV system design.** They depend in particular on whether PV modules are mounted on the ground or on rooftops, and on their ability to track the sun. For instance, in the US, implementing a tracking system can increase the cost of a PV system by 13% per unit of capacity, assuming all other variables are unchanged. However, it is estimated that adding tracking capability results in an increase in energy production of 20%-30% per year.
- **Overall, the system size of a solar photovoltaic (PV) generator has a considerable impact on its costs.** Large PV systems significantly reduce the cost per unit of capacity. Module costs slightly decrease with system size, but most of the economies of scale are achieved as a result of reductions in BOS and installation costs[6]. Capital costs also vary according to technology used, manufacturers and market conditions.

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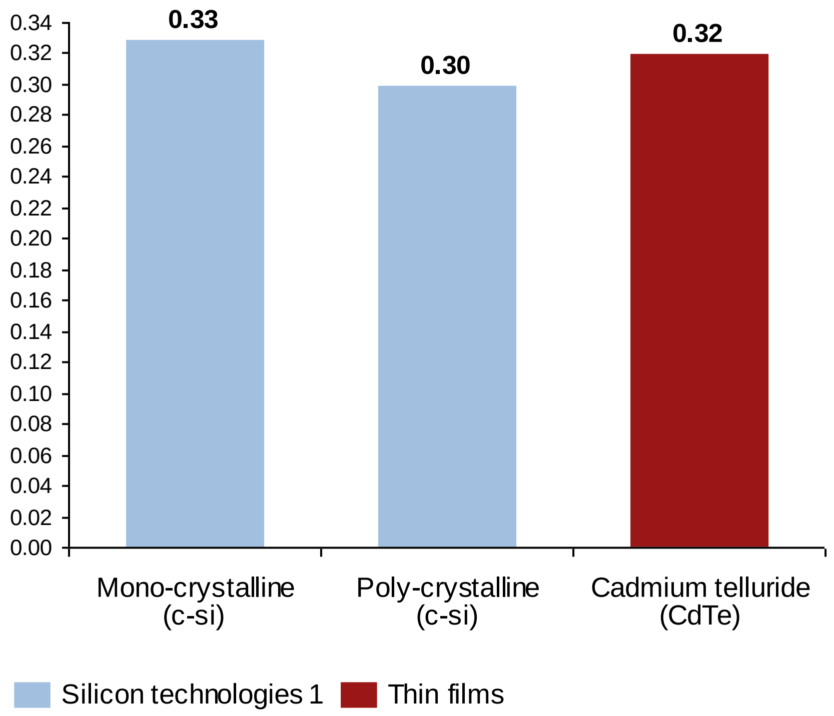
1. Reported prices can differ from estimated costs, especially for residential systems due to limited competition. For more information, refer to slide 47;
2. Includes logistics costs for residential systems; [3] Consists of engineering and construction costs for utility-scale systems; [4] PII for permitting, interconnection, and inspection; [5] General and administrative expenses; [6] Conversely, PV module costs only slightly decrease with system size.

Source: IRENA (2015), "Renewable Power Generation Costs in 2014"; MIT (2015), "The Future of Solar Energy"

The module costs of different PV technologies are converging

Typical PV module Cost by technology[1]

$ /W, Spring 2017



- In the past, cell technology had a significant effect on the cost of a PV module, with considerable differences between the costs of crystalline silicon (c-Si) and thin-film technologies. This variance, however, has reduced and cost differences between the main crystalline and thin-film technologies are now minimal.
- However, crystalline silicon technology still has a cost advantage over thin film. A thin-film PV cell requires a greater surface area (about 17% greater) to produce the same power as a crystalline module. Land requirements — and costs — therefore tend to be higher for thin-film.
- Different levels of efficiency also affect costs. For a given technology, it is estimated that a 1% increase in efficiency implies a $0.1 increase in costs, all other things being equal.

---

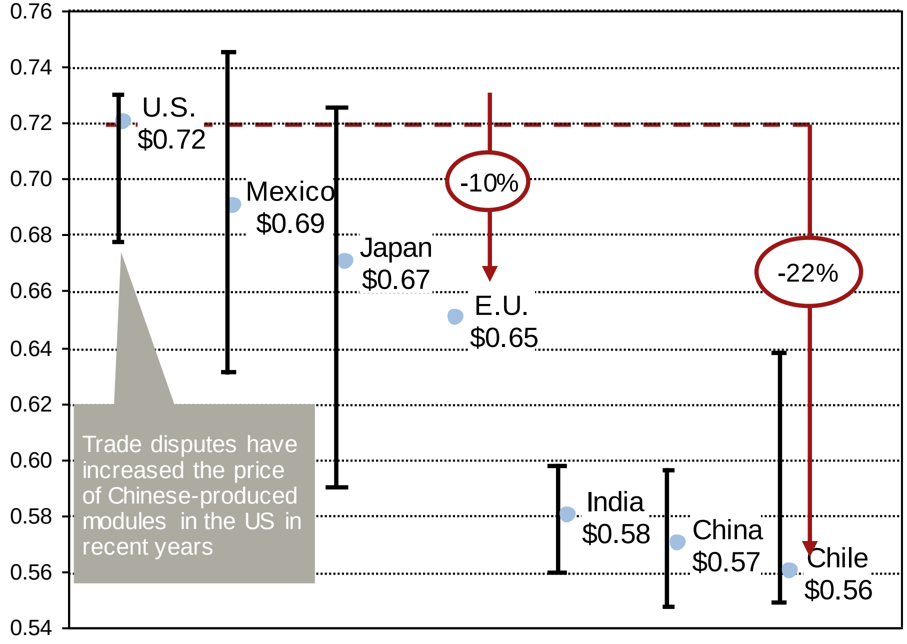
1. Including PERC cost of 0,01 $/W

Source: First Solar (2017); Canadian Solar (2017); Jinko Solar (2017)

PV module prices are very sensitive to manufacturer and market conditions, and China occupies the lower end of the price range

PV Module factory-gate prices by brand prices from tier-1 Chinese manufacturers

$ /W, Q4 2014



Trade disputes have increased the price of Chinese-produced modules in the US in recent years

- **PV module prices do not just reflect cell costs. They are also influenced by market conditions** (*e.g.* the level of competition, the supply-demand balance, the strategy of market players) and the origin of the manufacturing, leading to important discrepancies in cost and performance of modules from different manufacturers. PV modules are easier to ship over long distances than wind turbines, which are difficult to transport.
- **Chinese majors and emerging brands[1] are significantly cheaper than incumbent players in Japan and Western countries,** even if differences in price tend to narrow. In the US, crystalline silicon (c-Si)[2] modules supplied by Chinese majors are cheaper than those of Japanese, US or European suppliers. Emerging brands are also cheaper. This is the result of lower labor, processing and raw-materials costs, and of differing market-penetration strategies.
- **PV module factory-gate prices also vary according to end-market prices**. In Q4 2014, module prices from the main Chinese manufacturers were more expensive in the US than in other regions, such as Japan[3] or Europe. Discrepancies between countries depend mainly on local competition, local trade policies, module types and exchange rates. Retail prices are 35%-45% higher than factory-gate prices, reflecting the margins of the distributor (15%) and the retailer (20% to 30%, depending on the system size

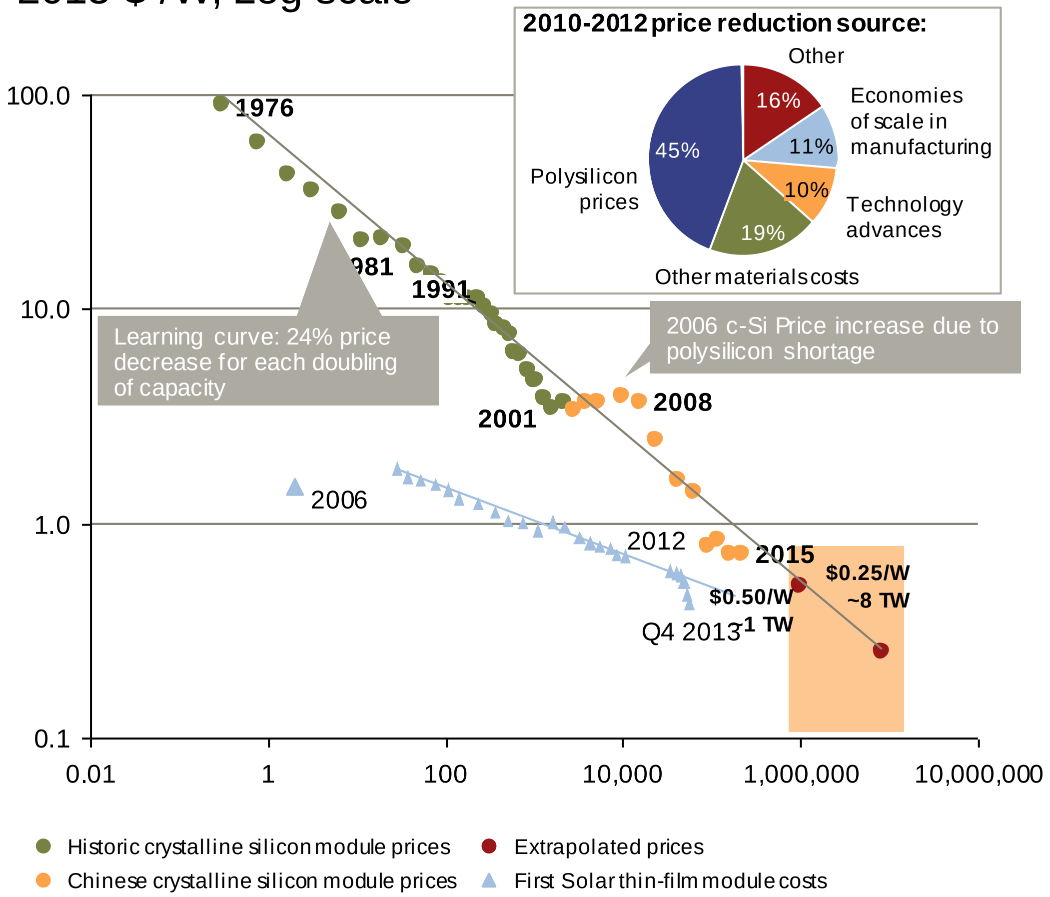
1. Emerging brands include Chinese, Korean and Indian manufacturers, Chinese majors means established Chinese companies; 2. c-Si for crystalline silicon; 3. Japan use to be the highest-priced regional market.

Source: IRENA (2012), "Renewable energy technologies: cost analysis series"; US DoE (2011), "2010 Solar Technologies Market Report"; GTM Research (2015), "Global PV pricing Outlook"

PV module prices have fallen sharply by an average of 22% for each doubling of cumulative sales

Global average module price

2015 $ /W, Log scale



- **Since 2009, solar PV modules have experienced very significant declines in price.** This trend accelerated between 2009 and 2014 for crystalline modules (c-Si), with price reductions exceeding historical learning rates of 24%.
- **This is the result of a combination of lower production costs and changing market conditions (price)**: (i) a drop in price of silicon and other materials since the 2008 recession; (ii) greater economies of scale in module manufacturing; and (iii) overcapacity[1] in module-production capacity and harsh competition.
- **The rapid decline in c-Si PV module prices has reduced the price advantage of thin-film PV** module manufacturers and contributed to c-Si technologies' market dominance.
- **Nevertheless, reductions in average module selling prices are stabilising[2] around $0.6 /W in 2014.** While prices might continue to fall, based on experienced learning rates of 18-22% (depending on the technology), cost-reduction potential is now expected to be more constrained than over the past decade.

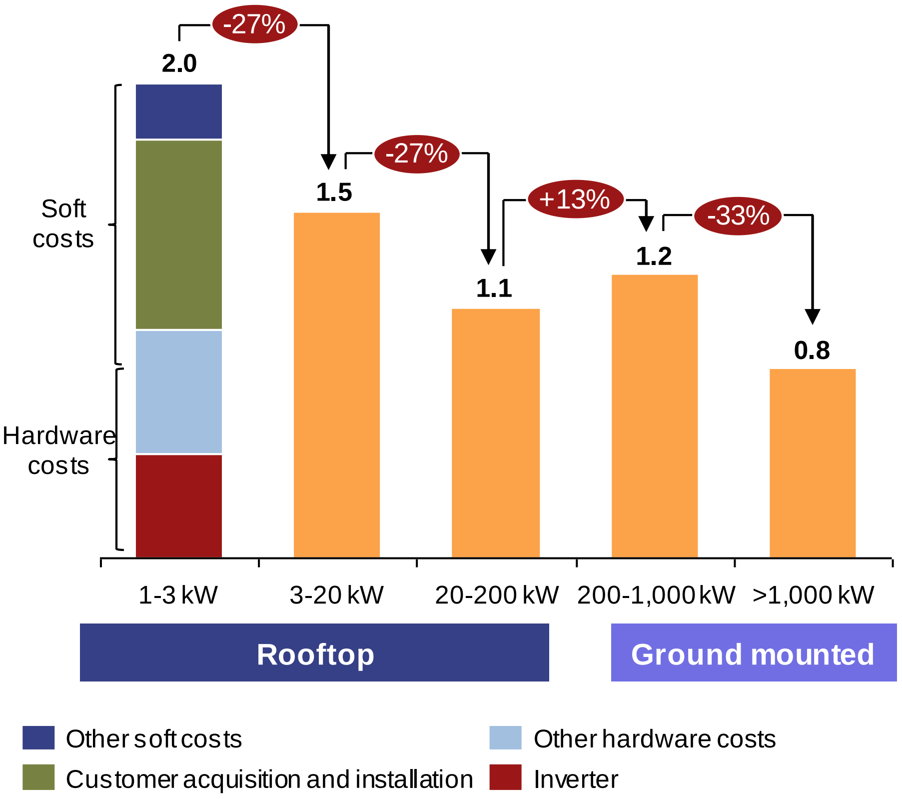
1. In 2011, estimated annual production capacity was 50 GW, but only 29.7 GW of that capacity was utilized in that year; 2. Driven by solar PV module manufacturers consolidating margins and, in many cases, trying to return to positive margins after a period of manufacturing overcapacity and severe competitive pressures in the industry.

Source: IRENA (2015), "Renewable Power Generation Costs in 2014"; IEA (2014), "Technology Roadmap Solar Photovoltaic Energy"; BNEF (2015), "PV module makers: tiers and trends"

Balance of system (BOS) costs encompass hardware and soft costs, and vary by application

BOS cost breakdown by project size

2014 $ /Wp, based on a solar system installed in Italy[1]



- **Balance of system (BOS) costs include hardware, but also soft costs.** Hardware costs comprise both structural (*e.g.* racking) and electrical (*e.g.* inverter, transformer, wiring…) system costs. Soft costs encompass labor for PV installation, customer acquisition, engineering, permitting, as well as installer and integrator margins and up-front financing costs[2].
- **Balance of system costs depend on where PV modules are mounted (on the ground or on rooftops), on their ability to track the sun and on the scale of the project.** Site preparation and installation are major components of BOS and installation costs and cause the largest variance in costs between ground-mounted and rooftop systems: rooftop BOSs are around 15% more expensive than ground-mounted systems. Tracking systems also add around 15% to the initial investment per watt. This is due to the price of the tracking system, as well as higher land acquisition and site preparation costs, given that modules need sufficient space between each others to avoid row-to-row shadowing.
- **Finally, all external factors being equal, utility-scale systems have lower BOS costs than small-scale residential systems per unit of power installed.** This is due to large economies of scale and procurement optimization. For the same reasons, the economics of large commercial rooftop installations are comparable to those of medium-scale ground-mounted systems.

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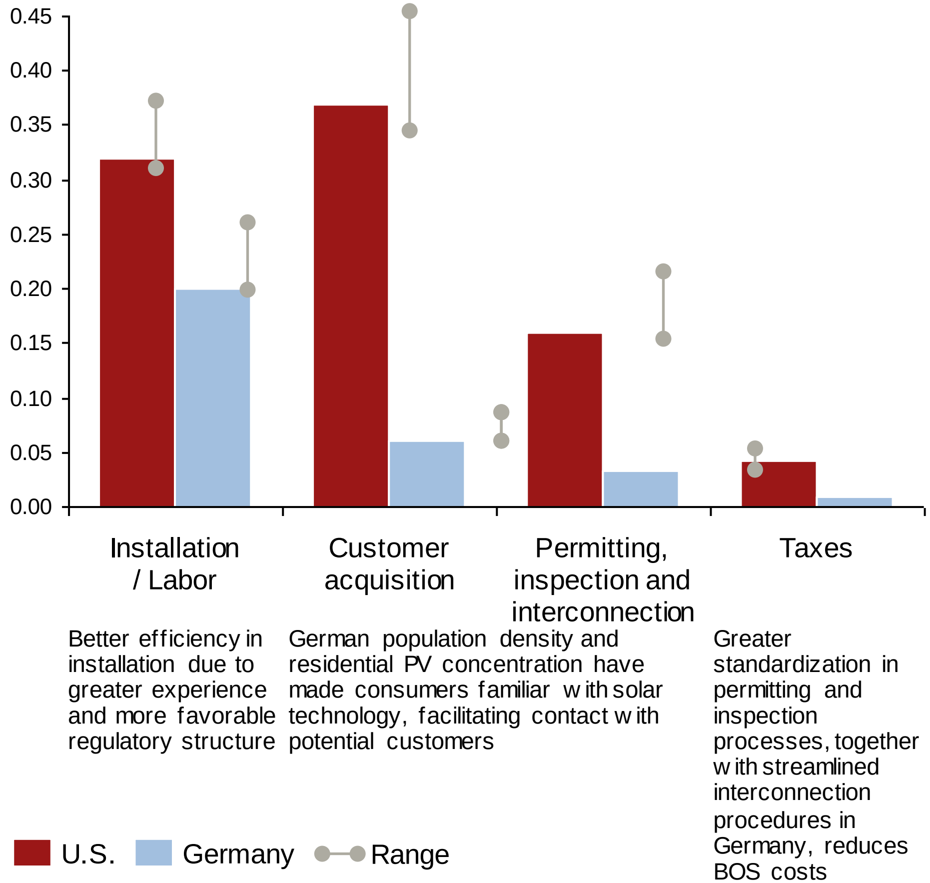
1. BOS costs are based on a best-practice solar system installed in Italy. Breakdown for 1-3 kW rooftops is based on US residential systems. Note that this breakdown is on an indicative basis and varies according to location and system size; 2. It can include legal fees, professional fees, O&M costs, production guarantees, reserves and warranty costs. Depending on how BOS is defined, BOS costs can be restricted to inverters, mounting hardware, and labor costs. For more information on BOS cost breakdown, refer to slide 46.

Source: IRENA (2015), "Renewable Power Generation Costs in 2014"

BOS costs vary significantly according to local market conditions, due to labor costs and regulatory environments

BOS SOFT costs Breakdown in Germany and the U.S

$ /Wp, residential market



Better efficiency in installation due to greater experience and more favorable regulatory structure

German population density and residential PV concentration have made consumers familiar with solar technology, facilitating contact with potential customers

Greater standardization in permitting and inspection processes, together with streamlined interconnection procedures in Germany, reduces BOS costs

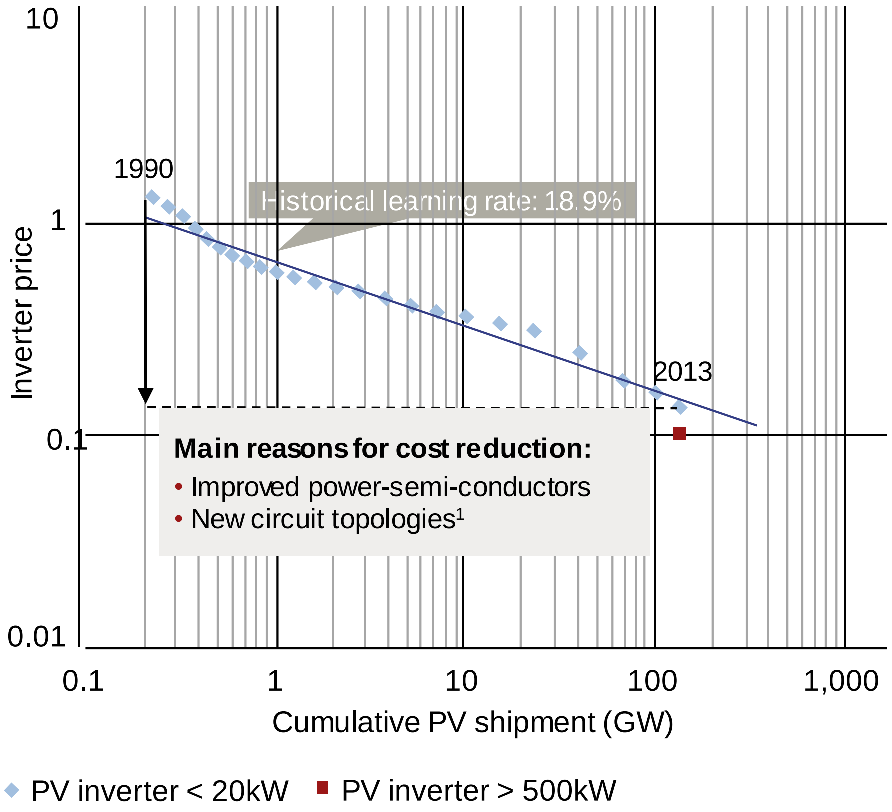
- **Local market conditions and regulatory environments tend to have an important impact on the BOS costs.** These variations can be explained by the fact that labor costs are an important component of BOS costs, but also by discrepancies in market maturity and by variations in the efficiency of support schemes[1].
- **Soft costs cause the largest variance in costs between projects and countries**. More specifically, customer acquisition, installation, and permitting, inspection and interconnection (PII) vary significantly between countries, as illustrated by the comparison between Germany and the US, two of the most mature solar markets in the world.
- **At the national level, variations in BOS costs are typically largest in small-scale residential systems and vary the least in utility-scale projects.** BOS costs in the latter are expected to converge further as best-practice spreads, as the market grows and as competition increases.

Source: IRENA (2015), "Renewable Power Generation Costs in 2014"; MIT (2015), "The Future of Solar Energy"

Reducing balance of system (BOS) costs is a priority in driving down overall PV system costs

Price experience curve of PV inverters

2014 € /Wp



Main reasons for cost reduction:

- Improved power-semi-conductors
- New circuit topologies[1]

- **Reducing BOS costs is critical in lowering overall solar PV system costs.** Since 2011, BOS costs have decreased globally. Inverter costs have decreased by 29%, racking and mounting structure costs by 12%, and other hardware costs by 20%. At the same time, soft costs[1] have, on average, remained unchanged (falling by 1% globally)[2].
- **Two main levers may further reduce BOS costs per unit of energy produced:** (i) reducing the cost of BOS hardware components through mass production, improved materials (*e.g.* mounting system manufacturers optimizing the quantity of steel and aluminum used) and competition (*e.g.* the entry of Chinese inverter suppliers may place downward pressure on prices in the coming years); (ii) improving module efficiency through increases in DC voltage and system size. Other potential cost reductions lie in the standardization and modularization of PV systems.
- **In some regions, market growth may also lead to reductions in soft costs** thanks to greater competition in installation markets, lower customer-acquisition costs and greater standardization in permitting, inspection and interconnection processes.
- **Nevertheless, reducing BOS costs may be more difficult to achieve than reducing module costs because BOS and installation costs fluctuate according to local labor costs.**

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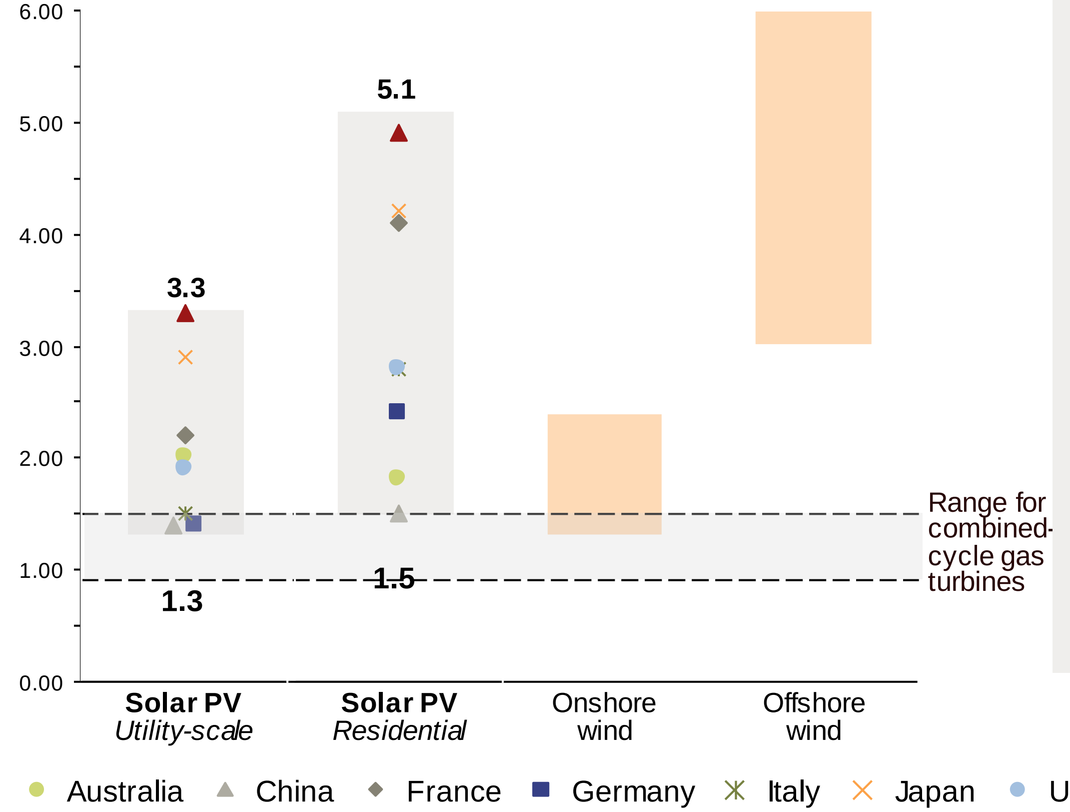
1. Include: installation, engineering, procurement, construction and development costs, as well as other service costs; 2. Mainly due to growth in small-scale systems in relatively high-cost markets in North America and Japan, and slowing down of lower-cost markets in 2013 and 2014.

source: Fraunhofer ISE (2015): "Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of utility-scale PV Systems"; IRENA (2015), "Renewable Power Generation Costs in 2014"

Total PV investment costs typically range between $1.3 and $5.1 per watt, depending on project location, scale and market conditions

Range of PV investment costs and typical system prices[1]

$ /W, 2014



- **Mirroring module and installation price dynamics, the full investment costs of PV systems vary significantly,** depending on their scale, their installation structure and their location.
- **The investment costs of utility-scale, ground-mounted PV systems ranged in 2014 from as low as $1.3/W, to $3.3/W** (down from $3.7-$7.1/MW in 2010). In favorable locations, capital requirements are thus very similar to those of onshore wind.
- **Despite important declines since 2010, the investment costs of residential rooftop PV systems can still be significantly higher**, ranging to up to $5.1/W. It is difficult to compare these systems with other technologies because of their distributed nature.
- **In all cases, PV investment ranges are higher than combined-cycle gas turbine investment** ranges.

---

1. Comparing investment costs per kW does not reflect the competitiveness of the technologies. It does not take account of capacity factors, project lifetimes or required transmission and distribution costs, all of which have a significant impact on the competitiveness of different technologies. Ranges were taken from IRENA and represent the range of average installed costs in 2014, while country data represent typical PV system prices in 2013, extracted from IEA.

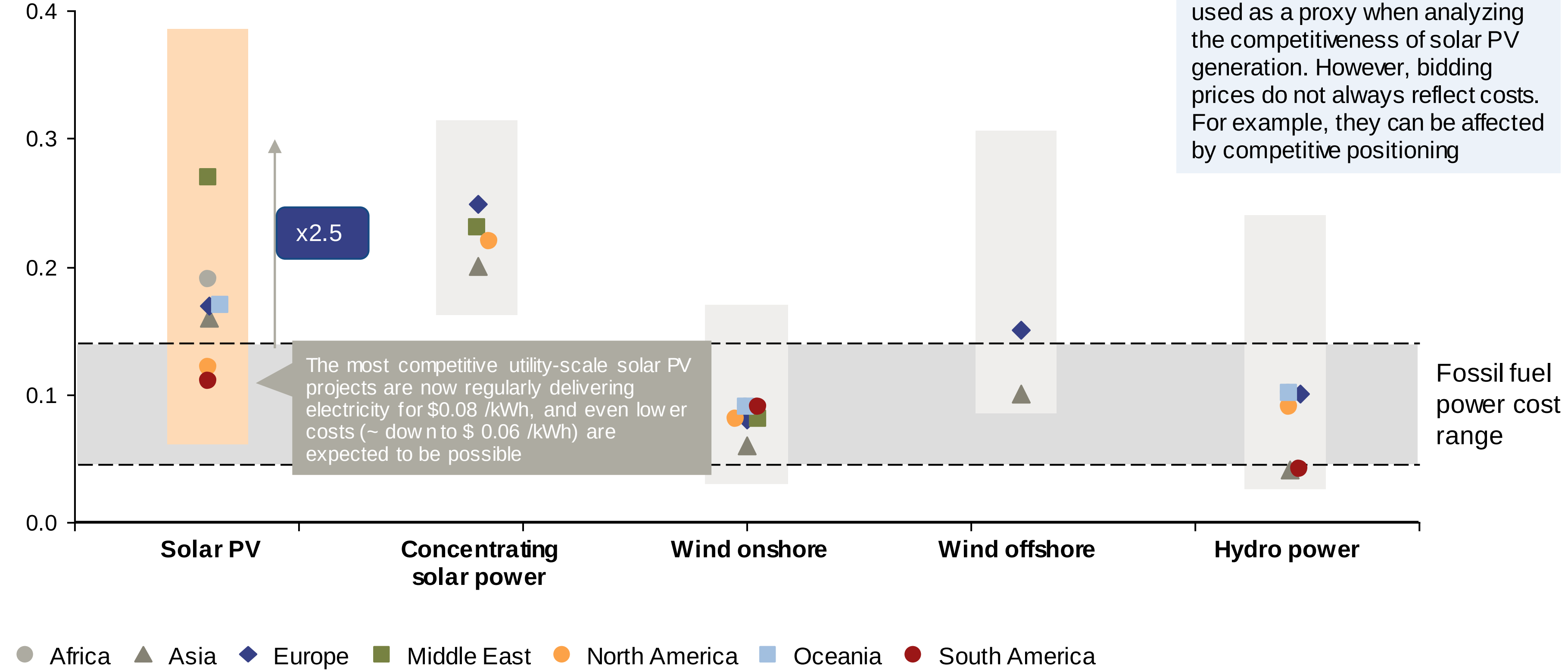
Source: A.T. Kearney Energy Transition Institute, adapted from IEA (2014), "Technology Roadmap Solar Photovoltaic Energy" and IRENA (2015), "Renewable Power Generation Costs in 2014"

Solar PV energy has become price competitive with fossil fuels in some geographical areas

Typical LCOE range for renewable technologies and regional weighted averages

2014 $ /kWh

Caution: Bidding prices are often used as a proxy when analyzing the competitiveness of solar PV generation. However, bidding prices do not always reflect costs. For example, they can be affected by competitive positioning



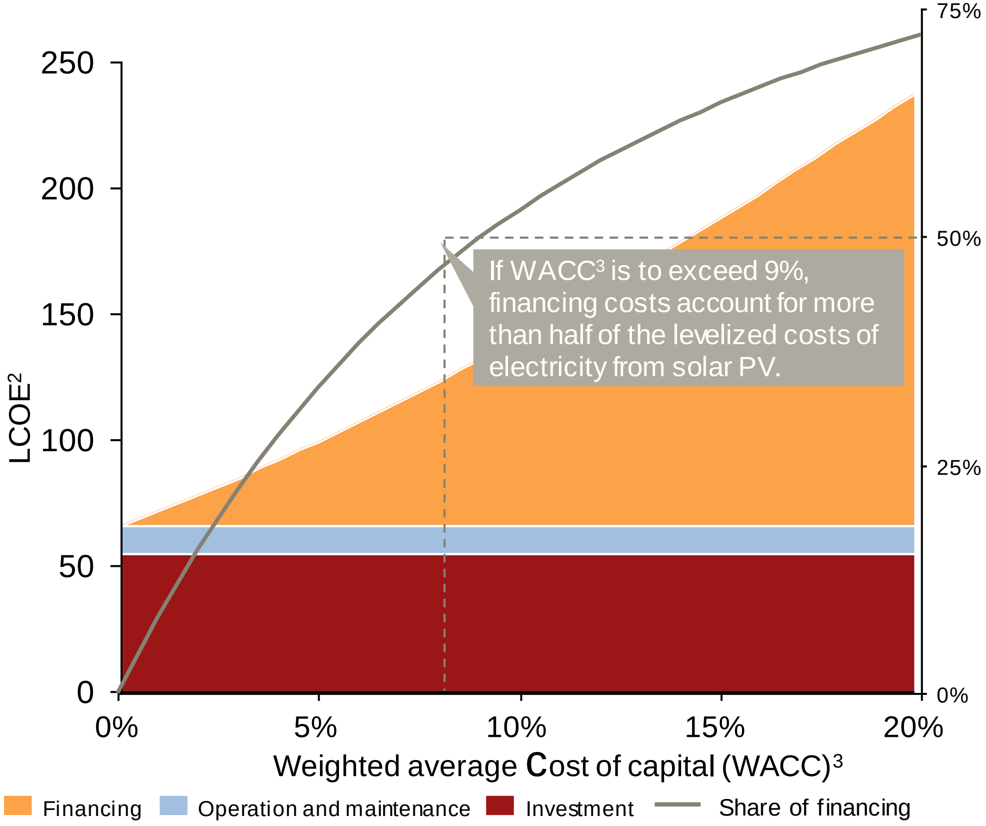
The most competitive utility-scale solar PV projects are now regularly delivering electricity for $0.08 /kWh, and even lower costs (~ down to $ 0.06 /kWh) are expected to be possible

Note: The levelized cost of electricity (LCOE) represents the per-kilowatt-hour cost of building and operating a generating plant over an assumed financial life and duty cycle. Its ranges reflect differences in resources available, local conditions and choice of sub-technology. Calculations are based on a 7.5% discount rate for OECD countries and China and 10% in the rest of the world. While LCOE allows comparison of costs among technologies, it may be an unreliable metric when comparing technologies at different stages of maturity. It can also be a misleading measure of technologies that perform different roles in an electricity system and that need to be valued based on their contribution to system reliability, flexibility and cost.

1. Source: A.T. Kearney Energy Transition Institute based on IRENA (2015), "Renewable Power Generation Costs in 2014"

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

Impact of cost of capital on the LCOE of solar PV[1] ($ /MWh (left), % (right)



If WACC[3] is to exceed 9%, financing costs account for more than half of the levelized costs of electricity from solar PV.

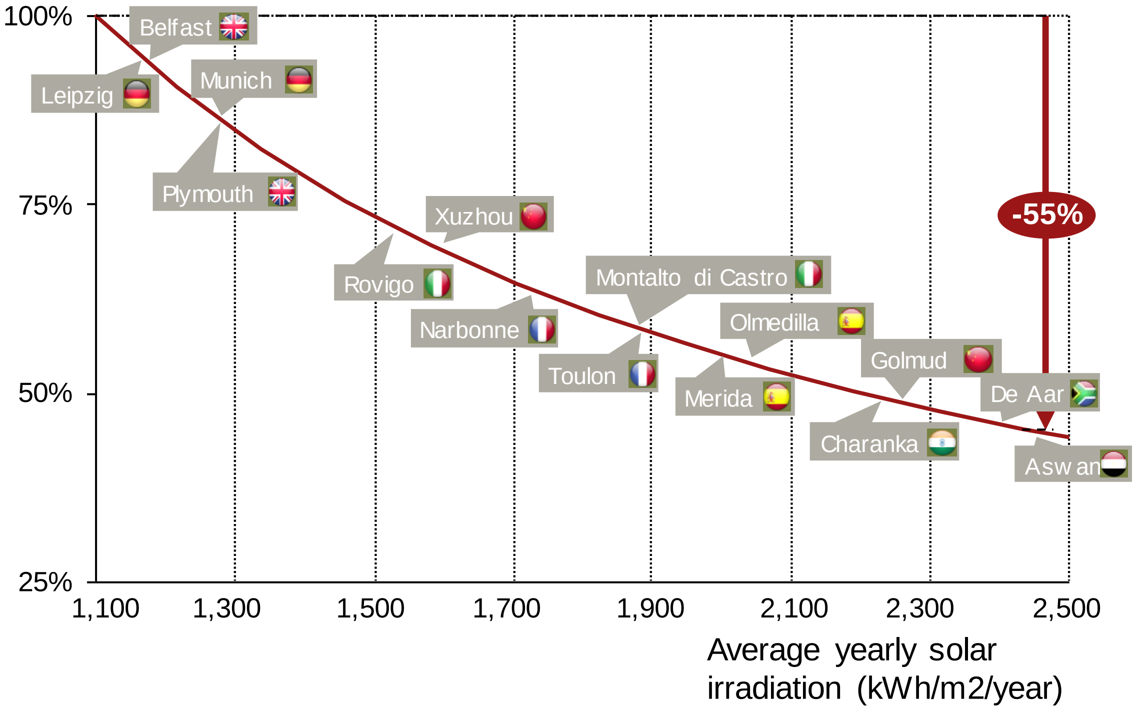
- **With zero fuel costs, solar PV is a capital-driven industry.** Operation and maintenance costs are low because of the absence of fuel costs and moving parts, and range annually between 0.5% and 1.5% of the initial investment.
- **Given the investment structure of PV systems, project economics are highly sensitive to the cost of capital measured by the discount rate.** Discount rates vary according to financing schemes (share of debt and equity, type of financing vehicles), project location (depends, in particular, on country risks and regulatory schemes) or to developers' credit ratings.
- It is believed that the best performing investment vehicles in the US use discount rates of 6-8%, whereas projects in high-risk countries are discounted with rates of around 15-20%. In such countries, lower labor costs are usually more than offset by higher financing costs.
- **Public-sector and institutional investors such as development banks have, therefore, an important role to play in helping to** reduce investment risks, facilitate access to financing and lower the cost of capital (*e.g.* loan guarantees, regulatory stability).

1. Reproduced from IEA; 2. Levelized cost of electricity represents the per kWh cost of building and operating a generating plant over an assumed financial life and duty cycle; 3. WACC is the calculation of an agent cost of capital in which each category of capital (e.g. debt, equity) is proportionately weighted

Source: IRENA (2015), "Renewable Power Generation Costs in 2014"; CPI (2014), Finance Mechanism for Lowering the Cost of Renewable Energy in Rapidly Developing Countries"; 1IEA (2015), "Energy Technology Perspective 2015"

The quality of the solar resource has a crucial impact on the economics of PV

Impact of the quality of solar irradiation on the relative Levelized cost of electricity[1] (% compared with a reference plant with average solar irradiation2 of 1,100 kWh/m2/year)



- **As with any renewable energy, the competitiveness of solar PV depends on the quality of the natural resources**. The latter, measured by solar irradiance1 (Watt per m2), affects the availability of the plant (capacity factor).
- **All other things being equal, the higher the solar irradiance, the lower the levelized costs of electricity produced[2]**. Significant variations in irradiance, by country and location, make the siting of a plant a critical factor in determining its economic viability.

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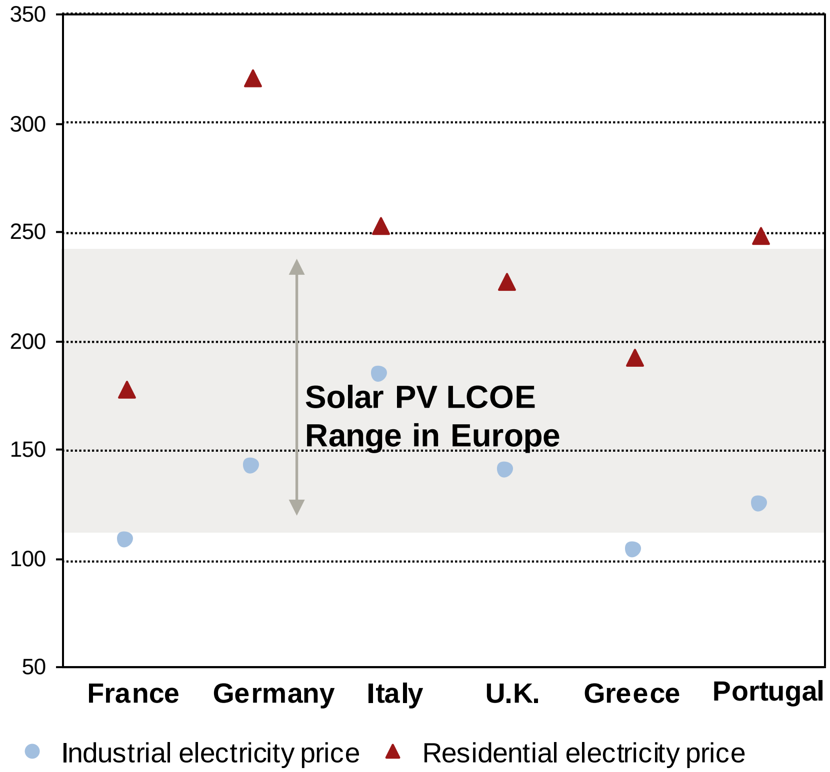
1. COE is calculated assuming Investment costs of $2.48 /Wp, yearly Opex of $0.085 /Wp, discount reel rate of 6.0% and degradation per year of 0.4%. Note that these parameters actually vary between countries; 2. Data have been extracted from PVGIS. They are me asures of the solar energy received over a given area (1 m2) for a given period of time (1 year). They correspond to the average irradi ance over the same period of time

Source: A.T. Kearney Energy Transition Institute based on PVGIS data (accessed July 2015)

The ability of solar PV generation costs to fall below electricity prices, known as grid parity, is not a sufficient metric for indicating the competitiveness of solar

Electricity prices and PV LCOE in Europe

$ /MWh



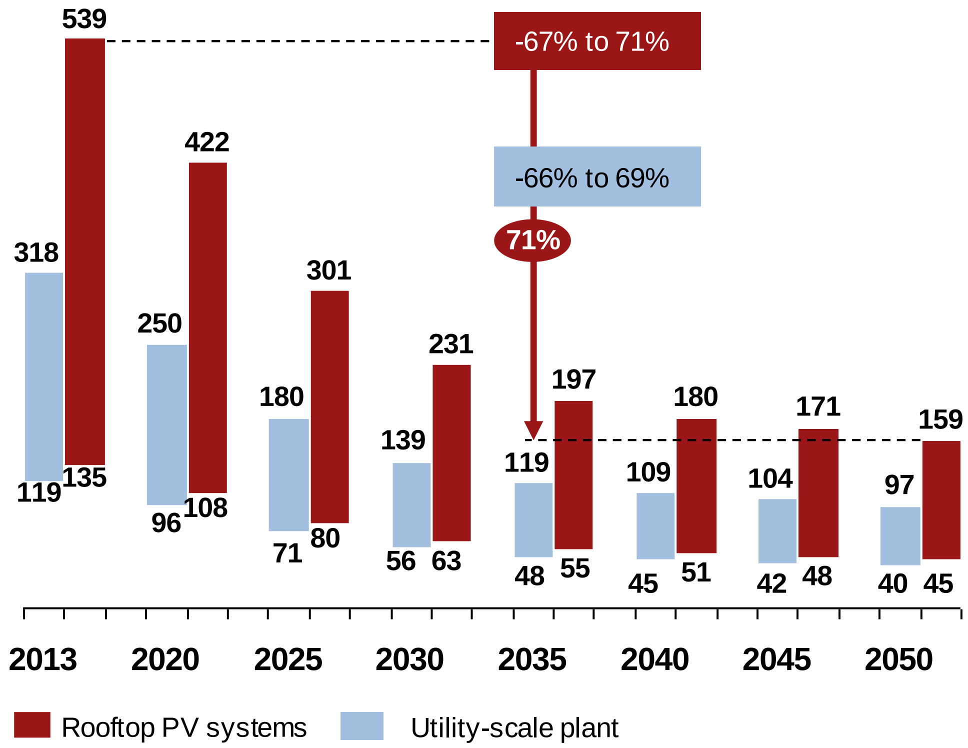
- **The concept of grid parity[1] is often used to assess the competitiveness of solar PV**. In fact, grid-parity refers to the tipping point at which the levelized cost of electricity (LCOE) from solar PV falls below the prices paid by end-consumers for electricity.
- **Grid-parity proximity varies significantly from country to country. The** Grid Parity Monitor[2] shows that "full grid parity" has been reached in the residential sector in several countries, including Australia, Chile, Germany, Italy, Japan and Mexico.
- **The ability of solar PV to reach grid parity is first and foremost conditioned by electricity prices.** While solar irradiance, local market conditions and regulatory support schemes determine the LCOE of solar, the competitiveness of solar PV with electricity prices is predominantly determined by the degree of electricity prices. Therefore, grid parity must be assessed carefully: electricity prices can vary widely, depending on customers and applications (*e.g.* wholesale, retail, industrial, but also peak and off-peak).
- **Grid-parity does not fully reflect the competitiveness of solar PV with alternative generation technologies.** Electricity prices paid by consumers include generation costs, but also, to varying degrees, transmission and distribution costs, taxes (*e.g.* especially to support the development of renewables) and services (especially to ensure power supply-demand matching, which is made more difficult by solar). In the long run and, except in the case of off-grid concepts, assessments of the competitiveness of PV systems should incorporate some taxes, as well as some services and grid costs.

1. Also known as socket parity; 2. Indicator developed by CREARA.
Source: A.T. Kearney Energy Transition Institute based on Creara (2015), "Grid Parity Monitor - Residential Sector 3rd issue"; IEA (2014), "Technology Roadmap Solar Photovoltaic Energy"; IEA (2016), "Energy prices and taxes, Q4 2016"; IRENA database (accessed July 2015) (link)

If its most ambitious climate-change mitigation scenario is to be met, the IEA believes the LCOE of PV would need to fall by more than two-thirds by 2050

LCOE decrease in IEA 2DS hiren scenario[1]

$ /MWh, global average



- **Most stakeholders predict that the LCOE of solar PV will continue to decrease.** This is due to a combination of factors, including: (i) reduced solar panel costs, as a result of improved panel efficiency and manufacturing processes[2]; (ii) reduced financing costs, as new business models emerge; and (iii) reduced balance-of-system costs, as a result of declining mounting-system costs, further enhancements to inverters and lower customer-acquisition costs[2].
- **In addition, regional differences are expected to diminish and solar costs to converge progressively** as markets mature. Capital and labor costs are likely to become the main factors behind regional differences in the cost of solar generation, ahead of variations in solar irradiance, although these two things may balance each other out[3].
- **The competitiveness of solar will still largely depend on the costs of other power-generation technologies and local electricity prices.** However, the combination of falling costs and rising electricity prices across the world should lead to overall growth in the competitiveness of PV. Deutsche Bank, for instance, expects solar to reach grid parity in up to 80% of the global market by 2017.

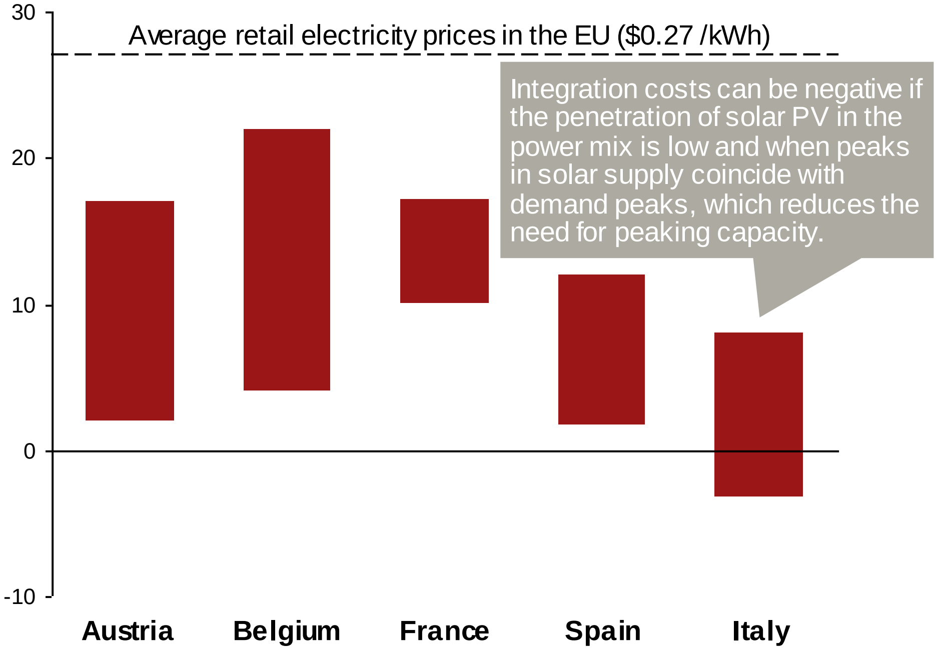
1. The 2DS hiRen scenario is a variant of 2DS, with lesser contributions from nuclear, and carbon capture and storage. It corresponds to "an energy system consistent with an emissions trajectory that recent climate-science research indicates would give an 80% chance of limiting the average global temperature increase to 2°C"; 2. According to GTM research, China's tier I crystalline-silicon PV module may be produced at costs as low as 36c per watt by the end of 2017 (a reduction of 14c compared to late 2012); 3. Costs of financing tend to be higher in countries with low labor costs.

Source: IEA (2014), "Technology Roadmap Solar Photovoltaic Energy"; Carus (2013), "PV module costs to fall to 36c per watt by 2017: GTM Research"; Fraunhofer ISE (2015), "Current and Future Cost of Photovoltaics"; Deutsche Bank (2015), "Crossing the chasm"

Expenditure on grid integration to compensate for the intermittent nature of PV will add to the cost of PV, depending on power systems and the penetration rate

Integration costs for solar PV in the EU

€ /MWh



Integration costs can be negative if the penetration of solar PV in the power mix is low and when peaks in solar supply coincide with demand peaks, which reduces the need for peaking capacity.

How to read this graph: the lower limit of the range is for 2% solar PV penetration and the upper limit is for 18% solar PV penetration. The studies take into account the implementation of demand-side responses.

- **The full cost of PV comprises levelized costs and incremental system costs of matching intermittent output with demand**.
- **Additional system costs for integrating solar PV into the grid depend on the penetration rate and power systems.** (1) The penetration rate: costs are negligible when penetration rates are low, as other flexible resources can accommodate variations in the availability of solar, but rise as the share of intermittent capacity in the generation mix grows. (2) Power system: costs depend on the structure of the power system, especially on the existence of low-cost resources that enhance system flexibility, such as market interconnections, storage capacity, demand response potential and dispatchable power plants.
- **Grid-integration costs resulting from solar PV are hard to assess and highly system-specific**. They are thus usually not taken into account in calculations. According to a study on solar PV in Europe, grid-integration costs would be, on average, $2/MWh if solar PV were supplying 10% of EU electricity demand, and up to $25/MWh for 18%. If demand-response measures were implemented, these costs could be reduced on average by 20%.
- There is a lack of research into penetration rates higher than 20%, making solar's ability to account for a large share of the generation mix uncertain.

Source: IRENA (2015), “Renewable Power Generation Costs in 2014”

Support policies can mandate a minimum quantity of solar PV energy or capacity, or alter the prices or costs to which investors are exposed

Options For Policy Support[1]

Price-based instruments ➡ Influence solar deployment levels by altering prices investors are exposed to (increasing revenues or lowering costs).

Feed-in tariffs (FITs)	Guarantee electricity will be bought at a certain price per kilowatt-hour (kWh) over a long period of time (typically 20 years)[2].
Contracts for difference	Long-term PPA[2], under which electricity is directly sold to the market and investors receive or refund the gap between the market price and a predetermined price.
Electricity compensation	Allow self-produced electricity to reduce the electricity bill of the PV-system owner through self consumption and/or net-metering systems[3].
Market premiums	Supplement revenues from the sale of electrical power by paying investors an additional fee for the quantity of electricity generated or capacity built.
Tax incentives or credits	Reduce the cost to investors of renewable energy projects through tax breaks or an accelerated depreciation of assets.
Direct cash grants/ rebates[4]	Reduce investment costs / improve returns by refunding developers a percentage of investment costs in cash.

Quantity-based instruments ➡ Mandate a certain quantity of energy or capacity. Prices are thus determined by the costs of the projects required to meet this obligation

Renewable portfolio standards (RPS)	Set a target share or total amount of energy generation from renewable energy sources for electricity producers or suppliers[5].
Quotas wit tradable green certificates	Set specific minimum targets for electricity generation from renewable sources and issue tradable certificates for each unit of green electricity produced. This aims to meet renewable obligations more efficiently.
Centralized procurement	Usually implemented by a government or public body by organizing auctions to contract a predetermined quantity of renewable energy. The price is set in a competitive bidding process.

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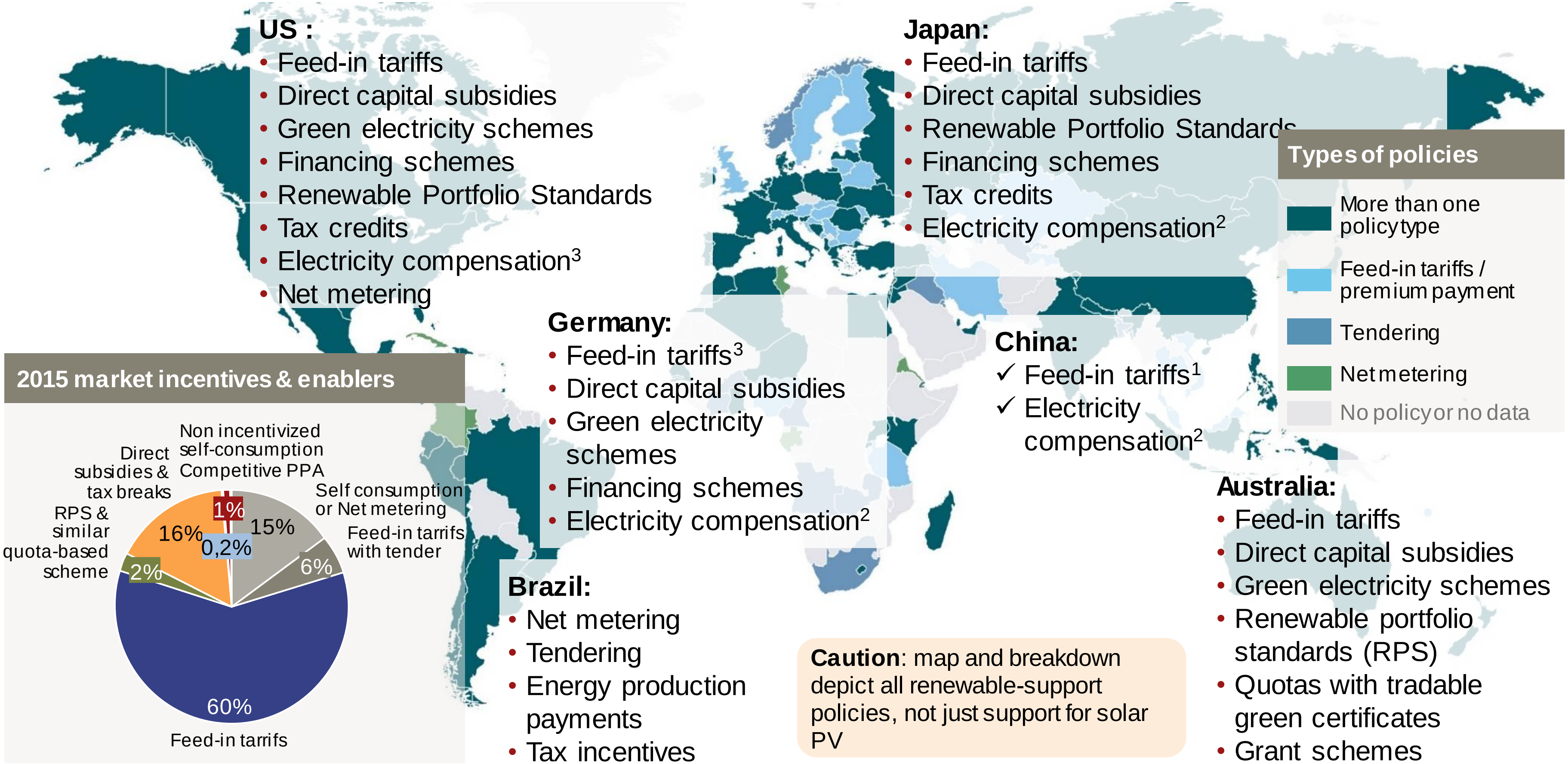
1. Policy mechanisms can also be categorized according to how they are financed. Renewable policy support is usually financed by making additional charges to electricity consumers' bills, via payments through the general budget or dedicated government funds, or by the government accepting reduced tax revenues; 2. A FIT is a standardized, long-term power-purchasing agreement (PPA). A FIT can also be combined with a tendering process; 3. Refer to slide 62; 4. Also known as direct capital subsidies; 5. RPS builds on the assumption that the producer or supplier has sufficient opportunities to build or purchase renewable energy directly. Where this is not the case, a quantity obligation can be combined with the trading of green certificates.

Source: IEA (2015), "Energy Technology Perspective 2015"; IEA (2014), "Trends 2014 in Photovoltaic Applications"

Support policies vary according to regions and are typically combined

Renewable Energy Policies and main solar policy incentives for Selected countries (2015)



US :
- Feed-in tariffs
- Direct capital subsidies
- Green electricity schemes
- Financing schemes
- Renewable Portfolio Standards
- Tax credits
- Electricity compensation[3]
- Net metering

Japan:
- Feed-in tariffs
- Direct capital subsidies
- Renewable Portfolio Standards
- Financing schemes
- Tax credits
- Electricity compensation[2]

Germany:
- Feed-in tariffs[3]
- Direct capital subsidies
- Green electricity schemes
- Financing schemes
- Electricity compensation[2]

China:
- ✓ Feed-in tariffs[1]
- ✓ Electricity compensation[2]

Brazil:
- Net metering
- Tendering
- Energy production payments
- Tax incentives

Australia:
- Feed-in tariffs
- Direct capital subsidies
- Green electricity schemes
- Renewable portfolio standards (RPS)
- Quotas with tradable green certificates
- Grant schemes

Types of policies

- ■ More than one policy type
- 🟦 Feed-in tariffs / premium payment
- 🟦 Tendering
- 🟩 Net metering
- ⬜ No policy or no data

Caution: map and breakdown depict all renewable-support policies, not just support for solar PV

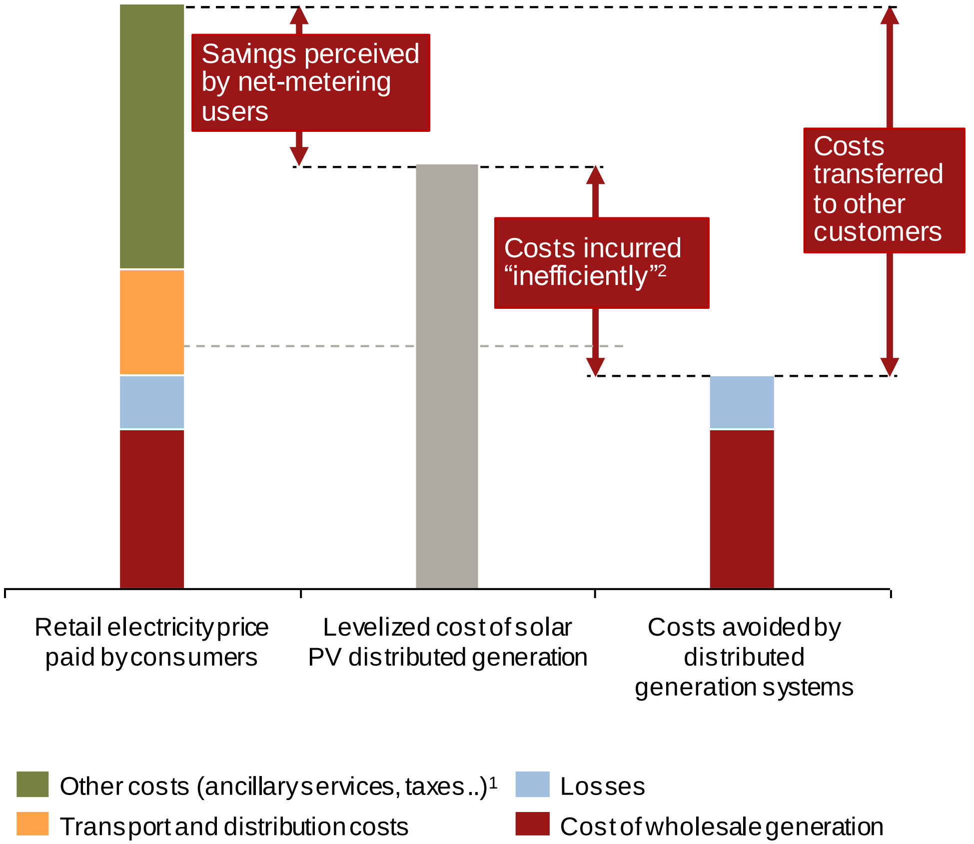
[1] Three regionally differentiated FIT support schemes with reduced rates for ground-mounted solar PV projects in solar-rich regions; [2] Can be net energy metering, net billing or self consumption incentives

Source: REN21 (2016), "Global Status Report"; IEA-PVPS (2016), "Trends 2016 in Photovoltaic Applications"

Net energy metering proved efficient in bolstering distributed solar PV, but may not be sustainable or efficient as PV penetration rises

Net-metering cost transfers

Illustrative



- **Net energy metering (NEM) is a support policy** that credits PV system owners *(e.g.* a households with rooftop solar PV) for electricity generated and fed into the grid.
- **While NEM schemes have proved efficient in fostering solar PV deployment, they have been criticized for being unfair and unsustainable**. Distributed solar PV does not necessarily reduce the need for distribution, transmission, generation capacity or social tariffs. In the long run, NEM could develop into a vicious circle: as self-generation becomes more attractive and more consumers choose it, electricity prices to other consumers are forced up, making self generation even more attractive.
- **Several options are being explored to limit the downsides of NEM**. If NEM is not to be simply proscribed, the rationale is to make the cost saving for the customer equal to the cost avoided to the system. This could be achieved by (i) applying a tariff to self-generation systems to finance back-up capacity, (ii) recovering non-avoided costs by levying charges on capacity (per kW) or by customer, (iii) or removing the costs of government policies from electricity tariffs[3]. However, these alternatives have not yet been widely implemented[4].

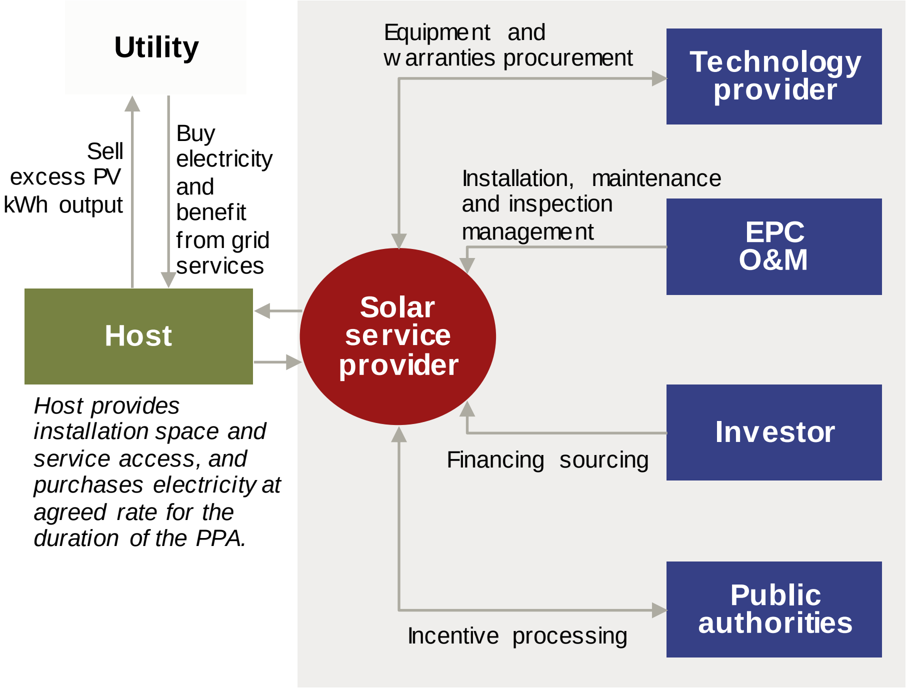
1. Include generation capacities, ancillary services and government policy costs; 2. Costs incurred “inefficiently” due to the high costs of distributed solar PV, compared with the current electricity mix, and requirements regarding network and generation capacity; 3. These options are not exclusive; 4. In the US, 43 states have some form of NEM and only two have adopted alternatives (known as value of solar tariffs) whereby customers buy their electricity at the retail price and are remunerated by selling electricity they produced based on its environmental value and impact on network and generation requirements and losses.

Source: EPIA (2013), “Self consumption of PV Electricity”; MIT (2015), "The Future of Solar Energy”; NERA (2014) “Self-Consumption and Net Balancing: Issues and solutions”

New business models, led by leasing and power-purchase agreements, have emerged to foster the deployment of solar PV

Role of solar PPA scheme

Illustrative



Utility

Sell excess PV kWh output

Buy electricity and benefit from grid services

Host

Host provides installation space and service access, and purchases electricity at agreed rate for the duration of the PPA.

Solar service provider

Equipment and warranties procurement

Technology provider

Installation, maintenance and inspection management

EPC O&M

Financing sourcing

Investor

Incentive processing

Public authorities

A solar service provider coordinates PV stakeholders, owns the PV system installed at the host's property, bears the risk and captures part of the financial reward.

- **A number of innovative business models have emerged in recent years to overcome existing barriers to solar PV deployment.** These business models seek to address reticence among residential customers and the difficulties they face in financing high-up-front investments, as well as the tasks of managing complex support policies, and dealing with permitting and maintenance.
- **A major trend has been the rise of third-party ownership** (TPO): leasing or power-purchase agreements (PPAs). With TPO, site owners host solar PV installations, but do not own them. A third party coordinates the financing, design, permitting, construction and maintenance of the system, and processes the various incentives. The customer pays a monthly lease (typically 15-20 years) or signs a long-term contract to purchase the electricity generated on its property (PPA). TPO first became popular in 2011 in the US and accounted for 62% of the US residential solar market in 2015[1].
- **However, TPO constitutes a trade-off between financial rewards and simplicity.** Ownership of solar capacity, whether financed or purchased in cash, provides better value in the medium term[2] and lowers the societal burden of solar PV development due to the high cost of TPO middlemen. Therefore, ownership is becoming popular again, encouraged by low-cost financing supplied by solar manufacturers, crowd-funding platforms or banks, which are more comfortable with solar risk than previously.
- **Leasing could still have an important role to play in developing countries,** where it is not yet available as an option for unlocking solar growth. It could be particularly effective if backed by an institutional investor and combined with emerging business models, such as pay-as-you-go.

1. According to a study published by GTM Research in 2016 (link); 2. Borlick finds, for instance, that solar homeowners in South California lose 80% of their project value over the first 10 years by opting for a lease

Source: EPA.gov (2015), "Solar Power Purchase Agreement" (link); Borlick (2014), "An Empirical Analysis of Net Metering"; NREL (2015), "To Own or Lease Solar: Understanding Commercial Retailers' Decisions to Use Alternative Financing Models"

The emergence of new financing players, combined with the introduction of new investment vehicles, have been game changers for the solar sector

The Yieldco landscape[1]

Name	Date listed	Country	Market capitalization[2]	PV capacity (% of asset portfolio)[2]
NRG Yield Inc.	2013	US	$M 3125.7	353 (12%)
Abengoa Yield	2013	U.S	$M 2040.4	n.a.
Pattern Energy Group	2014	US	$M 1872.4	n.a.
Next Era Energy Partners	2014	US	$M 1764.9	40 MW (6%)
Terra Form Power	2015	US	$M 1720.4	808 MW (n.a.)
8point3 Energy Partners	2015	US	$M 979.8	n.a. (100%)
Next Energy Capital Solar Fund	2013	U.K.	$£ 516.86	235 MW (100%)
Bluefield Solar Income Fund	2014	U.K.	$£ 420.2	149.2 MW (100%)

A yieldco is a dividend growth-oriented public company, typically set up by a parent company, which bundles a portfolio of operating assets into a new subsidiary to separate risky projects from de-risked assets and provide stable and predictable cash flows in liquid investment vehicles.

- **New financing players have entered the solar market, providing both debt and equity.** In addition to incumbent debt financiers, such as banks and insurance companies, new investors, such as funds (mutual, pension or infrastructure funds), are playing an increasing role in providing debt to the solar sector. These players have been attracted by the yields offered by solar projects and by the development of new liquid investment vehicles, such as project bonds and asset-backed securitization. The same has occurred on the equity side, with private-equity funds (*e.g.* infrastructure funds) and hedge funds becoming increasingly attracted to solar investments, and the development of Yeldcos.
- **Yieldcos have grown considerably in the US since 2013** (and to a lesser extent in the U.K). Deemed to have been the main game changer for solar PV in 2014, Yieldcos lower the cost of financing, helping to raise capital at lower rates (~3-6%) than conventional tax equity finance.
- **Yieldcos could pay a crucial role in solar deployment worldwide** by reducing the cost of capital in emerging PV markets and in residential applications. However, there are concerns that rising interest rates could negatively affect the outlook for Yieldcos and on a potential rush for projects leading to over-prices acquisitions. Finally, it is worth noting that attempts to introduce Yieldcos in continental Europe have failed so far.

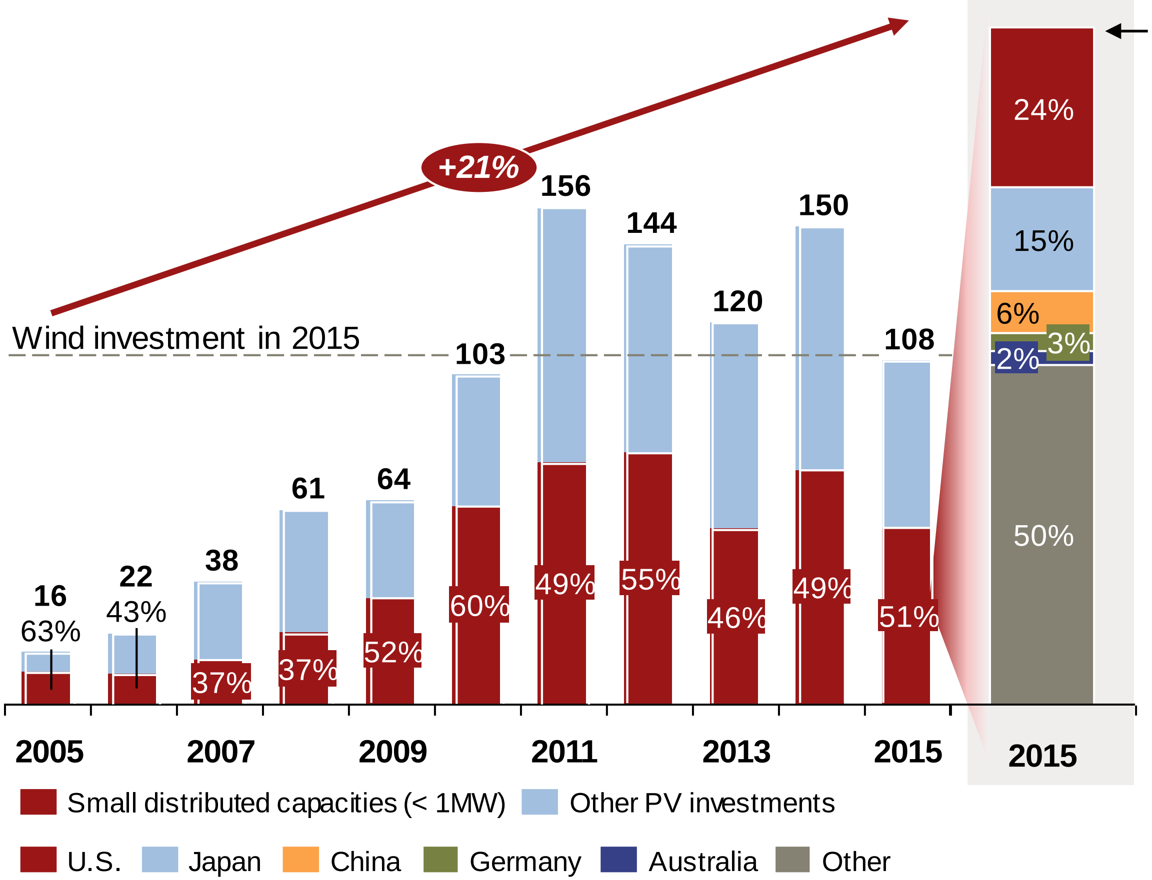
1. The list is non-exhaustive. Several players are considering launching their own yieldcos, notably Canadian Solar. In the US yieldcos have been spin-offs of large industry players, including large utilities (e.g. NextEra), renewable developers, service providers and operators (e.g. SunEdison created TerraForm as a yieldco) or solar players; 2. such as the joint venture formed by First Solar and SunPower for 8point3 Energy Partners. In the U.K., both are pure solar-fund players; 3. Data from Bloomberg extracted on April 20th 2017. PV and renewable generation portfolio as communicated on July 2015.

Source: NREL (2015), “A Deeper Look into Yieldco Structuring” (link); Deutsche Bank (2015), “Crossing the chasm”; Bloomberg (2015), “Higher Interest Rates Pose Threat to $28 Billion Yieldco Market” (link); Bloomberg (2015), “SunEdison Thirst for Yield Growth Drove $2.2 Billion Vivint Deal” (link)

Solar PV investment boomed in the late 2000s and now exceed $100 billion a year, driven equally by utility-scale and small projects

Global investment in solar PV and country breakdown for distributed capacity

$ billion



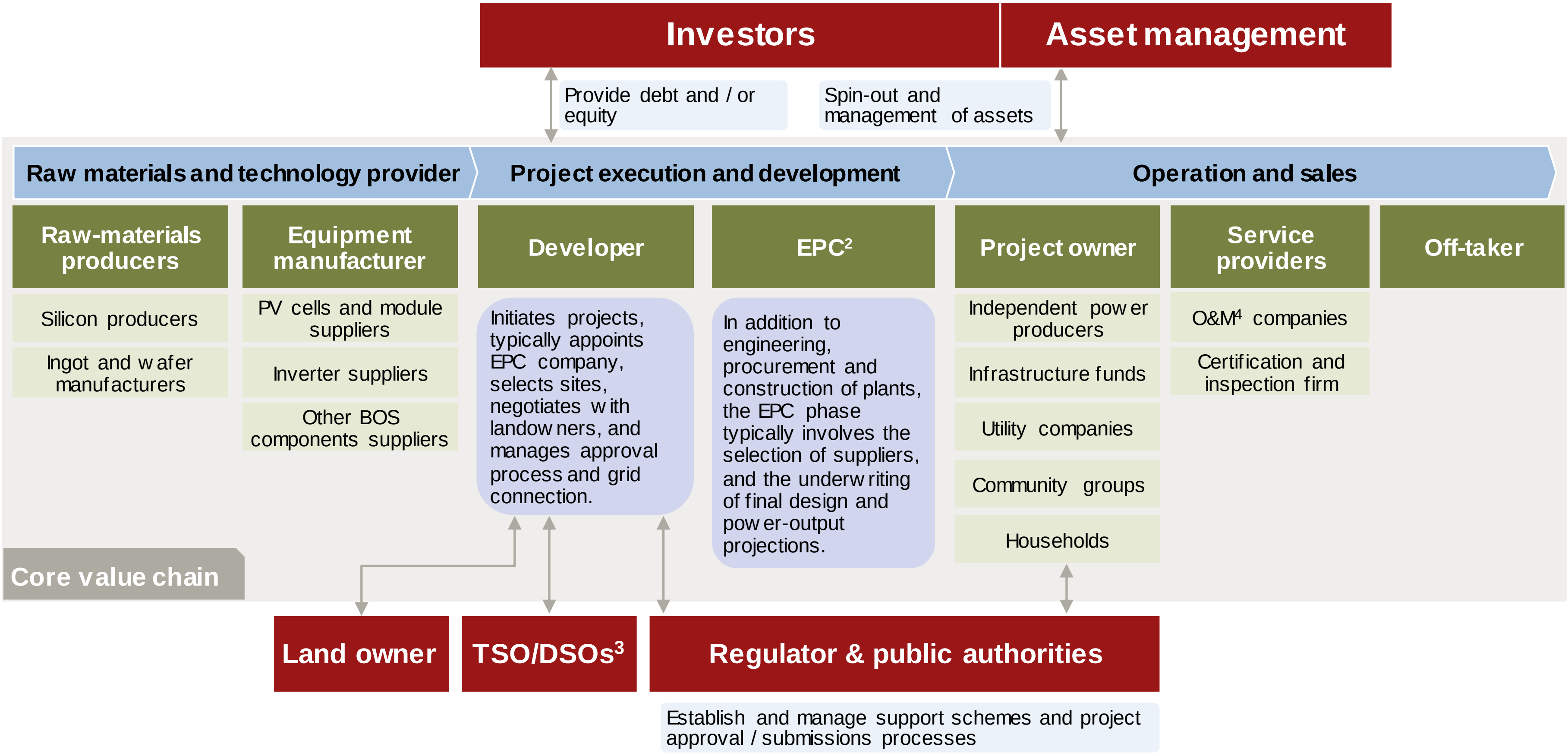
- **Together with wind power, solar PV accounts for the vast majority of renewable energy investments, excluding large hydro**power plants[1]. After a steep increase between 2004 and 2011, driven by the German and Italian solar boom, investment in solar PV now amounts to between $120bn and $150bn per year.
- **While investment in solar PV was driven by small-size distributed capacity in the 2000s, it is increasingly being driven by utility-scale projects, which form the backbone of the** solar market in the new leading regions, China and the US In 2016, small-scale projects in Japan[2] accounted for the bulk of distributed solar investments, with investment in distributed solar in Europe falling by 18%[3]. At the same time, in 2014, 75% of all other PV investments involved Chinese utility-scale projects.

1. In 2014, solar PV contributed a record 55% of renewable energy investment, excluding hydro-electric projects of more than 50MW; of less than 1MW; 2. Small-scale solar investment declined in several European countries with Germany, UK and the Netherlands the three biggest contributing to this

Source: Bloomberg New Energy Finance (2017), Global trend in renewable energy investment"

The ecosystem of solar PV has developed and matured in recent years with a growing role of financing players

Solar PV Ecosystem[1]



Investors

Asset management

Provide debt and / or equity

Spin-out and management of assets

Raw materials and technology provider

Project execution and development

Operation and sales

Raw-materials producers
- Silicon producers
- Ingot and wafer manufacturers

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

Developer

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

EPC[2]

In addition to engineering, procurement and construction of plants, the EPC phase typically involves the selection of suppliers, and the underwriting of final design and power-output projections.

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

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

Off-taker

Core value chain

Land owner

TSO/DSOs[3]

Regulator & public authorities

Establish and manage support schemes and project approval / submissions processes

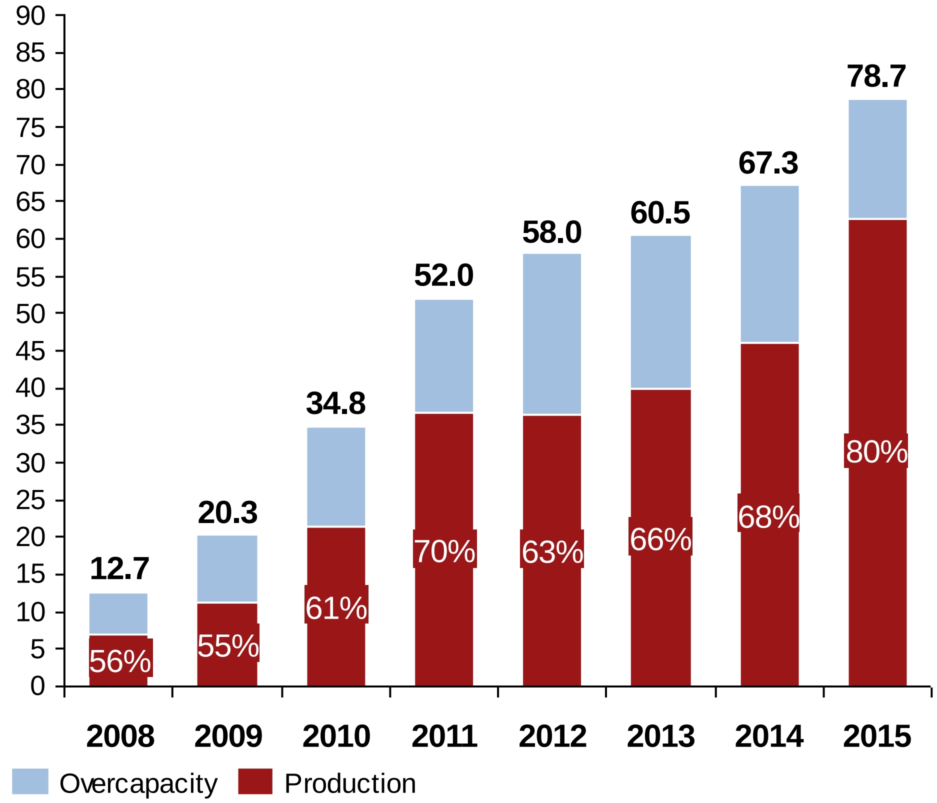
1. For illustrative purposes only. Note that many solar companies are involved at several stages of the chain (e.g. technology providers can also be developers, provide EPC services and act as independent power producers); 2. EPC for engineering, procurement and construction; 3 DSO/TSO for distribution system operator and transmission system operator; 3. O&M for operation and maintenance.

Source: A.T. Kearney Energy Transition Institute analysis based on interviews.

The solar PV market is characterized by fierce competition and significant production overcapacity, and subject to numerous trade disputes

PV Module production and overcapacity

MW



- **Solar PV manufacturing is characterized by fierce competition and significant production overcapacity.** The industry developed at a rapid pace in the 2000s. In 2011 and 2012, it began to consolidate, after China changed market dynamics by granting large loans to its PV manufacturers (resulting in declining prices, negative profitability, merger and acquisition activity, and bankruptcy of the weakest players). The industry recovered in 2013 as a result of robust market-growth in China, Japan and the US Nevertheless, some manufacturers continue to make a loss.
- **Significant trade tensions in recent years have resulted from China's emergence as a world leader in PV manufacturing.** European and US incumbents have claimed Chinese support for its manufacturers is tantamount to concealed dumping and that Chinese manufacturers are benefiting from support policies in Europe and the US intended for local manufacturers. This resulted in trade barriers being put in place, such as volume limits on imports to Europe or duties on Chinese panels in North America. However, Chinese companies are dodging these barriers by locating their production abroad (*e.g.* in Jinko Solar in Malaysia or Trina in Thailand).
- **PV-module manufacturers are climbing the solar PV value chain** and moving into engineering, procurement and construction (EPC), project development, leasing, ownership and operation. For instance, in 2015, US-based manufacturer SunPower bought 1.5 GW of projects from Australian developer Infigen Energy, and formed a yieldco[2] with First Solar.

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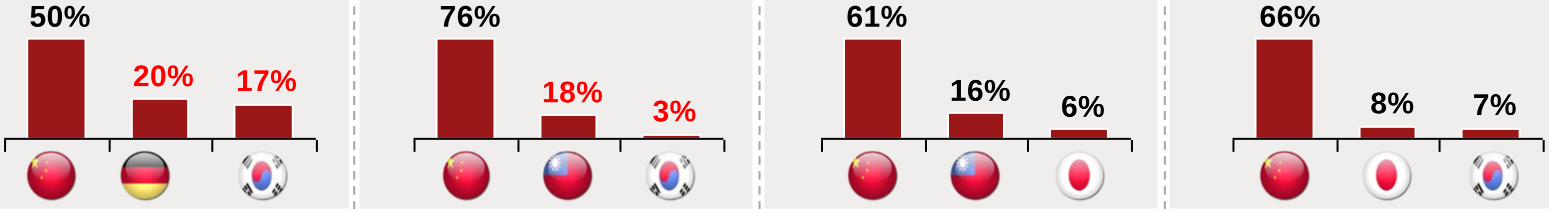
1. Chinese manufacturers are also locating their production in these countries to target local markets and to benefit from low production costs, in the context of rising labor costs in China; 2. For more information on Yieldcos, refer to slide 64

Source: IEA PVPS (2015), "Trends 2016 in Photovoltaic Applications"; Mehta (2014), "Global 2013 PV Module Production Hits 39. 8GW, Yingli is the Shipment Leader"; Bloomberg (2015), "SunPower Buys Infigen's 5-Gigawatt US Solar Power Pipeline" (link)

Asian companies are the main players in the silicon value chain, even though market rationalization has eliminated several companies

Overview of solar PV value chain (focus on main commercial technologies)[1]



	Silicon feedstock	Ingot and wafer	PV cell	PV module
Description	Highly purified polysilicon production (solar grade)	Ingot (single-crystalline or multi-crystalline) and wafer-manufacturing process	Solar-cell manufacturing process	Manufacturing of PV module components[2] and assembly
Top 3 countries by market share[3]	🇨🇳 50% 🇩🇪 20% 🇰🇷 17%	🇨🇳 76% 🇹🇼 18% 🇰🇷 3%	🇨🇳 61% 🇹🇼 16% 🇯🇵 6%	🇨🇳 66% 🇯🇵 8% 🇰🇷 7%

Main players in crystalline silicon market

WACKER 🇩🇪 — OCI 🇰🇷 — Trinasolar 🇨🇳 — YINGLI SOLAR 🇨🇳 — CanadianSolar 🇨🇦 — Hanwha Solar 🇰🇷

GCL 🇨🇳 — LDK 🇺🇸 — SUNPOWER 🇺🇸

Main players in thin-film market

Not applicable — First Solar 🇺🇸 — SHARP 🇯🇵 — Kaneka KANEKA Solar Energy 🇯🇵 — SOLAR FRONTIER 🇯🇵

1. Around 90% of PV modules produced in 2013 were crystalline silicon. Conversely, thin-film production accounted for only 10% of the market. Thin-films were mainly produced in Malaysia, Japan, China, Germany and the US The main producers are US company First Solar, with 1,63 GW of CdTe PV modules produced in its US and Malaysian factories in 2013; Sharp, Kaneka and Solar Frontier. Solar Frontier announced in July 2015 that it has shipped more than 3 GW of thin film in eight years; 2Involves glass, backsheet, encapsulant film (EVA), junction box and frame; 2. Includes string box, cabling and inverter; 3. Data are for 2014.

Source: A.T. Kearney Energy Transition Institute analysis; IEA-PVPS (2014), "Trends 2014 in photovoltaic Applications"; Bloomberg New Energy Finance (accessed July 2015, link); Mehta (2014), "Global 2013 PV Module Production Hits 39.8GW; Yingli is the Shipment Leader"

North American and European companies remain dominant in EPC and development activities as Chinese companies make progress

Major EPC contractors and developers for utility-scale in 2016[1]

EPC contractors

Company	Capacity (MW$_{AC}$)	Main regions of activity					
First Solar 🇺🇸	3,497	⬜	🟦		🟩	⬛	🟧
Juwi Solar 🇩🇪	980	⬜	🟦		🟩		🟧
Swinerton Renewable 🇺🇸	967		🟦				
Belectric 🇩🇪	959	⬜	🟦		🟩	⬛	🟧
Sterling & Wilson 🇮🇳	835						🟧
Enerpac 🇩🇪	825	⬜	🟦			⬛	🟧

Developers

Company	Capacity (MW$_p$)	Main regions of activity					
First Solar 🇺🇸	2,959		🟦		🟩	⬛	
China Power Inv. 🇨🇳	2,498			🟥			
SunEdison 🇺🇸	1,759		🟦		🟩		🟧
Hareon Solar 🇨🇳	1,074	⬜	🟦	🟥			🟧
Shunfeng 🇨🇳	951	⬜		🟥			🟧
8minutenergy 🇺🇸	938		🟦				

⬜ Europe
⬛ MENA
🟥 China
🟧 Asia (Exc. China)
🟩 Latin America
🟦 North America

- **Unlike in technology supply, which is largely dominated by Asian manufacturers, the largest solar developers are North America companies.** The latter have been very successful in winning projects across the world (*e.g.* First Solar has solar projects with combined capacity of 700 MW operating in India)
- **Engineering, procurement and construction (EPC) activities remain relatively fragmented.** EPC activities are usually performed by local companies. European incumbents from Spain and Germany are still very strong, but are facing increasing competition from their US peers and from Chinese companies[1]. In emerging PV markets, EPC contracts are usually awarded to a consortium of PV system integrator and established local construction companies.
- **Solar companies are become vertically integrated,** in order to be involved all along the solar PV value chain, from module manufacturing to project development, EPC and even financing. For instance, in 2014, leading US developer SolarCity bought a module manufacturer (Silevo), while technology provider SunPower moved into selling and financing solar systems (*e.g.* Sunpower bought 1.5 GW of project from Infigen Energy), and Japanese thin-films company Solar Frontier purchased 280 MW of projects from Gestamp. Attempts to diversify along the value chain reflect companies' determination to reduce competition, hedge against the growing market power of financiers and protect top-tier technology advantages from reverse engineering.

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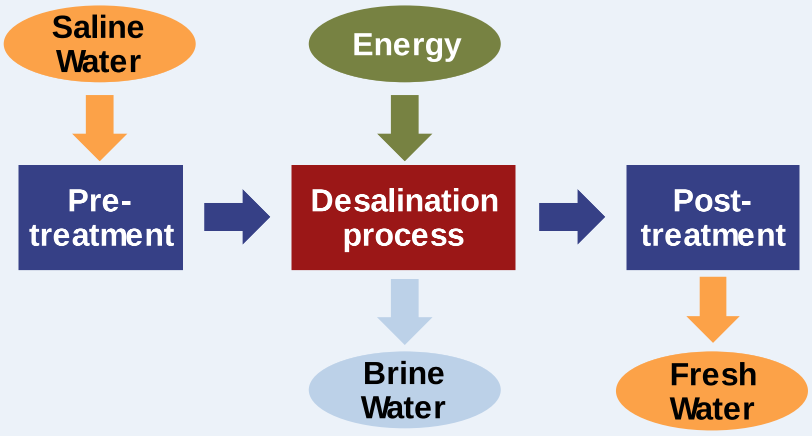
1. Chinese companies are under-represented on the EPC list. This is because separate EPC contractors are seldom announced for projects in China, with the role often undertaken by the project developers' in-house construction team.

Source: IHS (2014), "Solar EPC Landscape Consolidates in 2013 as Tight Margins Pressure Medium-Sized Integrators"; Neidlen (2014), "Chinese EPCs dominate"; McIntosh and Mandel (2014), "Why Solar Installers Are Becoming Vertically Integrated"; Wiki solar website (accessed, April 2017)

The desalination process converts saline water into fresh water, using various technologies and energy sources

Desalination scheme


Saline Water

Energy

Pre-treatment

Desalination process

Post-treatment

Brine Water

Fresh Water

Possible energy sources

- **Thermal energy:**
  - Conventional fuels (oil/gas/fuel oil)
  - Renewables
- **Electrical energy:**
  - Conventional fuels (oil/gas/coal)
  - Renewables

Main desalination technologies

Not exhaustive

Thermal distillation processes	
Multistage Flash (MSF)	• Steam heats seawater that cascades through multiple stages of incrementally lower pressure, causing small amounts of pure water to vaporize (flash) from the feed with each drop in small pressure • Requires both thermal and electrical energy
Multi-effect distillation (MED)	• Like MSF, produces vapor by flashing, but also incorporates thin-film evaporation to generate additional vapor in each stage (effect) • Requires both thermal and electrical energy
Vapor compression (VC)	• The feed water enters the vapor compression (VC) process through a heat exchanger, and vapor is generated in the evaporator before being compressed by mechanical (MVC) or thermal (TVC) means • MVC uses electrical energy, TVC employs thermal energy
Membrane desalination processes	
Reverse osmosis (RO)	• A form of pressurized filtration in which the filter is a semi permeable membrane allowing only water to pass through • Requires only electrical energy
Electro-dialysis and electro-dialysis reversal (ED/EDR)	• An electro-chemical separation process that operates at atmospheric pressure and uses direct electrical current to move salt ions selectively through a membrane (ED). In EDR, the polarity of the electrodes is switched periodically • Requires only electrical energy

Note: Typical seawater desalination plants operate at around 50% water recovery with seawater of about 35g/kg salinity
Source: A.T. Kearney Energy Transition Institute analysis

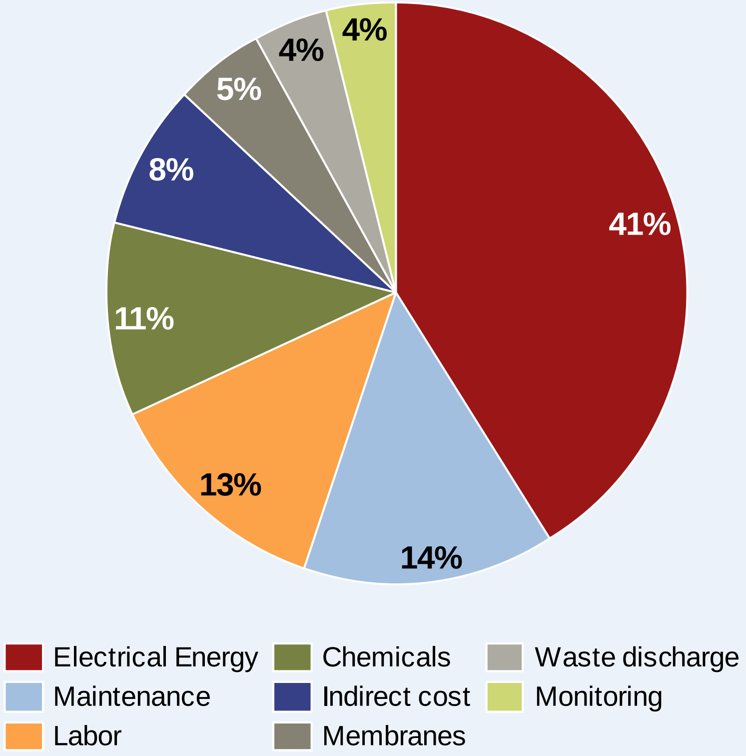
Desalination[1] provides only 0.7% of global water needs but consumes about 75 TWh of electricity per year

Global desalination market overview

- Around **19,000 plants** operate globally with a total capacity of **15 billion cubic meter/year.**
- **150 countries** are practicing desalination and more than **300 million people** globally rely on desalination for some or all of their daily needs.
- **MENA, EU and USA** constitute **80%** of the global installed capacity.
- **65%** of global installed desalination capacity is equipped with **Reverse Osmosis (RO)** membranes with sea-water (SW) being the dominant feed type at 60%.
- **Less than 1% of the global desalination energy consumption is based on renewables.**
- Desalination is an energy intensive process and consumes **75.2 TWh of electricity per year globally.**

SWRO[2] Desalination plant, MENA region

O&M cost breakdown



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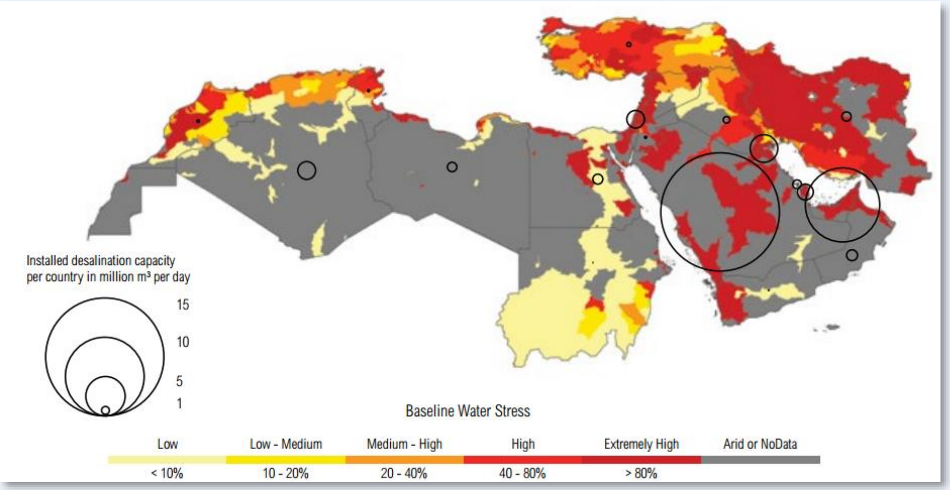
1. Desalination includes water re-use however currently water re-use doesn't play an important role from an energy consumption perspective; 2. SWRO: Spiral wound reverse osmosis

Source: IEA WEO 2016; IRENA (2012); A.T. Kearney Energy Transition Institute analysis

More than half of the global desalination capacity is in MENA region which is characterized by high water stress levels

Baseline Water Stress and Desalination Capacity

Middle East & North Africa, 2015



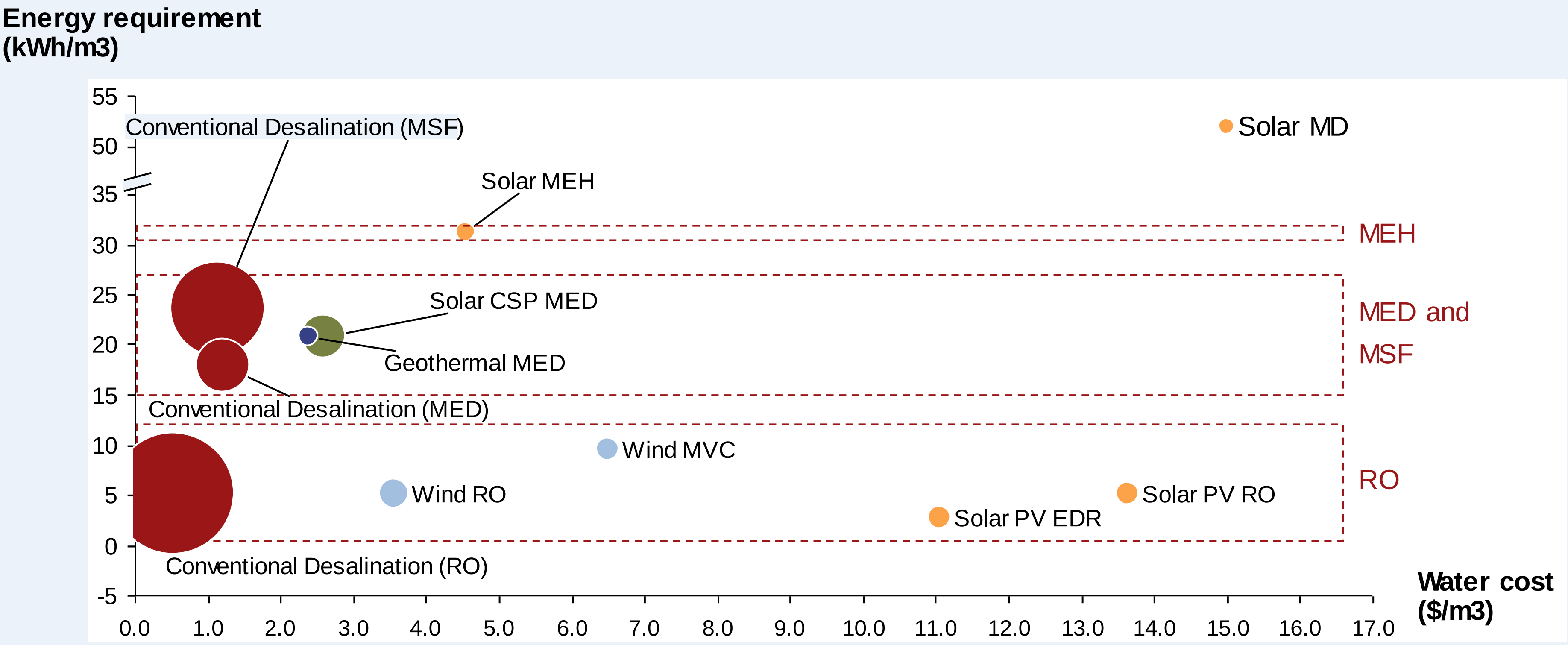
- *The Middle East, where the water sector accounts for 9% of electricity consumption, is the only region where desalination accounts for more than a quarter of water-related energy consumption* (WEO 2016).
- Eight out of top ten countries with lowest renewable water resources on per capita basis are in MENA.
- Due to population growth, economic development and climate change, the region is forecasted to experience a water gap between 85 - 283 bcm/year by 2050.
- Presently countries are diverting significant O&G resources to power thermal desalination (main process type in the region).
- Projected increase in desalination capacity in the region will entail an additional electricity consumption of around 250 TWh (10x current levels) by 2040.

Source: World Resources Institute, IEA WEO 2016, A.T. Kearney Energy Transition Institute analysis

Due to high investment and generation costs, existing renewables based desalination plants are expensive compared to conventional fuels plants

Comparative analysis of desalination combinations[1,2]

Indicative



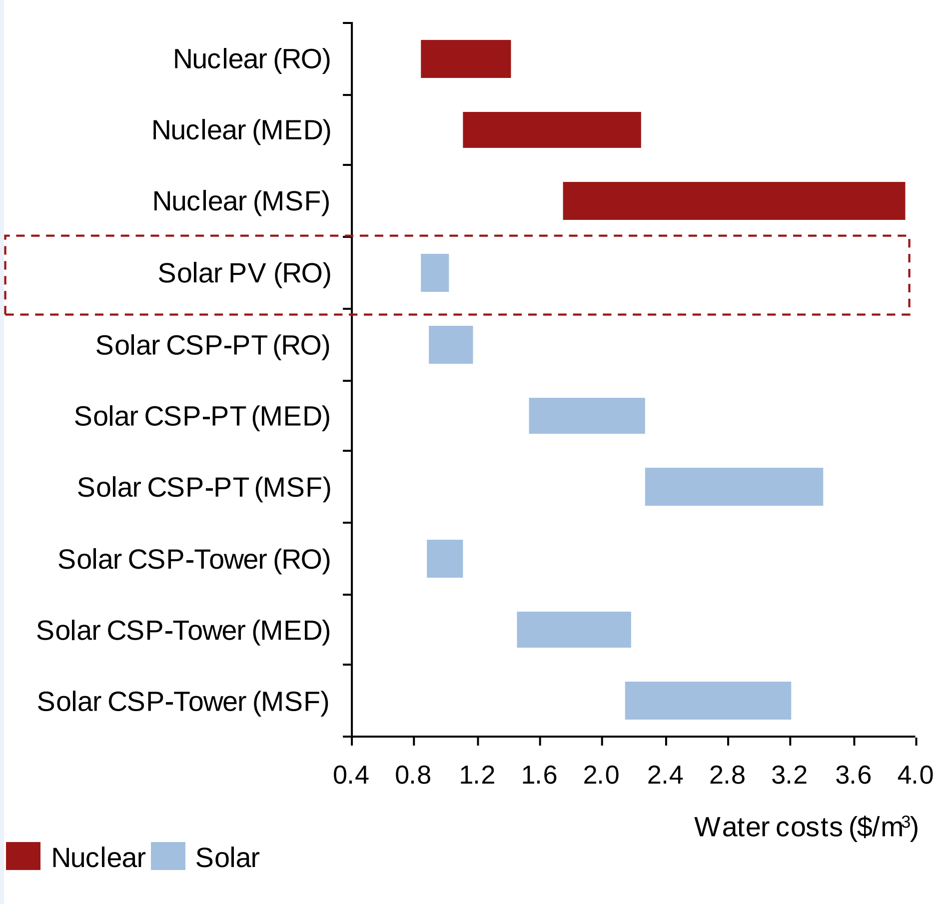
○ Bubble size corresponds to typical technical capacity in m3/day

1. Multiple Effect Humidification (MEH) : Use of heat from highly efficient solar thermal collectors to induce multiple evaporation/condensation cycles; Multiple-effect distillation (MED), Multi-stage flash distillation (MSF), Membrane Distillation (MD): Thermally driven distillation process with membrane separation; Electrodialysis Reversed (EDR): Same principle as Electrodialysis (ED) except for the fact that the polarity is reversed several times per hour; RO: Reverse Osmosis; MVC: Mechanical Vapor Compression; CSP: Concentrated Solar Power
2. Average values taken for energy requirement and water costs calculations for sea-water feed (SW)

Source: Renewable and Sustainable Energy Reviews 2013, IEA-ETSAP and IRENA, A.T. Kearney Energy Transition Institute analysis

Solar PV coupled with Reverse Osmosis offers most economical low emission solution in the Middle East

Solar & Nuclear desalination costs in the Middle East

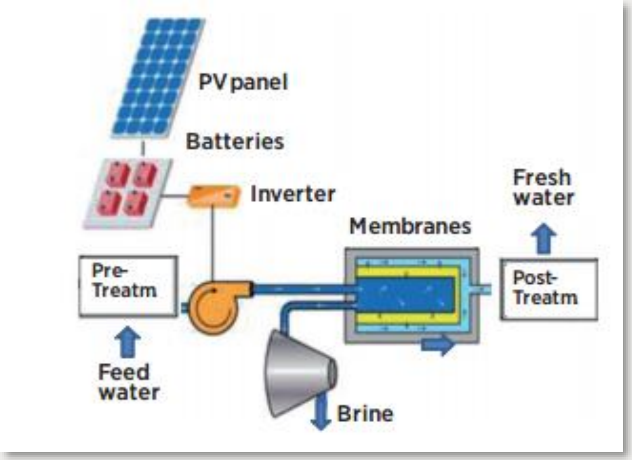


- Lower value corresponds to low interest rates, low capital costs and short construction periods.
- Energy cost is the major factor in water desalination cost, especially for thermal processes.
- Average water cost for a plant running on reverse osmosis coupled with solar PV panels is approx. $0.85/m3 compared to $0.91/m3 for a RO plant run on nuclear power. However, nuclear is more economical for thermal processes (MED and MSF) than solar CSP due to higher costs of incorporate costs of thermal storage capacity up to six hours.
- Declining costs of solar photovoltaics offers further cost reduction in generation costs (in 2030, projected capital costs of PV panels are roughly half of the current values).

Note: RO: Reserve Osmosis, MED: Multiple Effect Desalination, MSF: Multi Stage Flashing, CSP: Concentrated Solar Power, PT: Parabolic Trough
Source: AUB Policy Institute (February 2017); A.T. Kearney Energy Transition Institute analysis

Solar PV powered desalination can be used to store water as a proxy for energy

Concept



- Harnessing energy generated from solar PV to run desalination plants
  - When PV generation exceeds current demand, energy can be stored in the form of desalinated water instead of electricity
  - Excess freshwater is stored, to be used to meet demand in solar deficit times
- Primarily being used and developed in remote areas and off-grid islands

Solar PV Desalination with Water Storage

- Recent research results in Saudi Arabia indicate:
  - Reverse Osmosis (RO) solar PV with water storage (desalination costs, ~$2.1/m3) is cheaper than RO solar PV with electric storage (desalination cost, ~$2.6/m3) as storing excess electricity (NaS battery capital cost - $6,100/kW) is more costly than storing excess water
  - RO solar PV with water storage will be competitive with grid powered RO if fuel costs > $100/BOE assuming (1) PV capital costs of $2000/MW and (2) RO plant capital costs of $800/m3

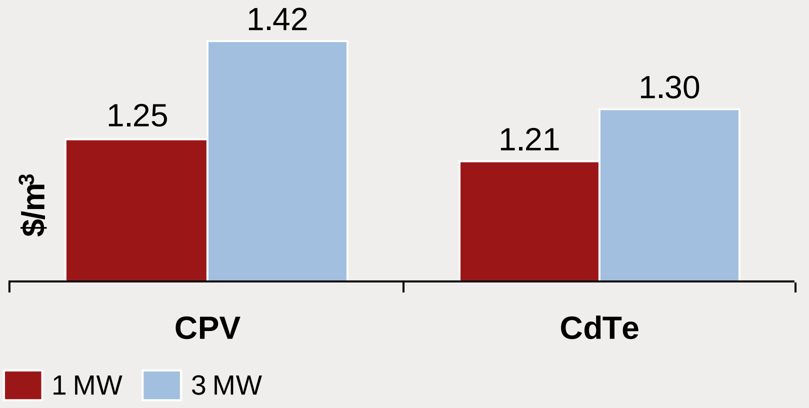
- Integrating and operating spare RO capacity with a variable power supply remains a technical challenge however, accelerated rate of declining costs of RO plants, PV systems and storage systems will continue to improve economics

Source: IRENA - Water Desalination Using Renewable Energy; KAPSARC - A Framework for Comparing the Viability of Different Desalination Approaches (August 2015); A.T. Kearney Energy Transition Institute

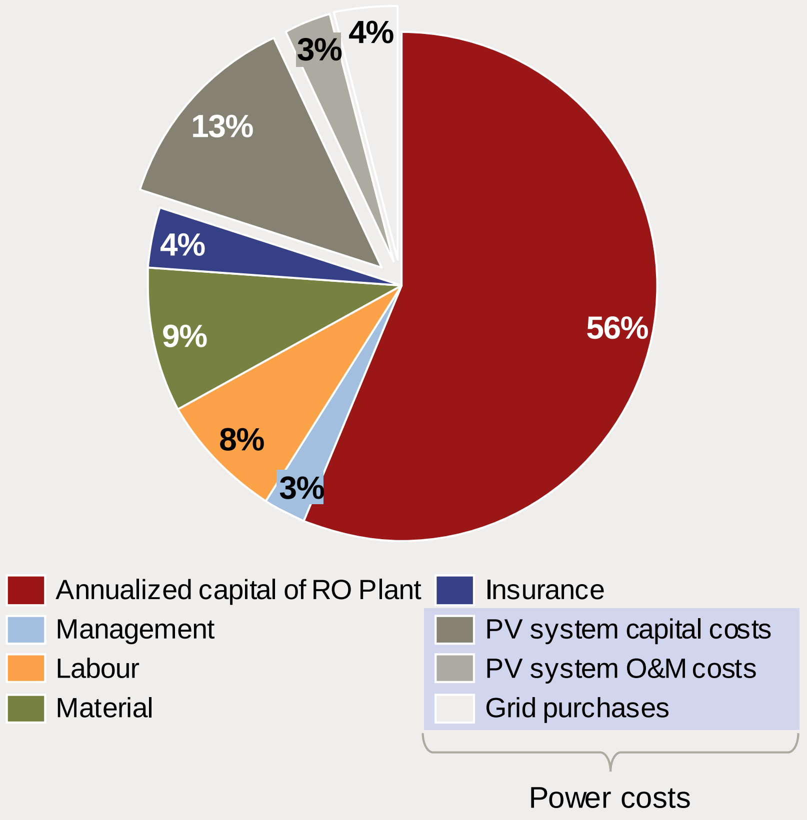
Studies have been conducted in Saudi Arabia exploring economics of PV-RO desalination plants

PV CdTe modules are more economical than CPV[1]

- The graph below depicts the estimates of total water production costs for a 6,550 m3/day RO sea-water desalination plant in Saudi Arabia powered by 1MW or 3MW CPV or CdTe PV plants and grid electricity
- CdTe PV systems have both lower LCOE and capital costs as compared to CPV systems
- For a medium-scale desalination plant with a 1 MW CdTe PV system, water production costs can be as low as $1.21/m3



Water production cost breakdown [2]



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1. CPV: Concentrator photovoltaics; CdTe: Cadmium telluride photovoltaics; 2. For a 6,550 m3/per day RO (Reverse Osmosis) seawater desalination powered by a 3MW CdTe PV plant

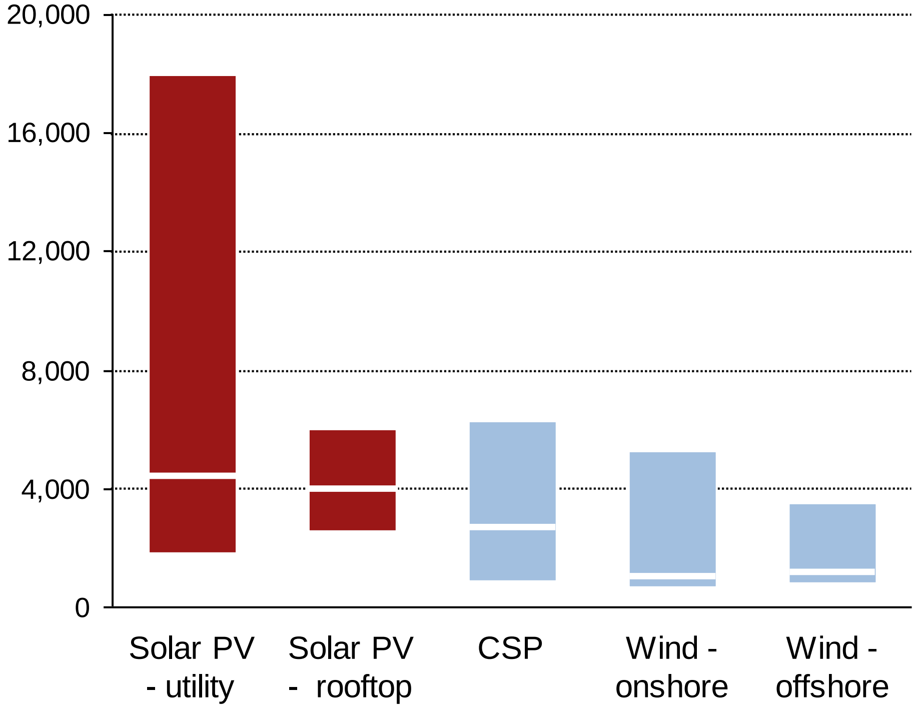
Source: Vasilis Fthenakis et al, New prospects for PV powered water desalination plants: case studies in Saudi Arabia (2014); A.T. Kearney Energy Transition Institute

5. Environmental & Social Impacts

Greenhouse-gas emissions from solar PV are low, but the technology's overall environmental impact depends on power-system integration

Lifecycle greenhouse gas (GHG) Emissions

g CO2eq /kWh



Median g CO2 eq / kWh	45	41	27	11	12

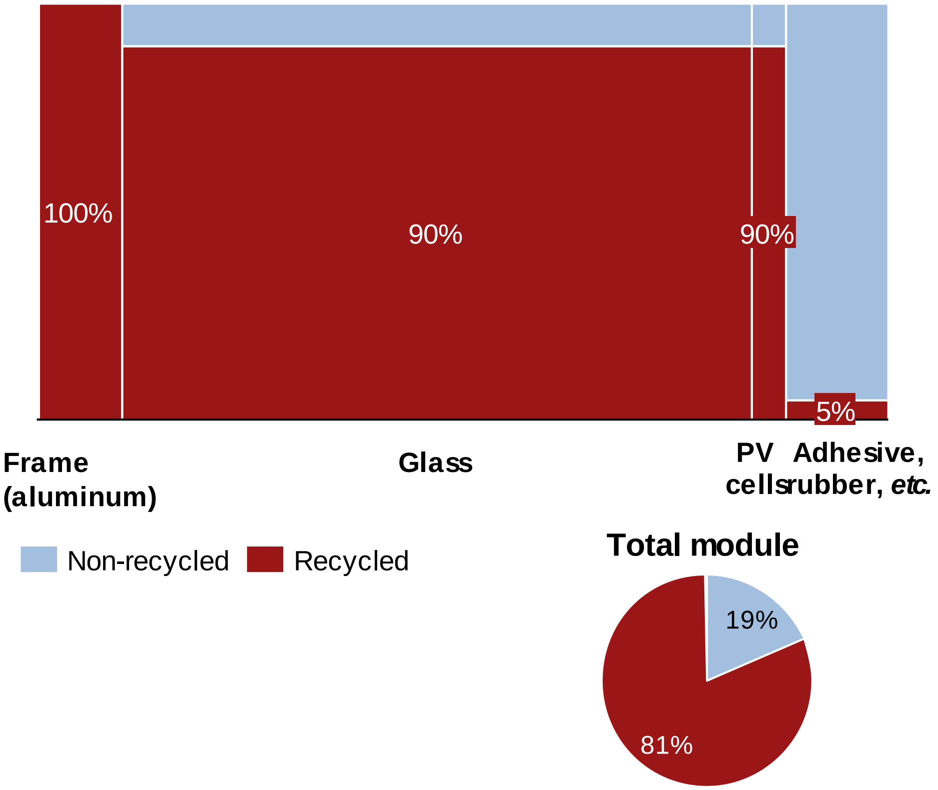
- Solar photovoltaic (PV) does not directly emit GHGs or other pollutants. However, median solar PV emissions range between 41 and 45 g CO2 equivalent per kWh over the entire lifecycle, depending upon application[1]. This range is close to concentrating solar power and wind, and a small fraction of that of natural gas and coal-fired power plants, which range from around 500 to 1,000 g CO2eq/kWh, respectively, for conventional combustion turbines in the US
- Lifecycle emissions depend on control and recycling measures during the manufacturing process, as well as installation, operation and maintenance, and disposal procedures. They tend to be prevalent during upstream processes[2], which typically account for 60-70% of lifecycle emissions. Crystalline silicon production is electricity-intensive, so lifecycle emissions depend on the carbon content of the electricity used.
- Replacing fossil-fuel power-generation capacity with solar PV may result in an increase in the use of flexible back-up plants. This could lead to a rise in GHG emissions, although the impact would be highly system specific. In general, however, greater use of solar PV should reduce significantly pollutants and GHG emissions.

1. Figures aim to provide an order of magnitude, as lifecycle emissions are inherently specific to location and technology; 2. From raw material extraction to plant construction / installation.
Source: IPCC (2014), “Fifth assessment report”; NREL (2012), “Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics”

Recycling is crucial in ensuring the solar PV industry is sustainable

Recyclability of a typical Crystalline PV Module

% of total mass



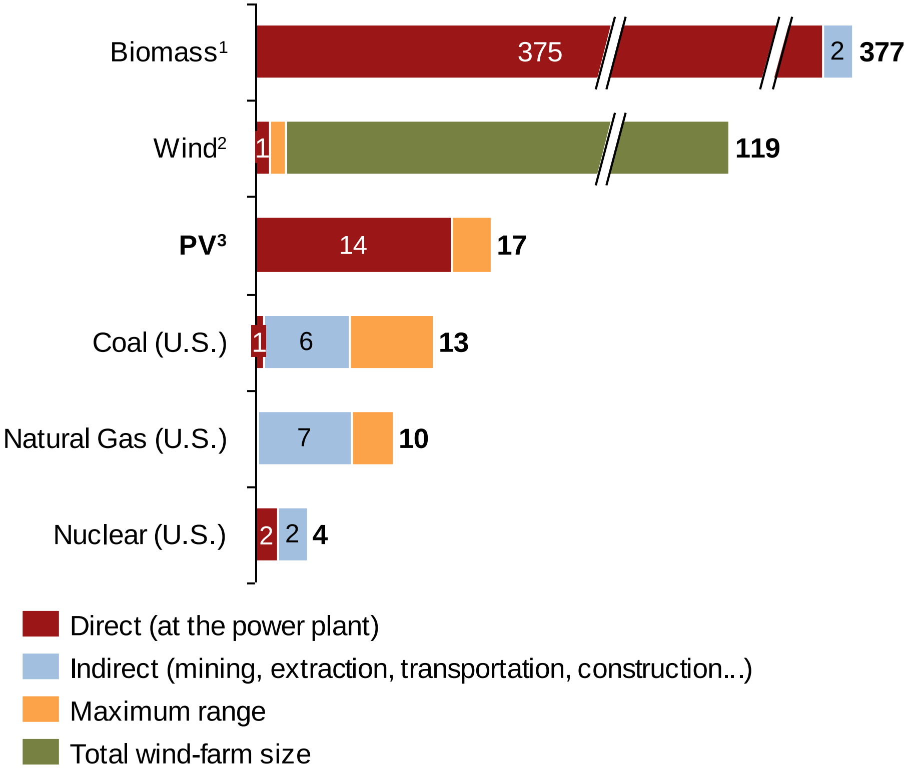
- **Production of crystalline silicon modules generates a large amount of electronic waste**, as in the semi-conductor industry.
- **Recycling and disposal processes are therefore essential** and will be even more crucial for thin films because of the use of rare metals.
- **Recycling is already a core part of the PV industry** as:
  - It is economically viable for large-scale applications. It is predicted that 80%-96% of glass, ethylene vinyl acetate and metals will be recycled;
  - Modules are being designed to aid recycling;
  - Solar PV manufacturers are increasingly being held responsible for the lifecycle impact of their products;
  - Collective take-back and recycling solutions for PV modules, such as PV Cycle in Europe, have emerged for the treatment of photovoltaic wastes.

Source: IPCC (2011), "Special report on renewable energy"

PV technologies appear to have limited land requirements

Lifecycle land transformation requirement

m²/MWh/year



- **Land requirements for solar PV vary significantly,** according to solar irradiance, conversion efficiency, spacing, and tracking and mounting systems.
- **Overall, the land footprint of PV technologies is minimal.** The MIT estimated that if solar energy were to meet 100% of all electricity demand in the US, it would take up 0.4% of the total area in the US, half the amount of land currently used for corn ethanol production[4].
- **Land use and public acceptance challenges depend on application and system size**. The largest utility-scale solar PV plants are installed in arid, relatively uninhabited areas, where visual impact and land footprint concerns are limited. In rural areas, efforts have been carried out to help PV-farms cohabiting with agricultural activities, such as sheep farming or wine production.
- **Rooftop solar benefits from its distributed nature and from public support**. Most studies carried out on public acceptance come out with a higher public acceptance of solar PV than onshore wind because it is perceived to be relatively undetrimental aesthetically, and to have more limited noise and wildlife impacts

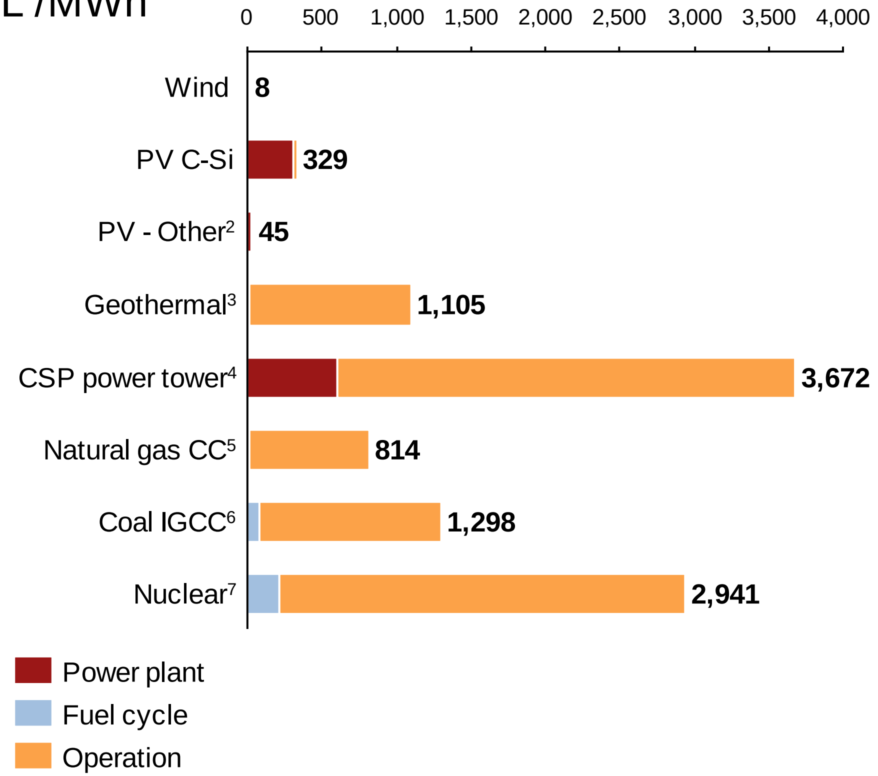
1. Based on willow gasification, New York; 2. Land requirement for wind was calculated using direct land impact (mainly service roads and pads) and averaged 0.3 ± 0.3 ha/MW. The lower bound of land requirement assumes a maximum capacity factor of 33% and only factors in the area of each wind pad. The upper bound factors in the total plant area. This is very large because wind turbines must be erected at a minimum distance to each other in order to avoid wind turbulence. However, most of the surface area of a wind farm is physically undisturbed. For more information, refer to A.T. Kearney -ETI Wind Power FactBook, 3. The upper bound of the land requirement for solar PV is based on total average land use in small, ground-mounted utility-scale PV projects in the United States, as reported by NREL.

Source: Fthenakis and Kim (2009), "Land use and electricity generation: A life-cycle analysis"; World Policy Institute (2011), "The Water-Energy Nexus"; Cater and Campbell (2009), "Water issues of Concentrating Solar Power Electricity in the US Southwest"

The water consumption of solar PV is relatively low compared with thermal alternatives

Median lifecycle Water consumption[1]

L /MWh



- **Unlike thermal power plants, solar PV does not need water for cooling processes, resulting in low water consumption.** Solar PV may therefore help mitigate water stress in areas where water availability may constrain the development of thermal electricity generation[8].
- **Solar PV power uses virtually no water to operate except for cleaning the panels** when weather conditions (wind or rain) are not sufficient[9]. Almost all of the life-cycle water used in solar PV occurs during the manufacturing of solar panels and construction of power facilities, mainly to produce the energy needed during these processes[10].
- **Water use varies, depending on technology and manufacturing process**. Crystalline silicon PV tends to require more water than thin-film technologies, as silicon processing is water-intensive.
- **There are different levers for further reducing solar-PV water use,** including (i) reducing the amount of materials used, (ii) introducing better manufacturing processes; (iii) improving system efficiencies and extending the lifetime of equipment; (iv) and optimizing logistics and transportation.

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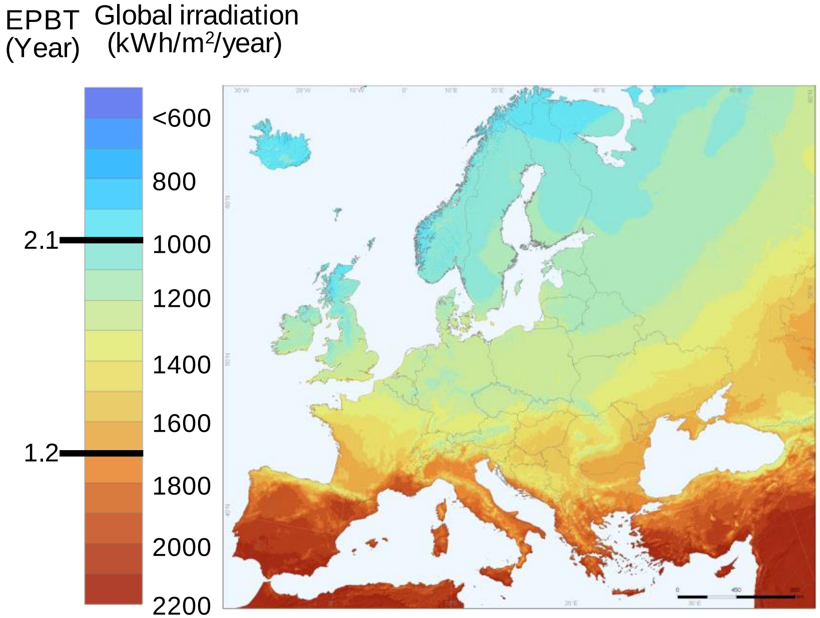
1. Data were calculated using mean data from Meldrum et al. (2013); 2. Principally thin-film technologies; 3. With binary dry-cooling; 4. with cooling tower; 5. Conventional gas with cooling tower; 6. Surface-mining with cooling tower; 7. Centrifugal enrichment cooling tower; 8. In the GCC region, many countries have announced renewable-energy plans focusing largely on solar PV that can result in a 22% reduction in water consumption; 9. DOE reports that few operators wash PV panels in practice; 10. Usage of renewable sources in the energy mix can consequently further reduce the water footprint of solar PV.

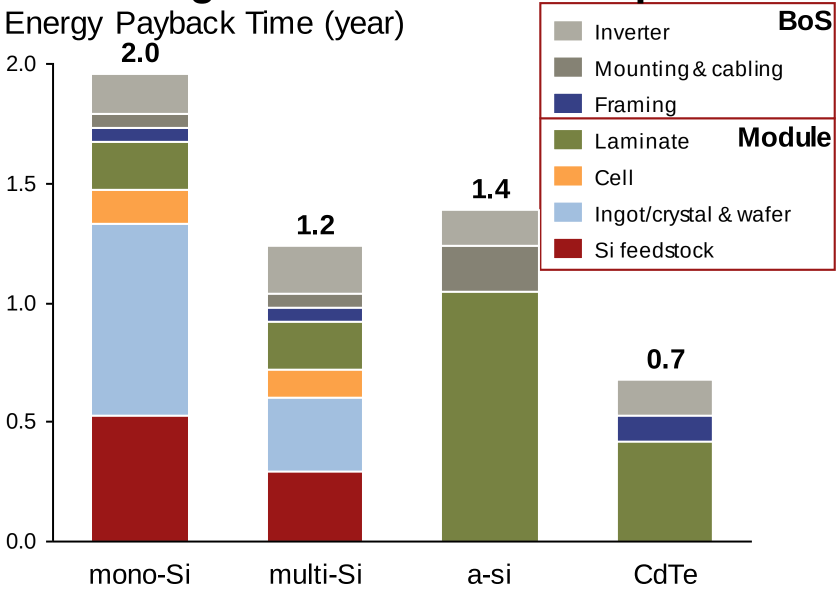
Source: A.T. Kearney Energy Transition Institute based on Meldrum et al. (2013), "Life cycle water use for electricity generation: a review and harmonization of literature estimates"; IRENA (2015), "Renewable Energy in the water, energy & food nexus"; EPIA (2009); "Sustainability of Solar Photovoltaic systems, The Water Footprint"

Contrary to common belief, the energy payback time of solar PV tends to be relatively short

Energy Payback Time of multi-crystalline silicon PV systems



Energy payback time for different PV Technologies In Southern Europe[2]



- The energy payback time (EPBT) of solar panels is defined as the time required for solar panels to produce the energy used to manufacture them[1]. EPBT is sensitive to solar technology and solar irradiance. Nevertheless, even under conservative solar-irradiance assumptions, the EPBT of the most energy-intensive solar panels is no more than 3.5 years. Given their lifespan of 25 to 30 years, solar PV systems will therefore produce clean net electricity over approximately 90 to 95% of their lifetime.

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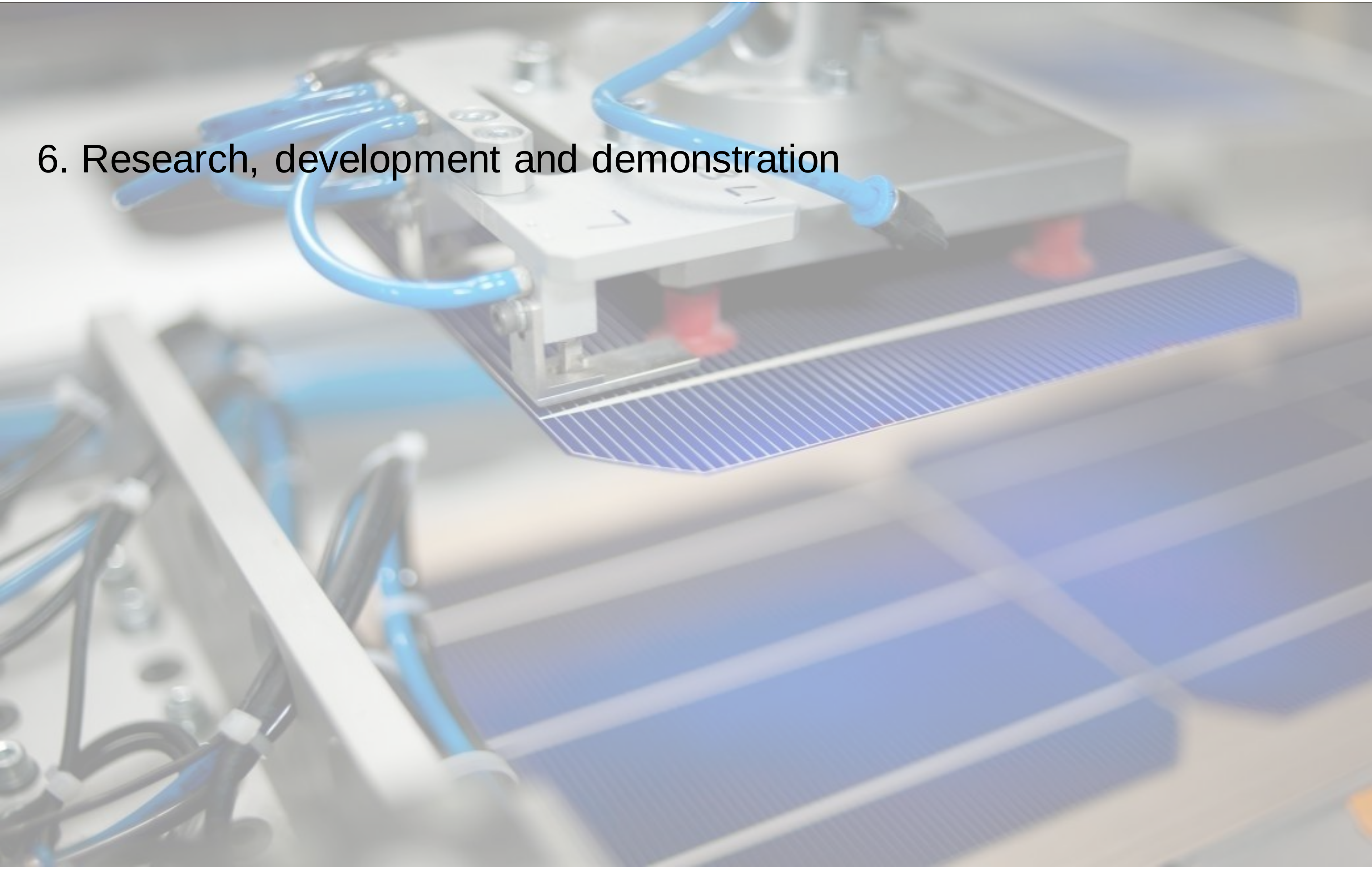
1. EPBT may also take into account the energy required over the entire lifetime of solar panels, including manufacturing, but also transport, installation, maintenance and recycling. The figures provided in this slide refer to manufacturing only, which accounts for the vast majority of energy requirement; 2. Calculations are given for average irradiance of 1700kWh/m2/yr. on optimally inclined modules using IEA PVPS life-cycle assessment methodology, excluding installation, operation, maintenance and end-of-life phase.

Source: M.J. de Wild-Scholten (2013), "Energy payback time and carbon footprint of commercial photovoltaic systems"; Fraunhoffer (2014), "Photovoltaic Report"



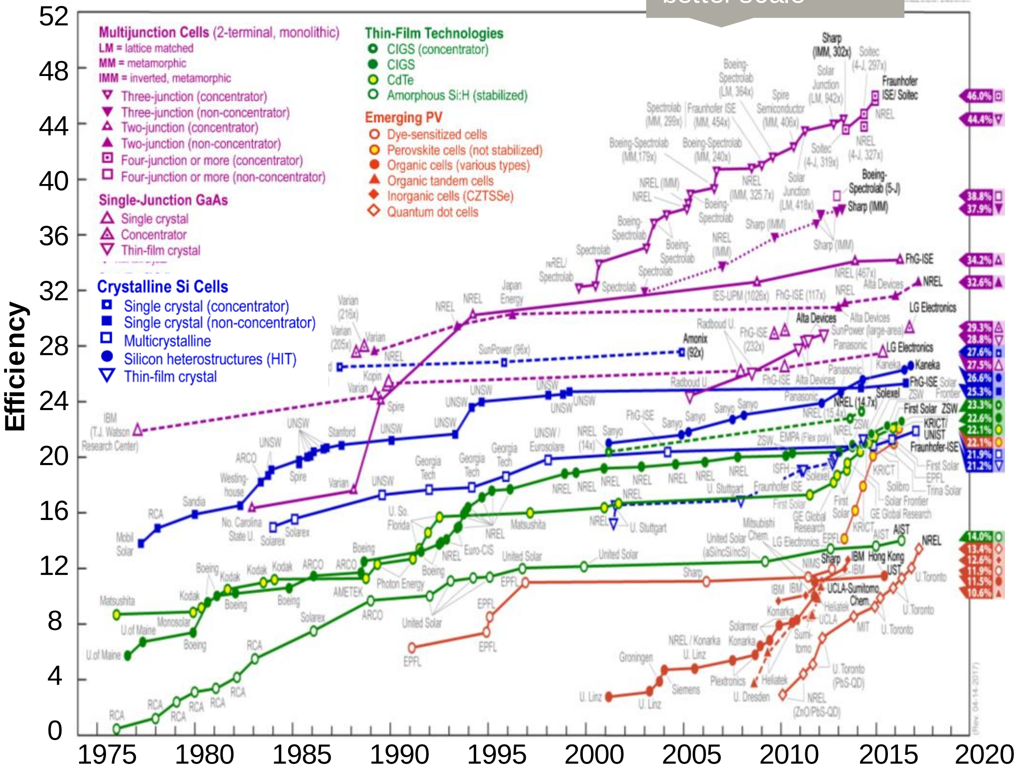
6. Research, development and demonstration

Most research & development is focused on improving the cost and efficiency of cell materials and the power density of PV modules

Best research-cell efficiencies[1]

%

See slide 101 for a better scale



- **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.
- **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.

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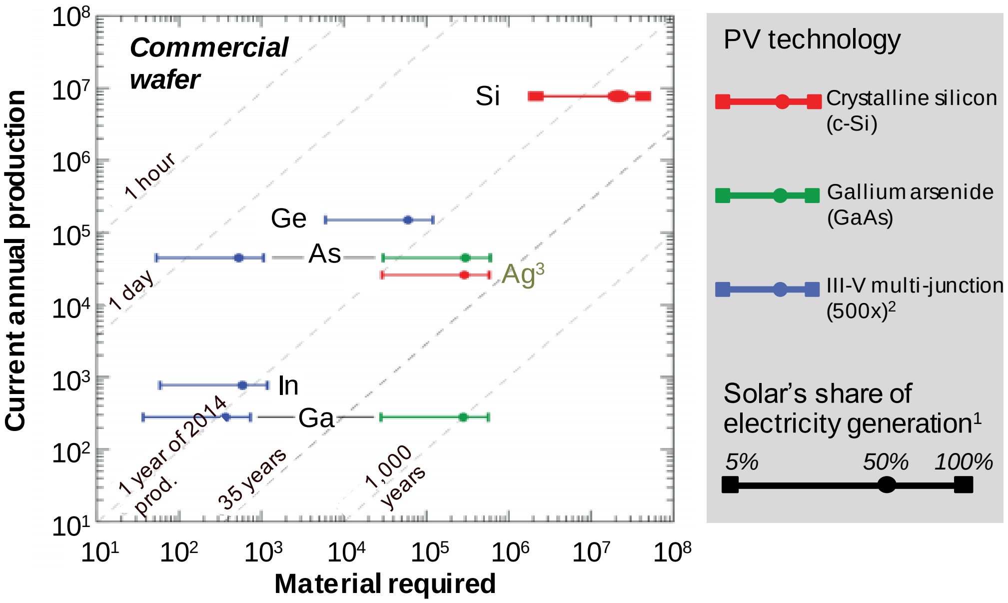
1. Graph courtesy of NREL. For a more detailed version of this diagram, refer to appendix 4. Note that test cells are manufactured with small sizes in research laboratories and may face some stability issues; 2. Refer to slide 19 for more information on discrepancies between cell and module efficiencies. First Solar recently reached a record 18.6 % thin-film module efficiency.

Source: NREL (2017), "Research Cell Efficiency Records"; European Photovoltaic Technology Platform (2011), "A Strategic Research Agenda for Photovoltaic Solar Energy Technology – Edition 2"; Jean et al. (2015), "Pathways for solar photovoltaics"; FirstSolar website (accessed July 2015)

Reducing the requirement for materials is becoming an increasing area of focus, as PV penetration increases

Requirements for critical materials

Current annual production (t/y), material required (t)



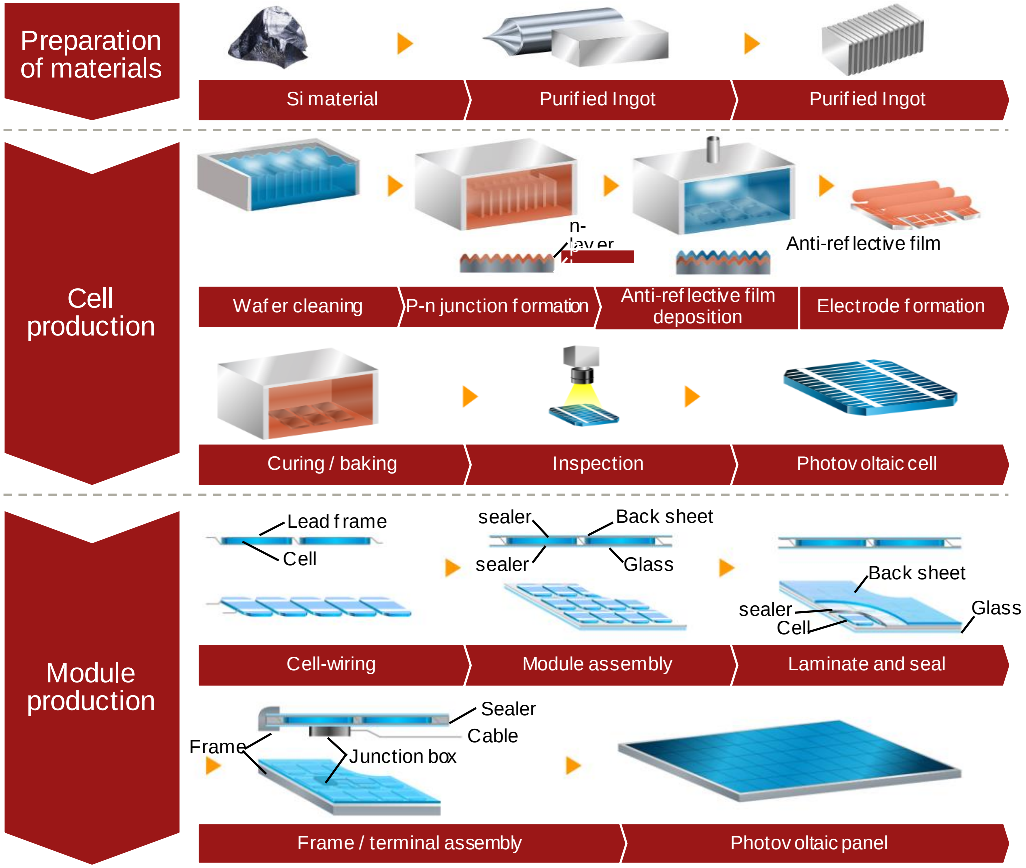
How to read this graph: This figure shows the quantity of material that would be required to satisfy 5%, 50%, or 100% of global electricity demand in 2050[1] for three PV technologies. The dashed grey lines indicate requirements for materials as a multiple of current production. For instance, meeting 5% of electricity demand in 2050 with c-Si would require less than 1 year of global silicon production.

- **Solar PV development may be limited by a scarcity of materials and a commensurate rise in costs.** Therefore, reducing the use of rare or expensive materials is set to play an important role in helping solar PV deployment. Except for silver and silicon, all critical elements of current PV systems are made of byproducts of abundant metals, obtained by refining or mining. Economies of scale could help reduce costs, but may also make PV's economics dependent on the price and availability of primary products, such as copper.
- **Material requirements and scaling concerns could impact the development of PV-cell technology.** Several commercial, thin-film technologies could avoid critical material constraints if solar were to achieve high deployment rates. In addition, R&D is focused on developing lighter and more flexible cells, mainly because of thinner substrates and active layers. The latter would not only reduce the cost of materials, but could also lower transportation costs, and avoid breakage during transport and operations.
- **Finally, solar-cell manufacturers are exploring the reuse of materials and recycling** as a way to mitigate concerns about toxicity and the scarcity of materials.

Note: Graph courtesy of MIT; 1. Corresponding to a total installed capacity of ~1.25 TWp, 12.5 TWp, or 25 TWp, respectively; 2. Under 500 concentration ratio; 3. Unlike other material on this graph, silver is not a semiconductor. It is used as a catalyst to conduct electricity out of solar cells.
Source: Jean *et al.* (2015), "Pathways for solar photovoltaics"; NREL (2015), "Research Cell Efficiency Records"; Office of Energy Efficiency & Renewable Energy (accessed June 2015), "Cadmium Telluride"; UNEP (2015), "Global Trend in Renewable Energy Investment"; Jean *et al.* (2015), "Pathways for solar photovoltaics"

Manufacturing processes are being improved in order to reduce costs

Typical-crystalline-silicon manufacturing process[1]



- **Improving manufacturing processes is a promising route to PV cost reduction.** Currently, around half of PV module production costs are incurred during wafer production. Cell processing accounts for a further 20%.
- **In recent years, processes for manufacturing crystalline-silicon PV cells have greatly improved as a result of increases in** uptime and yield at the machine and factory levels. Incremental reductions in manufacturing costs could be achieved by making factories larger and by improving supply-chain efficiency. For thin films, moving from lab-scale batch processes to large-scale continuous processes is expected to reduce manufacturing complexity and cost.
- **The use of new technologies and processes should enable to cut costs by reducing the amount of raw materials used and energy consumed**. Diamond-wire cutting to produce multi-crystalline wafers[1] is seen as a promising way to reduce waste, and consumption of electricity and water. Other process improvements are also under way, notably the introduction of fluidized bed reactors that require less energy than current technology for producing high-purity silicon[2], or the development of more efficient and cost-efficient strategies for extracting and producing materials.

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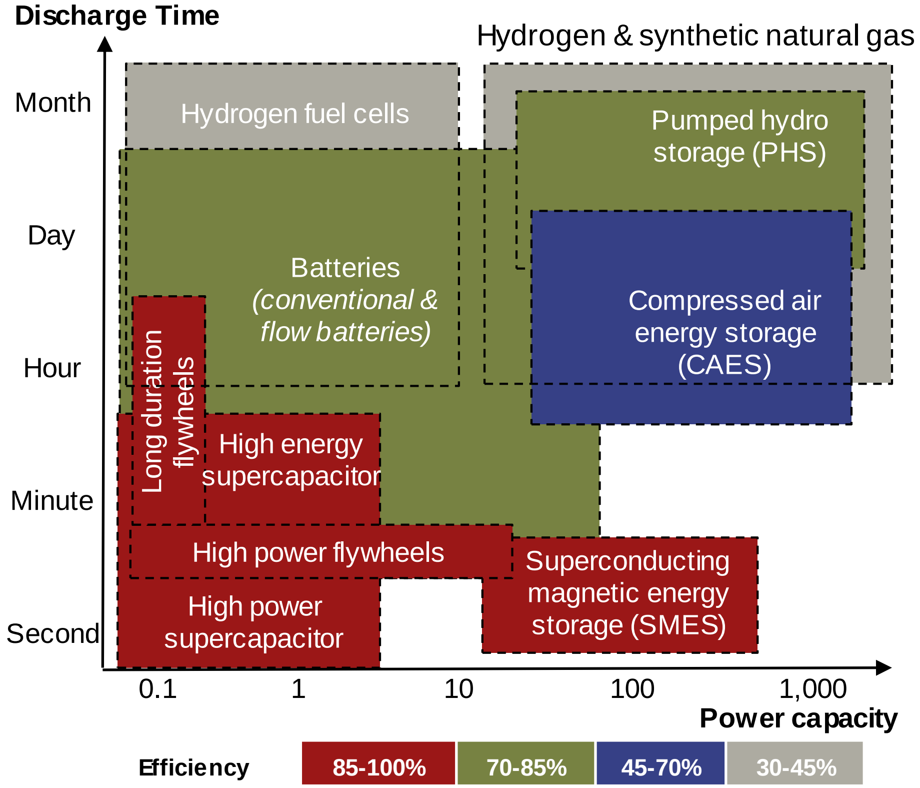
1. Historically, diamond wire saw have been used only for monocrystalline silicon ingots;
2. Purification of silicon is a major part of energy consumption associated with the production of solar cells.

Source: Recsilicon.com (accessed June 2015), "REC Silicon fluidized bed reactor (FBR) process"; UNEP (2015), "Global Trend in Renewable Energy Investment"; MIT(2015), "Study on the Future of Solar Energy"

Grid integration and power reliability are important R&D targets for solar PV industry

Electricity Storage Technologies

Discharge Time vs. Power capacity (MW)



- **Grid integration and distributed generation challenges are expected to become more acute as solar PV penetration[1] increases**. Solar PV still mostly accounts for a limited share of the power mix, and utility-scale systems account for the bulk of solar PV capacity. However, its deployment is expected to continue at a strong pace and to be driven increasingly by distributed off-grid and grid-connected systems.
- **R,D&D is, therefore, under way to improve the economics of electricity storage**. The main aims of battery-storage R,D&D are to lower costs, and produce more durable chemicals and materials. The priorities for existing batteries and the methods for achieving them are highly specific (*e.g.* find lower-cost materials for the negative electrode of lithium-ion batteries and replace water-based electrolytes with organic solutions to improve specific energy and cycle life of flow batteries). R,D&D is also trying to identify alternative electrochemical solutions that would achieve higher energy densities, such as metal-air and multivalent-ion. Finally, electric-vehicle batteries could be given a second life if they are used for electricity storage.
- **Improvements in power electronics and hardware technologies could enable distributed PV generation to develop a large share of electricity supply without putting power reliability at risk.** Advanced inverter functionality could, for instance, allow safe and cost-effective PV deployment on distribution systems[2].

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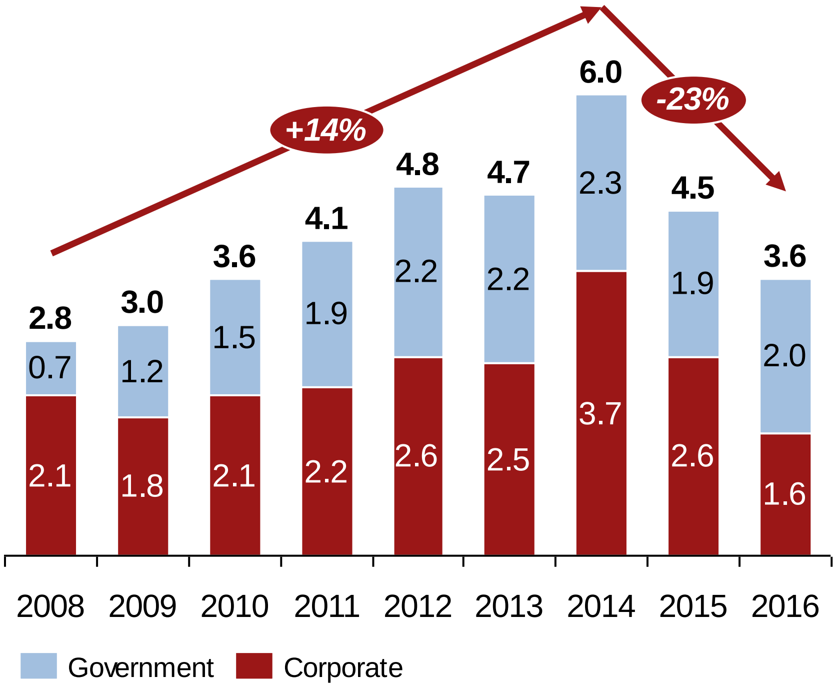
1. For more information on challenges associated with intermittence, refer to slide 31 to 33; 2. Maximum power point tracking (MPPT) is a feedback control technique whereby the power transferred from a source having output impedance to the input of a loading device is maximized by dynamically adjusting the voltage and/or current at the input of the loading device. This is so far widely used only in battery charge controllers and grid-connected inverters). For more information on electricity storage, refer to Appendix

Sources: A.T. Kearney Energy Transition Institute based on EPRI (2010), "Electricity Energy Storage Technology Options", Bradbury (2010), "Energy Storage Technology Review"

Despite receding from a peak of $6 billion in 2014, solar R&D spending continues to outstrip R&D spending on other renewables

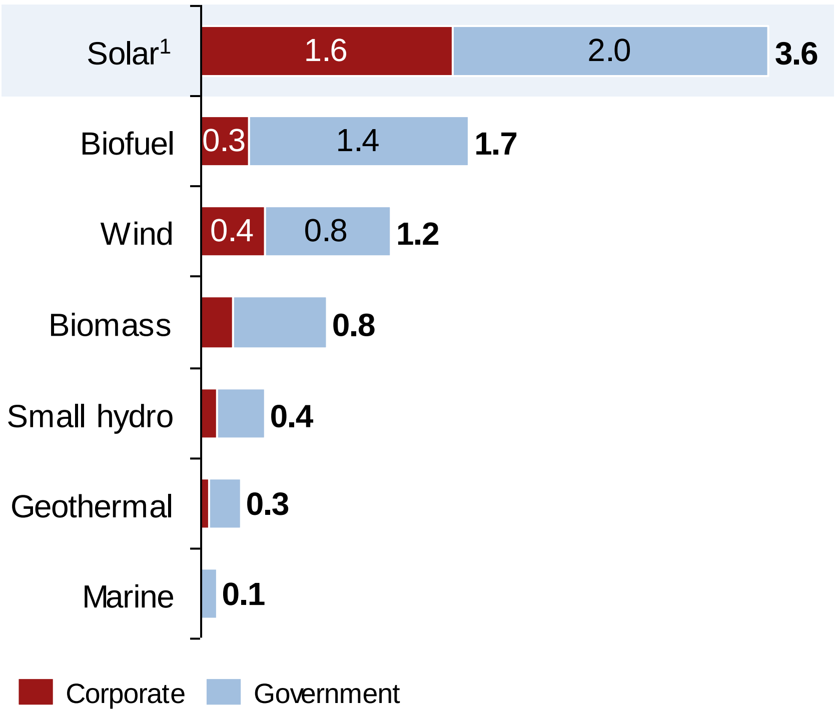
R&D investments in solar

$ billion, 2010 - 2016



- Solar R&D funding increased steadily from 2008 to 2014, but declined in 2015 and 2016

2016 R&D investments in renewable energy $ billion



- Solar R&D funding remains significantly higher than R&D funding for other renewable technologies

1. Caution: global breakdown of solar R&D investment between PV and CSP is not available. The ratio of public R&D funding for PV and CSP in the OECD was 5:1, in favor of PV (2014)

Source: UNEP (2017, 2016, 2015, 2014, 2013, 2012, 2011, 2010, 2009) "Global Trend in Renewable Energy Investment". Results based on Bloomberg, Bloomberg New Energy Finance, IEA, IMF, and various government agencies

Appendix & bibliography

Acronyms (1/2)

a-Si: Amorphous silicon
BOS: Balance of system
DC: Direct current
CAGR: Compound annual (average) growth rate
CAPEX: Capital expenditures
CCGT: Combined-cycle gas turbine
CdTe: Cadmium telluride
CIGS: Copper-Indium Gallium Diselenide
CIS: Copper-Indium Diselenide
CO2eq: carbon dioxide equivalent
CPV: Concentrated photovoltaic
c-Si: crystalline silicon
CSP: Concentrating solar power
CZTS: Copper-Zinc-tin-Sulfide
DG: Distributed generation
DSSC: Dye-sensitized solar cells
DSO: Distribution system operator
EJ: Exajoule
EPBT: Energy payback time
EPA: Environmental Protection Agency
EPC: Engineering, procurement and construction
EU: European Union
FIT: Feed-in-tarrifs
G&A: General and administrative expenses
GaAs: Gallium Arsenide
GHG: Greenhouse gas
IEA: International Energy Agency
IGCC: Integrated gasification combined-cycle
IMF: International Monetary Fund
IPCC: Intergovernmental Panel on Climate Change
IPP: Independent power producer
IRENA: International Renewable Energy Agency
LCOE: Levelized cost of electricity
MIT: Massachusetts Institute of Technology
MJ: Multijunction
mc-Si: Multicrystalline Silicon
MW: Megawatt
NEM: Net energy metering
NREL: National Renewable Energy Laboratory
O&M: Operation and Maintenance
OCDE: Organization for Economic Co-operation and Development
OPV: Organic photovoltaic
PII: Permitting, interconnection, and inspection
PPA: Power purchase agreement
PV: Photovoltaic
PV/T: Photovoltaic/thermal
PVPS: Photovoltaic Power Systems programme
QDPV: Quantum dot photovoltaic
R&D: Research and development
R,D&D: Research, development and demonstration
REC: Renewable energy certificate
ROW: Rest of the world
RPS: Renewable portfolio standard
sc-Si: Monocrystalline silicon
SPPA: Solar power purchase agreements

Acronyms (2/2)

TF: Thin film
TPO: Third party ownership
TSO: Transmission system operator
U.K.: United Kingdom
US: United States
UNEP: United Nations Environment Programme
W/m2: watt per square meter
WACC: Weighted average cost of capital

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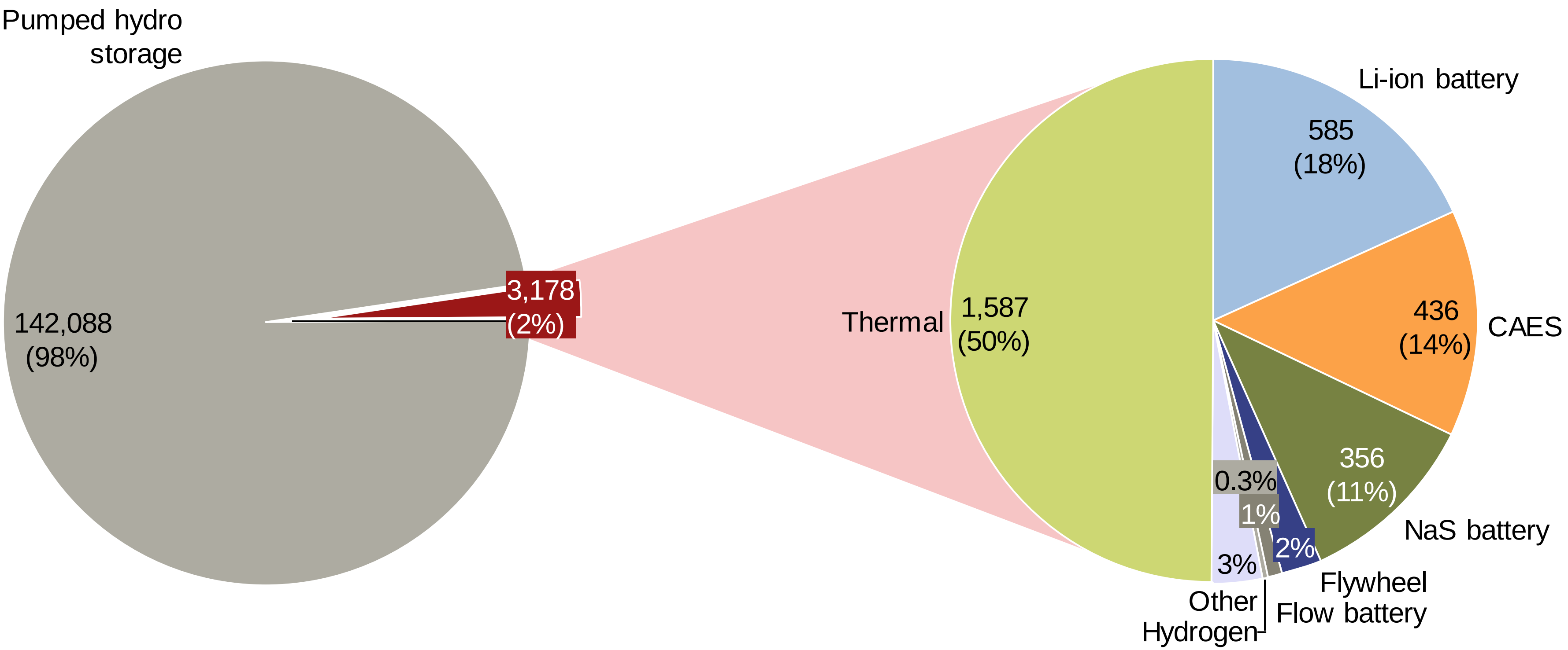
Appendix 1 - Worldwide stationary storage capacity currently stands at 153 GW, 98% of which is pumped hydro storage

Existing Worldwide storage capacity
MW, November 2015

Existing non-hydro storage capacity
MW, November 2015



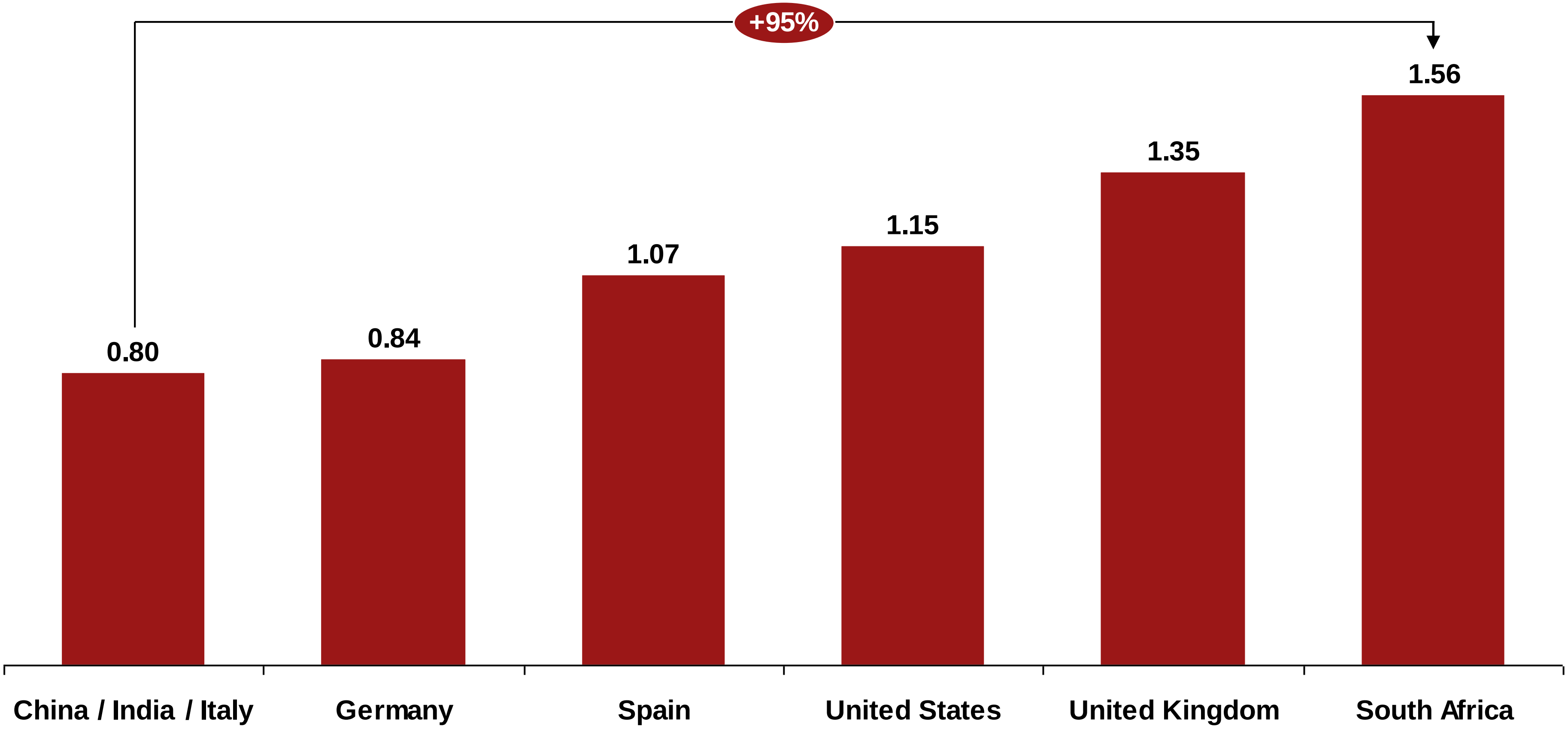
1. Other includes lead-acid or nickel-based batteries, superconducting magnets and supercapacitors.
2. Hydrogen includes power-to-gas projects

Source: A.T. Kearney Energy Transition Institute analysis based on BNEF database, extracted on Nov 16th, 2015; IRENA database extracted on Nov 16th 2015

Appendix 2 – Balance of system (BOS) costs vary significantly, according to country

BOS cost for utility-scale solar system in different locations

$ /W

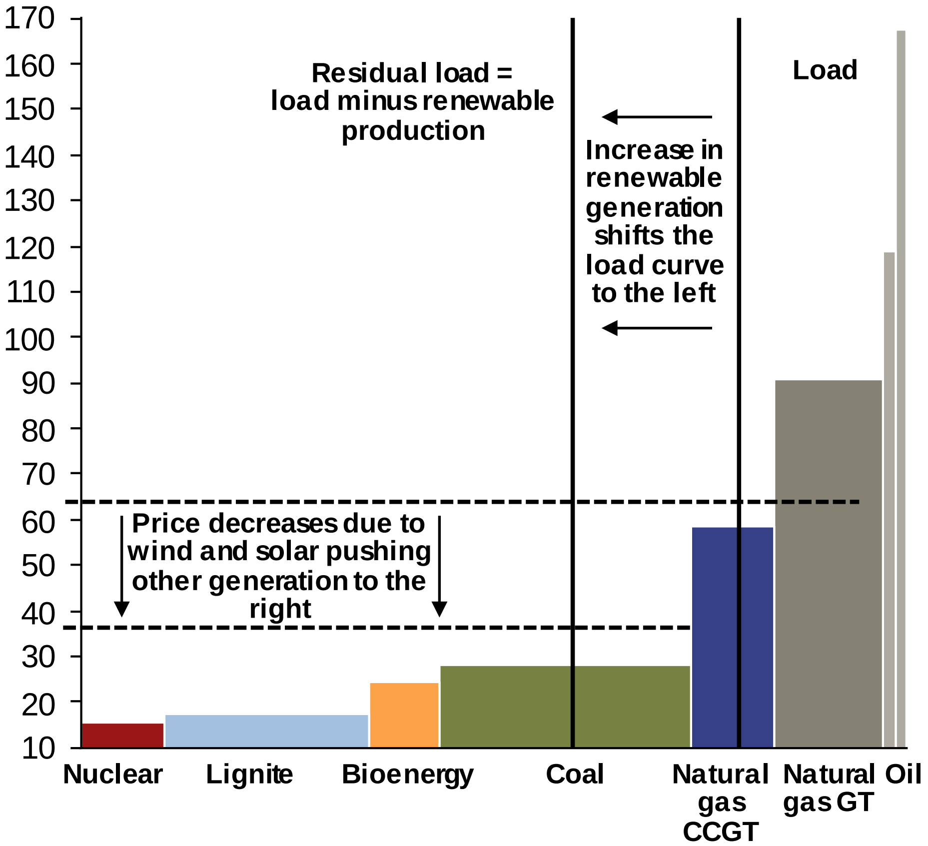


Source: IRENA (2015), "Renewable Power Generation Costs in 2014"; MIT (2015), "The Future of Solar Energy";

Appendix 3 – The value of solar PV in the power system varies according to penetration rates and the generation mix

Merit-order effect – illustrative

Marginal production cost in $ /MWh



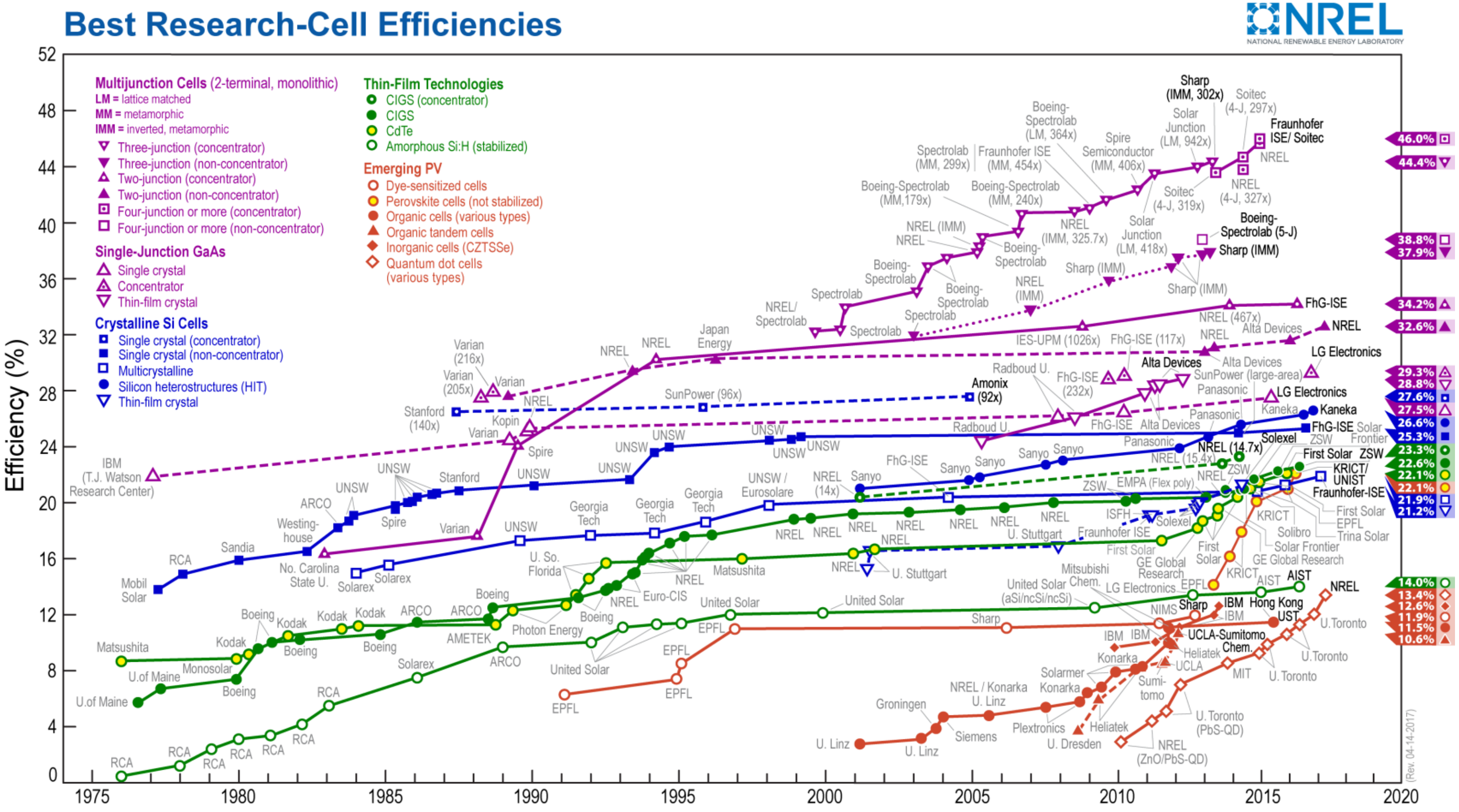
- Power-system operation relies on the precise balancing of supply and demand at all times. In the current operating paradigm, generation must follow the load: system operators activate dispatchable generators, depending on their flexibility and their marginal cost of production. Because of the absence of fuel costs, solar PV comes first in the merit order. However, its intermittent nature increases flexibility and makes balancing power and supply more complex. Therefore, its economic impact will vary according to generation mix, demand profile and penetration rate[1].
- For low penetration rates in thermal-based power systems – and subject to solar PV output fitting well with the demand profile – PV generators will benefit, on average, from higher prices than baseload-generation units. For example, while the 2011 base price in Germany was €51/MWh, solar power received an average price of €56/MWh on the market, because it is typically generated when demand is high. This may have an impact on the profitability of peak power units that are used less often during the year, as has been the case in Europe. When the penetration rate increases, the merit-order effect tends to reduce the relative competitiveness of solar PV. The supply of renewable energy reduces power prices during windy and sunny hours. The more capacity is installed, the larger the price drop. This phenomenon can already be observed in a number of European markets[1].

1. In order to value the impact of solar PV on the power system, Hirth introduced the concept of value-factors and the EIA recently introduced the levelized avoided cost of energy (LACE). 2. Such as Spain, Italy and Germany; 3. Such low prices can, at some point, trigger the retirement or mothballing of generation capacity, which can raise concerns about security of supply and also affect the plant's business plan and returns expected by investors.

Source: Hirth (2013), "The market value of variable renewables, The effect of solar wind power variability on their relative price"

Appendix 4 - Cell materials efficiencies have significantly increased over the past decades

Best research-cell efficiencies – graph credit NREL



Source: NREL (2017), "Research Cell Efficiency Records" (https://www.nrel.gov/pv/assets/images/efficiency-chart.png)

The A.T. Kearney Energy Transition Institute is a nonprofit organization. It 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 economical 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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