Solar Technologies: Cross-cutting applications across multiple sectors

The radiation from the Sun –the primary energy source, using different technologies, is directly transformed into two types of energy forms, in general: electricity using solar Photovoltaic (PV) and Concentrated Solar Power (CSP) systems, and solar heating, cooling and industrial process heat using solar thermal systems respectively where the first one dominates in the energy sector.

Solar energy conversion technologies encompass various methods to harness the Sun's energy and convert it into usable forms, electricity and heat, the primary technologies are illustrated in Figure 11 and discussed.

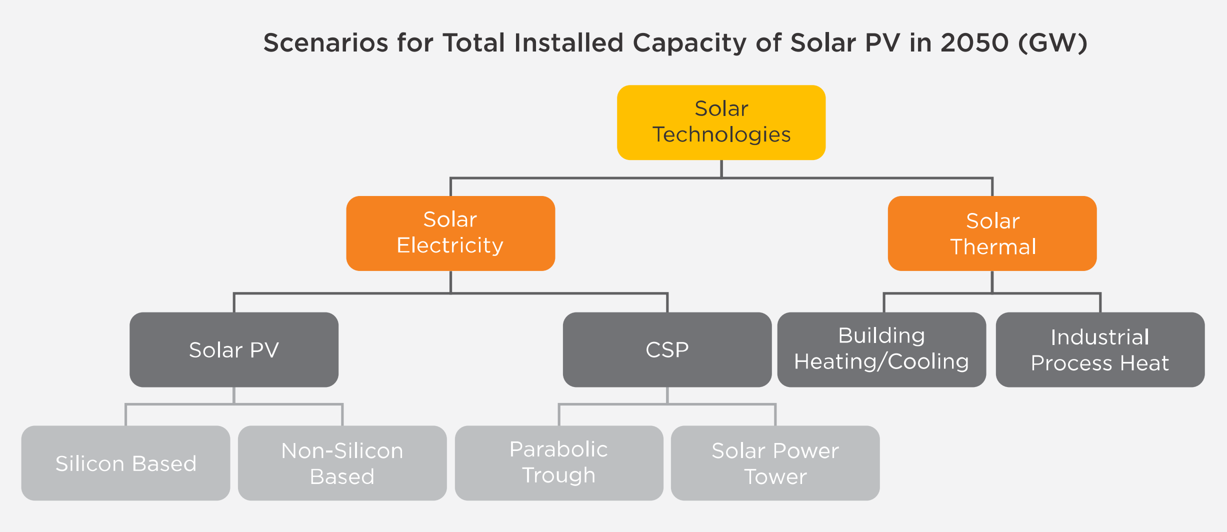

Figure 11: Different Solar Technologies

Source: ISA Analysis

Solar Photo-voltaic (PV) System converts the sunlight into electricity directly using devices based on semiconductor material which are made of an ensemble of solar cells – solar PV modules. A solar cell, referred to as a solar photovoltaic cell is fabricated from either silicon-based crystal such as monocrystalline, polycrystalline, amorphous silicon, or non-silicon-based crystals such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), organic materials. Solar PV has become the key solar technology to generate electricity over the past two decades and has evolved into a mature technology owing to widespread global deployment.

Concentrated solar power (CSP) generate electricity from solar radiation which is primarily converted into heat. This system consists of a collector to absorbs solar energy, storage system which usually comprised of water or a phase change fluid and a boiler that act as a heat exchanger between the fluid and heat engines. In CSP plants the heat engine is a steam engine which converts thermal energy to mechanical energy which can be further used to drive an electrical generator to produce electricity.

It is also practical to utilize the heat energy generated by the collector and stored in thermal storage devices for industrial purposes where heating is one of the major energy intensive segments.

Solar thermal system utilizes solar radiation to produce heat, which can be then used for multiple applications such as heating, cooling, drying, and cooking, in the residential, industrial, and utility sectors. In a solar thermal systems sunlight is collected and converted into heat. The collected heat is then transferred to a fluid such as water or air, which carries the heat to where it is needed – termed as solar heating and cooling which can be further used in domestic or industrial segments.

Comparing the two main solar power technologies available to generate electricity, solar PV and CSP, it is evident that solar PV has been the dominating technology. In the last decade, with rising deployment of solar PV the already small share of Solar CSP has shrunk further, while Solar PV has taken center-stage, as illustrated in Figure 12.

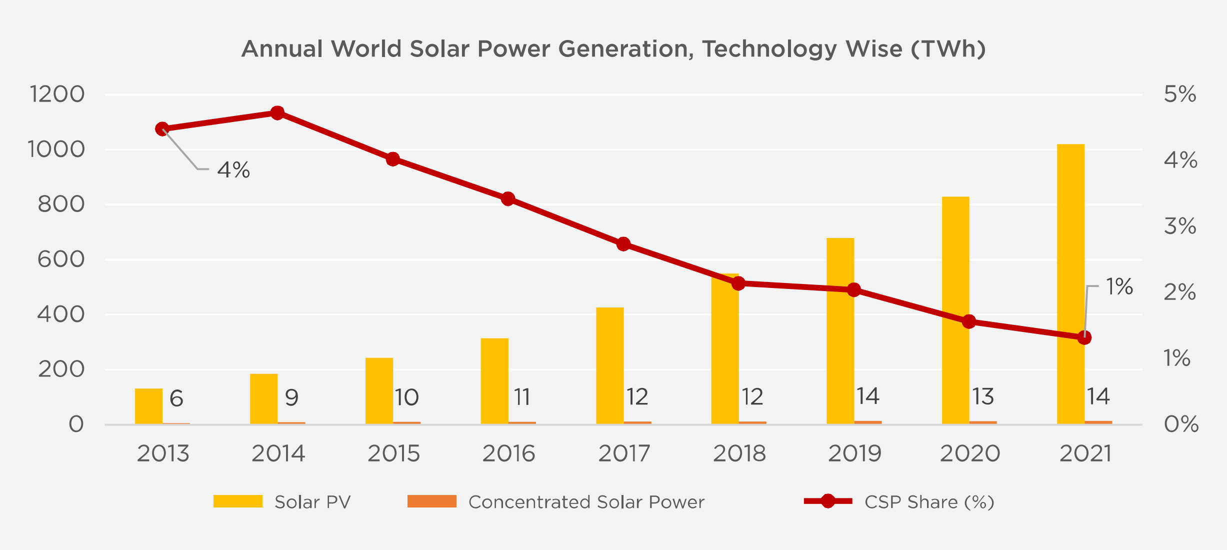

Figure 12: Annual Solar Power Generation Technologies

Source: IRENA - Renewable Energy Statistics 2023

CSP has seen limited deployment globally, and installations have primarily taken place in certain key countries like Spain and the United States, which have been the main markets in the past but have not added significant capacity in recent years. However, integration of CSP with other renewable energy resources and replacement of fossil fuels with solar provides promising solutions out of which combination of CSP and conventional power plants such as coal based, and natural gas based are noticeable for the last few years[4]. Both CSP and coal plants generate electricity from thermal energy; therefore, coal can be replaced with solar via central receiver CSP in coal power plants. The idea of repurposing the coal power plants by CSP is attracting considerable attention. The main advantage of CSP technologies over PV is thermal energy storage, which costs much less than battery storage and can have a very long life without degradation.

3.1 Solar Photovoltaics: Leading the way for solar technologies

Solar PV technology has evolved significantly over the years leading to increased efficiency, lower cost, and broader adoption. Solar cells are the building blocks of solar PV modules. The task of a solar cell is to generate electricity. To implement large terawatt scale projects of solar photovoltaics, the material used for the cell manufacturing should be nontoxic, abundant, and cheap. The abundance of the elements used is therefore important for the upscaling of the different technologies. Different PV cell technologies are demonstrated in Figure 13 below.

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[4] *Perspective on integration of concentrated solar power plants - ctab034.pdf (silverchair.com)*

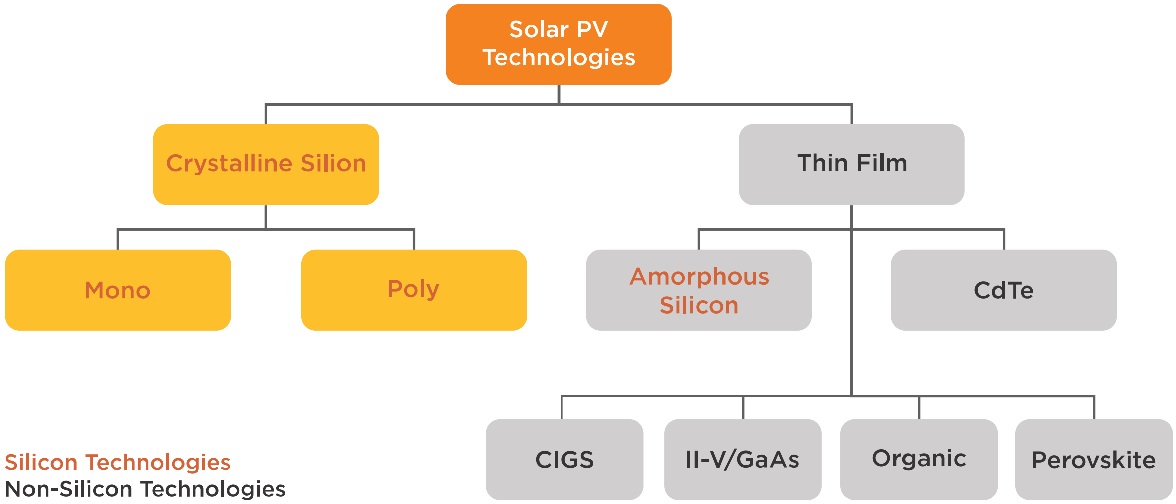

Figure 13: Different PV Technologies

The first category of solar PV technology is referred to as crystalline PV which is traditionally bifurcated into two, multi and mono crystalline silicon. The second stream of PV technologies are termed as thin film technology. Thin film solar cells are made from films that are much thinner than the wafers, and therefore use much less material. The processing techniques used for thin film solar cells are very different from the techniques used for crystalline silicon. There are different classes of thin film solar cells, namely, amorphous silicon, chalcogenide solar cells – CdTe and CIGS, III-V material or Gallium Arsenide (GaAs), organic, and perovskites. Many of the elements used in the thin film technology are rare, expensive, and toxic, due to which the upscaling of these technologies might be limited. Furthermore, the expensive technology like GaAs is used in specific applications for space where the generated power density is the important matric. All of these constrains limit the acceptance of the thin film technology in the market.

Figure 14 summarizes the worldwide research efforts of last three decade and depicts efficiencies of solar cell at the research scale.

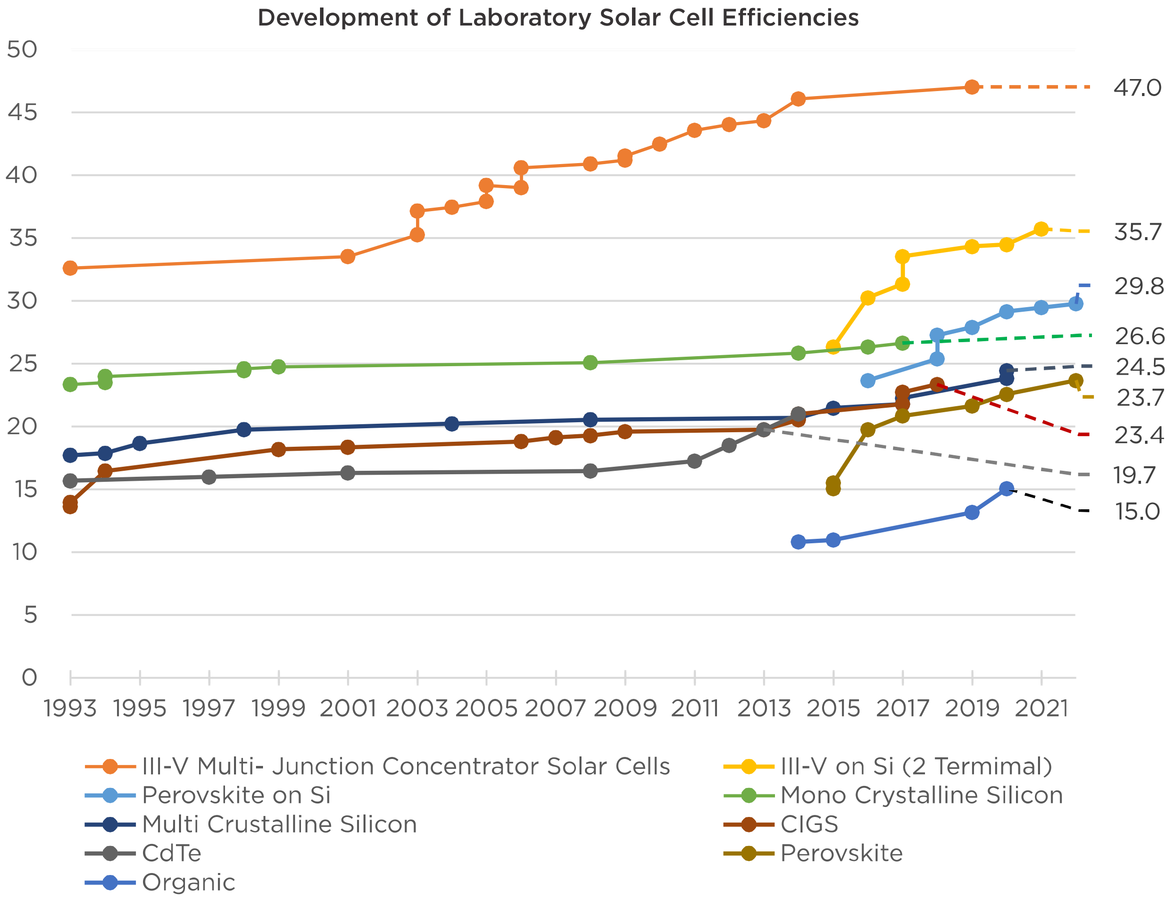

Figure 14: Solar Cell Efficiency at Laboratory Level

Source: Photovoltaic Report, Fraunhofer

Multi and mono crystalline silicon, have seen efficiency growth over the past decade to hit a maximum efficiency of 24.5% and 26.6% respectively from 17.2% and 25.1% over the last decade.

III-V multi junction concentrator solar cell, the technology with highest efficiency at lab scale has reached a maximum efficiency of 47% from an efficiency of 40.9% in 2009 whereas the efficiency of III-V on silicon is increased from 26.3% in 2016 to a maximum efficiency of 35.7% in 2021.

Other newer technologies in earlier stages of development have seen significant efficiency gains, with organic PV which attained a maximum efficiency of 15.0% in 2021 from 10.8% in 2015. Similarly, perovskite has seen an advancement in the efficiency from 15.5% in 2015 to 23.6% in 2022.

However, significant research and work needs to be done to convert these technologies from being promising newcomers to genuine contenders with proven stability and reliability to displace crystalline Silicon based PV.

Crystalline Silicon Technology

The first successful solar cell was made from crystalline silicon, which still is by far the most widely used PV material. The research and development of crystalline silicon has been going on for several years. The record efficiency of crystalline silicon has increased from about 14% in 1975, to a current record of 27.6% of Kaneka, for an advanced crystalline silicon solar cell without light concentration . Using a single solar cell, however, is not practical for most applications. This is because a single solar cell delivers a limited amount of power under fixed current and voltage conditions. To use solar electricity in practice, several solar cells must be connected to form a solar module, or PV module.

In addition to the solar modules, several components are required to complete the solar system such as solar inverter, wiring components, meters, junction boxes, AC and DC disconnects, combiner boxes, transformers, electrical panels, and mounting structures. These additional components serve as the Balance of System (BoS) that complete a solar system.

It is important to consider the other materials that make up most of the bill of materials (BoM) for a solar module. Silicon makes up only 3-4% of the mass of a PV module, and glass, polymers, aluminum, and other metals such as silver are important materials used that affect the quality of a module and its output. The share of different materials in the composition of solar PV module is illustrated in Figure 15.

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[5] *Delft University- Database*

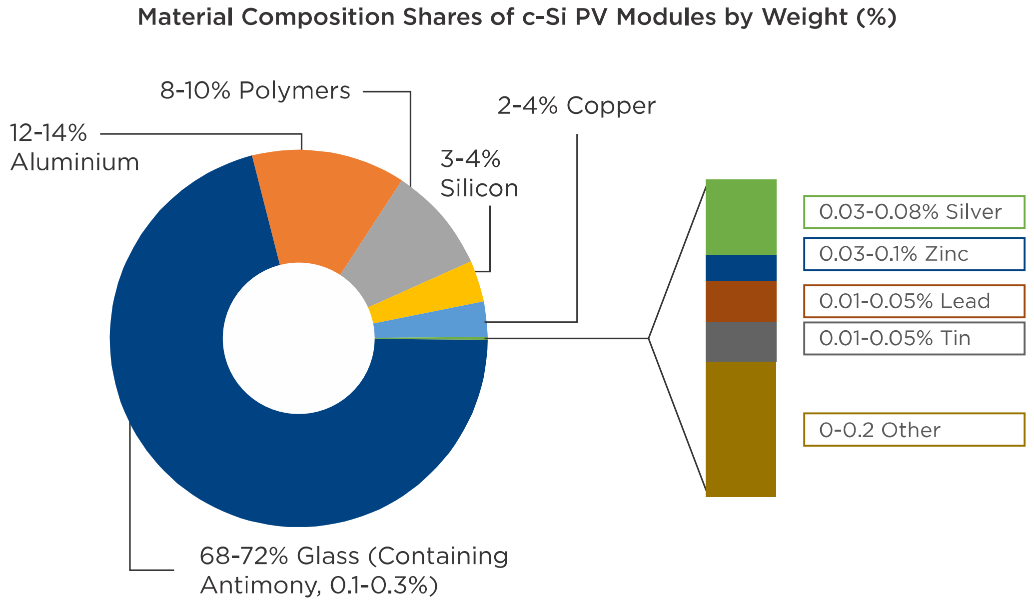


Figure 15: Material Composition Shares of c-Si PV Modules by Weight (%)

Source: IEA - Special Report on Solar PV Global Supply Chain

In contrast to weights, silicon is the valuable material in the module (34-45%) followed by silver, glass, aluminum etc. The value share of different material in a solar PV module is given in Figure 16.

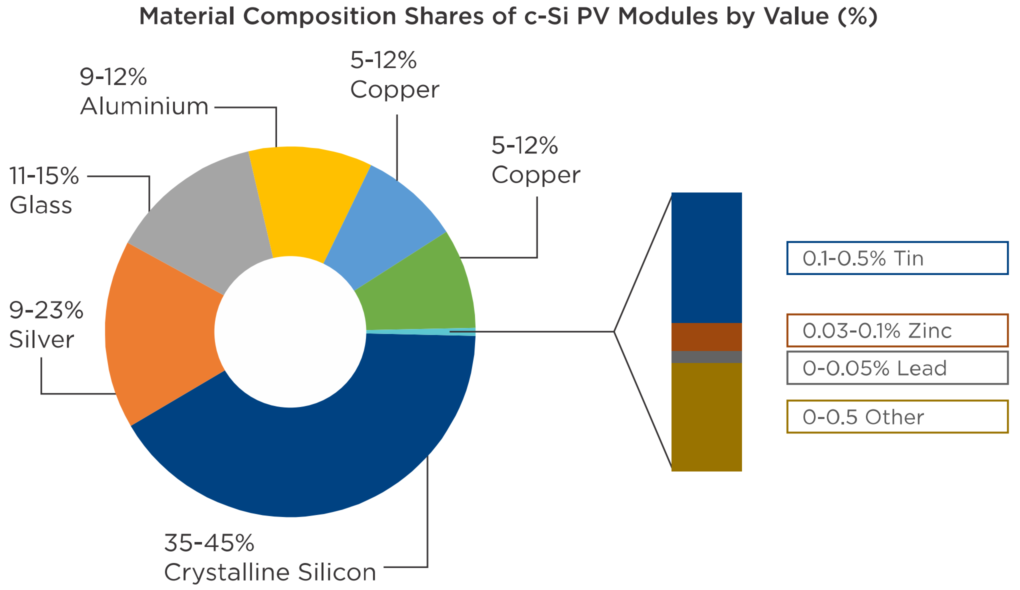


Figure 16: Material Composition Shares of c-Si PV Modules by Value (%)

Source: IEA - Special Report on Solar PV Global Supply Chain

3.1.1 Solar PV technologies & learning curve

Solar cells have a history dating back to the 19th century. However, it wasn't until 1954 that first efficient silicon solar cells were developed by Bell labs. Subsequently, in 1980s and 1990s, silicon based solar cells have seen significant growth compared to the technologies like silicon based and non-silicon based thin film technologies. The market share of different technologies for the last decade has been plotted as in Figure 17.

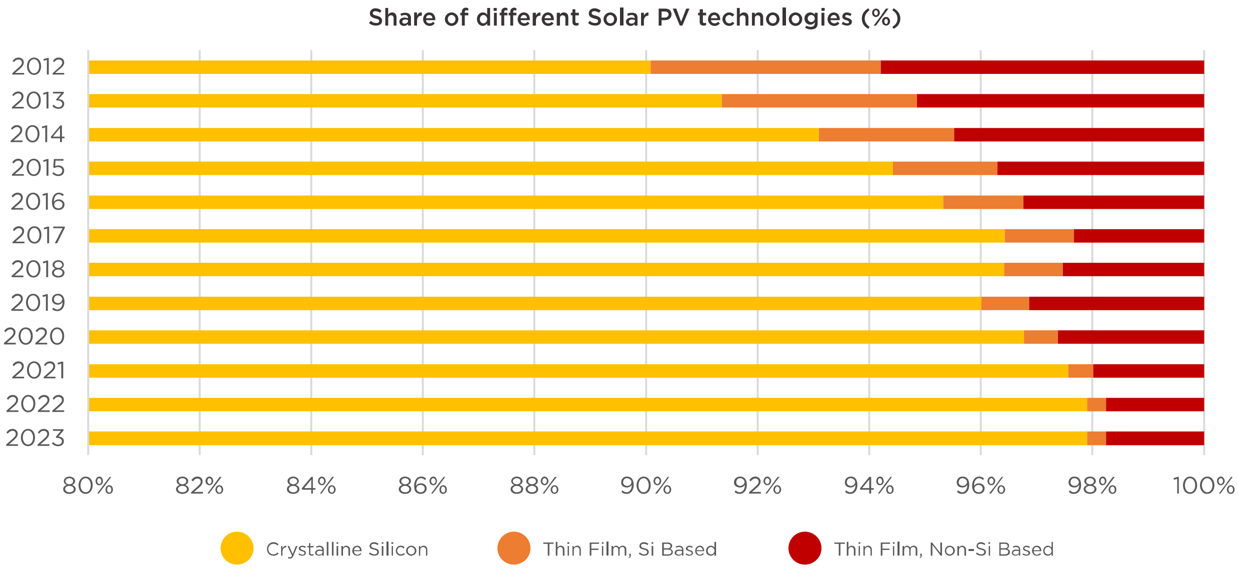


Figure 17: Share of Different Solar PV Technologies (%)

Source: BNEF Database-ISA Analysis

The growth of silicon based solar cell is significant in the last decade and is expected to continue as silicon-based technologies cement their status as the PV technology of choice around the world. While the amorphous silicon-based PV did have a notable presence over a decade ago, it diminished successively. Likewise, non-silicon based thin film technology witnessed a decline in the market share for the last decade. Evidently, crystalline Si based solar technologies have been the dominant technology for solar PV, when compared with thin film Si and thin film non-Si technologies. In today's context, crystalline silicon PV evolved as synonymous to the silicon-based PV. In addition, within crystalline solar PV technology, mono crystalline silicon PV dominates in the market share over the multi crystalline PV technology as illustrated in Figure 18.

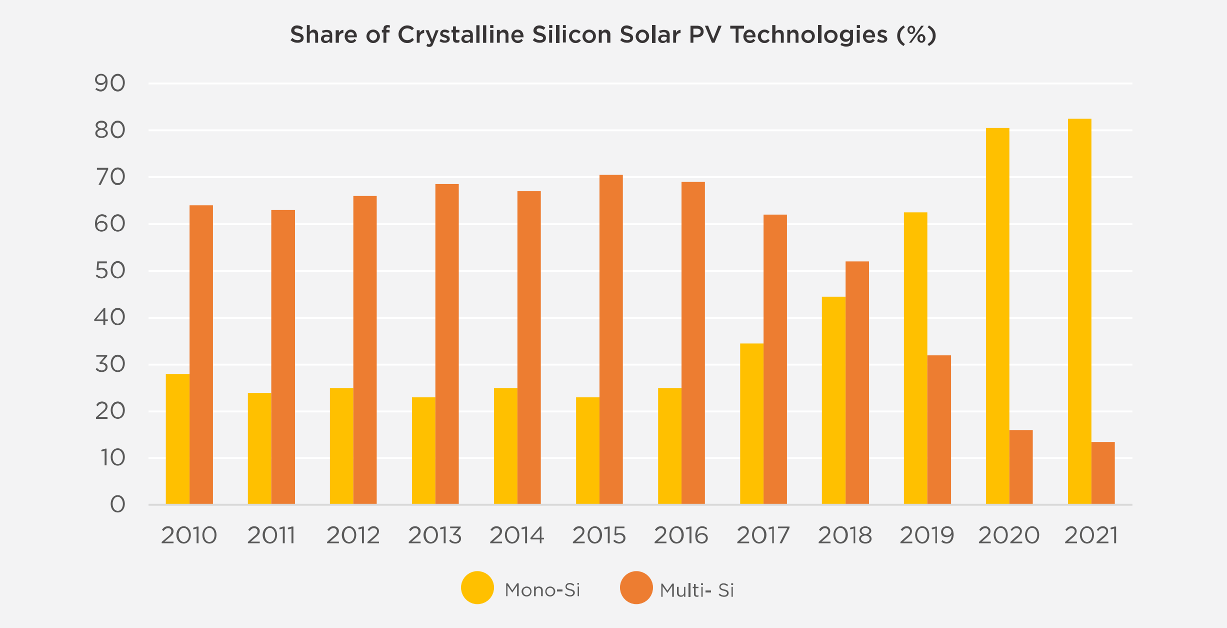


Figure 18: Share of Crystalline Silicon Solar PV Technologies

Source: Photovoltaic Report, Fraunhofer

Crystalline solar modules, both monocrystalline and polycrystalline, are popular for several reasons. In the last decade, there has been significant improvements in efficiency and power ratings of solar PV modules. Off-scaling of production leads to low cost of the source material. It is evident from the variation of average selling price of crystalline module as a function of cumulative capacity between 1976 and 2022, plotted as a learning curve and depicted in Figure 19.

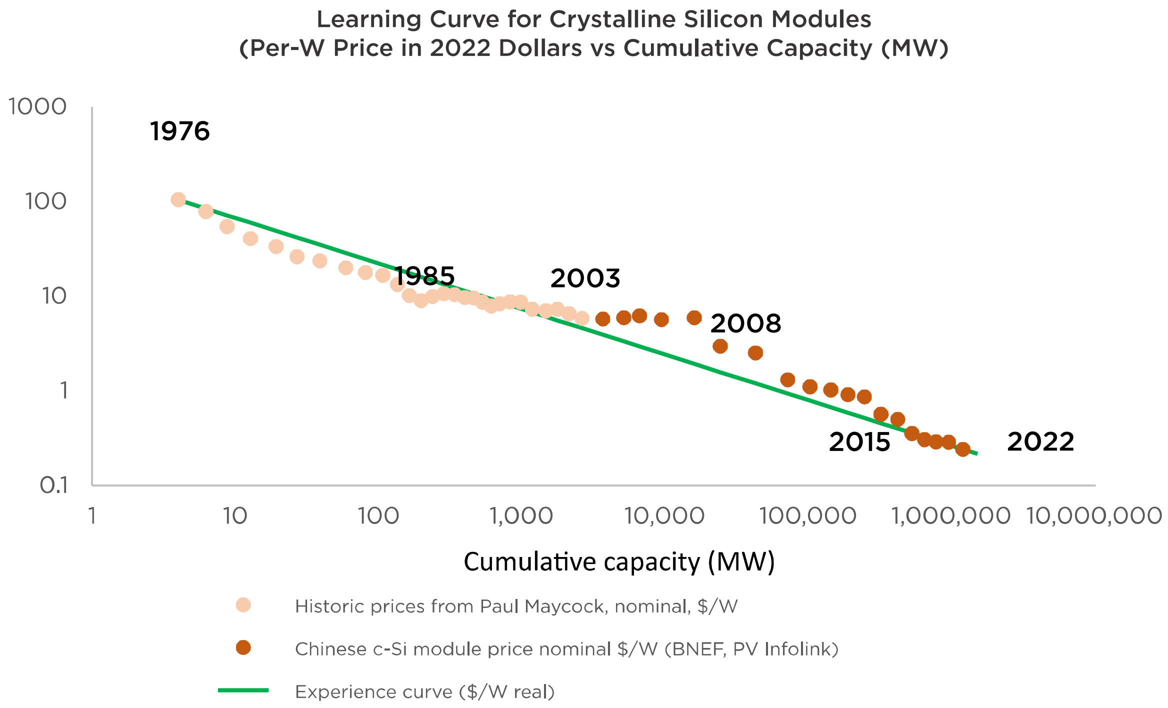


Figure 19: Learning Cure

Source: 2Q 2023 Global PV Market Outlook, BNEF

Learning curve usually shown exponentially decreasing cost price in time until the technology of product is fully developed. Important to note is that the sales prices, discounting some fluctuations, follow a largely exponential decay. The price of solar module price has been reduced significantly over the last 15 years; going from $5.8 per watt in 2008 to $0.21 per watt in the first quarter of 2023. The same period has seen cumulative capacity growth by two orders of magnitudes. The plot further indicates that for every doubling of the cumulative PV shipment the average selling prices decreases according to the learning rate, which is about 24.1% from 1976 to 2022, though a slight increase over previous level accounted for 1976 to 2020. That's because of the increase of the price of solar module compared to previous years, which is mainly attributed to the short supply of the key feedstock polysilicon.

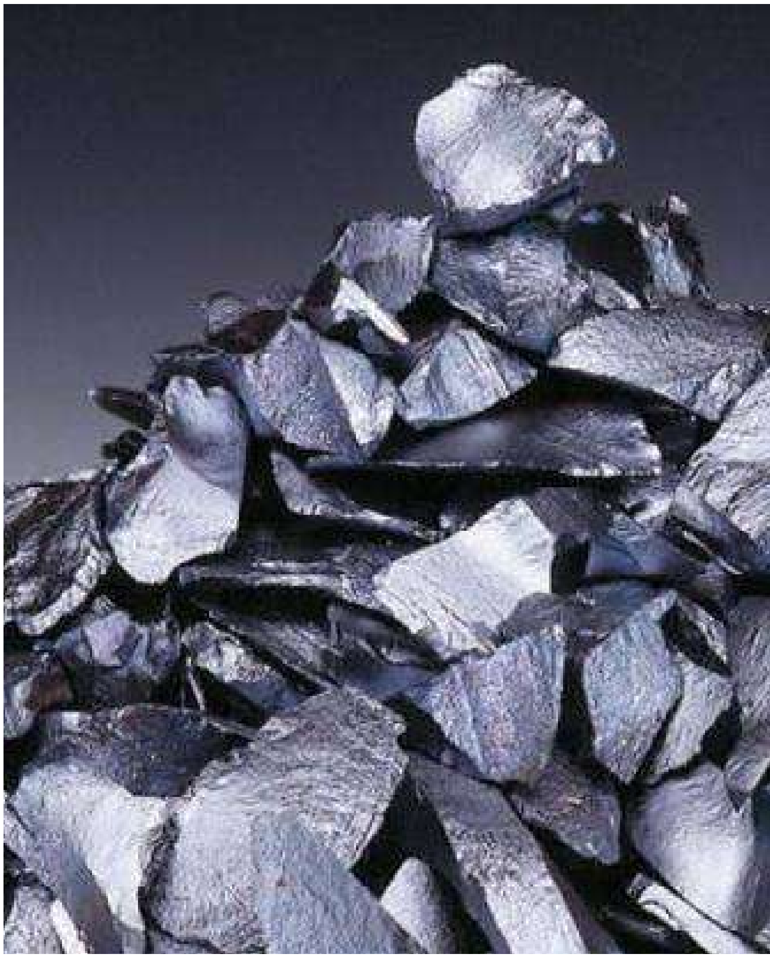
3.2. Crystalline Silicon Solar PV Technologies

The global solar value and supply chain is largest for Crystalline Silicon solar PV and consists of four main stages - polysilicon, ingot & wafer, cells, and modules. Although, these steps are discussed in detail in the successive sections of the report, here is the brief overview.

Polysilicon is a very high pure form of silicon and is considered as the starting raw material for the crystalline silicon PV. The polysilicon is supplied either as chunks or granules to ingot makers, who melt it in crucible and pull either a monocrystalline cylindrical ingot using Czochralski process or cast into a multicrystalline rectangular ingot with directional solidification method. In either the case, the ingots are cut into brick and then further sliced into square (or pseudo square) thin slices using wire saws. A base dopant is already introduced at the ingot making station, thus the wafers entering the cell factories are based doped (either p or n). After the surface treatment, these wafers are doped with opposite polarity of the base dopant to form a p-n junction. while a silicon wafer is already processed into a cell at this stage, metallic patterns are applied to extract generated change carriers. Several of these finished cells are interconnected the encapsulated to take the shape of the modules.

3.2.1. Polysilicon:

Although polysilicon cannot be seen as the starting point of the value chain, it considered as solar specific feedstock. Unlike the other parts of the PV value chain, which have processes similar from the semiconductor industry, polysilicon production is accomplished in a chemical factory environment. The lowest quality of silicon is the metallurgical silicon, considered as the raw material to produce polysilicon that is also used in other industries. The source material of metallurgical silicon is quartzite, a rock of pure silicon oxide. During the production process, from the quartzite, the silicon is purified by removing the oxide-metallurgical silicon with a purity of 98% to 99%. The silicon material with the next level of purity is called polysilicon, produced by three different methods - chemical vapor deposition (CVD) or Siemens process, fluidized bed reactor (FBR), and upgraded metallurgical grade silicon (UMG-Si). The Siemens process uses trichloro silane (TCS) gas – output of reactions between metallurgical silicon and hydrogen chloride, as a feedstock and the process are energy intensive, while FBR technology can use either TCS or silane as a feed and it consume much lesser energy compared to CVD[6]. Although, UMG-Si is a low-cost method alternate to the other process, the purity of its silicon produced is low compared to the other two process and the technology was not very successful.



The polysilicon is typically supplied in two forms - chunks of silicon and granular -, the difference for which originates from the manufacturing process. While the silicon produced from the CVD process is supplied as chunks, FBR technology produces granular polysilicon. Most of the industry relies on the time-tested CVD process and it remains as the workhorse of the solar industry and enjoys a near monopoly for producing solar silicon. The expected market share of different polysilicon manufacturing technology is illustrated in Figure 20.

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[6] *Solar Energy, Delft University of Technology - https://courses.edx.org/c4x/DelftX/ET.3034TU/asset/solar_energy_v1.1.pdf*

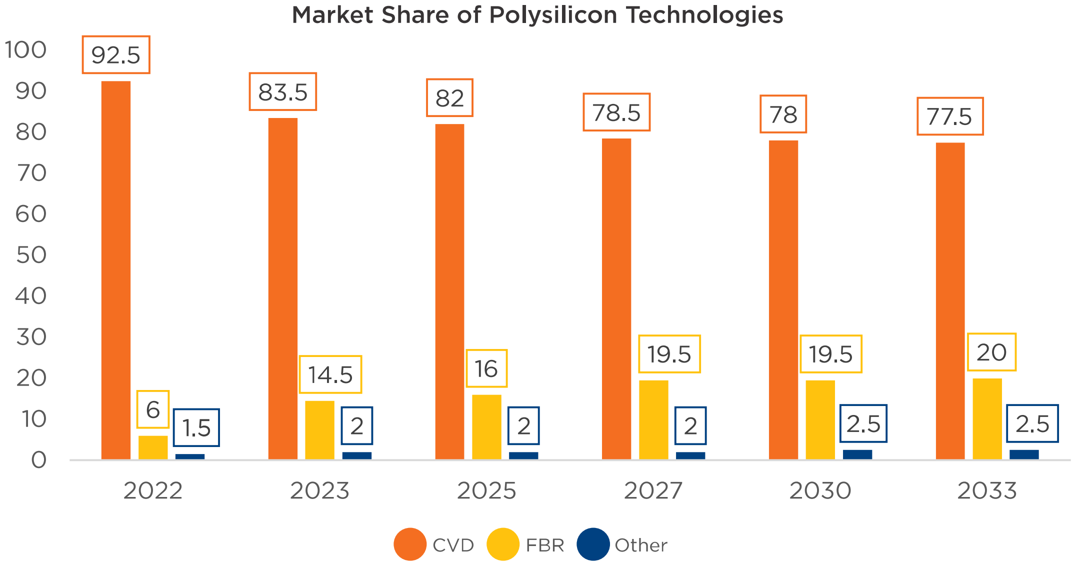

Figure 20: Market Share of Polysilicon Manufacturing Technologies

Source: ITRPV 2023

Insights and Trends

The key development related to polysilicon, not only affecting the segment but also the PV industry at large, is the short supply of polysilicon and subsequent price hike after 2020, hit a maximum price during the last ten years, followed by subsequent decline 2022 afterwards. The variation of polysilicon price during 2011 to 2023 is illustrated in Figure 21.the technology was not very successful.

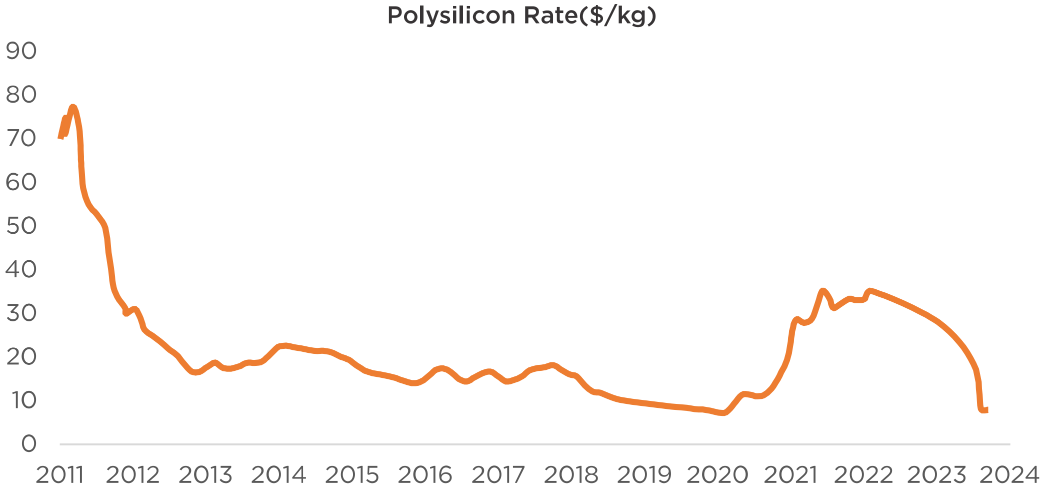

Figure 21: Polysilicon Rate

Source: BNEF, 2Q 2023 Global PV Market Report – ISA Analysis

Polysilicon prices were very high around 2011, but subsequently, an oversupply situation led to very low prices. A trade conflict between the US and China and low prices led several longtime leaders in this field not to invest further (Wacker, Hemlock), partly suspend production (REC Silicon) or even withdraw from silicon production altogether (Hanwha Chemical).

Setting up silicon factories takes longer and is more expensive than investments in wafering, cell & module production. While gigantic wafer and cell capacities have been announced and partly built, silicon expansion is lagging, even though very large capacities have been announced. The supply of polysilicon witnessed a glut 2015 onwards has normalized, and the balance of supply and demand become constricted in 2021[7]. Polysilicon supply is tight after wafer manufacturers have increased capacities very quickly and demand for solar installations has increased. As a result of the strong demand from wafer manufacturers, the polysilicon price in China skyrocketed from $9.5 /kg at the beginning of 2020 to about four times that level, reaching $32-35 /kg last year. However, the price has dropped to an average selling price of $28/kg in first quarter (Q1) of 2023, further to $7.85/kg in the week of July[8]. The total polysilicon production in 2023 is expected to be 1,570,000 tones, primarily from Chinese manufactures. The supply will be adequate to manufacture 600GW solar PV module in 2023, comparing with the most optimistic demand of 380GW. Considering the large supply glut, the possible year-end polysilicon price is estimated to be $10-13/kg.

3.1.2 Ingot and Wafers:

While ingot making and wafering are two different steps, they are typically accomplished under one roof. Here the polysilicon melted and solidified into a large and solid block of crystalline silicon- ingots, weighing several hundred kilograms. The ingot is then cut into thin slices called wafers.

Ingots

Depending on the method, ingots being produced, silicon material classified as monocrystalline or multi crystalline. Two process, Czochralski and float zone, are employed to produce monocrystalline ingots. Using a Czochralski method, monocrystalline ingots are carefully pulled from the molten silicon in a quartz crucible. While in float zone process, end of the polysilicon rod is heated up and melted using a radio frequent heating coil and the melted part is allowed to contact with a seed crystal where it solidifies afresh and adopts the orientation of the seed crystal.

Next to monocrystalline silicon ingots, multi crystalline silicon ingots can be processed, termed as silicon casting. The multi crystalline silicon consist of many small crystalline grains, made by melting highly purified silicon in a dedicated crucible and pouring the molten silicon in a cubic shaped growth- crucible. Subsequently, the molten silicon solidifies into multi crystalline ingots.

Crystallization is also the station where the base doping is done. The p-type base doping is achieved with either boron or gallium and n-type doping is achieved with phosphorus. While multi crystalline is low cost with lower efficiency potential, in contrast to the monocrystalline. In fact, multi crystalline was dominating the segment till 2017, the advent of PERC and compatibility of this cell architecture with monocrystalline has facilitated the unprecedented progress of monocrystalline. The trend of two type of crystals in the market is plotted in Figure 22 below.

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[7] *Special Report on Solar PV Global Supply Chains, IEA- https://iea.blob.core.windows.net/assets/d2ee601d-6b1a-4cd2-a0e8-db02dc64332c/SpecialReportonSolarPVGlobalSupplyChains.pdf*

[8] *BNEF - Bimonthly PV Index, July.*

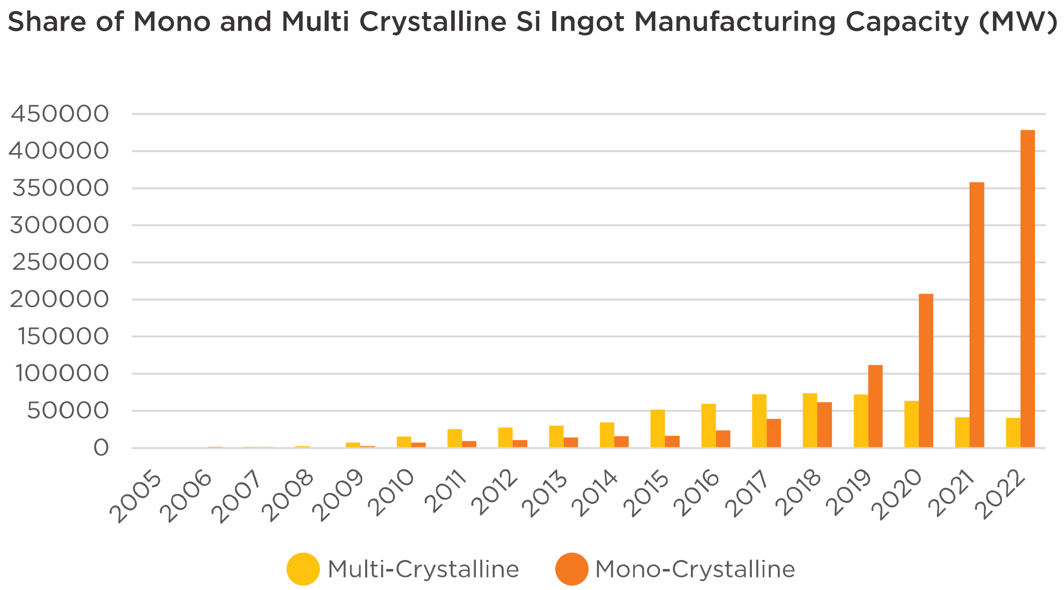

Figure 22: Share of Mono and Multi Crystalline Si Ingot Manufacturing Capacity (MW)

Source: BNEF Database- ISA Analysis

As shown in the graph, monocrystalline silicon is now by far the dominant technology being utilized for solar cell production, while multi crystalline silicon manufacturing capacity has stagnated and started to fall as the technology which is no longer the preferred material for crystalline silicon cells. The trends to larger ingot mass production are expected to continue and Czochralski process growth is found to be the mainstream technology in crystallization[9].

A major development related to crystal growth segment is the usage of gallium doping for p-type instead of the more established practice of using boron. The switch helps in protecting the PV substrate from Light Induced Degradation (LID) in p-type modules that originates from the formation of boron-oxygen complex. Within just a few years, the approach became the state of the art; ITRPV estimates the disappearance of boron as dopant for p-type material by the end of 2023. In addition, all advanced cell architectures beyond PERC are typically employed on n-type base wafer. The phosphorus doped silicon substrates have longer lifetimes, as the holes of n-type material are less sensitive to many common metallic impurities in silicon, such as iron. Thus, n-type wafers come with higher efficiency potential. Since the base wafer is doped with phosphorus, there is no possibility for the formation of a boron-oxygen complex, the root cause for light-induced degradation (LID). As a result, the efficiency loss can be avoided.

Wafer

When it comes to wafering, primarily there are two process- sawing and silicon ribbon method. As the name indicate, in sawing, silicon ingots are sawed into thin wafers using wires. While in the silicon ribbon method, silicon solidified on a high temperature resistant string which is pulled up from a silicon melt to form thin film of silicon, ribbon, which is further cut into wafers. The electronic quality of ribbon silicon is not as good as that of monocrystalline produced through the first method, hence become less

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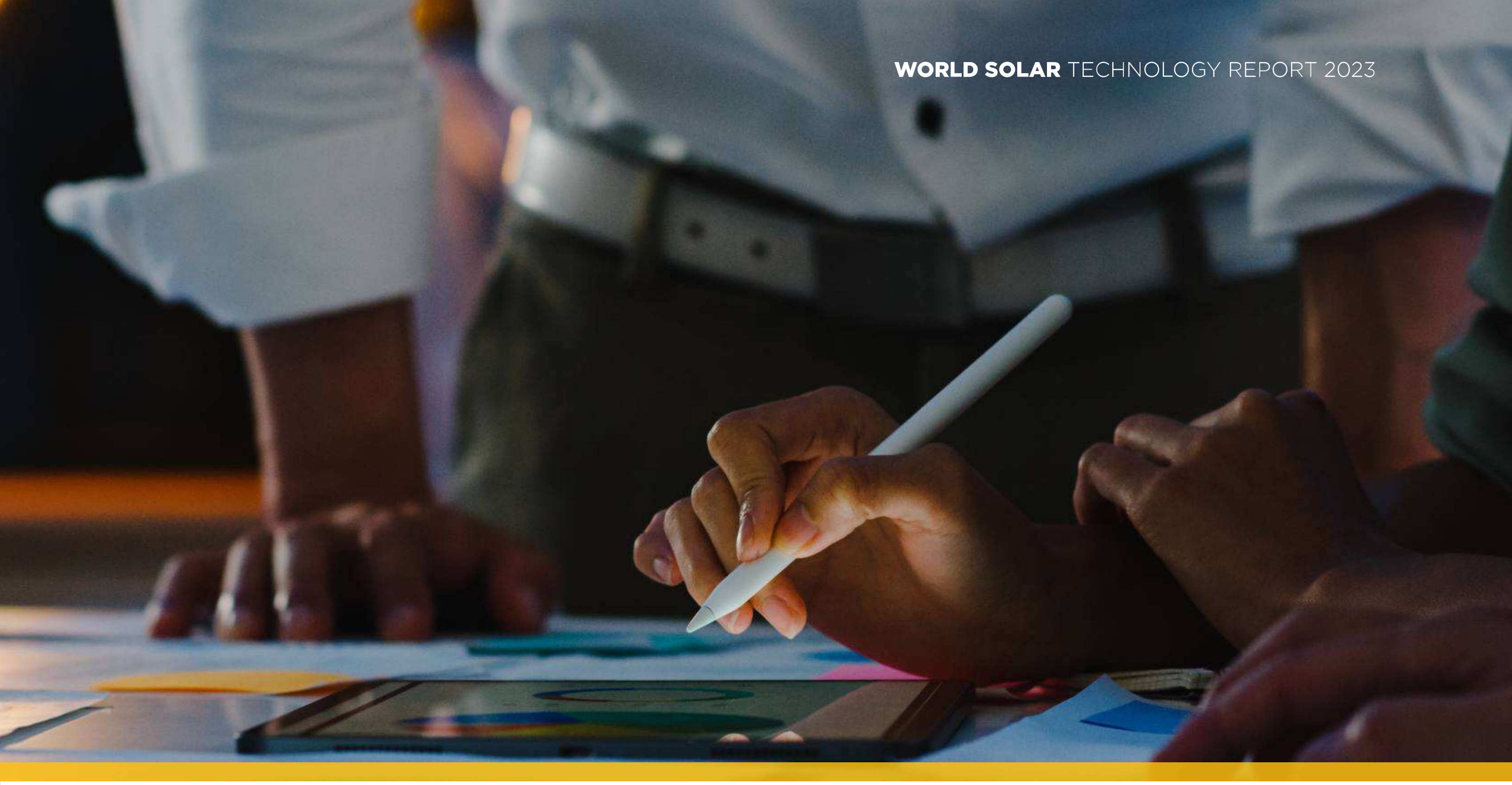
[9] *ITRPV 2023 - https://www.vdma.org/international-technology-roadmap-photovoltaic*



popular. The most important development in the sawing technology has been the shift to diamond wire (DW) based sawing post 2018, from the slurry technology resulted in reduction of silicon consumption significantly along with increase in wafer size. The DW based sawing is now considered as the most suitable method available for wafering and offers significant cost reduction. Increased availability of the low-cost monocrystalline wafers produced with DW sawing has clearly facilitated the wide adaptation of PERC cell architecture. Nevertheless, significant amount of silicon has been wasted while sawing, referred to as kerf loss.

The key performance indicators of the wafers are wafer size and thickness. One of the most important developments related to wafering that has influenced the downstream value chain components has been larger wafer formats. The rationale behind the approach is that the output power of a PV device is a function of surface area. Thus, increasing the cell size by employing larger wafers is the simplest way to boost module power. The PV industry has only just started to identify the potential of using larger wafers. The 5-inch (125 mm) wafer size was the de facto standard until 2006, which was then replaced by 156 mm for about a decade. In 2017, a marginally larger wafer size of 156.75mm called M2 was commercialized, which account for about a 1% gain in surface area. Around the same time, a few vertically integrated companies ventured into even larger sizes such as 158.75 mm full square called G1 and 161.75 mm wafers denoted as M4. In 2018, M6 was first introduced on multicrystalline followed by monocrystalline during 2019. M6- 160 mm wafers have about 12% higher surface area compared to the M2 format. It appeared like M6 was the largest wafer size and would remain so for some time, a notion that was short lived. Less than 3 months later, in August 2019, a 210 mm wafer-G12 was introduced. In response to this move, vertically integrated companies came out with M10-182 mm wafers in 2020. In current market M6, M10 and G12 are the mainstream wafer sizes, dominated by M10, and the larger formats are expected to take over the market as shown in Figure 23 below.

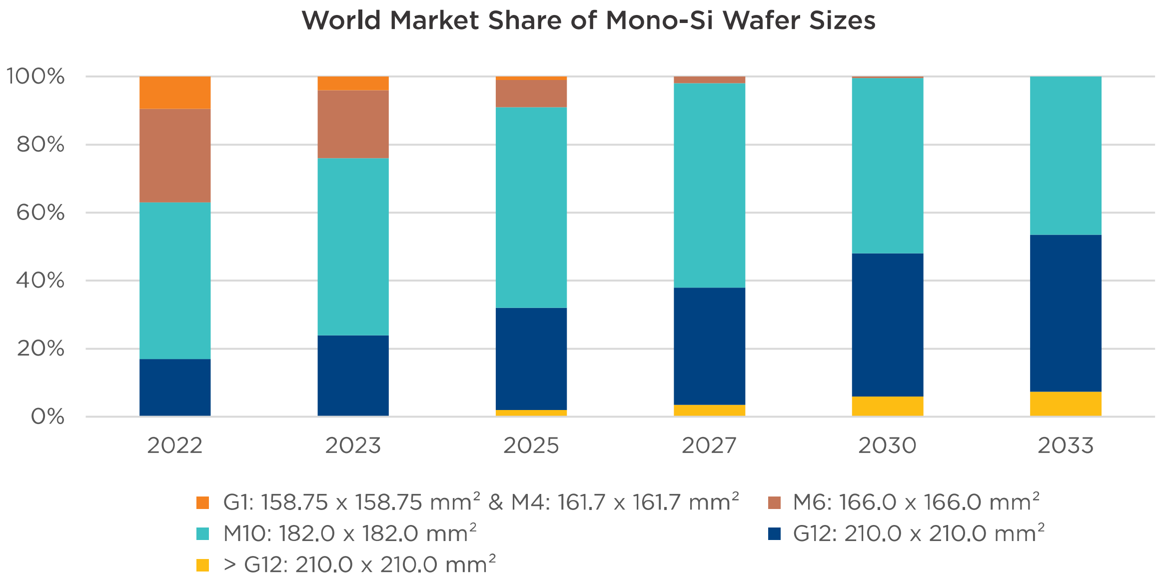


Figure 23: World Market Share of Mono-Si Wafer Sizes

Source: ITRPV 2023

Reduction in the silicon consumption per watt has always been a subject of the optimization and it became even more important with the polysilicon shortage. Even during the time of the oversupply of the silicon, wafers have been the significant cost contributors to cells. The cost of silicon wafer in turn is mainly governed by the amount of silicon used, which can be lowered by reducing either thickness of wafer or the kerf. The Figure 24 below summarizes the trend of wafer thickness and silicon consumption per watt.

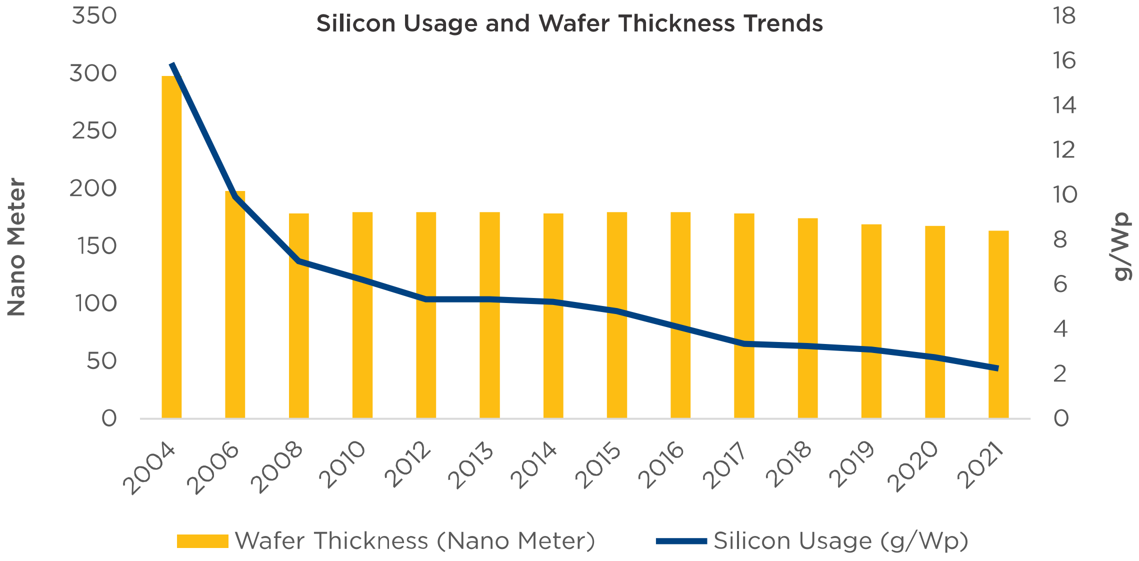


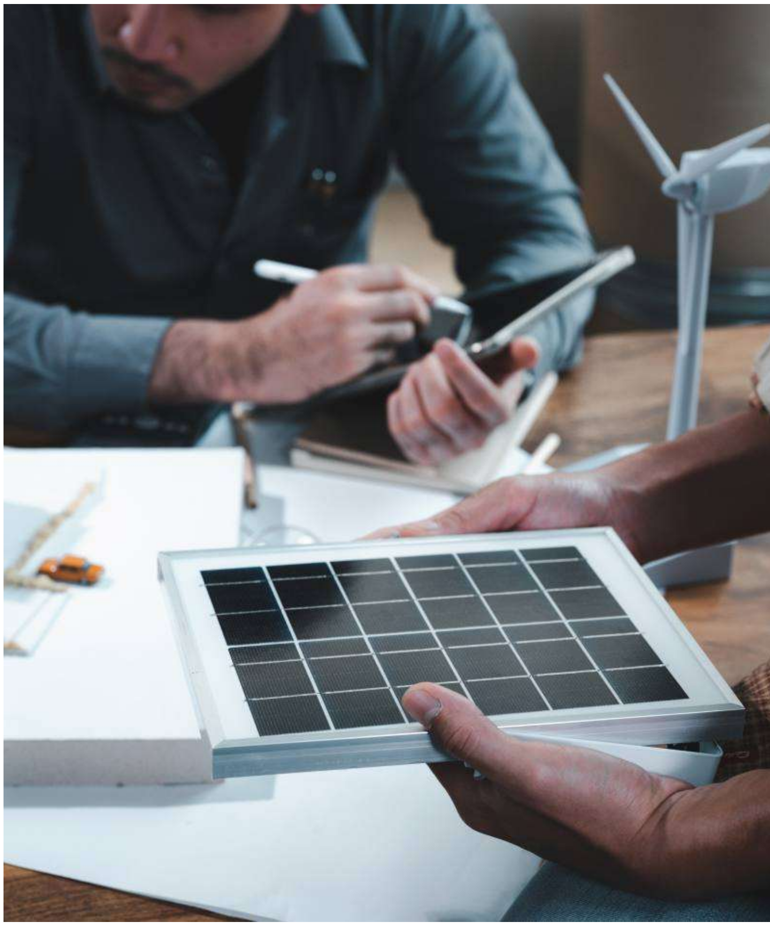
Figure 24: Silicon Usage and Wafer Thickness Trends

Source: Photovoltaic Report, 2023 - Fraunhofer

As per the Photovoltaic Report,2023-Fraunhofer, the silicon usage per Wp has dropped by approximately 85% in 2021 in comparison with 2004. For wafer thickness, 180 Qm remained the mainstream for quite a long time from 2008 to very till 2016. Since the silicon shortage hit the industry, the industry is gradually thinning down the wafers.

Monocrystalline silicon wafer thickness is seeing a remarkable reduction post 2020. For p-type mono wafers, ≤M6 wafers with a thickness of 160 µm was standard in 2022. Furthermore, p-type wafers are anticipated to undergo a fasted thickness reduction to reach 130 µm, for both M6 and M10, in the next 10 years. The present standard wafer thickness for n-type monocrystalline silicon wafer, for ≤ M6 wafer, is 150 µm. In the current year, ITRPV-2023 anticipated a 5 to 10 µm reduction in the n-type wafer thickness for all the corresponding formats of p-type wafers. The minimum thickness by 2023 would be around 125 µm.

Reducing the kerf loss, which is the silicon lost during the slicing process for wafering, is also an effective way of cutting-down the silicon consumption per watt. The kerf loss can be reduced by using thinner tungsten diamond wire. The continuous optimization of the wafer slicing process has resulted a kerf width reduction from 85 µm in 2017 to current level of about 55 µm, which is expected to decline to 43 µm in next 10 years, according to ITRPV-2023. A point to be noted about kerf is that a few companies and institutes were working on approaches that can avoid kerf completely. These kerf-less technologies are most based on cleaving of wafer directly from silicon bricks and were in focus during the days of silicon short supply but are no longer in focus due to the improved silicon supply situation. Even with recent silicon shortages, kerf-fewer wafering technologies are not a significant focus area.



Thinner wafers and reduction in kerf losses will yield overall cost savings. Multicrystalline wafers are cheaper than all mono variants due to the lower quality input material used. Additionally, within monocrystalline wafers, the G12 wafer size is the most expensive, considering its larger size and greater polysilicon usage. The variation in the wafer price for the last decade is summarized and plotted in Figure 25.

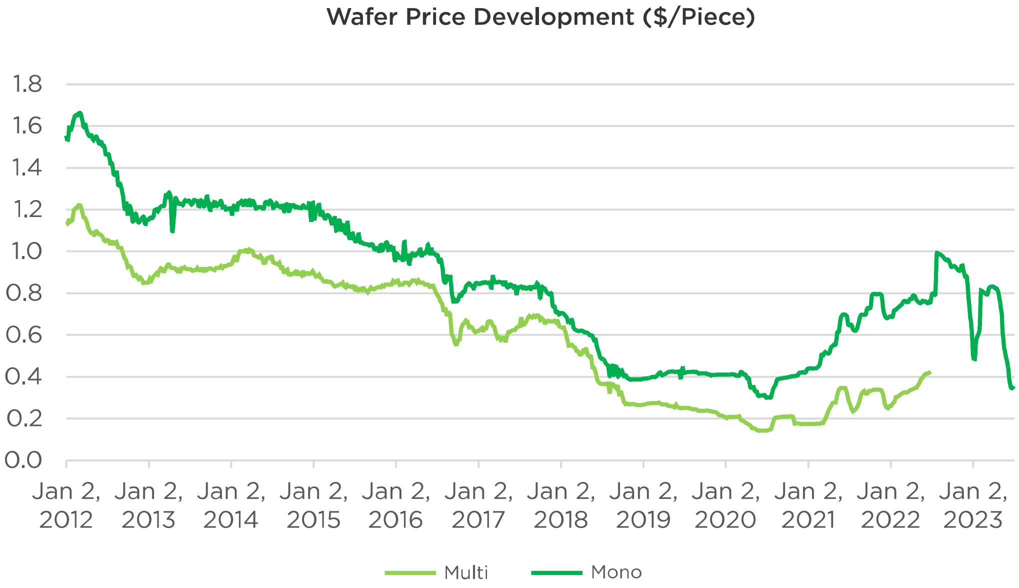


Figure 25: Wafer Price Development ($/Piece)

Source: BNEF- Bimonthly PV Index July 2023

Wafer prices for all categories have steadily increased since 2020, driven by disrupted supply due to the Covid-19 pandemic and the high price of solar polysilicon. Price increased vary across categories but range from 150-200% from 2020 to August 2022. Post 2022, price dropped by more than half to reach $0.34 and $0.48 per piece in the week of July 2023 for M10 and G12 respectively. It is also envisaged a 4% hike in the wafer production cost due to a five-fold rise in the prices of solar crucible – a consumable to make solar ingots, compared with a year ago. Though, solar installation not being affected by the increase in the rate either in short or long term[10].

3.1.3 Crystalline PV Cell

Solar cell development is the heart of the solar PV manufacturing process, as a fully functional PV device is formed at the end of the cell manufacturing lines. The silicon wafers, the incoming raw material for cell lines, are processed into cells by various design principle and high-efficient device architectures like starting from Back Surface Field (BSF), Passivated Emitter Rear Contact (PERC), Tunnel Oxide Passivated Contact (TOPCon), to Hetero-Junction solar cells (HJ). In addition, the recent marker observed a few designs principle behind various contacting architectures like interdigitated back contact (IBC), Bifacial and Metal Wrap Through (MWT). On a broader perceptive the, the design principles of crystalline silicon solar cell technology are highlighted in Figure 26 below and discussed in brief in the succeeding sections of the report.

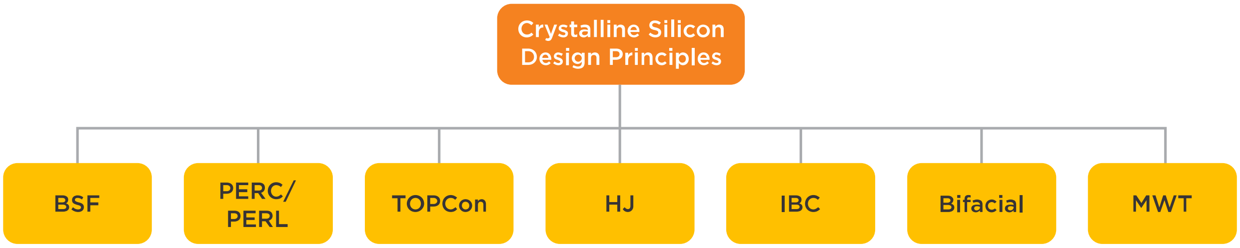


Figure 26: Various Crystalline Silicon Design Principles

All these design rules are based on the objectives to reduce charge carrier recombination losses and optical losses. To reduce charge carrier recombination losses, different concepts such as surface passivation of cells, reduction of contact area, selective highly doped emitters, back surface field, and the metal contact grid are incorporated, whereas in the case of reduction in optical losses, shading contacts, anti-reflection coating, texturing surface and interfaces, parasitic absorption by non-active photovoltaic layers, and back reflectors play the key roles.

Back Surface Filed (BSF) technology was once the dominant silicon-based cell technology for many decades till 2014 or 2015. The light hit on the top of the solar wafer will pass through and may reach the back surface, where it needs to be absorbed in between. When light has not been absorbed in the silicon wafer after passing through the bulk, part of the light might escape at the back surface that will cause reduction in the conversion efficiency of solar cells. The transmitting light at the back surface can be reflected to the absorber layer using a reflector, which is in a standard crystalline silicon solar cell design is present in the form of a fully metallized back contact referred to as BSF technology. The reflection at a metal back contact is roughly 90% for aluminum and thus it is used as a BSF contact. With surface texturing, light will be scattered and coupled into the device at an angle. Texturing the wafers is therefore also a useful tool to limit the thickness of the wafer while maintaining the short circuit current density and increasing open circuit voltage.

Passivated Emitter Rear Locally diffused (PERL), which uses a p-type float-zone silicon wafer, has been an example for various technology developed afterwards. In PERL, the emitter is passivated with a silicon oxide layer on top of the emitter to suppress the surface recombination velocity, a parameter that is a key impediment to increasing a solar cells efficiency, as much as possible. The surface recombination velocity has been suppressed to the level that the open-circuit voltages with values of above 700 mV have been obtained using the PERL concept. At the rear surface of the solar cell, point contacts have been used in combination with thermal oxide passivation layers. The oxide operates as a passivation layer of the noncontacted area, to reduce the unwelcome surface recombination. The PERL concept was the first crystalline silicon device in which a conversion efficiency of 25 % was demonstrated. Since the PERL concept includes some expensive processing steps and the unprecedented progress of the PERC in inters of both lowering costs as well as improving efficiency has made the PERL less attractive.

Passivated Emitter Rear Contact (PERC) architecture is a more commercially viable crystalline silicon wafer technology, which is inspired on the PERL cell configuration. The PERC concept decreases back recombination by inserting a patterned dielectric layer between the silicon and aluminum layers, so that only the aluminum contacts a small portion of the cell area. Furthermore, the local point contacts do not use a local BSF but an additional dielectric to reduce the surface recombination. PERC is currently the state-of-the art cell architecture in the mainstream and still provides the best cost performance ratio.

Tunnel Oxide Passivated Contact (TOPCon) Solar Cell technology, in front surface processing, is almost like PERL and PERC solar cells in which localized contacts with a back surface are introduced to reduce recombination at back contact. In the TOPCon solar cell, to prevent the minority carriers to recombine at the back contact, a very thin oxide layer of approximately 2 nanometers is placed in between the n-type base and a phosphorous doped n+ layer. Now, since the oxide layer is present, it is almost impossible for the minority carriers, which are holes for the n-type wafer, to reach the back contact of the cell as they cannot pass the potential barrier introduced by the oxide layer. In addition, the electrons experience a smaller barrier than the holes. Thus, a large fraction of the electrons can move through this barrier and this phenomenon is called tunnelling. Therefore, electrons are able to tunnel through the barrier and be collected at the back contact with virtually zero loss. Contact patterning, which is a relatively difficult and expensive processing step, is therefore not necessary and the back side of the wafer can be entirely metallized making this technology cheap in processing.

Heterojunction (HJ) solar cells, a junction by two different semiconductor materials, is an alternative concept with high efficiency cell architecture. In the crystalline silicon wafer-based heterojunction two types of silicon-based semiconductor materials, one is a n-type float zone monocrystalline silicon wafer, the other material is hydrogenated amorphous silicon. For high-quality wafers, like this n-type float-zone monocrystalline silicon wafer, the recombination of charge carriers at the surface determines the lifetime of the charge carriers. The advantage of the hetero-junction solar cell concept is that the amorphous silicon acts like a very good passivation material. In this approach the highest possible lifetimes for charge carriers are accomplished. The crystalline silicon wafer-based heterojunction solar cell has the highest achieved open-circuit voltages among the crystalline silicon technologies. Panasonic and Kaneka achieved an open-circuit voltage of over 750 mV. In a hetero-junction solar cell, the charge carriers are transported to contact through a transparent conductive oxide material, like indium tin oxide (ITO), which is deposited on top of the p-doped layer. The ITO is needed as the conductivity of the p-type layer is too poor. One of the benefits of the hetero-junction solar cell concept is that it allows to introduce the same contact scheme at the n-type back side. It means that this solar cell can be used in a bifacial configuration, it can collect light from the front, and scattered and diffuse light falling on the backside of the solar cell.

Interdigitated Back Contact (IBC) solar cell concept does not suffer from shading losses of a front metal contact grid. All the contacts responsible for collecting of charge carriers at the n- and p-side are positioned at the back of the crystalline wafer solar cell. The fact that the contacts do not cause any shading losses at the back, allows them to become larger. An interdigitated back contact is lacking one large p-n junction, instead, the cell has many localized junctions. The passivation layer can have a low refractive index such that it operates like a backside mirror which will reflect the light, that is not absorbed during the first pass through the solar cell back into the absorber layer.

Bifacial solar cell is an architecture in which both at the front and at the back side metal contact grid has been placed. This allows light incident from both the front and back to be absorbed in the PV active layers, increasing the cell's performance. Normal solar cells including a non-transparent back sheet are referred to as mono facial, where in the case of bifacial modules, transparent sheet is used as back sheet which can transmit the light from the backside of cell.

Metal Wrap Through (MWT) is the latest concept in the market demonstrated some years ago by SCHOTT Solar and Solland Solar . For a solar module based on standard crystalline silicon solar cells, the individual wafers that form the cells are connected in series by connecting the front metallization grid of one cell to the back contact of the next cell. This process is called contact tabbing. A consequence of these interconnections is that the cells cannot be placed directly side by side, but that spacing is needed between the cells. This area is accounted as loss when looking at the aperture area of a solar module. The MWT prevents this loss in the module area, as it 'wraps' the metal front contact through the base of each cell and places both front and back contacts side by side on the backside of the cells. In this way the electrons collected by the front emitter are transported to the back of the solar cell. Evidently, care must be taken that the via does not create a short circuit. Individual cells can now be placed much closer to each other.

All the above-mentioned technologies are limited by physical constraints in terms of the efficiencies they can achieve. These constraints can be overcome using tandem cells, which involve stacking of p-n junctions, each of which form semiconductors that respond to a different section of the solar spectrum. This allows for greater absorption of incident sunlight, and thus leads to higher efficiencies.

Insights and Trends

TOPCon, HJ and IBC are seeing initial stages of commercial production. Major manufacturers have commercial offerings across these technologies that feature amongst their "top of the line" modules. However, further Research and Development is required to obtain full efficiency gains and to bring down manufacturing costs to competitive levels with respect to the current dominant cell technology, PERC. Bifacial and MWT are also expected to contribute significant share in the market in future but presently it is nominal as compared to the PERC. The market share of different technologies is shown in Figure 27.

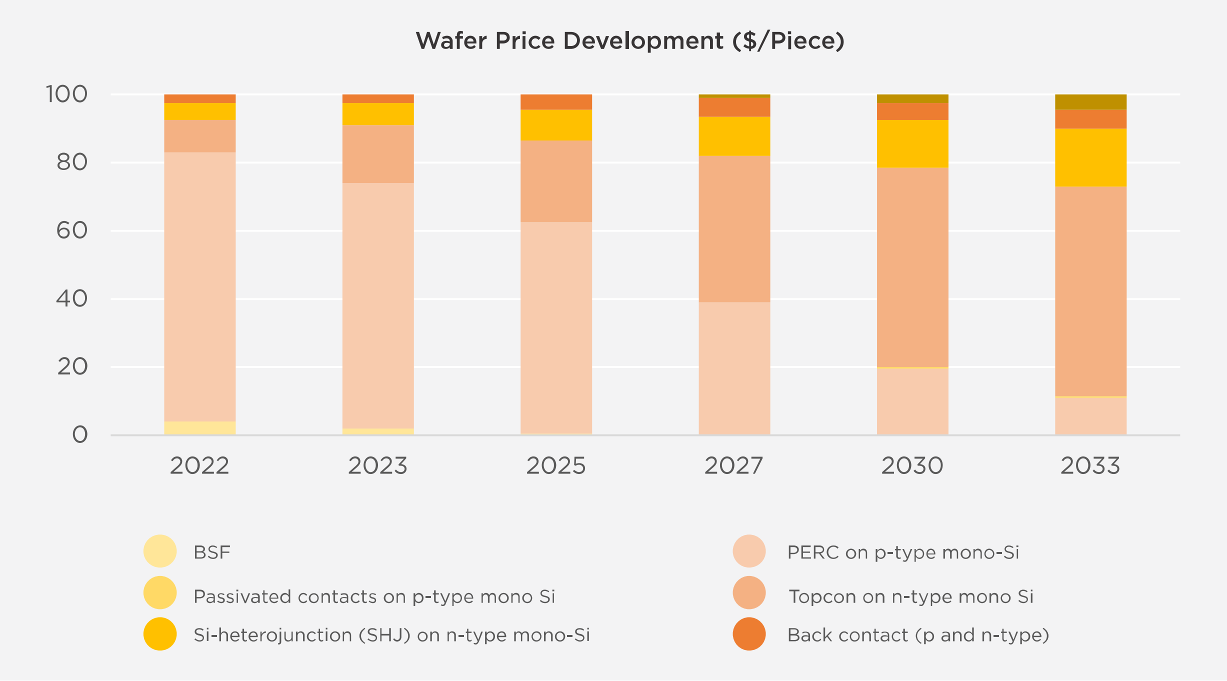


Figure 27: World Market Share of c-Si Cell Architecture (%)

Source: ITRPV- 2023

Every technology has a limit and so has PERC. The PERC technology has reached its practical cell efficiency limit at about 22.5% in mainstream and going beyond does not make economic sense. As a result, PV manufactures have again started focusing on advanced cell architectures. According to ITRPV, it is expected that TOPcon solar cell concept will take over the major market by 2033 followed by HJ solar cells that will cross-over PERC.

The advancements of conversion efficiency achieved by different technologies which have significant share in the market is plotted as in Figure 28.

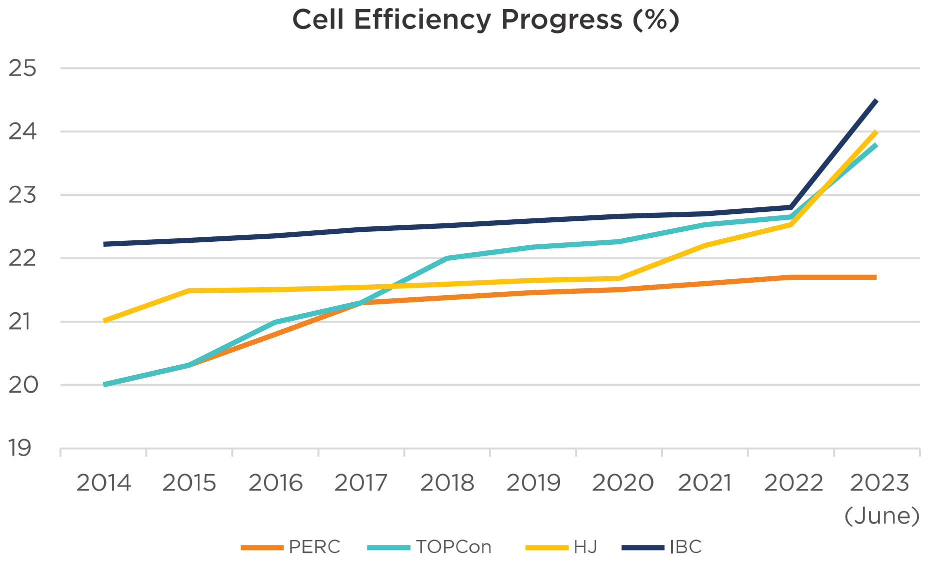


Figure 28: Cell Efficiency Progress

Source: TOP SOLAR MODULES 2022 / H1-2023, Taiyangnews

All these advanced cell technologies are at different levels of efficiency and are progressing at a different pace. IBC so far remined most effacement technology in the commercial space with an achieved cell efficiency of 24.5% in 2023, which has consistently increased from an already high base of 22% in the last 10 years. TOPCon and HJ are the next with cell efficiency of 23.8% and 24% respectively in 2023. TOPCon and has seen the highest increase in efficiency, 13%, likely due to realizing it as the in-focus technology at least in the next 10 years. It is also clear that certain technologies are no longer relevant for state-of-the-art installations. BSF-Multi, BSF-Mono and Multi PERC can now be considered old technologies and should be avoided for future projects due to low efficiencies, unless the cost of land and the module prices are exceptionally attractive. However, Mono PERC may be overtaken by higher efficiency technologies such as TOPCon, HJT, and IBC if cost-effective manufacturing is achieved.

Average cost per watt of solar cell is depicted in Figure 29 as below which nearly follow the trends of wafer.

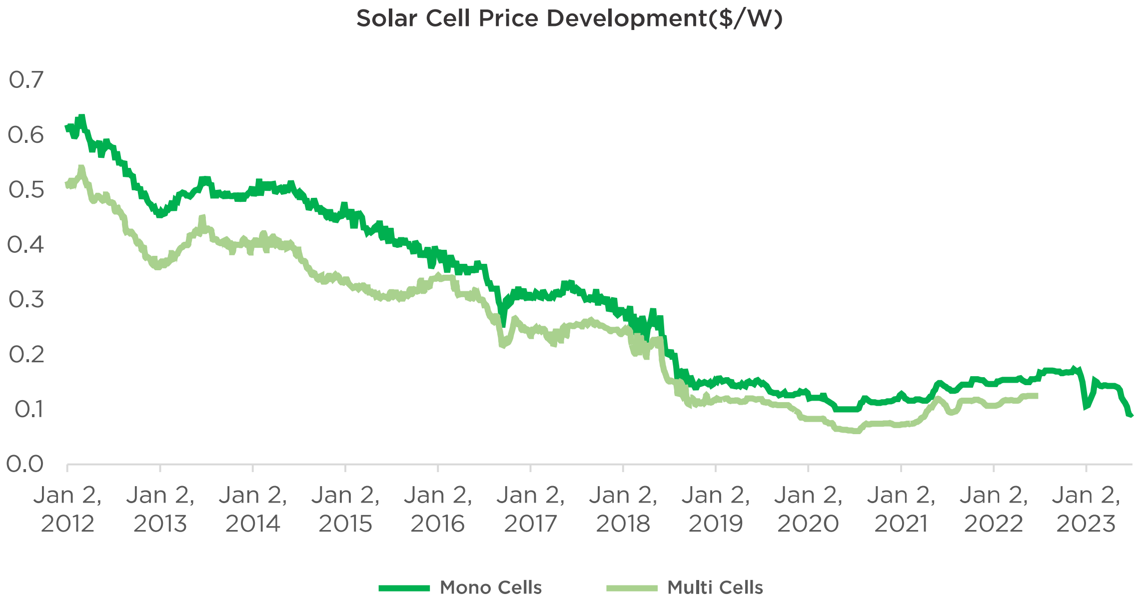


Figure 29: Solar Cell Price Development

Source: BNEF- Bimonthly PV Index July 2023

As we know, the mono crystalline is costlier compared to multi crystalline silicon. The cell price of mono crystalline silicon has dropped from $0.62 in 2012 to $0.10 per watt by 2020. Subsequently, due to Covid pandemic and silicon shortage experienced, cell price has taken a upward track to hit a maximum of $0.17 per watt at the end of 2022, thereafter reduced to $0.09 per watt in June 2023, which is the lowest price for the last decade. The price of multicrystalline silicon followed similar trend as seen in the case of monocrystalline. As per the latest data from BNEF, the price of multicrystalline silicon is $0.13 per watt in 2022.

3.2.4. Solar Module

Assembly of cells to Solar PV Module is the final stage of the solar PV manufacturing process. Unlike other parts of the c-Si value chain, this step involves assembly of different materials rather than manufacturing. As a result, it does not require the same level of technical skill, and assembly lines can be built in relatively short periods of time and in diverse locations.

Nowadays, wafer-based c-Si PV modules occupy about 95% of the market globally, while the rest of it is occupied by thin film PV modules. To generate the desirable voltage and current, solar cells are interconnected after which modules are formed by encapsulating the cells with several layers of polymers and glass to protect the electrical circuit from physical damage and weather. The pictorial representation of a crystalline PV module is given in Figure 30.

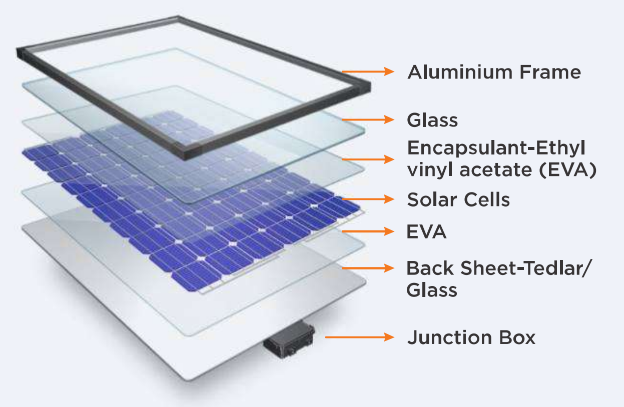


Figure 30: Crystalline Silicon PV Module Evolution

Source: Trina Solar

In general, it consists of a transparent front cover, a polymeric encapsulation, mono- or polycrystalline silicon cells with metal grids on the front and rear and solder bonds electrically connecting the individual cells. Following these layers, a rear layer, tedlar or glass, is placed at the back of the cells and a frame is mounted around the outer edge. Solar PV module can be referred to as solar panels if the modules are panelized with a metallic frame to strengthen and protect the modules.

An additional PV module component, namely the junction box-a plastic box, located at the rear of the module. The junction box encompasses busbar that enables all or some of the cells to be connected in series and some rows in parallel. The output connection of a module is enabled by the junction boxes. All the elements used for crystalline silicon are abundant, and none of them are toxic, rare, or precious. This is one of the major reasons why crystalline silicon is the dominant technology in the market.

Cell Efficiency

The key performance indicators of the module are power, efficiency and reliability. A solar module is a rare commodity that comes with a warranty of 25 years or 30 years (in case of glass-glass), which is why it contains several protective layers. Figure 31 represents the development of module efficiency in the last decade.

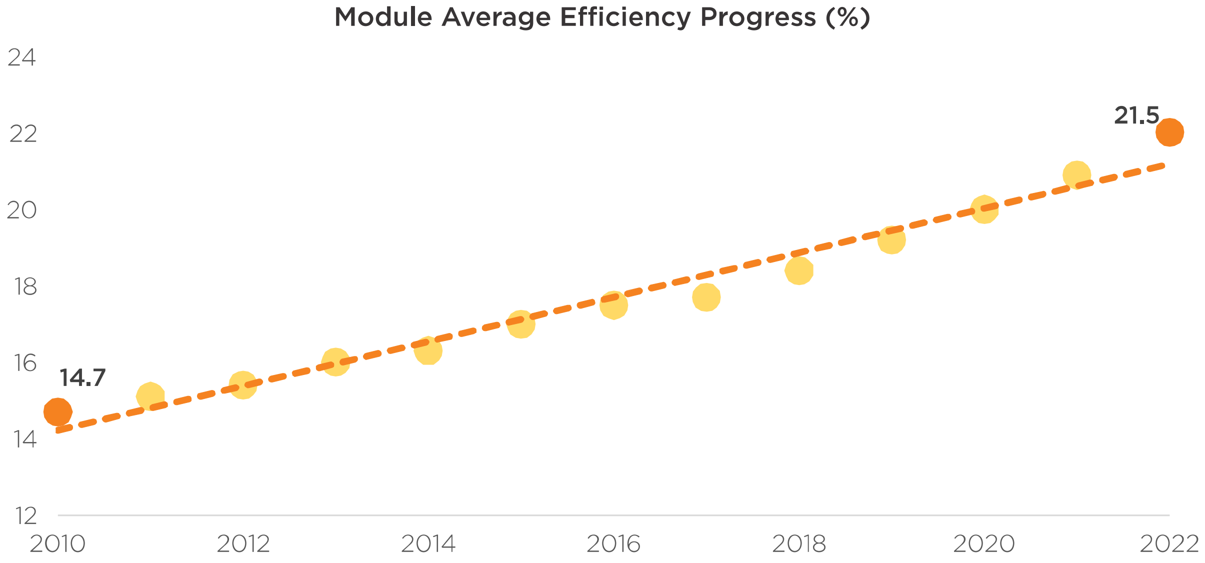


Figure 31: PV Module Average Efficiency Progress

Source: ITRPV-2023, ISA Analysis

The average efficiency of a solar module has been ever increasing with many advancements taking place at both the cell and module levels. The average module efficiency in 2022 was 21.5%, a leap of 2.8% absolute over 2021's level of 20.9. According to ITRPV-2023, PERC technology is anticipated to show an average efficiency of 21.4% by 2023 and up to 22.5% by 2033. TOPCon and HJ technologies are expected to be ahead of PERC with an efficiency of 22.2% and 22.4% respectively in 2023 and both will attain 24% in 2033. The report also refer Si based tandem concepts, which are supposed to be in the market post 2025 with a module efficiency of 26% in 2027 and 27.5% in 2033.

Module Power Rating

While selecting a PV module, more than efficiency, the rated power has higher prominence at the module level. The power output generated by each individual PV module has been steadily increasing over time. The development of power rating over the last decade is demonstrated in Figure 32.

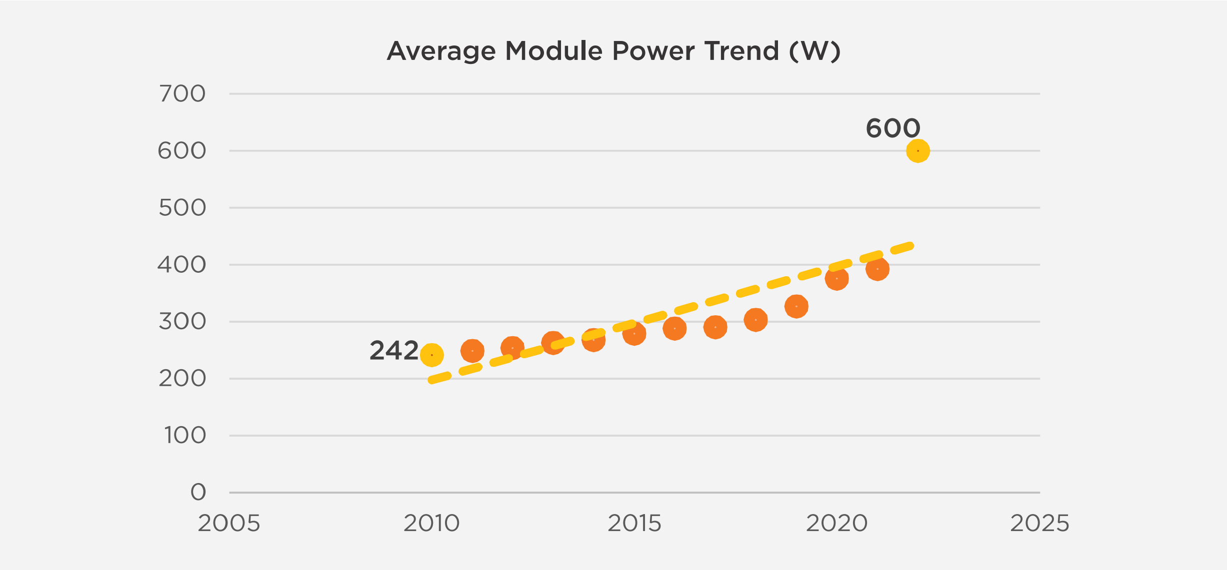


Figure 32: Average Module Power Trend

Source: ITRPV-2023, ISA Analysis

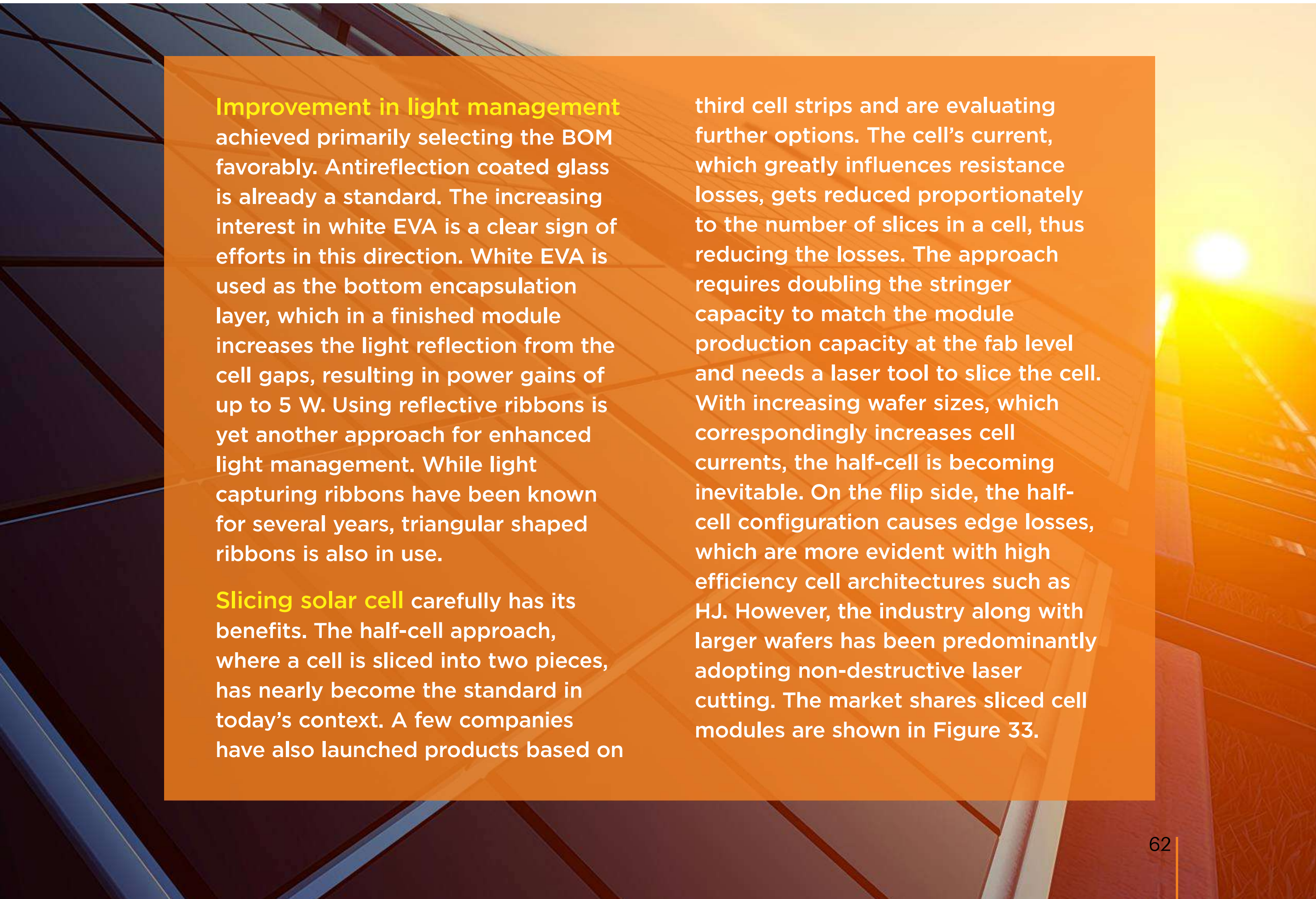
Average module power has increased from 242 W in 2010 to approximately 400 W in 2021. This trend in power increase has accelerated rapidly in recent years. 2011-2018 witnessed an increase of ~50 W while 2018-2021 has seen an increase of ~100 W whereas in 2021-2022 development in power rating observed an upsurge of ~200 W. This increase in average module power can be attributed to increase in wafer and module size.

Solar modules made of larger wafers are becoming the new mainstream product, driving increase in power output, with approximately the same or a smaller number of cells assembled. Large manufacturers have accelerated the transition from smaller sizes of wafer to larger one in the past two years. The newer, larger wafers have a side length of 210mm- G12, or 182mm-M10 compared to previous wafers of 166mm-M6. Power rating is, likewise, depended on number of cells and the design concepts. Increasing number of cells and moving to larger wafer formats has mainly boosted the power of the solar modules. Today, modules with power rating near to 700 Wp are being available in the market, using advanced cell architectures and larger G12 wafer formats.

Cell to Module Power Ratio

Assessing module power improvements independent from the cell level is also possible. The so-called cell-to-module (CTM) power ratio, which is the ratio of module output power to the sum of power output of each of cells embedded in the module, is a good metric to assess developments and the stability of the entire module production process. Interestingly, several module processing steps, such as interconnection, stringing and lamination, lead to better light management and optical gains, which will contribute to a CTM above unity or more than 100%. But module manufacturing also induces various loss mechanisms, such as resistive, mismatch and optical losses, which offset the optical gains and result in a net power loss.

Despite the dominating role of various loss mechanisms, today's PV modules have the capability to reach a CTM power ratio of more than 100%. In simple terms, this can be achieved with the proper choice and mix of complementing materials that result in higher optical gains than combined optical and electrical losses. Advanced interconnection will also help in reducing the resistance losses, pushing CTM power ratios further up. The half-cell approach is one good example here. Some of the strategies to improve CTM ratio is discussed below.



Improvement in light management achieved primarily selecting the BOM favorably. Antireflection coated glass is already a standard. The increasing interest in white EVA is a clear sign of efforts in this direction. White EVA is used as the bottom encapsulation layer, which in a finished module increases the light reflection from the cell gaps, resulting in power gains of up to 5 W. Using reflective ribbons is yet another approach for enhanced light management. While light capturing ribbons have been known for several years, triangular shaped ribbons is also in use.

Slicing solar cell carefully has its benefits. The half-cell approach, where a cell is sliced into two pieces, has nearly become the standard in today's context. A few companies have also launched products based on third cell strips and are evaluating further options. The cell's current, which greatly influences resistance losses, gets reduced proportionately to the number of slices in a cell, thus reducing the losses. The approach requires doubling the stringer capacity to match the module production capacity at the fab level and needs a laser tool to slice the cell. With increasing wafer sizes, which correspondingly increases cell currents, the half-cell is becoming inevitable. On the flip side, the half-cell configuration causes edge losses, which are more evident with high efficiency cell architectures such as HJ. However, the industry along with larger wafers has been predominantly adopting non-destructive laser cutting. The market shares sliced cell modules are shown in Figure 33.

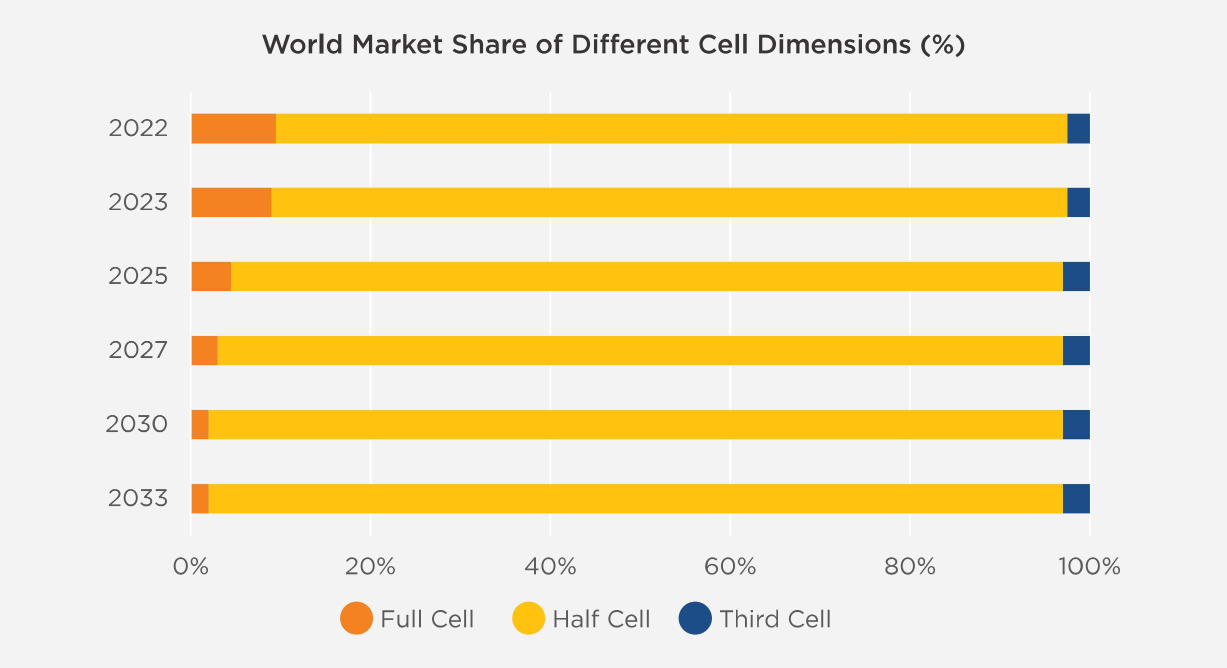


Figure 33: World Market Share of Sliced Cells

Source: ITRPV- 2023

As displayed in the figure, the half-cells modules are the dominating mainstream today for cells < M10 and expected to continue for the next 10 years. Market share of full cell technology will be reduced to below 2% in 2023 which will be used for IBC and in special module applications. Third and quarter cells will also exist for niche applications in this cell format, but not expected to rise the share beyond 2%.

For the cells > M10, half-cells module will be at the center-stage. But it is projected to have a significant increase in market share for third cell modules from 13% in 2023 to 25% by 2033. Furthermore, quarter cells are also likely to be introduced in 2025 to the market which will bear a share of 5% in 2033.

The CTM ratio increases as the solar cell is cut into smaller sizes[11]. Full cells are expected to be unable to cross a 1:1 CTM ratio by 2032, while half cut and third cut cells will likely cross 101% and 102% CTM ratio respectively by the same date.

Reduced/no gap technologies aids to save material, where the solar cells in a PV module are be packed as densely as possible. The practice traditionally has been to space the cells in a string to provide cushion for mechanical stress during operation. However, developments in materials, production equipment and manufacturing technologies have enabled manufacturers to reduce this gap and gain on active module area, and even eliminate this gap altogether. In fact, it was the latter, called shingling, that hit the commercial space first. Here, the cells are sliced into several strips and connected to each other in a similar fashion to a shingle structure of tiles placed on roofs using conductive adhesives. This concept has gained a lot of interest and garnered several followers.

[11] *ITRPV-2022*

Jinko Solar developed another zero-gap technology called Tiling Ribbon (TR), as a workaround for the IP situation with shingling. Here, the stringer is equipped with a special functionality to press the round wire to make it flat exactly to a length where it would bend to connect the top of the next cell. Instead of placing the cells side by side, the cells slightly overlap at the edges. Compared to shingling, TR technology uses an interconnection media as well as avoids laser stripping of cells into several pieces. To cushion the region of cell overlap during the lamination process, TR uses structured EVA that would compensate for the inconsistencies due to overlapping.

Following the TR technology template, several companies have successfully reduced cell gaps. That means the interconnection media is still flat and slightly bent, but instead of overlapping, the cells are placed very close. While the cell spacing is typically 2 mm in the traditional module design, the latest product generations of leading companies can reduce this gap to between 0.6 mm to 0.9 mm. Companies like LONGi use a so-called segmented ribbon for interconnection, which contains parts of triangular shape and flat sections. The triangular side is soldered on the sunny side of the cell to enhance optical gains.

Bifacial Modules are PV device which are light sensitive on both sides. Every advanced cell technology is naturally bifacial, and tweaking PERC into bifacial is easy. It does, however, require a considerable change in BOM. The first one is to make rear cover transparent - glass, instead of opaque back sheet. The glass-glass configuration is the key enabler of bifacial technology. While 3.2 mm glass is used for the front cover in mono facial modules, using two sheets of glass with 2 mm thickness is the mainstream practice with bifacial modules, as efforts are on to reduce thickness without compromising on reliability. A bifacial module requires one more change in BOM when using glass-glass. With respect to PERC bifacial modules, the current practice is to use polyolefin elastomers (POE) on the rear to provide extra protection from Potential Induced Degradation (PID).

Bifacial technology has one inherent limitation in that it cannibalizes front power due to the loss of sunlight that hits cell gaps. First glass makers, then followed by back sheet makers, devised a workaround where they print a reflective film to fill in the empty spaces, while the areas occupied by the cells remain transparent. This mimics the role of a white back sheet in a standard module, giving the bifacial solar panel the appearance of a mono facial module from both sides. Bifacial technology is a vast subject on its own with developments across the supply and value chain.

Since bifacial PV modules are light sensitive on both sides it is capable to generate electricity from incident light on both the front and back surface. Thus, bifacial modules are able to increase power generation. The markets share of bifacial module is demonstrated in Figure 34.

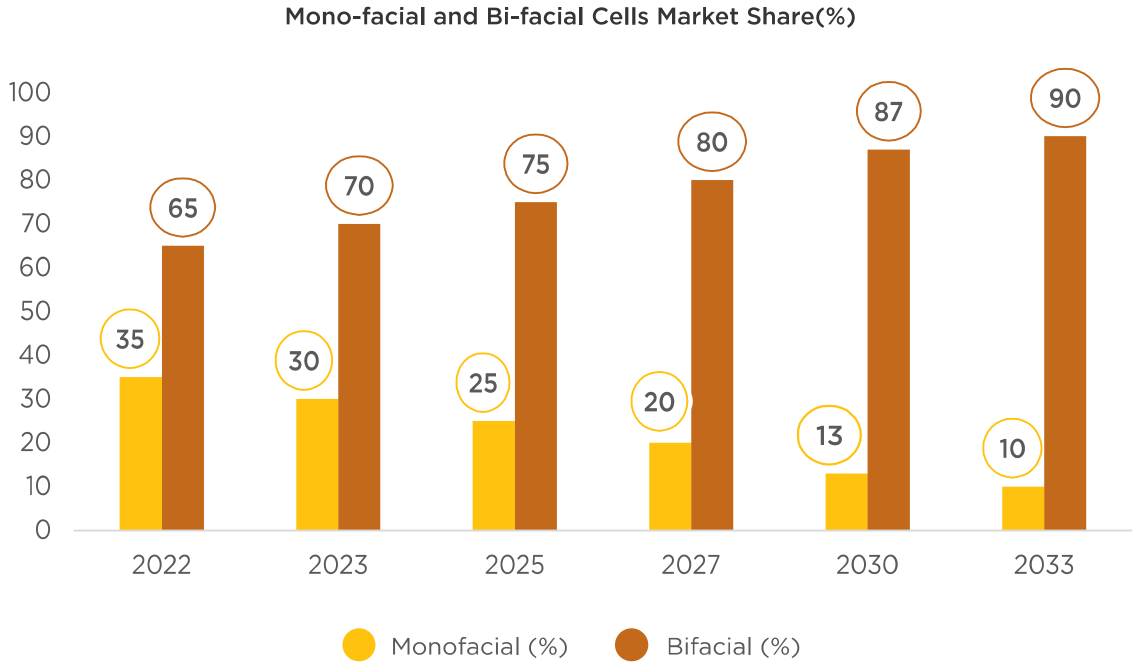


Figure 34: Mono-facial and Bi-facial Cells Market Share

Source: ITRPV-2023s

Bifacial PV modules will be the dominant solar PV technology globally within one or two years; in the utility scale sector, their market share is already above 70% and it is expected to attain near to 95% of the market share in 2033. The successful implementation of bifacial technology can help a PV installation maximize its system performance and minimize levelized cost of electricity (LCoE).

Multi Busbar (MBB) cells are introduced to reduce electrical losses which mainly involves changes to the interconnection process. A first step in this direction was to increase the number of busbars. The PV industry quickly adapted to 5-busbars a few years ago. However, instead of following the incremental path of going to 6-busbars, which was adapted only by Hanwha Q Cells, the industry took a big leap to MBB where the number of busbars ranges from 9 to 12. Employing circular copper wires instead of flat ribbons was part and parcel of MBB. MBB requires special combined tabber and stringing tools, which are now available in the market. The Smart Wire Connection Technology (SWCT) from Meyer Burger is also a high-end variant of the MBB approach. In addition to power gain, the MBB approach enables the reduction of finger width to a greater extent. The benefit of reducing the finger width is twofold — it cuts shading losses and lowers paste consumption. A few HJ makers have already commercialized products with 15- busbars and are evaluating the options to increase further up to 24. The trends in number of busbars in the market is captured and demonstrated in Figure 35.

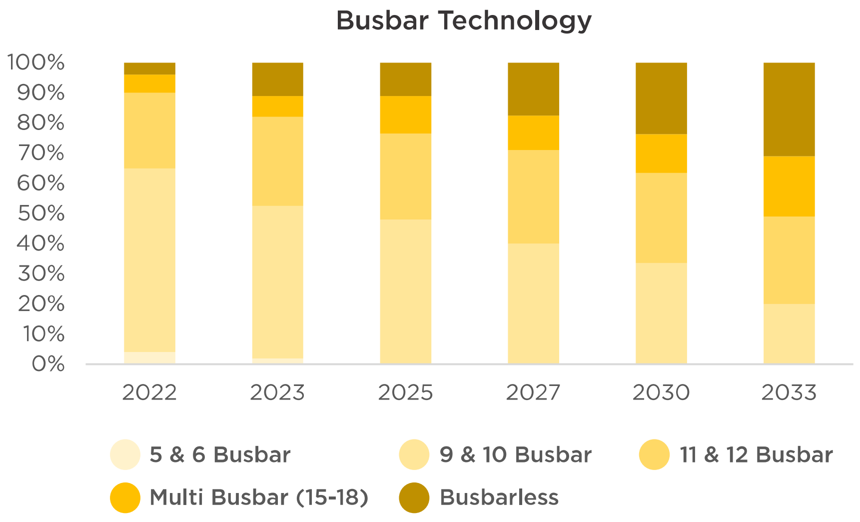


Figure 35: Busbar Technology

Source: ITRPV-2023

As shown in figure, for M10 wafer configuration, 9 &10 busbar technology is at the mainstream in 2023 followed by 11 & 12 busbar technology. It is anticipated the vanishing of 5 & 6 busbar technology by 2025. In addition, by 2033, all remaining technologies are projected to be co-exist with significant market share for each of them.

Price Movement of Solar Module

It is interesting to note that despite multifold increases in polysilicon and shipping costs, as well as substantial increases in aluminum and copper costs, standard solar module prices have only increased by 20% over the last two years. This underscores the resilience of the solar PV market, ensuring that despite significant increases in input costs, PV supply can be maintained with limited disruption to project costs. The price movement of different components of solar module is shown in Figure 36.

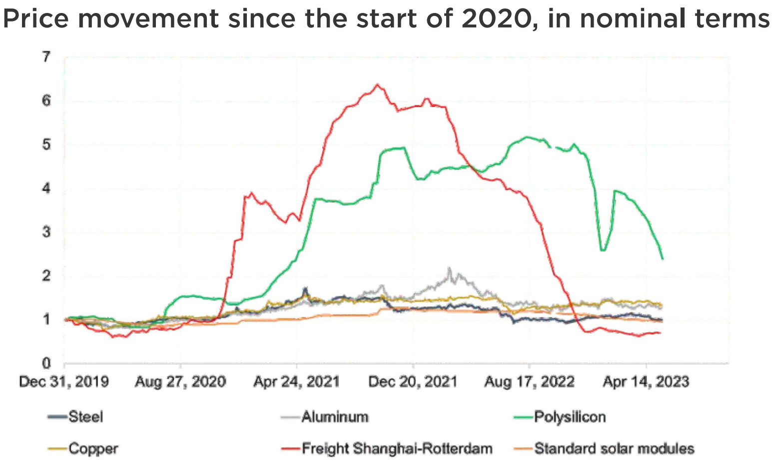


Figure 36: Price Movement of Solar Modules

Source: 2Q 2023 Global PV Market Outlook, BNEF

When it comes to module level costs, which is contributed by wafer price, cell conversion costs, module material cost, labor, utilities maintenance, depreciation, and R&D, the cost differential between modules of different types do not differ significantly. Variations in cell conversion costs and the module materials utilized were the main drivers for cost difference among the others.

The price development of for the last decade is shown in Figure 37.

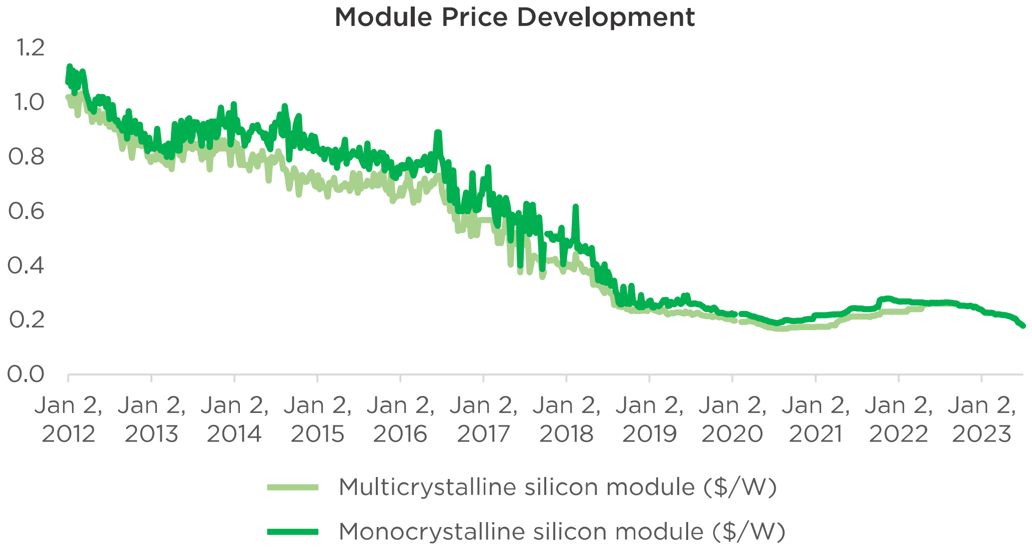


Figure 37: Module Price Development

Source: BNEF- Bimonthly PV Index July 2023

As we know, the mono crystalline is costlier compared to multi crystalline silicon. The module price of mono crystalline silicon has dropped from $01.08 in 2012 to $0.19 per watt by 2020. Subsequently, due to Covid pandemic and silicon shortage experienced, module price has increased but not in the same way of wafer or cells. Instead, module price has seen a small increment in price as compared to that of wafer and cells to reach $0.27 per watt in 2022. Subsequently, module price reduced to $0.18 per watt in June 2023. According to the latest available data from BNEF, the price of multi crystalline silicon is $0.26 per watt and it follows the same trend of mono crystalline silicon.

Solar Module Bill of Material (BoM)

Although the primary function of the solar module has not changed, its Bill of Materials has been altered to generate electricity more efficiently and drive down costs. A solar module comprises of various components such as solar cells, cell interconnectors, encapsulant, back sheet, front glass. Over the years, a lot of research has taken place about each component, in pursuit of improving the overall module efficiency. Small changes and improvements in module characteristics can help eke out additional efficiency and/or material usage improvements that further translate to cost competitiveness improvements for solar power. The trend in usage of component by mass is shown in Figure 38.

Cell interconnectors

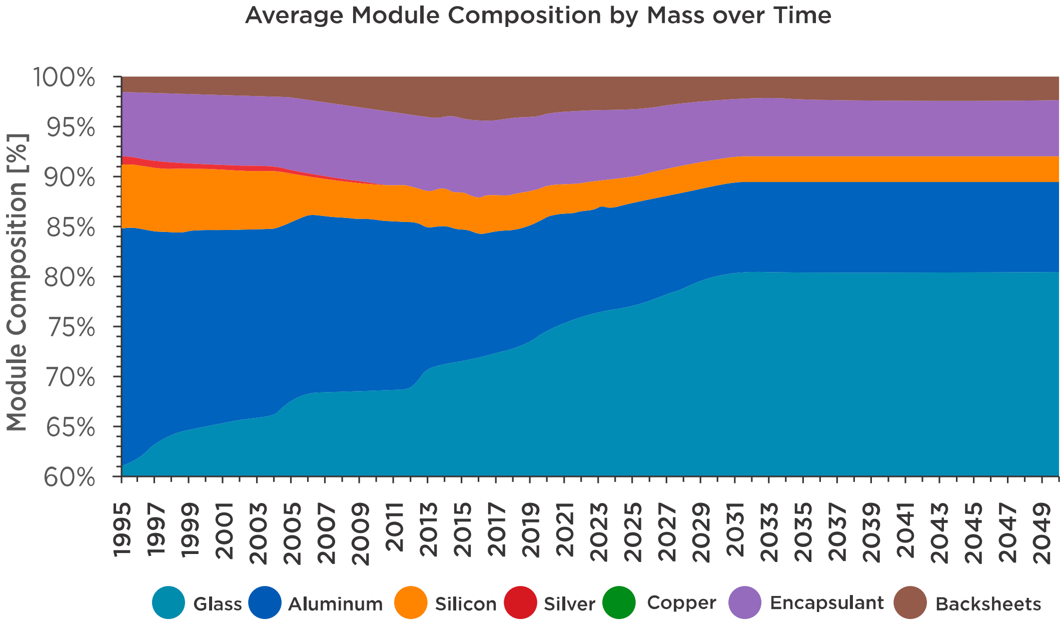


Figure 38: Average Module Composition by Mass over Time

As can be observed in the above figure, there has been a considerable amount of shift in the percentage of each material used to produce a solar module. Glass, which used to be around 61% of the composition of a solar module in 1995 has risen to about 76% of the average module composition by 2022, and is expected to compose 80% of a solar module by the year 2033. Similarly, with constant evolution, the composition of other materials being used, such as encapsulants, copper, silver etc., is also changing. This shift in module material shows the evolving nature of the solar PV industry. The major components of solar modules are discussed below.

Cell interconnections are established primarily by three different technologies – lead containing soldering, lead free soldering, and electric conductive adhesives. Now, lead containing soldering technology is considered as the mature and standard one which is reliable and cost-efficient. Lead-free interconnections are used for special applications like HJ and IBC. The expected market trends of different interconnection technology are illustrated in Figure 39.

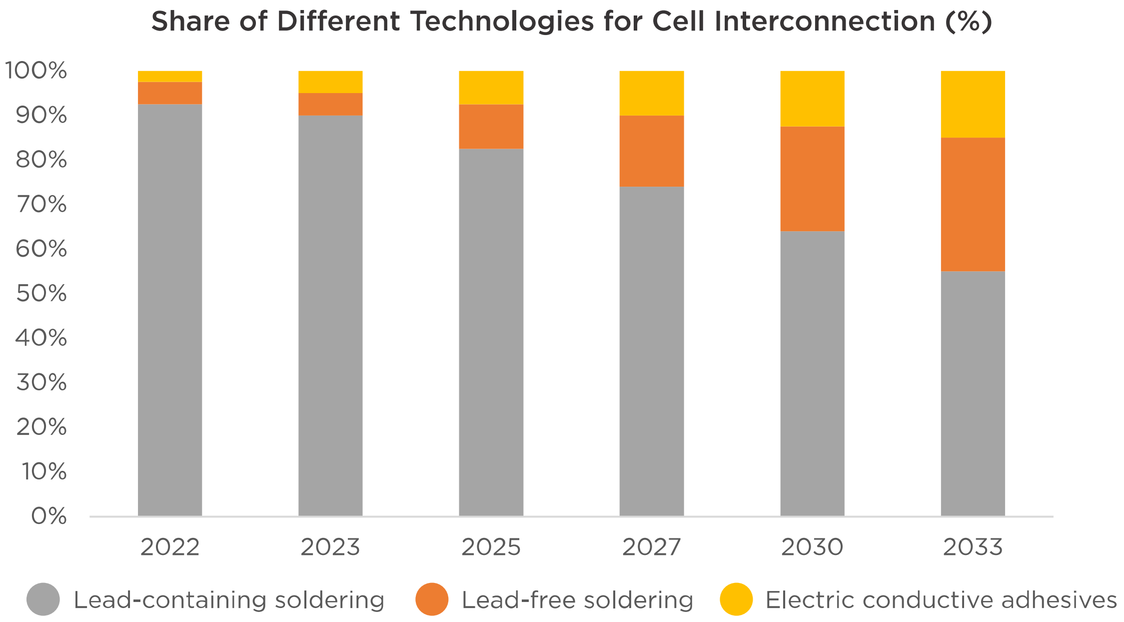


Figure 39: Share of Different Technologies for Cell Interconnection

Source: ITRPV-2023

Lead containing soldering is the expected to continue at the centerstage for the next decade. Though, the lead-free soldering and conductive adhesives technology will strengthen the market share by 2033. Lead-free soldering for string connection is expected to gain market share from about 5% in 2023 to about 30% in 2033. Similarly, conductive adhesive technology for string interconnection, mainly driven by HJ, is projected to reach market share from 2.5% in 2023 to 15% in 2033. The trends for cell interconnection technologies follow the similar fashion. The development in the different cell interconnection material used is illustrated in Figure 40.

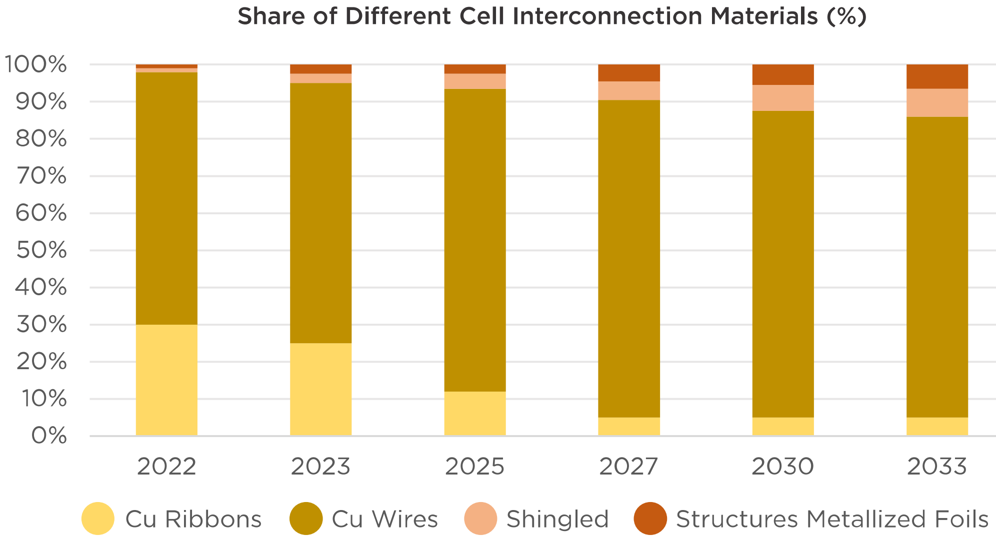


Figure 40: Share of Different Cell Interconnection Materials

Source: ITRPV-2023

As depicted in figure above, copper wire, which is introduced few years back, for half-cell technology is dominating cell interconnection material and it will continue at the mainstream for the next 10 years. In 2033, the other technologies like cu ribbon, shingled, structures metallized foils will advance the market share to a cumulative share of 19%. The remaining 81% of the segment will be shared by copper wire.

Encapsulant and back sheet are key components used in module to ensures long time stability. Since both components have a significant share in the module composition, they are major cost contributors in the module manufacturing. Optimization and improvement in these components are mandatory to ensure the performance of module and module service time and to reduce the overall cost of the module. The different encapsulation material and projected market share is given in Figure 41.

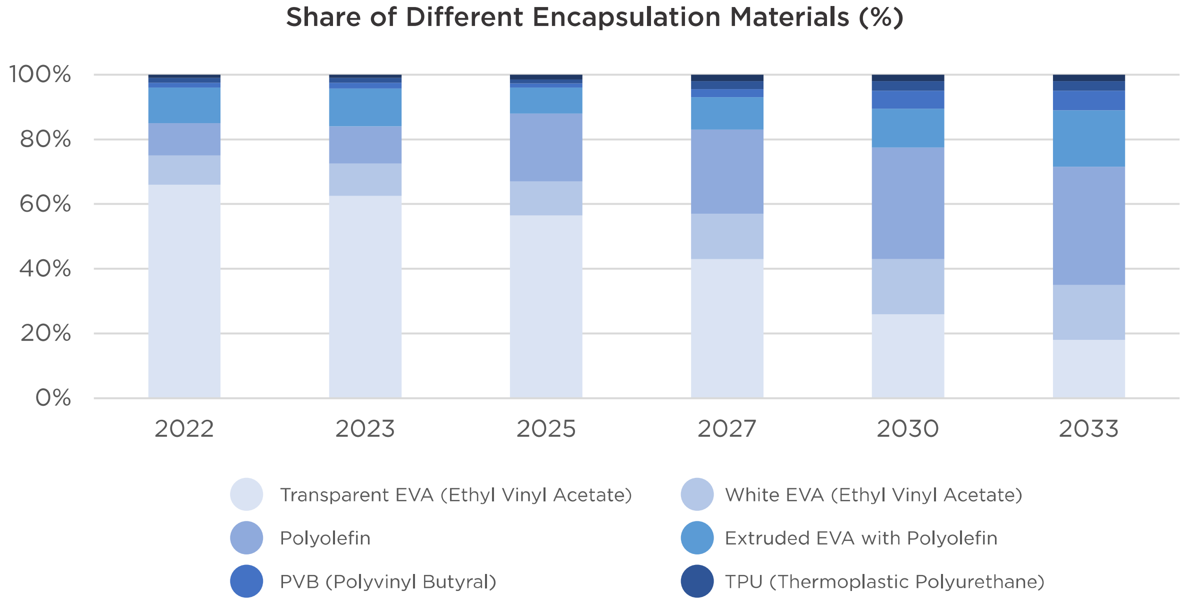


Figure 41: Share of Different Encapsulation Materials

Source: ITRPV-2023

As per the figure, EVA holds the major market share (70%) in 2023. But it is expected to lose the market share in next few years, eventually, polyolefin will be at mainstream with market share more than 50% by 2033. Polyolefins are used for bifacial products in glass-glass combination and for HJ.

Regarding the back cover material, glass will be the leading back cover material in near future. The development in the material used as back cover is demonstrated in Figure 42.

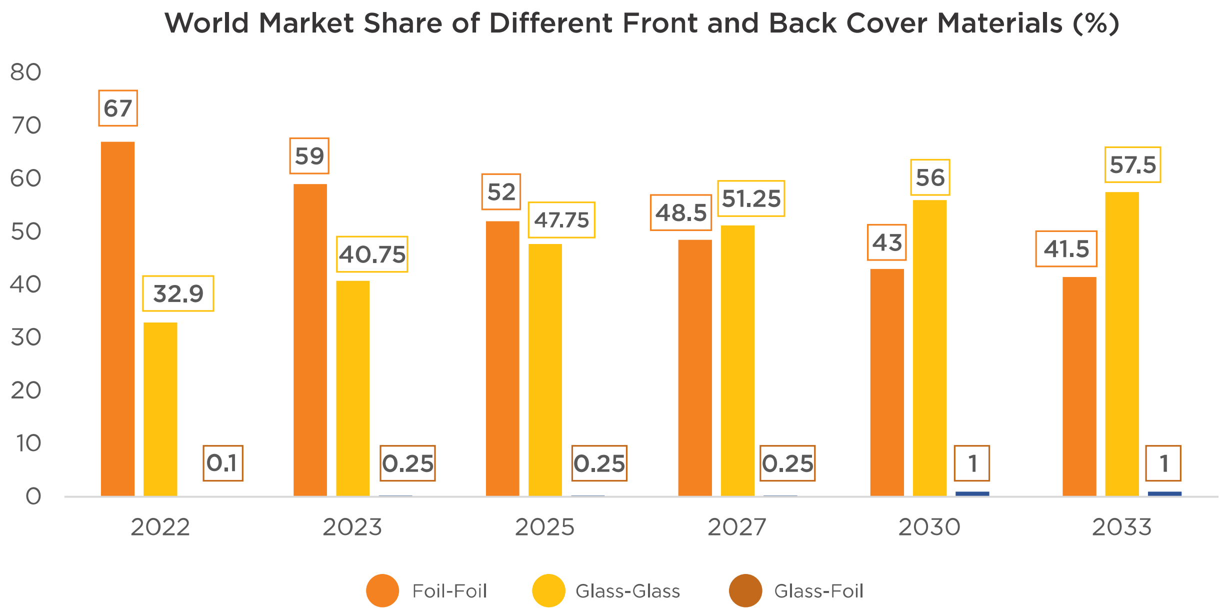


Figure 42: World Market Share of Different Front and Back Cover Materials

Source: ITRPV-2023

Evidently, foils as back cover material will observe a reduction in their market share to 40% within the next 10 years from the present 66% market share. Glass will double the present market share to attain about 60% by 2033. Foil based front side covers will stay a nominal.

Front glass thickness is relevant as it is the most significant material by weight in a PV module. Glass thickness is not only relevant for the mechanical stability of the overall module but also it determined weight and light transmission properties of the module. The development of glass thickness is summarized and plotted in Figure 43.

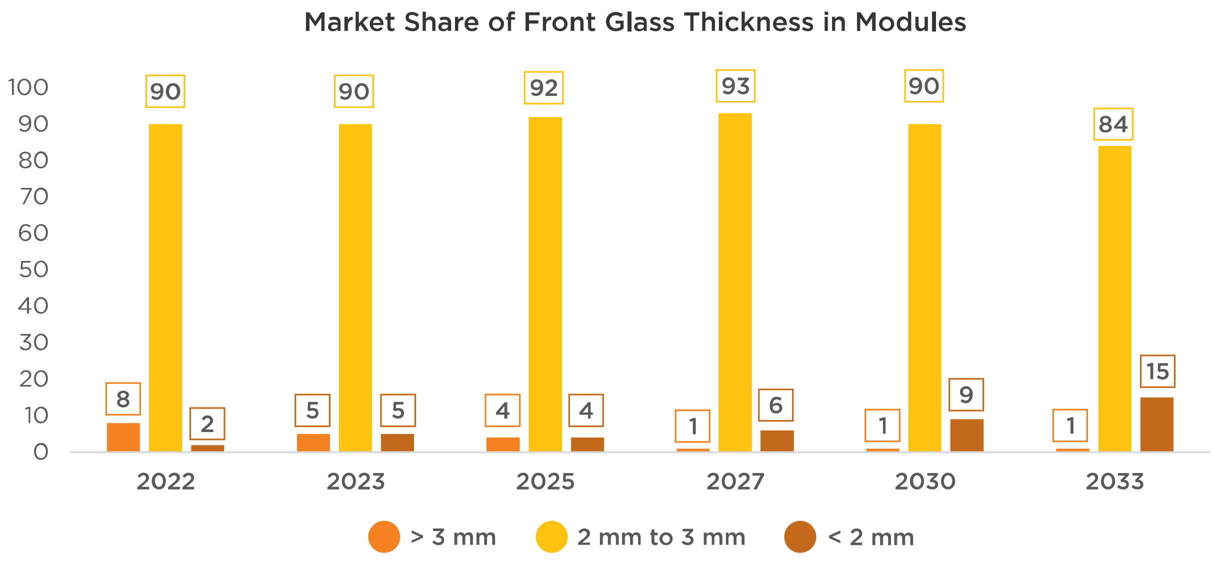


Figure 43: Market Share of Front Glass Thickness in Modules

Source: ITRPV-2023

Evidently, glass with thickness between 3 mm and 2 mm is at the mainstream. Furthermore, the industry is now tending towards thinner glass with thickness less than 2 mm, therefore, the glass with thickness greater than 3 mm will experience a considerable reduction in the market share in next few years.

Warranty

Module manufacturers are increasingly confident in their ability to guarantee module lifetime and performance over long periods of time. This is reflected in long term performance warranties of 25 years, which are expected to further increase to 30 years soon. This performance warranty is accompanied with the expected reduction of initial module degradation as manufacturing processes. Figure 44 shows the trends of warranty of modules.

Warranty Requirements and Degradation for C-Si PV Modules

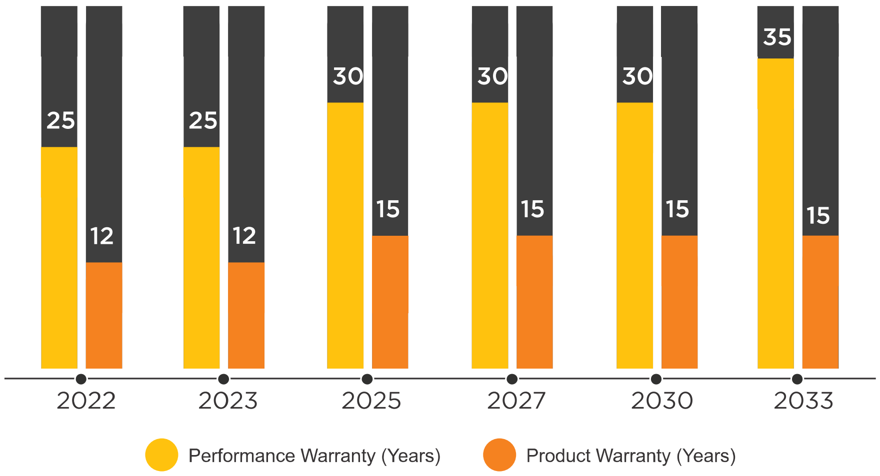


Figure 44: Warranty Details

Source: ITRPV-2023

The product warranty is expected to increase from present 12 to 15 years by 2033 whereas the performance warranty is expected to increase from 25 to 35 years by 2033.

3.3. Thin Film PV Technologies:

Although crystalline silicon-based PV has become the dominant technology worldwide, PV cells based on non-crystalline silicon materials are also available, termed thin film PV technology. Thin film solar cells consist of thin, at the order of microns, photon-absorbing material layers deposited over the substrate. As a result, thin film PV cells are significantly thinner, lighter, and more flexible than the crystalline silicon PV cells that dominate the market. The technology saw initial usage in small electronic appliances such as watches and calculators. The flexible nature of the technology has opened avenues for its deployment in other specific applications such as Building Integrated Photovoltaics (BIPV) as they can be installed on curved surfaces. The overview of thin film PV technology is demonstrated in Figure 45 and explained.

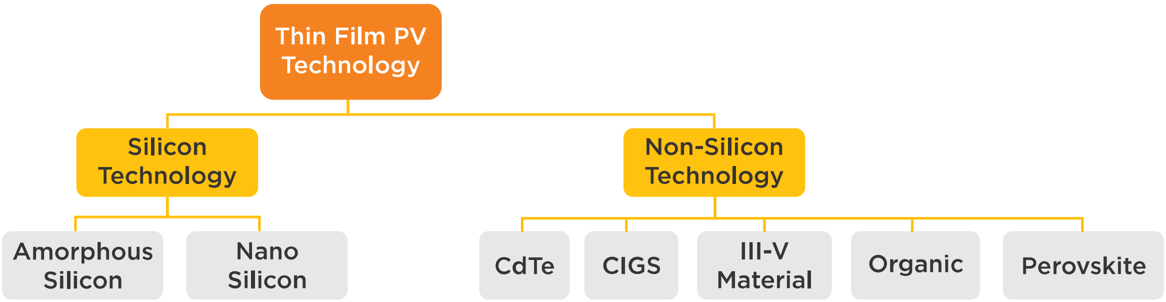


Figure 45: Overview of Thin Film Technology

Amorphous silicon: Amorphous silicon is a continuous random network of silicon atoms. The silicon bond angles and silicon-silicon bond lengths are slightly distorted concerning a crystalline silicon network. Therefore, at long-range order, the lattice no longer looks, or behaves, as crystalline. Indeed, different types of imperfections occur in the amorphous silicon lattice. Unlike crystalline silicon, in the amorphous silicon lattice, not every silicon atom is connected to four neighboring silicon atoms creating unconnected valance bonds referred to as dangling bonds. The dangling bonds are defects and consequently amorphous silicon has a much higher defect density, compared to crystalline silicon. The defects lead to fast recombination of photoexcited charge carriers and cause amorphous silicon to have poor conductivity about crystalline silicon. Therefore, amorphous silicon is hydrogenated. The small hydrogen atoms attach to the dangling bond, thereby passivating the defect and increasing conductivity. The optical bandgap (the energy needed to excite an electron from its atom into a state where the electron can move freely) of amorphous silicon ranges from 1.6 to about 1.8 electron-volts (eV) where that of crystalline silicon is near 1.1 eV. Starting from 1.8 eV, the absorption coefficient of amorphous silicon becomes at least an order of magnitude larger than that of crystalline silicon and amorphous silicon therefore already starts absorbing from very low energy levels. This means that in the visible and ultraviolet parts of the spectrum, which are the parts with the highest photon energies, amorphous silicon is much more absorbing than crystalline silicon. This makes it such an interesting material for thin-film solar cells. Apart from hydrogen, other elements like germanium and carbon are also alloyed with amorphous silicon to create hydrogenated silicon-germanium alloy and hydrogenated silicon carbide respectively, which also falls under the category of amorphous silicon.

Nanocrystalline silicon: The amorphous phase is not the only silicon phase used in thin film solar cells. The microcrystalline silicon phase is a hydrogenated silicon alloy with a very complex structure. Micro-crystalline silicon, which is also known as nano-crystalline silicon, consists of small grains that have a crystalline lattice and are in the range of nanometers in size. The grains are embedded in hydrogenated amorphous silicon tissue. A measure of the crystalline volume fraction is called crystallinity, which is defined as the volume fraction of the crystalline phase concerning the total silicon volume. Depending on the deposition conditions, the crystallinity of the nanocrystalline material can range anywhere from fully amorphous, to a mixed phase with a few small crystalline grains, to a phase which is dominated by large crystalline grains and only a small fraction of amorphous tissue. Research has shown that the best nanocrystalline bulk materials used in solar cells have a network close to the transition region between nanocrystalline and amorphous silicon, with a crystallinity of about 60-70%. An interesting alloy is obtained when oxygen, a group-six material with six valence electrons, is incorporated into the lattice. The resulting hydrogenated nanocrystalline silicon oxide is often used in thin films due to its favorable optical qualities.

Nanocrystalline silicon has a bandgap energy ranging from that of silicon, 1.1 eV, to about 1.3 eV as it becomes more amorphous and hydrogenated. This means it already starts absorbing in the infrared part of the spectrum. In addition, silicon oxide has the highest bandgap energy of over 2 eV. The high bandgap energies of silicon oxide allow it to absorb the highly energetic blue and ultraviolet part of the spectrum, with minimal thermalization losses. All of these imply that nanocrystalline silicon is capable to utilize infrared, visible, and ultraviolet parts of the spectrum.

With this range of silicon alloys, it is possible to design several multijunction thin-film silicon solar cells. Probably, the most studied concept is the micromorph solar cell. A micromorph cell consists of an amorphous and nanocrystalline silicon junction. The spectral utilization is relatively high, especially in the ultraviolet and visible part of the spectrum. Though, optimizing thin films silicon multijunction solar cells is a complex interplay between the various absorber thicknesses and light management concepts.

Cadmium-Telluride (CdTe): Cadmium telluride, thin film technology, is a semiconductor that belongs to the chalcogenide materials since the element tellurium belongs to group six in the periodic table of elements. Together with cadmium, a transition metal, it forms II-VI semiconductor compound.

Cadmium telluride has a bandgap of 1.44 eV, which lies remarkably close to the optimum value for the bandgap of a single junction solar cell resulting in a high absorption coefficient. A layer of a few micrometres is enough to absorb all photons with an energy above the bandgap. Cadmium telluride material can be grown in both p- and n-type. The n-type cadmium telluride can be obtained by substitutional doping of cadmium atoms by group three elements such as aluminium, gallium, or indium whereas p-type cadmium telluride can be obtained by substitutional doping of the cadmium atom by group one elements, including the alkali metals lithium and sodium. The dopping and intrinsic defects in the material also contribute to the conductivity type. There are various processes available to produce cadmium telluride layers, such as close space sublimation (CCS)- usual method, vapor transport deposition (VTD), electrodeposition or physical vapor deposition.

CdTe solar cells are the second most common photovoltaic (PV) technology in the world marketplace after crystalline silicon which is more efficient than its thin-film technological predecessor, amorphous silicon.

Copper indium gallium selenide sulfide (CIGS): Chalcopyrite materials consist of elements in groups one, three and six. Many combinations of the elements are potential solar cell materials; however, the electronic bandgap of most materials is too wide. The most common combination is a mixture of copper indium diselenide (often indicated by CIS) and copper gallium diselenide (CGS). Also, sulfur can be included in the structure partially replacing the selenide fraction in the material. The doping is a result of intrinsic defects in the material. The deficiency of Cu efficiently acts as an acceptor, which means electrons excited from the valence band can get easily trapped or function as hole-rich regions. As a result, the holes become the majority charge carrier density, thus p-type CIGS which act as the absorber layer in classic CIGS cells. The n-type CIGS is an indium-rich alloy. The p-type CIGS absorber layers used in industrial modules have a typical band gap of 1.1 to 1.2 eV. It requires only a thickness of 1 to 2 microns to absorb a large fraction of the light above the band gap. A variety of CIGS alloys exist. The typical CIGS alloy is heterogeneous material that is comprised of CIS, and copper indium gallium selenide.

One of the important aspects of CIGS solar cells is the role of sodium. Low contamination of sodium increases the conductivity in the p-type CIGS materials, it leads to a welcome texture and an increase in the average grain size. This results in higher band gap utilization and higher open-circuit voltages. The normal optimum concentration of sodium in the CIGS layers is 0.1%.

CIGS films can be deposited using a variety of deposition technologies. As many of these activities are developed within companies, not much detailed information is available on many of these processing techniques. Two types of production processes are a three-stage process, and a two-step precursor and salinization process, the latter is adopted by the Japanese company Solar Frontier, a market leader in this field, and they have reached conversion efficiencies larger than 22% with this two-step process.

Indium, one of the main components of CIGS, is a relatively rare element in the Earth's crust. This element is already being used extensively in the display industry, so it has been foreseen that this element may limit the upscaling of the CIGS industry. For this reason, research has been conducted on the so-called kesterite semiconductors, for instance, zinc tin sulphide, copper zinc tin selenide, or a combination. Though, the highest conversion efficiency of a cell based on this non-toxic and abundant semiconductor material is still significantly smaller than that of the traditional CIGS solar cells.

III-V materials: As the name implies, III-V material uses elements of group 3 and group 5 in the periodic table of elements. One of the most common III-V absorber materials is formed by bonding the group 3 material gallium, with the group 5 material arsenic- gallium arsenide (GaAs) with a band gap of 1.4 eV. Several such combinations are possible, however, and many different III-V alloys are used as absorber materials by the PV industry. Examples include Gallium phosphide, Indium phosphide, gallium indium phosphide, aluminium-gallium-indium-arsenide, and aluminium-gallium-indium-phosphide. One of the challenges of the III-V technology is the elemental abundance; Gallium, arsenide and germanium are not rare or precious metals, but they are much less abundant than silicon. Indium is rare and in high demand. Moreover, the processing methods to deposit high-quality III-V alloys are slow and expensive. As a result, III-V materials like GaAs are expensive to produce in contrast to other PV materials like silicon. Additionally, Arsenic is highly toxic.

The III-V technologies are the best choice for applications that require a high output power density. The current record triple junction solar cell without light concentration, developed by NREL, has an efficiency of 39.5%. The record multi-junction solar cell with light concentration, also developed by NREL, consists of a whopping 6 junctions and has a conversion efficiency of over 47%. This makes the III-V PV technology an attractive option for niche applications where a very high-power output per unit area is crucial. The high-cost-high-performance III-V technology is therefore primarily used for space applications and concentrator photovoltaics (CPV).

Considering the design of a III-V material solar cell, a single cell is composed of more than one p-n junction or subcells, typically three, with different band gap energy, referred to as multi junctions. Therefore, the utilization of energy that belongs to various parts of the spectrum can be ensured. The spectral utilization can be even increased further by moving to multi-junction solar cells consisting of five or even six junctions. However, adding more junctions in a III-V device poses a serious challenge.

For III-V depositions, epitaxial processes are used. There are two main epitaxial deposition techniques; molecular beam epitaxy - the expensive technique that produces a higher-quality material, and metal-organic chemical vapor deposition - a faster and cheaper deposition process that produces slightly lower-quality, material.

Organic Solar Cells: Organic solar cells can be defined as solar cells containing an absorber material made of conductive organic polymers or organic molecules that are carbon-based which may form a cyclic, an acyclic, a linear or a mixed compound structure. Due to the use of different absorber materials, these solar cells can be produced in a variety of colors. A few examples of organic absorber materials used in these solar cells are phenyl-C61-butyric acid methyl ester (PCBM-C61), Poly(3-hexylthiophene) (P3HT) and phthalocyanine. Intermixing of these compounds can produce the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) which is analogous to the valance band and conduction bands respectively as in the case of semiconductors which enable organic material to exhibit semiconductor properties.

Dopping is not preferred in organic cell material, instead, by intelligently using intrinsic materials, 'electron acceptor' and 'electron donor' can be formulated. It is theorized that by bringing together an electron donor and an electron acceptor the interface formed will resemble that of a heterojunction. In a normal heterojunction organic solar cell, the organic absorber material exhibits a high absorption coefficient and hence requires an absorber layer with a thickness of anything more than just 100 nanometers (nm) to maximize the utilization of the solar spectrum. The conventional cell architecture of organic-molecule and polymer solar cells is based on blended heterojunction solar cells. The donor and acceptor materials are blended in the absorber layers. This allows the excitation of electron-hole pair to reach a donor-acceptor interface before they recombine. The separated electrons travel through the acceptor layers and are collected at the electron collecting layers (ECL), while the holes move through the donor material

and are collected at the hole collecting layers (HCL). As a typical electron-collecting layer, zinc oxide (ZnO) or titanium oxide (TiOx) has been used in many organic device concepts. poly polystyrene sulfonate (PEDOT: PSS) is often used as a hole-collecting layer.

The lightweight and flexible nature of thin-film modules allows many new PV applications and integrations in comparison to glass-encapsulated modules.

Perovskite solar cells: A rapidly emerging PV technology is that of perovskite solar cells. Perovskites have seen a tremendous increase in initial efficiency in recent years. The first Perovskite cells with conversion efficiencies of 2.2% were only reported in 2006. Non-certified cell efficiencies higher than 23% have been reported only 17 years later. Perovskites are minerals with the general formula ABX3, where X is an anion, and both A and B are cations. An anion is a negatively charged ion, whereas a cation is a positively charged ion. For photovoltaics, organic-inorganic perovskites are used, where the large cation A is organic; often methylammonium (CH3NH3+) abbreviated with MA or formamidnium (CH(NH2)2) abbreviated with FA, is used. Cation B usually contains lead (Pb) or tin (Sn). Halogens, such as iodine, chlorine, bromine, or a mixture of halide materials are used as the anion. Cation B usually contains lead (Pb). While tin (Sn) can also be used. The halide perovskite materials have received extensive attention in PV research due to their promising physical properties.

Perovskites can be deposited using several processing methods. Various deposition technologies can result in high-quality perovskite films. The method most explored on the lab scale is solution-based crystallization, using a spin coating of a precursor solution. Many other processing methods have been reported like blade coating, slot-die coating, spray coating, inkjet printing, co-evaporation, flash evaporation, and pulsed laser deposition.

The perovskite absorber layer is sandwiched between a hole transport layer and an electron transport layer. Common electron transport layers include titanium oxide (TiO2), ZnO, tin oxide (SnO2) and phenyl-C 61-butyric acid methyl ester (PCBM). Common hole transport layers include spiro-MeOTAD, poly(triaryl amine) (PTAA), PEDOT-PSS and nickel oxide (NiO).

The record efficiencies of the halide perovskite PV technology have increased rapidly on a lab scale in the last decades. Nevertheless, the perovskites PV technology is facing a crucial challenge of lifetime of cells before it can be commercialized. Therefore, the research is still focused on fundamental questions and the PV technology is still in the phase of medium technical readiness level. However, the pace at which the technology is developing, perovskite PV technology could become commercial in the near future.

3.4. Balance of System

Balance of System (BoS) is a term used to broadly refer to all components, equipment, structures, and services necessary to create an operational solar generation project, beyond the PV modules themselves. Hardware BoS components can be subdivided into the following categories as demonstrated in Figure 46.

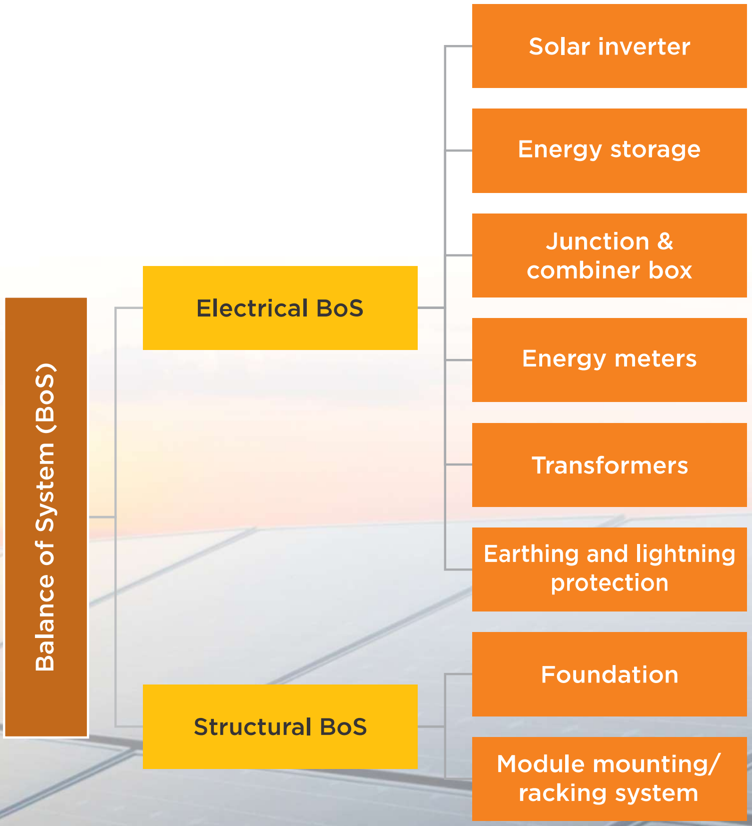


Figure 46: Balance of System

According to IEA, the major share of the total project cost is contributed by solar PV modules (34%). However, the BoS that include the cost of the inverter, module mounting structure, and electrical components collectively constitute the second highest share of the total project cost, approximately 23%. Consequently, the optimization of BoS is decisive to lower the total project cost or LCOE. Trends in PV BoS improvements have been discussed below.

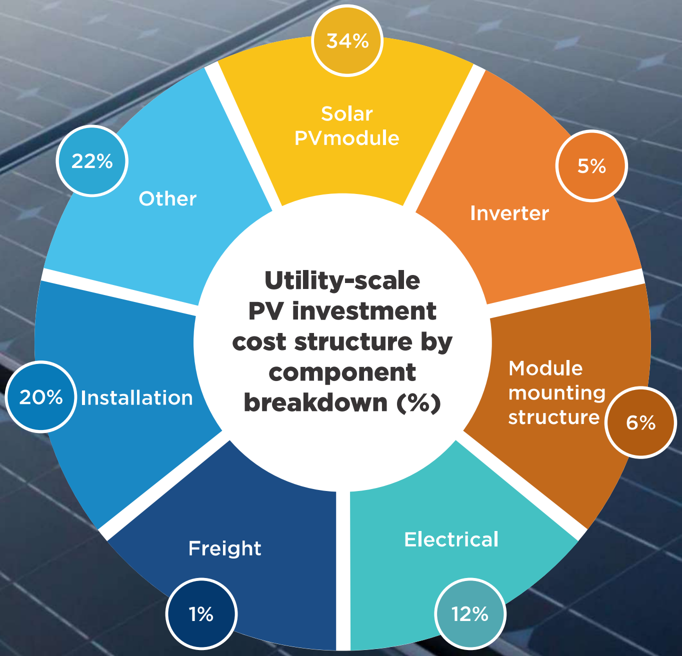


Figure 47: Utility-scale PV investment cost structure by component breakdown (%)

Source: IEA

3.4.1. Solar Inverter

The energy generated by a solar PV module is in the form of direct current (DC), which is supplied to the electricity grid, it needs to be converted into an Alternating Current (AC) signal. This conversion is done by power electronic devices termed solar inverters. PV inverters have varying levels of capacity and functions. A general overview of different system architectures that determines how PV modules are interconnected and how the interface with the grid is established is discussed below.

Central Inverter: PV modules are connected in strings (series connection of modules) leading to an increased system voltage and then the strings are connected in parallel forming a PV array, which is connected to one central inverter. This configuration is mostly employed in very large-scale PV power plants, where the central inverter performs maximum power point (MPP) tracking and converts the DC electric power into 3-phase AC power. Such a centralized configuration, with all the PV modules connected in a single array, offers the lowest specific cost (cost per kW). Notably, this is quite established architecture which means it is reliable enough to work for a couple of decades.

Despite their simplicity and low specific cost, central inverter systems suffer from some disadvantages. High possibility of DC faults, strings unable to match MPP tracking, low flexibility and expandability of the system are some of them. In general, central inverters are used in utility-scale projects, their size varies from 500 kW to 5 MW.

Module Inverter: Module inverters, also called micro-inverters, operate directly on one or several PV modules and have power ratings of several hundreds of watts. The output voltage has to be compatible with the grid, to which they are connected using an AC bus. Micro inverters are very small, and this is because inside they have a high-frequency transformer which is cheaper and smaller compared to the main transformer. Additionally, it provides full galvanic isolation, which enhances the system's flexibility and makes this concept easily expandable.

Though, it exhibits drawbacks that include incompatibility to operation in harsh environments, and the highest specific cost.

Power optimizers: The topology based on power optimizers relies on operations at the single module level where the DC-DC conversion, optimization of power output by MPPT, is achieved at the module level and DC-AC conversion for many of the power optimizers is performed by a single inverter. It is especially flexible for roofs in urban environments and expandable to a certain extent.

This topology needs a sturdy embodiment for the power optimizers to be mounted and operated safely at the back of each module. In addition, newer bifacial modules, which promise higher current levels, might not be supported by current technology.

String inverter: String inverters combine the advantages of central and module-integrated concepts with little trade-offs. PV modules are connected in series to form a string, like for the central inverter concept, with a power rating of up to 6 or 7 kWp in 1-phase configurations. String inverters are usually installed in households or office buildings.

In this installation concept, the input DC voltage will be high that demands special consideration in the protection of the system with emphasis on DC cabling and safety.

Multi-string inverter: The multi-string inverter architecture is a hybrid between central and string inverters. an optimizer box is attached to every string, and it contains an MPP tracker and a DC-DC converter. The DC to AC conversion, instead, is shifted to a power electronic unit just next to the grid, so all the string optimizer boxes are connected in parallel to each other and then to the central inverter. So, the main advantages of this architecture are that every string can operate at its MPP and the optimizers operate at voltages close to the voltage of the string, hence, the DC-DC conversion is very efficient and the optimizers consume very little power. In this architecture, the addition of strings is easy compared to the other installation topologies. Multi-string inverters are present in the market from the range of 5 kW to 250 kW.

Solar PV inverters are composed of many individual power electronic components, housed in an enclosure typically made of metal, along with thermal management systems (i.e., wiring, thermostat, and fan). Inverters' power electronics primarily consist of semiconductors and power circuits, power blocks (or power modules) and passive components such as capacitors and inductors. They also consist of various circuit breakers and fuses for equipment protection. According to NREL, semiconductor components (48%) cater to the major share of the cost followed by electronic components (30%).

Insights and Trends

According to Fraunhofer Photovoltaics Report, 2023, string and multi-string inverters (64.4%), and central inverters (33.7%) dominate the market. Solar inverter efficiencies have steadily increased from 2010-2020. As per NREL modelling assumptions, solar inverter efficiencies have increased from 94-95% in 2010 to ~98% in 2020. These efficiencies vary slightly based on inverter types, but in general show the trend of gradual technology improvement as reduction of LCOE became a key aspect of solar equipment in general rather than just the modules themselves.

Solar inverters are also seeing an increased trend in digitalization. Inverters with IoT capabilities are capable of monitoring near real-time data to provide electricity generation statistics to plant operators. The development of digitally connected microinverters allows for more granular module-level data gathering, allowing for clear identification of faults as and when they arise.

Solar PV plants usually have excess DC capacity in their system relative to the AC output of the inverters. This DC/AC ratio is known as the inverter loading ratio. The output of a solar PV system is dependent on the availability of the sun. Since the output of panels may only reach peak DC capacity a few hours out of the year, it may not be cost-effective to size an inverter to capture that full output. Additionally, PV output varies over its lifetime due to performance degradation, and this may also be accounted for while sizing inverters. In recent years, the upper bounds for inverter loading ratios have steadily increased, reaching up to 1.5, as decreasing module costs have made increasing DC capacity more cost-effective, and plant sizes have increased and allowed for higher inverter ratios.

A major component of solar inverters, for efficient power conversion, is the power conversion device. For power electronics, we have silicon, Silicon Carbide (SiC) and Gallium Nitride (GaN) based power devices. GaN has superior electron mobility and bandgap than SiC and Si and has other advantages over SiC and Si-based solar inverters. Although still in the research phase, GaN-based inverters offer superior characteristics like low conduction losses, high switching rates, and better power efficiency, when compared with SiC and Si-based inverters. Moreover, with the introduction of GaN, there is a further possibility of inverter size and weight reduction, ultimately leading to lower material consumption and costs, as well as lighter products. The variation in the cost of various inverters is illustrated in Figure 48.

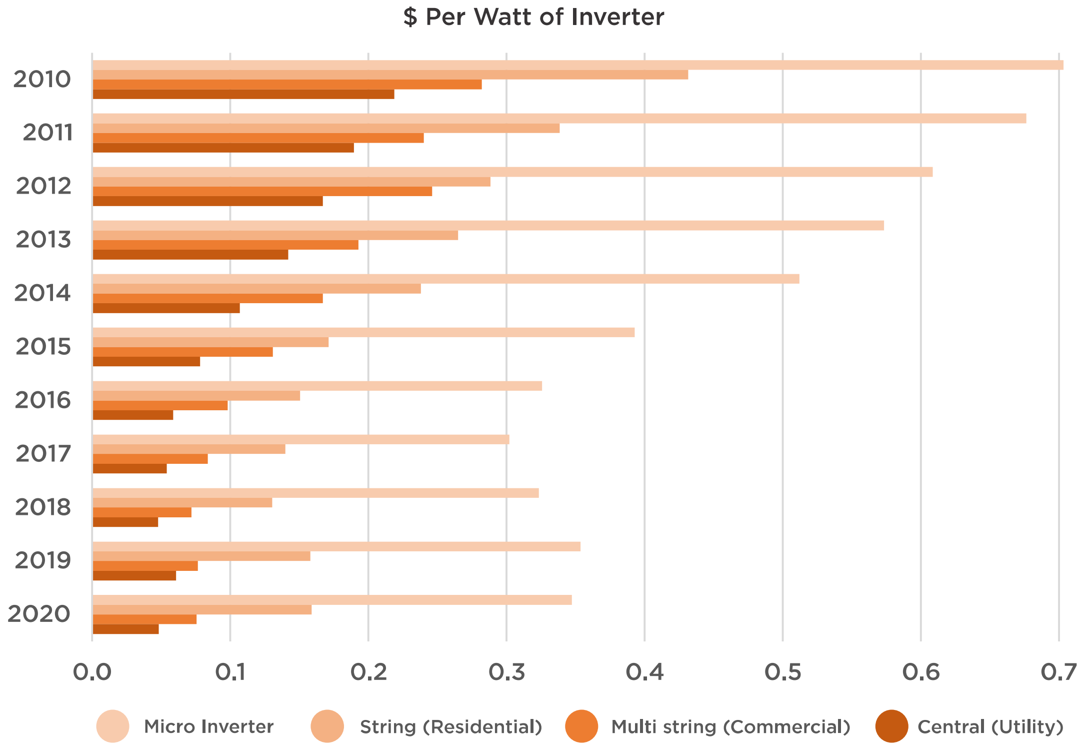


Figure 48: Cost of Inverter ($/W)

Source: U.S Inverter Pricing by Sector

As can be seen in the above figure, there has been a steady reduction in inverter costs across all types (Micro, String, Multi-String, and Central) over the past decade. As the costs are mainly driven by the inverter capacities, it can also be noted that larger inverters, manufactured on a kW or an MW scale for solar utility plants have the cheapest per-watt production rate, when compared to microinverters.

3.4.2. Module Mounting System/Racking

A solar PV mounting, or racking system helps safely affix PV panels to the surface on which they are to be installed. Racking systems thus vary based on where the plant must be deployed (usually on rooftops or the ground). Module mounting system encompasses structures, module rail, foundation and fasteners which should also ideally provide room for air circulation underneath to ensure that panels stay cool. The equipment is usually made with galvanized or stainless steel, or aluminium to protect it from corrosion.

Racking systems must consider the surface characteristics of where the PV system is to be installed. Rooftop systems may be mounted through penetrating fixtures for slanted rooftops, whereas flat rooftops may allow for ballasted systems that do not need to pierce the underlying roof. While in a ground-mounted system, the characteristics of land or soil must be considered at the time of design of the mounting structure, the foundation in particular. The racking system must also be weather resistant, which translates to having sufficient galvanization depth to withstand rain and other elements. BIPV and vertical solar installations on the sides of buildings are innovative forms of mounting solar PV in urban locations. The cost of various racking systems is plotted in Figure 49.

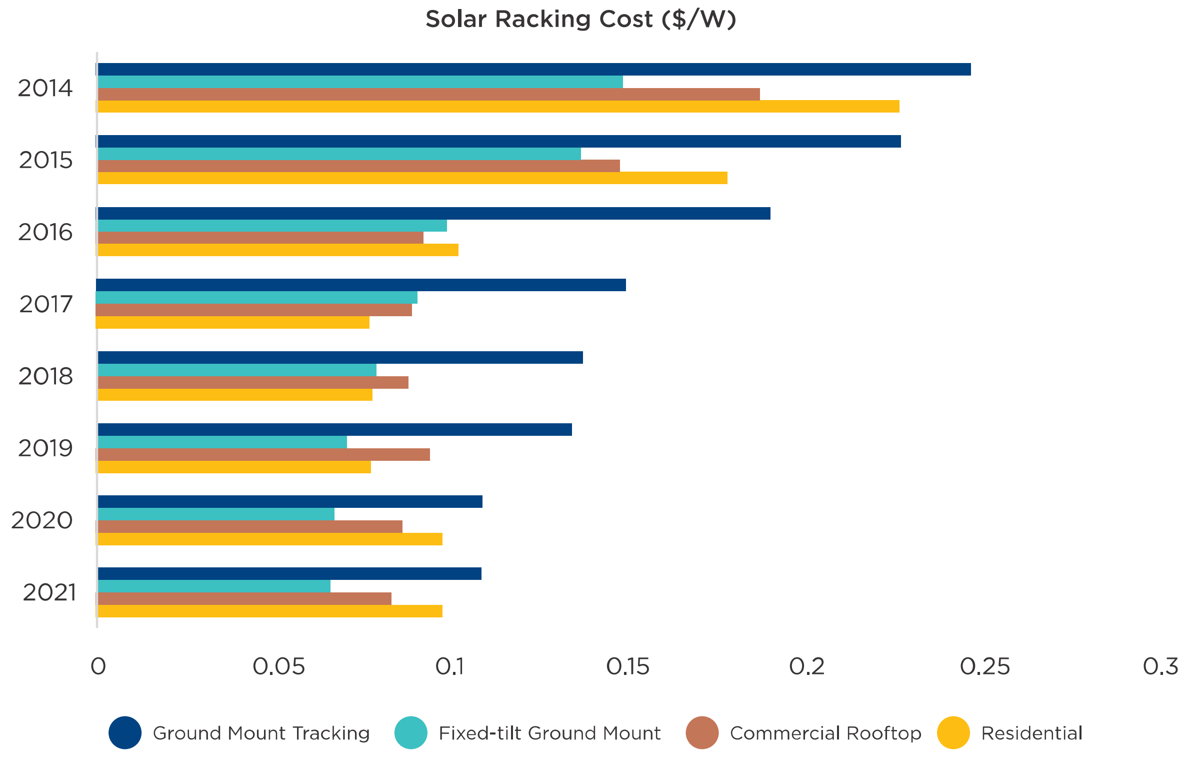


Figure 49: Solar Racking Cost ($/W)

Source: NREL Solar Photovoltaic Supply Chain Deep Dive

According to NREL, racking costs for the USA have reduced steadily over the past 7-8 years, and the cost differential between tracking and fixed tilt racking systems for major segments (Ground Mounted, Commercial, and Residential). Cost reductions of 50-60% have been seen for all racking types.

Mechanical Solar Trackers

Mechanical solar trackers or solar PV trackers are used to follow the Sun’s path and orient modules towards the sunlight to maximize energy production per module. Major components of the tracking system include torque tube bearings, drive motor, structure, foundation, and electronics components. Mechanical tracking systems are broadly divided into single-axis and dual-axis systems. For flat-panel photovoltaic systems, trackers are used to minimize the angle of incidence between the incident sunlight and a PV panel. The primary benefit of a tracking system is therefore that the solar panel is continually tilted at an optimal angle, thereby maximizing the incident irradiance.

Single-axis tracker, as the name implies, has one rotational axis, so one degree of freedom. The tracking system consists of an electric motor, controlled by a computer system that changes the tilt of the panel. The computer uses an algorithm, that requires the coordinates of the location and the day and the time, to compute the position of the sun. This sort of system is called a daily or vertical tracking system because the axis of rotation is aligned vertically concerning the ground. The electric motor can therefore tilt the panels during the day, such that they track the sun as it moves from East to West. Another option is when the axis of rotation is horizontal with concerning ground. When the axis is horizontal, the azimuth is kept constant and the module tilt angle is varied during the year, rather than during the day. These systems are called horizontal tracking systems and they adjust their position according to the altitude of the sun during the year. Unlike the vertical tracking system, the electric load is much lower because the rotation cycle lasts an entire year. Note that in both cases it is very important to consider the shading, to avoid unnecessary energy loss.

Dual axis approach with two degrees of freedom. The first rotational axis is parallel to the ground and changes only the tilt angle. The second axis is perpendicular to the ground and the other axis, which allows for a change in the azimuth of the panel. The dual-axis approach is often used for PV modules with solar concentrators that require the direct component of sunlight. The dual-axis approach always makes sure that the direction normal to the panel is aimed at the direct component of light. The trackers are further classified into two: centralized – moving multiple rows with a single motor and decentralized – individual motors are used to drive single or multiple rows. The cost implication of different components on the total cost of the tracking system is demonstrated in the Figure 50 below.

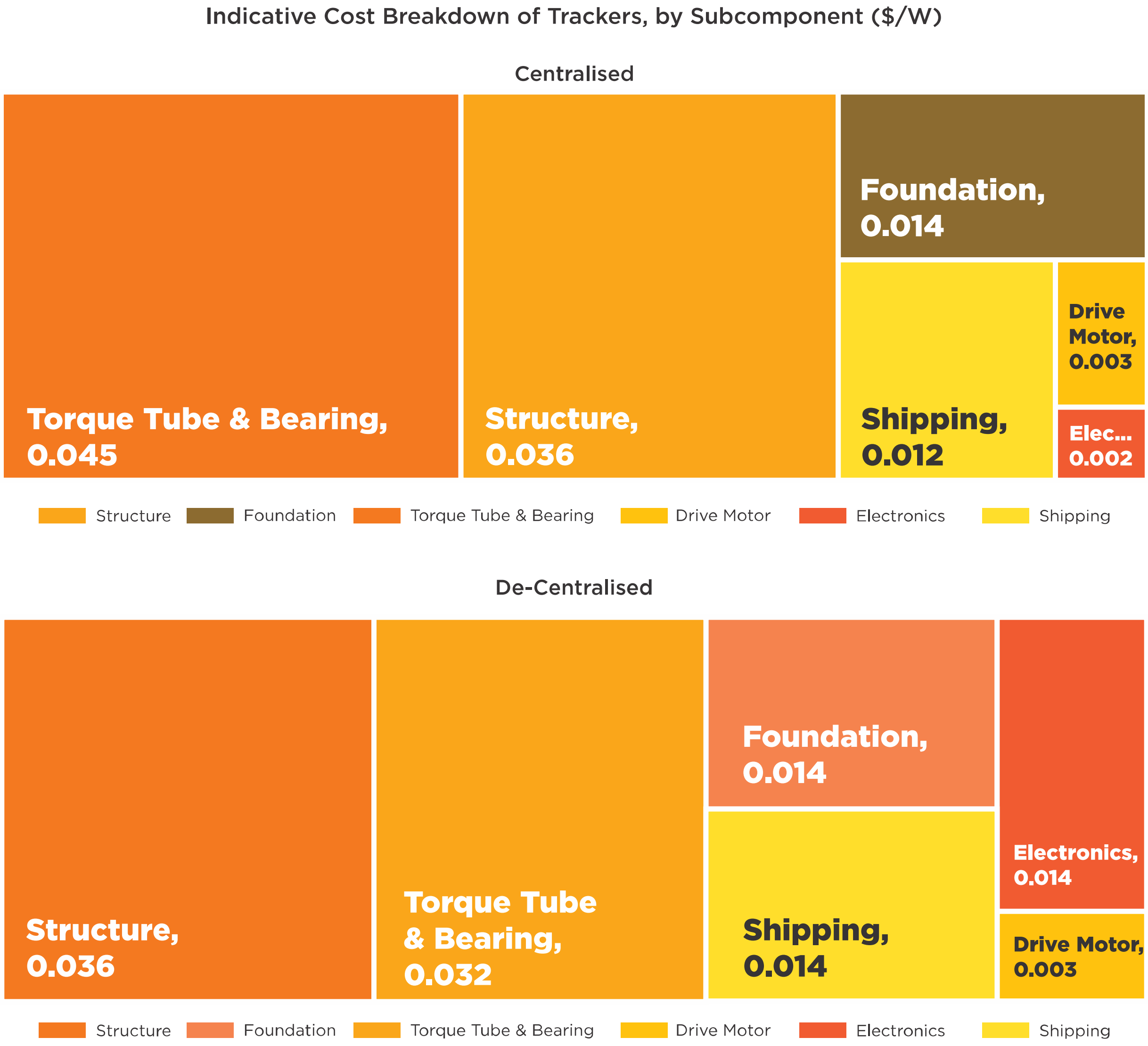


Figure 50: Indicative Cost Breakdown of Trackers, by Subcomponent ($/W)

Source: RINA Tech and Array Technologies 2020; NREL 2021

Centralized tracker configurations possess torque tube and bearing costs, but they save on fewer pieces of redundant electronic equipment, unlike decentralized ones.

Since solar trackers consist of moving machinery, this requires more material than fixed mounting systems, as well as more land use and higher operation and maintenance (O&M) costs. They are typically more expensive than fixed mounting systems. However, this premium is often outweighed by the increase in energy production. Tracking systems are thus being increasingly deployed in utility-scale solar PV projects. Although trackers were once traditionally installed in locations with high solar irradiance, their potential yield increase is making them a viable option in less sunny places as well. The tracker system also helps flatten the generation curve of solar power by optimizing generation from the plant, a relevant quality considering the potential grid integration challenges associated with a high share of solar in the future.

As solar PV costs continue to get optimized, several trends have emerged in the tracker industry to help improve their product offerings. Software components such as tracking algorithms are utilized to help optimize generation. This tracking software is primarily based on astronomical data, but recent tracking software includes more advanced smart algorithms. Additionally, a small portion of manufacturers have begun to offer Artificial Intelligence (AI) optimized tracker control. Such AI trackers can allow for optimal tracking under different weather conditions, such as partly cloudy and overcast weather, and can also consider inverter loading ratios and the use of bifacial modules to help maximize generation. As per BNEF, with the improvement in technology, as well as the growing demand, it is important to note that the cost of single-axis tracking systems has shown a 42.9% decrease in costs, from 2016 to 2022.

Another key trend for trackers has been the need to ensure tracker endurance and survivability in harsh conditions considering the number of moving elements involved when compared to rigid racking systems. Tracker material is designed to be resistant to harsh weather conditions, including protection from sand and rain. Additionally, trackers can be set in a stow position to avoid damage during extreme wind conditions. Major manufacturers may also opt to undergo wind tunnel testing to ensure their trackers are robust.

3.4.3. Batteries

There is a great need for energy storage at both small and large scales to tackle the intermittency of renewable energy sources. In the case of PV systems, the intermittency of the source is of two kinds - diurnal fluctuations, the difference of irradiance during the 24 hours: and seasonal fluctuations, the difference of the irradiance across the summer and winter months. There are several technological options to fulfil the storage requirements. For solar applications, depending on the scale of implementation, we need a high energy density, and a reasonably high-power density. For short-term to medium-term storage, the most common kind of storage in use is of course the batteries. They have just the right energy density and power density to meet the daily storage demand in the PV system. However, the seasonal storage problem at large scales is yet to be solved convincingly. The Figure 51 demonstrates various storage technologies available.

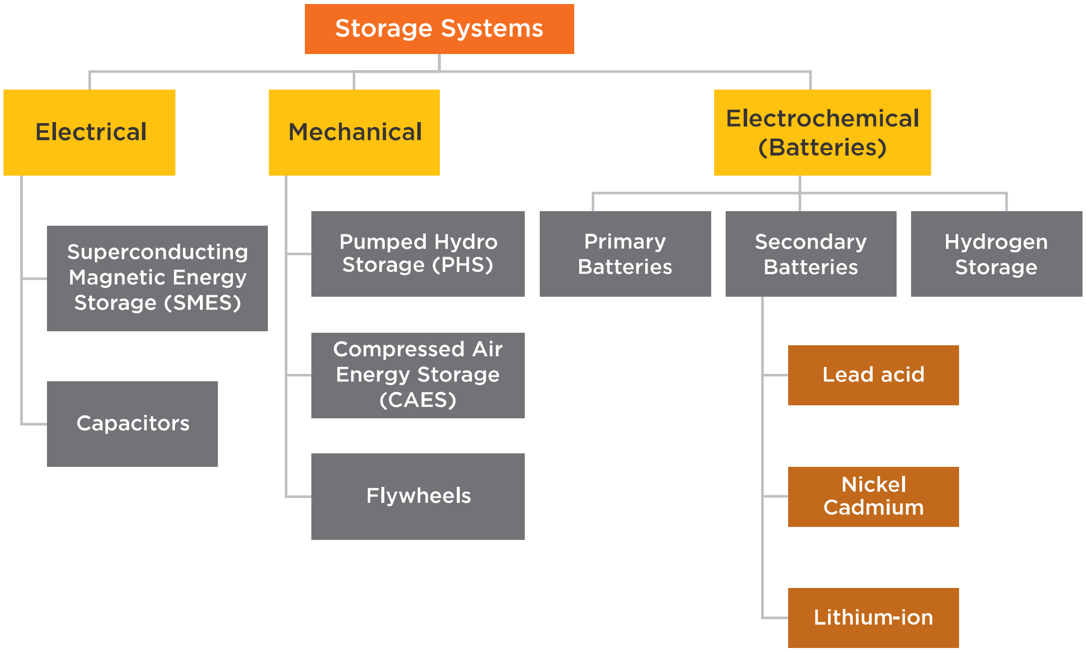


Figure 51: Energy Storage Technologies

Technologies such as a mechanical flywheel, and supercapacitors are often used in areas which require faster backups, such as for uninterrupted power supply units; whereas batteries, compressed air energy storage (CAES), pumped hydro storage (PHS), Green Hydrogen etc., may be used for higher capacity energy storage for longer durations. PHS and CAES technologies are typically used to provide bulk power management since they both can discharge for up to tens of hours economically. While many technologies exist for the storage of energy, PHS and Battery Energy Storage Systems (BESS) are the ones which are widely deployed. Energy storage in the form of green hydrogen is also an upcoming technology being researched.

According to IEA, with a total installed capacity of 160 GW in 2021, pumped-storage hydropower is still the most widely deployed grid-scale storage technology today. Most of these plants are used to provide daily balancing. Although the installed capacity of grid-scale battery energy storage systems is far smaller than pumped hydro energy storage, grid batteries are projected to account for most of the storage growth worldwide with a five-folded increase in the installed capacity batteries as of 2021.

For now, batteries still seem to be the most reliable option for PV systems on the small to medium scale. The ease of implementation and efficiency of the batteries is still unbeatable when compared to other technologies, like pumped hydro, compressed air energy storage, conversion to hydrogen and converting back into electricity, and others.

Batteries are electrochemical devices that convert chemical energy into electrical energy in which the secondary batteries, rechargeable batteries, are at the center stage, being suitable for integration with solar PV systems. Among the several kinds of secondary battery technologies available, lithium-ion technology is prominent. Lithium-ion technology is being heavily researched currently as a storage alternative in various applications. Their high energy density has already made them a favourite in lightweight storage applications, even though the high cost. The cost variation of lithium-ion batteries for the last decade is illustrated in Figure 52.

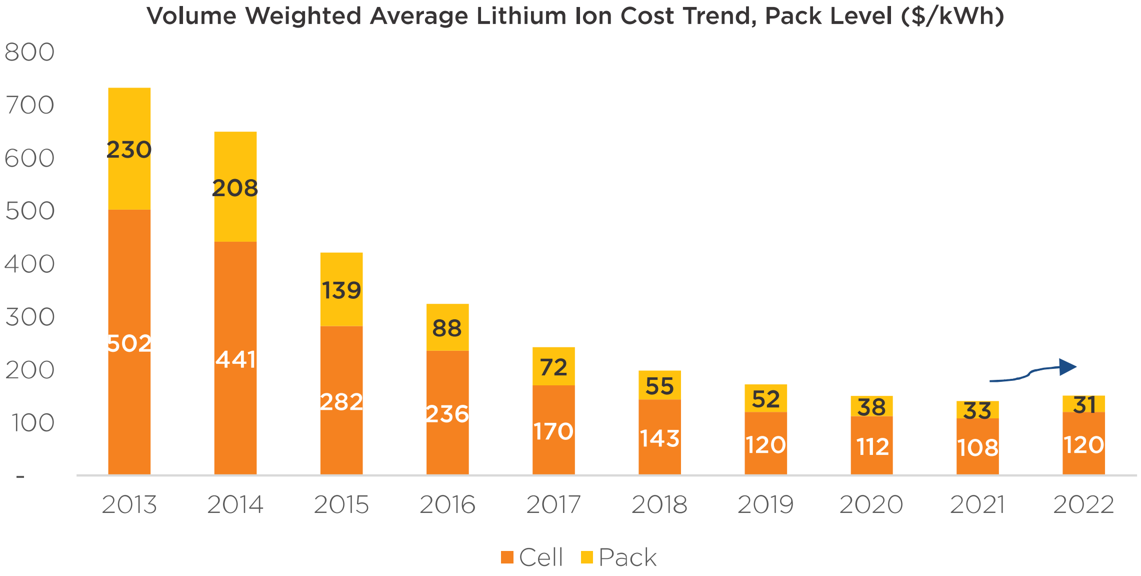


Figure 52: Volume Weighted Average Lithium Ion Cost Trend, Pack Level ($/kWh)

Source: BNEF

The cost of lithium-ion batteries is on a down track from 2013 to 2021 witnessing a total reduction of 80.7% in the total cost at pack level. Nevertheless, in 2022, the cost slightly moderated to 151 $/kWh with a 7% increase from the cost of 2021. BNEF projects the average battery pack prices to remain elevated at the end of 2023 at $152/kWh due to a predicted increase in the While prices for key battery metals like lithium, nickel and cobalt.

The use of batteries is more common in stand-alone PV systems in the residential sector, and it can help through blackouts and other grid instabilities. On a larger scale, a battery energy storage system (BESS) is installed directly with the distribution or transmission network primarily to manage the variation in load demand and is termed a utility-scale BESS. BESS is interconnected with the existing utility network, and it will deliver power and energy to the network as per the demand along with providing different ancillary services. BESS are increasingly being utilized to store the energy generated from solar PV system, being an intermittent energy resource, to ensure the round-the-clock supply and to maintain the stability of the grid. While renewable energy is taking a shift from a secondary source of energy to slowly aiming to become a primary source of energy, the role of energy storage is also taking center stage.

Battery electricity storage systems are developing rapidly with falling costs and improving performance. By 2030, the installed costs of battery storage systems could fall by 50-66%. As a result, the costs of storage to support ancillary services, including frequency response or capacity reserve, will be dramatically lower. This, in turn, is sure to open new economic opportunities. Battery storage technology is multifaceted. While lithium-ion batteries have garnered the most attention so far, other types are becoming more and more cost-effective. The applications for battery energy storage can widely be divided into three categories- Consumer Electronics, Stationary Energy Storage and Electric Vehicles. The current installed capacity of the battery and the projected demand by 2050 are shown in Figure 53.

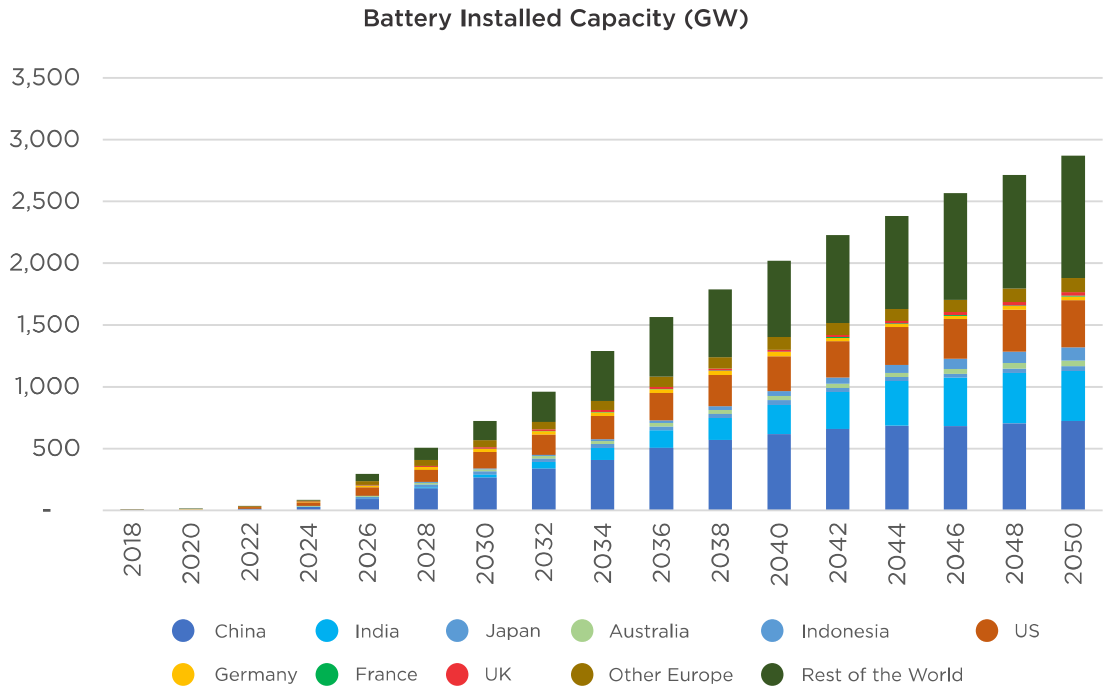


Figure 53: Projected Installed Capacity of Battery

Source: BNEF New Energy Outlook 2022

As can be seen in the Figure, global battery demand is expected to grow from 36 GW in 2022 to 722 GW in 2030 and to 2871 GW in 2050, driven significantly by electric transportation demand.

3.5. Solar PV Systems

The various solar equipment highlighted in previous sections come together to form a complete solar PV system. According to the components used and application the solar PV system can be classified as given in Figure 54.

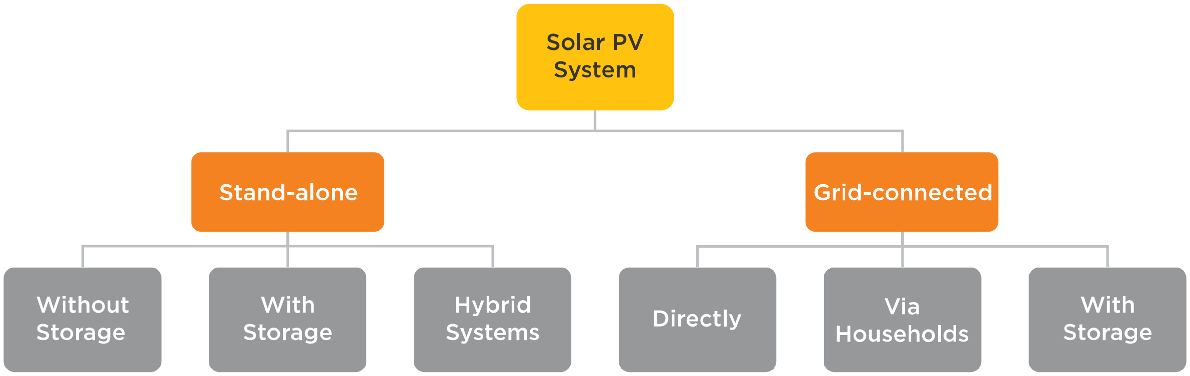


Figure 54: Classification of Solar PV System

Furthermore, based on key differing needs, the system can be categorized as a residential (which also meant to include commercial buildings), industrial, utility. All configurations of a stand-alone system are popular in the residential sector along with the grid-connected system which is connected via households. In utility-scale applications, a grid-connected system, connected either directly or with storage, is popular, whereas all types of systems are popular in the case of industrial applications.

Although component-level improvements drive increases in generation and efficiency, system-level decisions also play a role in optimizing output. Additionally, land requirements for large utility-scale projects may also raise concerns with other land-intensive applications such as agriculture.

Material Consumption

Solar PV plants are relatively lighter on material usage than the other major alternative renewable energy source such as wind energy. Both offshore and onshore wind require significant usage of concrete, steel, and other materials. Solar is unique in the fact that glass (33%) is the primary material by weight used in a solar plant installation of a capacity of 1 MW. The detailed material composition is shown in Figure 55.

Glass is closely followed by steel (27%) usage for various BoS structures and concrete for foundational structures. Material consumption for solar installations is expected to decline as solar plant designs and processes continue to improve.

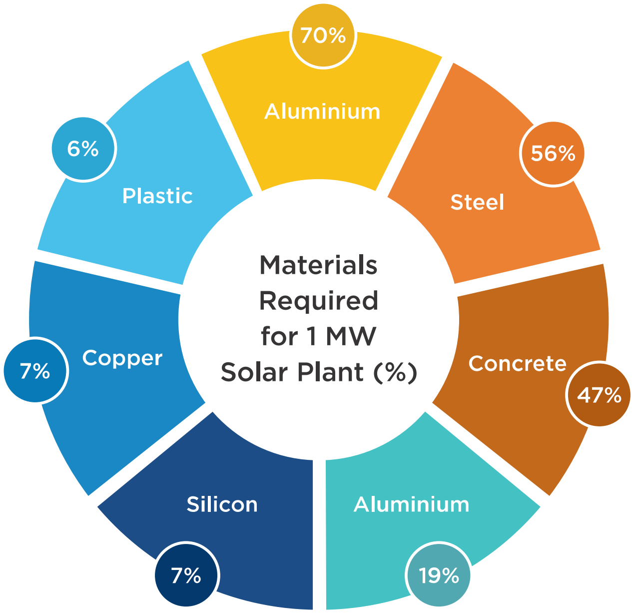


Figure 55: Materials Required for 1 MW Solar Plant (%)

Source: Materials Required for 1 MW Solar Plant (%)

Land Use

Utility-scale solar projects usually require large, relatively flat, continuous areas of land for effective development. Thus, considering the scale-up in solar deployment and continued growth expected in coming years, there is potential for significant land use requirements for solar energy. An analysis of land use requirements for various solar technologies was conducted by NREL, considering both direct land use due to module area, roads, and other infrastructure; and total land use which consisted of all land within the site boundary. This analysis found that total land-use requirements for solar power plants vary widely across tracking concepts which are given below in Table 2.

Table 2: Land Use Requirement for Solar Power Plant

Technology	Direct Area		Total Area	
	Capacity weighted average land use (acres/MWac)	Generation weighted average land use (acres/GWh/yr)	Capacity weighted average land use (acres/MWac)	Generation weighted average land use (acres/GWh/yr)
Small PV (>1 MW, <20 MW)	**5.9**	**3.1**	**8.3**	**4.1**
Fixed	5.5	3.2	7.6	4.4
1-axis	6.3	2.9	8.7	3.8
2-axis flat panel	9.4	4.1	13	5.5
Large PV (>20 MW)	**7.2**	**3.1**	**7.9**	**3.4**
Fixed	5.8	2.8	7.5	3.7
1-axis	9	3.5	8.3	3.3

Source: NREL Land-Use Requirements for Solar Power Plants in the United States

Discussions over solar land use are driven by the concern that rapidly increasing solar capacity in coming years will result in disruption of agricultural activity and encroachment on prime agricultural land. To address these potential land use challenges, the use of barren or uncultivable land to develop solar power projects may be considered. This can include built environments, salt-affected land, contaminated land such as former industrial sites with potential for remnants of pollution, desert land and other uncultivable terrain etc.

Additionally, estimates for solar project land usage make it apparent that the scale of land required is less than one might expect when put into context. Estimates by Carbon Brief show that total current and projected solar project land usage in the UK would amount to under 700 square kilometers, which is a little over half of the ~1250 square kilometers used for golf courses in the region. Solar projects may hold benefits that allow them to coexist with agriculture. Solar can be utilized by farmers to replace fossil fuel powered water pumps and other equipment and can also serve as an alternative revenue stream or source for self-consumption of electricity. Additionally, the development of agri-voltaics as a solar application has further opened the possibilities of integration between solar and agriculture for mutual benefit.

Life Cycle Carbon Emission and Payback Time

The US Department of Energy estimates Lifecycle greenhouse gas emissions for solar power) to range between 20 - 100 gCO_2e/kWh. Their analysis also found the maximum value to be around 250 gCO_2e/kWh, although this is a clear outlier figure. The wide range of figures can be attributed to variance due to the different locations of PV plants studied, which results in different yearly irradiation of the PV systems, which can vary by a factor of two. As per NREL Lifecycle Greenhouse Gas Emission estimates, Solar PV has a median lifecycle GHG 10 emissions of under 30 gCO_2e/kWh. Emissions for 1 kWh electricity from a 3 kWp residential system in Europe have been modelled for 4 cell types and found to be clearly under 50 gCO_2 eq.

The energy payback time for solar PV systems in Europe and China is given in Figure 56.

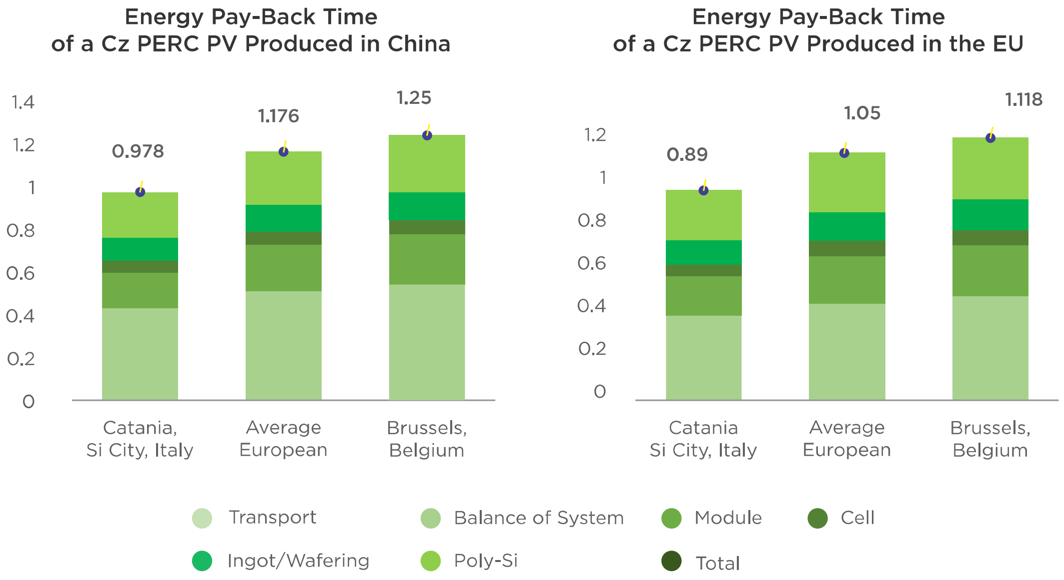


Figure 56: Energy Payback Time

Source: Fraunhofer 2021

The energy payback time for solar PV systems in Europe ranges from 11 months to ~1.1 years whereas in China it ranges from just under 1 year to 1.25 years.

In addition, tracker usage and plant design can be optimized to achieve the desired generation curve. It is important to recognize that the suitability of tracker systems and alternative panel orientations in achieving cost optimization is dependent on several factors. Thus, it is not simply enough to deploy trackers on any PV system and expect a reduction in LCOE. Single and double-axis trackers can maximize additional PV yield in locations with cheap land and high irradiance. East-West facing systems are land-use efficient, and this is relevant in areas with high land costs. Additionally, the flattened daily profile of the East-West orientation is well suited to locations or load patterns where early and late generation is valued highly. Vertically mounted plants may be used alongside fencing in solar plants and may also serve well in areas further from the equator.

LCOE and Auction Value Trends

Average solar PV LCOE has declined 88% since 2010, falling from 0.417 $/kWh in 2010 to 0.05 $/kWh in 2022. The LCOE in 2022 slightly moderated from the previous year's value of 0.048 $/kWh. The trends in LCOE and auction value is illustrated in Figure 57.

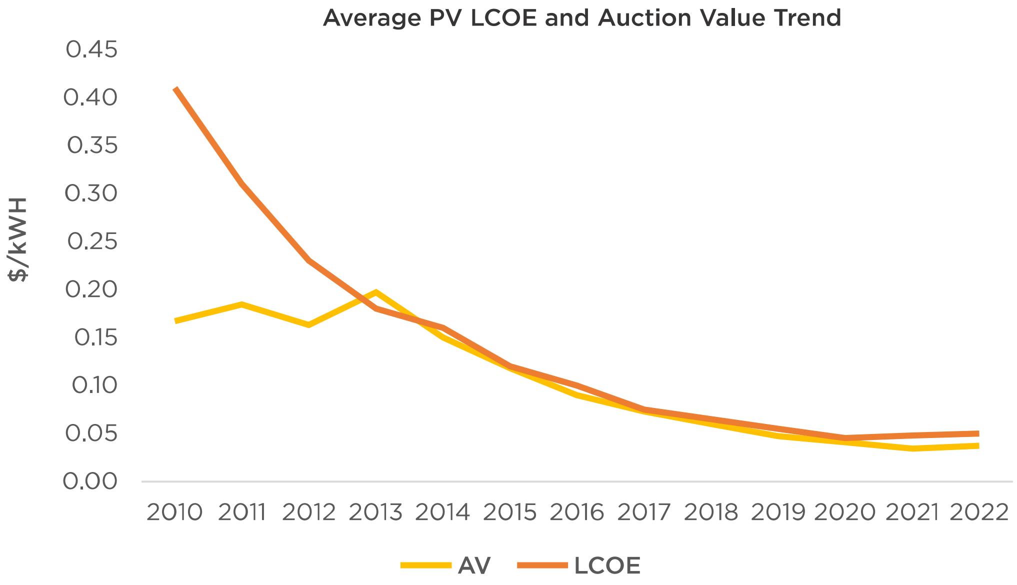


Figure 57: Average PV LCOE and Auction Value Trend

Source: IEA, PV Magazine, NREL, ISA Analysis

Alongside LCOE reductions, auction values have fallen as well, coming down to 0.034 $/kWh in 2022 from 0.17 $/kWh in 2010. These reductions underline solar PV status as an affordable renewable energy technology.

According to IRENA, the significant decline in solar PV LCOE has been largely driven by reductions in module cost, which account for around 45% of the decline. Other major drivers for cost reduction include reduction in soft costs (14%), Installation/EPC/Development costs (12%) and Inverter costs (9%). The fall in LCOE and auction values of solar PV has left them well below electricity prices in major countries, as demonstrated in Figure 58, further emphasizing the affordability of solar power.

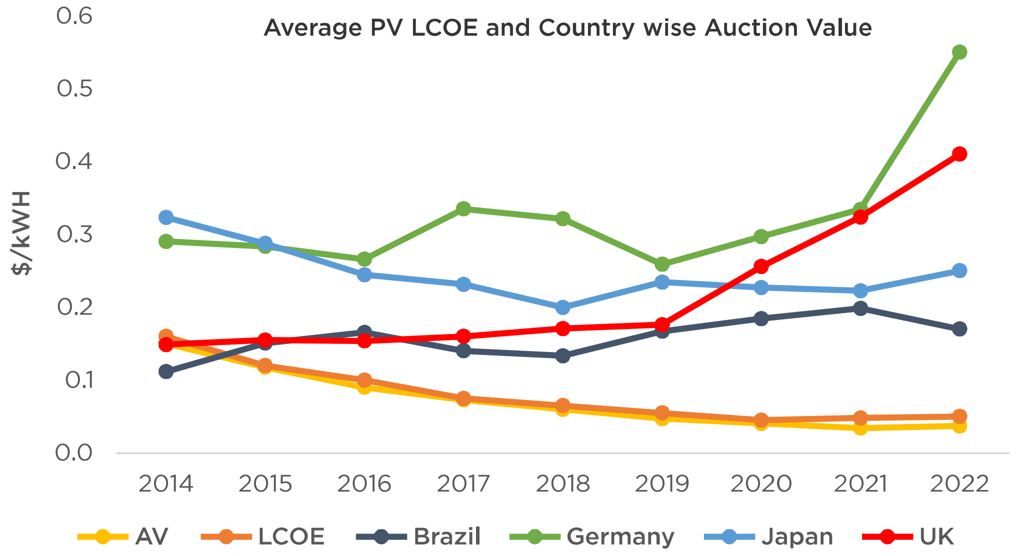
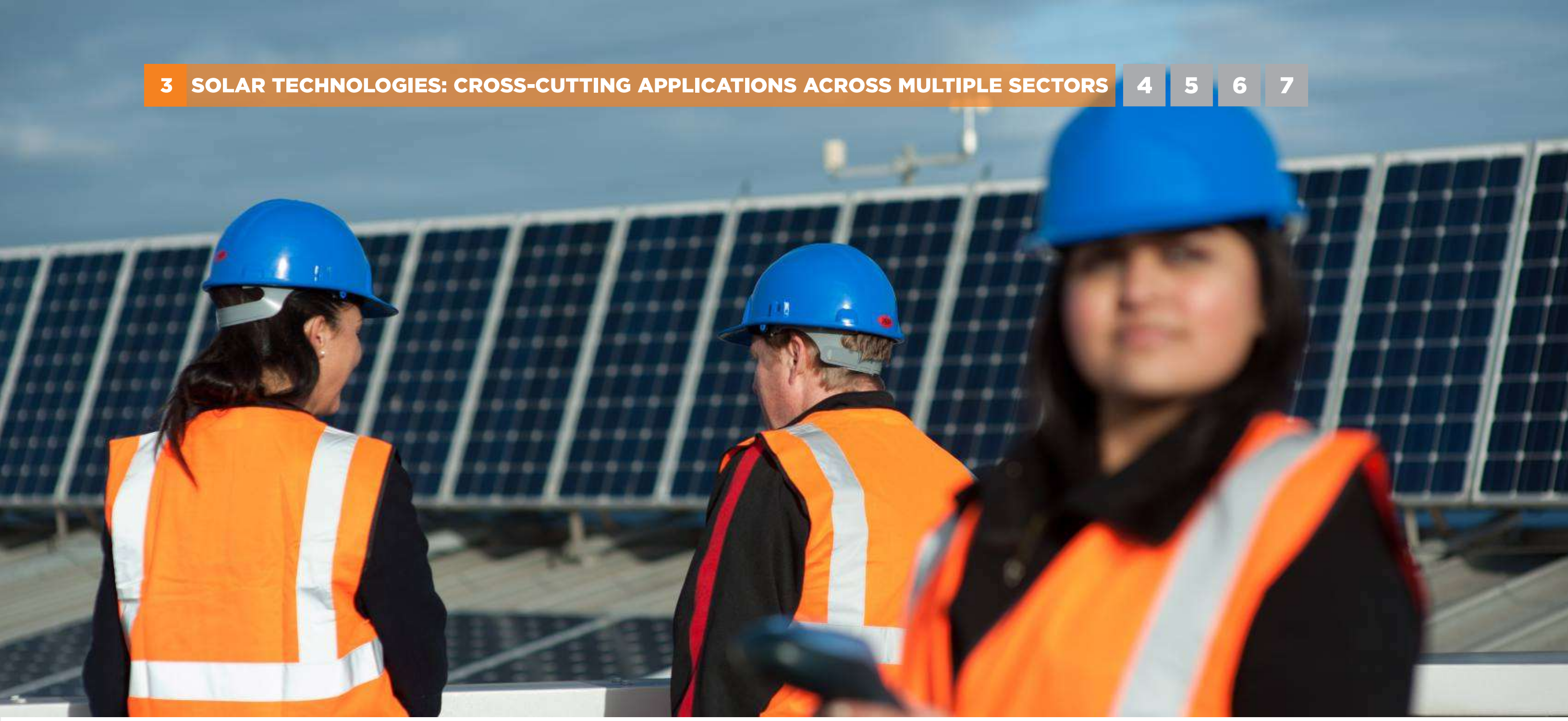


Figure 58: Average PV LCOE and Country wise Auction Value

Source: IEA, PV Magazine, NREL, ISA Analysis



3.6. Solar PV Plant Design

Consider the three key segments in which Solar PV systems are deployed, residential systems, industrial, and utility-scale systems. Significant variations exist across segments due to site characteristics, customer priorities, financial capabilities, installation size and other BoS considerations. Thus, PV plant design trends for each segment should be considered individually. As highlighted in the above chapters, renewable energy installations have been growing year on year since 2001, reaching a cumulative installed capacity of 6533.5 GW in 2022. Solar PV itself has shown a growth of more than twenty-fold, in the last decade, reaching an installed capacity of 1055 GW, in 2022 which is deployed in the three segments mentioned below.

3.6.1. Residential Segment

The residential sector has also seen a drop in the capex over the last decade. Figure 59 display the trend in residential capex.

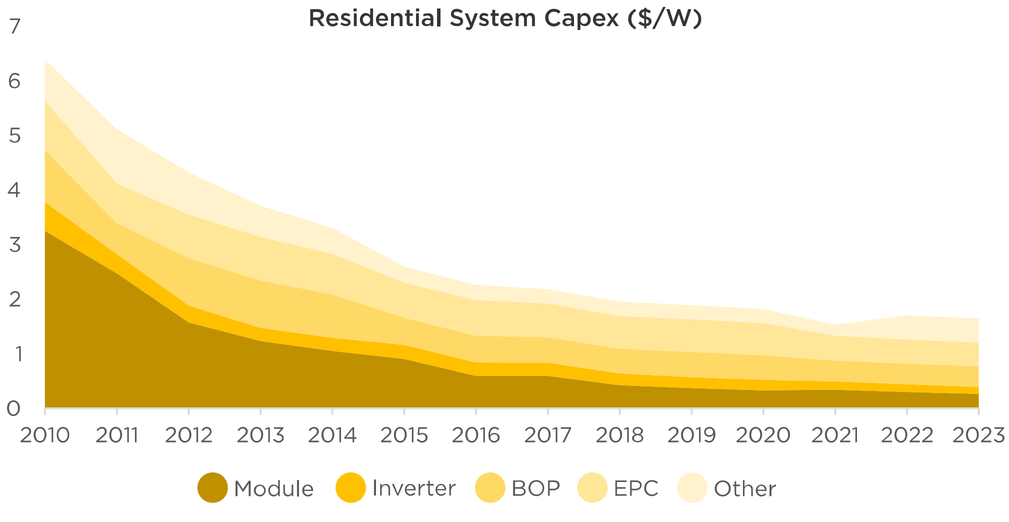


Figure 59: Residential System Capex ($/W)

Source: BNEF - 2Q 2023 Global PV Market Outlook On Track for Net Zero

This reduction in capex, from 6.39 $/W in 2010 to 1.64 $/W in 2023, a roughly 75% decrease, has primarily been driven by falling module costs, although more modest reductions have also been seen in other areas. Module costs accounted for the largest share of capex costs in 2010, but EPC and Balance of Plant components now account for the biggest share of capex costs.

It is important to recognize that capex estimates may vary significantly across different regions depending on supply chain considerations, local regulations and project compliance requirements, cost of labour and materials, taxation policies etc. The variation in residential PV capex is shown in Figure 60.

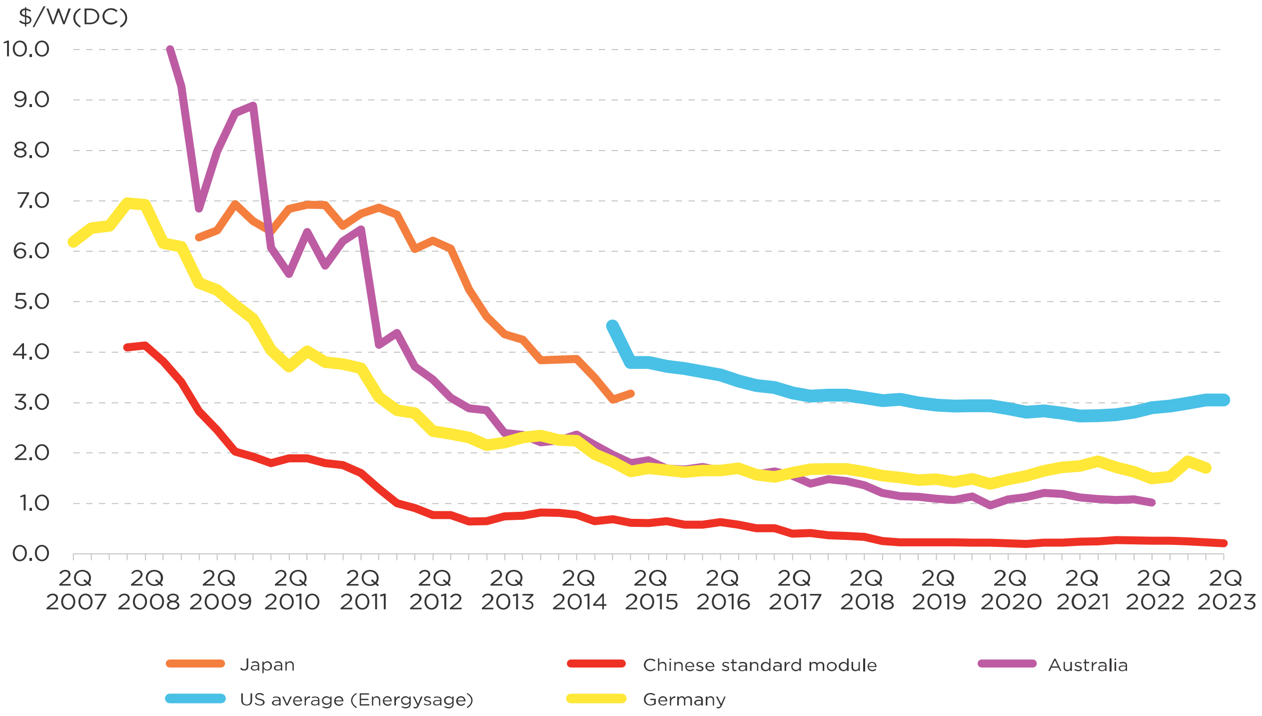


Figure 60: Residential PV Capex Around the World, $/W (DC)

Source: BNEF - 2Q 2023 Global PV Market Outlook on Track for Net Zero

In all the counties selected, residential capex follows a downward track. Notably, China retains the minimal capex among the countries for the last 15 years.

Residential PV systems are typically small-scale projects in the kW range and are often deployed as rooftop solar projects. Due to the limited space available on rooftops, the key consideration for the module selection is high power per unit area to maximize generation in the space available. However, modules used for rooftop solar plants cannot be as large as utility-scale modules due to the partial shading and limited space for installation. The residential deployment also precludes the usage of bifacial modules as there is little gain to be obtained for the system. Similarly, the lack of space on the rooftops prevents the usage of tracker systems in any cost-effective manner.

Depending on the grid connection capabilities in the region, the presence of bi-directional meters, and relevant regulations applicable, net or gross metering regulations may be in place for residential rooftop solar plants that are connected to the grid. Some residential PV plants may also opt for behind-the-meter battery storage to store excess generation and either sell it back to the grid, use it for general captive consumption, or use it for specialized applications requiring significant power, such as EV charging.

Another potential method for residential solar to be incorporated into markets is through Virtual Power Plants (VPPs). The VPP allows for distributed energy sources of various types to be aggregated and considered together for various market interactions, including monitoring, forecasting, and power trading. VPPs can help allow small renewable energy generators, including residential PV owners, to trade on the same markets as utility-scale power plants and industrial consumers.

3.6.2. Commercial & Industrial Segment

The industrial segment possesses lower capex compared to the residential sector. The Figure 61 shows the industrial system capex.

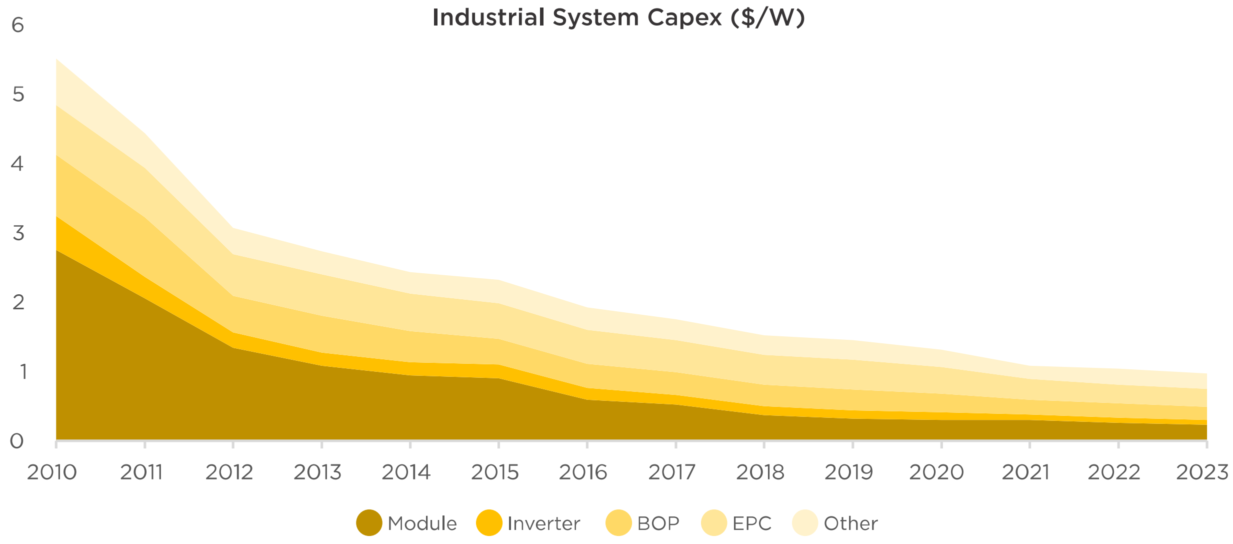


Figure 61: Commercial and Industrial System Capex ($/W)

Source: BNEF - 2Q 2023 Global PV Market Outlook On Track for Net Zero

The fall in Commercial system capex from 5.51 $/W in 2010 to 0.97 $/W in 2023, close to an 82% decrease, has been driven primarily by module costs declining from 2.75 $/W in 2010 to 0.23 $/W in 2023, like the residential sector Capex. However, unlike the residential sector, module and EPC costs are tied for the highest capex share for the sector.

In the case of the size of the system, the industrialsegment falls between residential and utility-scale systems. Systems may be ground-mounted, or rooftop-based, and plant capacities may range from low kW scale to two-digit MW scale. This allows for a wide variety of module types to be considered for installation depending on the site characteristics. For example, industrial sheds may require very lightweight modules, while the availability of flat reflective roofs of significant size or open land may open the door for bifacial modules to be deployed.

industriallocations may often have significant energy requirements and the energy produced by the PV system may be primarily used for self-consumption. Through the deployment of Behind the Meter (BTM) BESS, there is also significant potential for demand charge reduction, critical backup and industrial power quality applications, Time of Day (ToD) energy arbitrage etc.

3.6.3. Utility Segment

The CAPEX of utility also follows a similar trend to the previously discussed segments – residential and industrial and the Figure 62 below demonstrates the same.

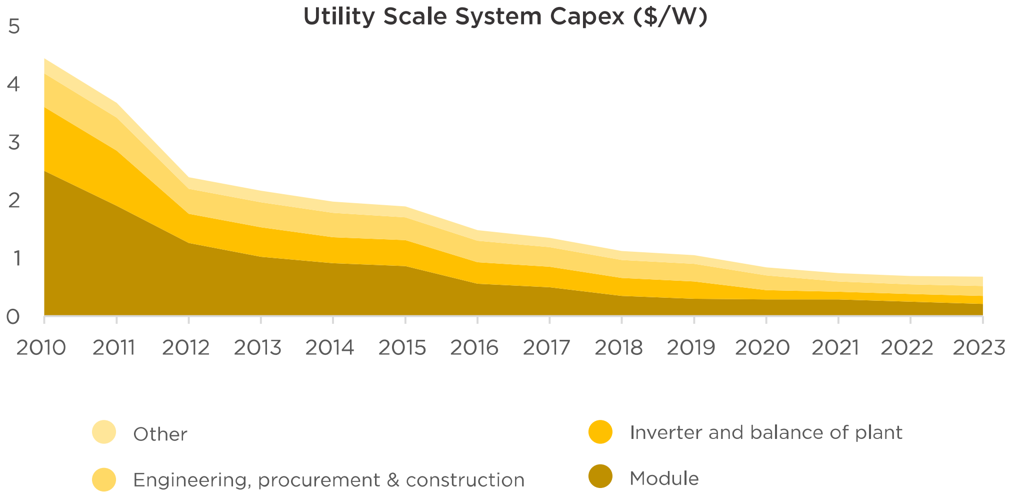


Figure 62: Utility Scale System Capex ($/W)

Source: BNEF - 2Q 2023 Global PV Market Outlook On Track for Net Zero

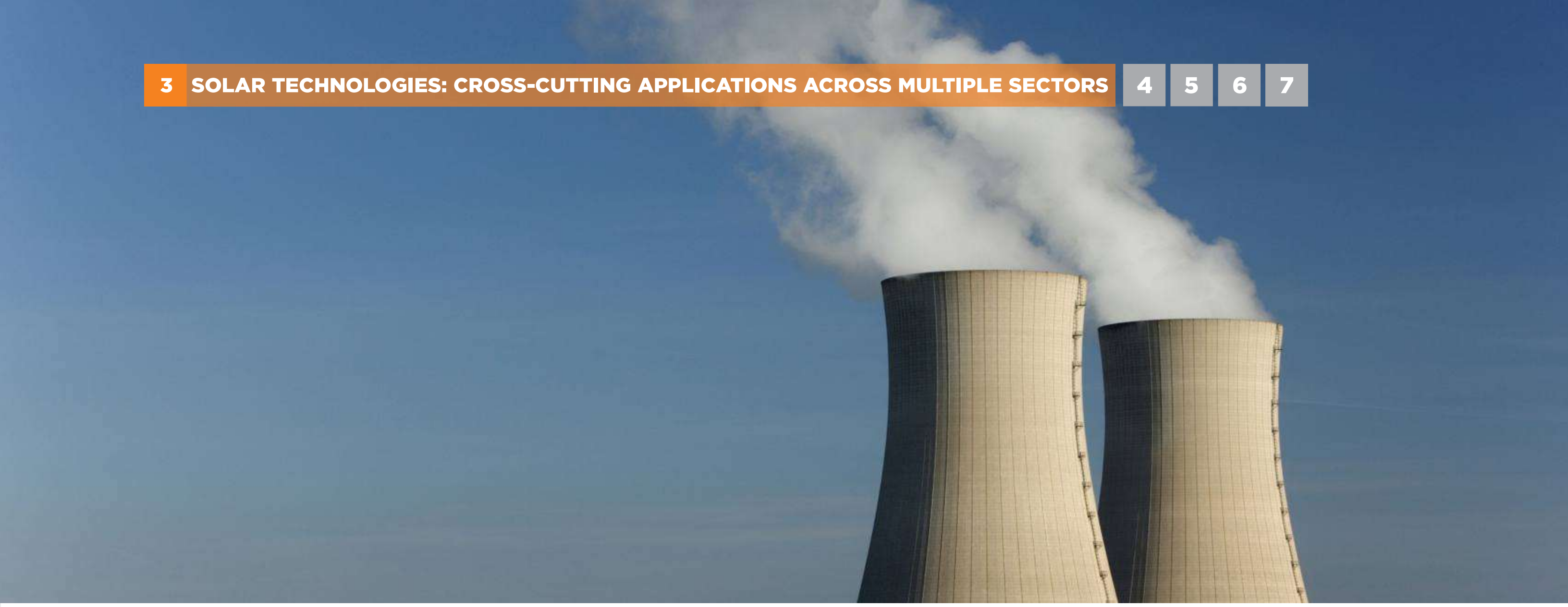
Among the three segments, utility-scale projects possess the minimum Capex. It exhibits a drop from system capex from 4.44 $/W in 2010 to 0.68 $/W in 2023, an 85% decrease, which has also been driven primarily by module costs. Modules are the highest cost component in the capex, followed by EPC costs.

For utility-scale projects that can reach the hundreds of MW or even GW scale, it is important to keep module costs allow. However, recent focus has shifted to the LCOE as the more relevant metric to evaluate a solar plant.

High-power modules can bring down project LCOE as they can optimize EPC and BoS costs. The focus for installations has shifted to the use of monocrystalline silicon technologies due to their superior efficiencies over polycrystalline technologies. The usage of bifacial technology is also helping optimize generation in locations with reflective ground surfaces (high Albedo factor). Additionally, the usage of advanced cell technologies such as TOPCon for utility-scale projects is also seeing traction.

As highlighted above, the optimization of the Balance of System components has become an important method to minimize LCOE for large solar power plants. The solar inverter is a key BoS component that directly affects plant output. Thus, in general, the use of high-efficiency central inverters can help optimize generation. But the selection of inverter topology highly depends on several site conditions. Furthermore, high inverter loading ratios recommended to optimize revenue and boost capacity factors.

Utility-scale projects can benefit significantly from the use of trackers to boost generation. However, tracker usage increases the land use requirements of the plant and needs greater spacing to avoid shadowing of panels. Appropriate spacing is also relevant considering the higher size of modern modules.



3.7. Solar Thermal Systems

Solar Thermal technologies can play an important role in achieving energy security and economic development, as well as in mitigating climate change. Unlike Solar PV, which is used for direct electrification, Solar Thermal technologies are used for storing the sun's heat energy, via the help of a working fluid, heat energy from which can be later utilized. Although Solar Thermal technologies are mainly used for heating purposes, there have been projects where the technology has been utilized to heat water, for electricity generation via a steam turbine.

These systems consist basically of a collector, where the solar energy is absorbed, a storage system, usually water or phase-change storage, a boiler that acts as a heat exchanger between the operational fluids of the collector and the heat engine, and the heat engine itself, which converts the thermal energy to mechanical energy. This mechanical energy can be further used in an electrical generator. Usually, collectors include concentrator systems, to be able to reach the high temperatures that heat engines need to operate at. Innovations in this field are leading to more and more energy-efficient and cost-effective systems. The technologies can be broadly divided into two - solar thermal heating and concentrated solar power (CSP). Different solar thermal technologies are listed in Figure 63.

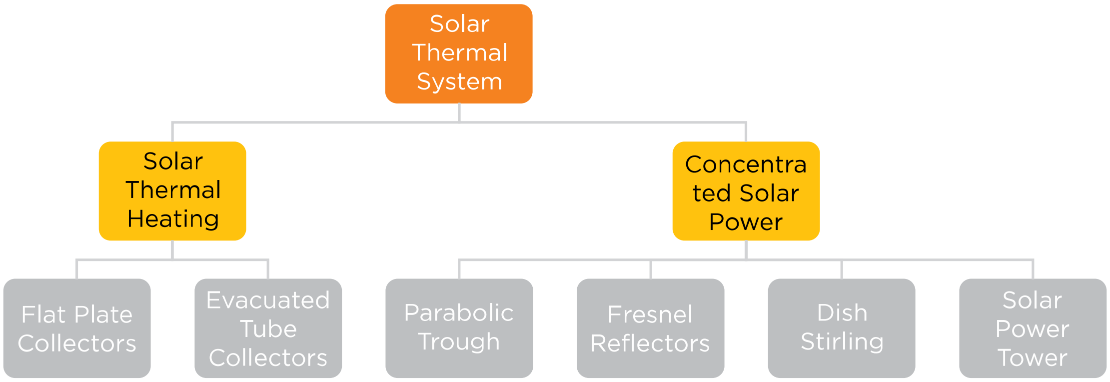
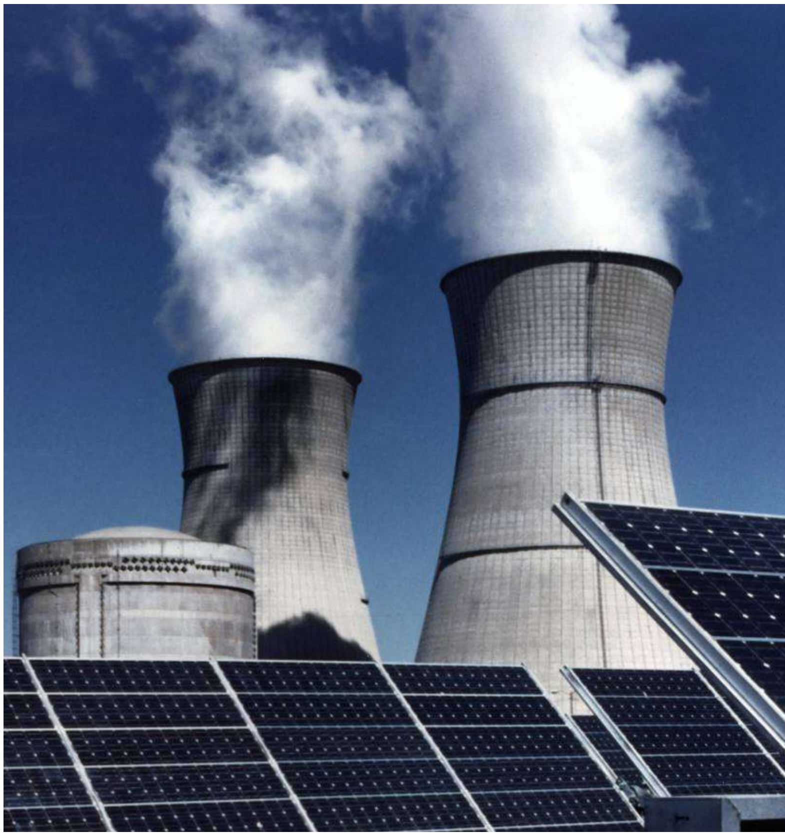


Figure 63: Solar Thermal Technologies

Flat plate collectors and evacuated plate collectors are technologies deployed for domestic heating and cooling purposes. Flat plate collectors are often used for domestic cooking purposes, in the form of solar cookers, or for space heating purposes, while evacuated tube collectors find their widespread use in the form of solar water heaters. Since both technologies are fixed systems and do not involve any type of tracking, they have varying efficiencies throughout the day. Due to their low efficiencies, they are not viable for large-scale generation of energy, commercially.

On the other hand, solar concentrators find their use for commercial-scale energy generation. With increased efficiencies, the addition of solar thermal energy storage, and possibilities of smooth functioning, when coupled with solar PV technologies as well, the scope for CSP is slowly rising again.

A parabolic trough consists of a linear parabolic reflector that concentrates the light onto an absorber tube located in the middle of the parabolic mirror, in which the working fluid is located. The fluid is heated to 150 to 350°C degrees Celsius (°C) and then used in a heat engine. Fresnel reflectors are similar, but use thin flat mirrors instead, to concentrate sunlight onto the tubes in which the fluid is pumped. Flat mirrors allow more reflection in the same amount of space as parabolic, reflect more sunlight, and are much cheaper. Another important concentrator system is dish stirling. A dish stirling or dish engine system consists of a parabolic reflector that concentrates light to the reflector's focal point, where the working fluid absorbs the energy, heating up to 500°C, and can operate a heat engine. These systems provide an overall efficiency of 31%, which is rather high. Solar power towers consist of an array of dual-axis tracking reflectors, commonly named heliostats, which concentrate the sunlight on a central receiver, which contains the working fluid. The fluid can be heated to 500 up to 1000 °C and then used in a power generator or energy storage system which is a very efficient system and have easier storage.



Solar concentrators are often deployed for heat requirements in industries, where process heat of less than 250°C is required. Steam is often pre-heated via solar thermal processes, for industrial purposes. Since concentrated solar thermal technologies use a working fluid for energy generation, the energy generated can be easily stored in phase change materials, instead of batteries, to be utilized later. The use of solar trackers further enhances the efficiency of a solar thermal system.

CSP has seen limited deployment globally, and installations have primarily taken place in certain key markets. The status of the installation of CSP is projected in Figure 64.

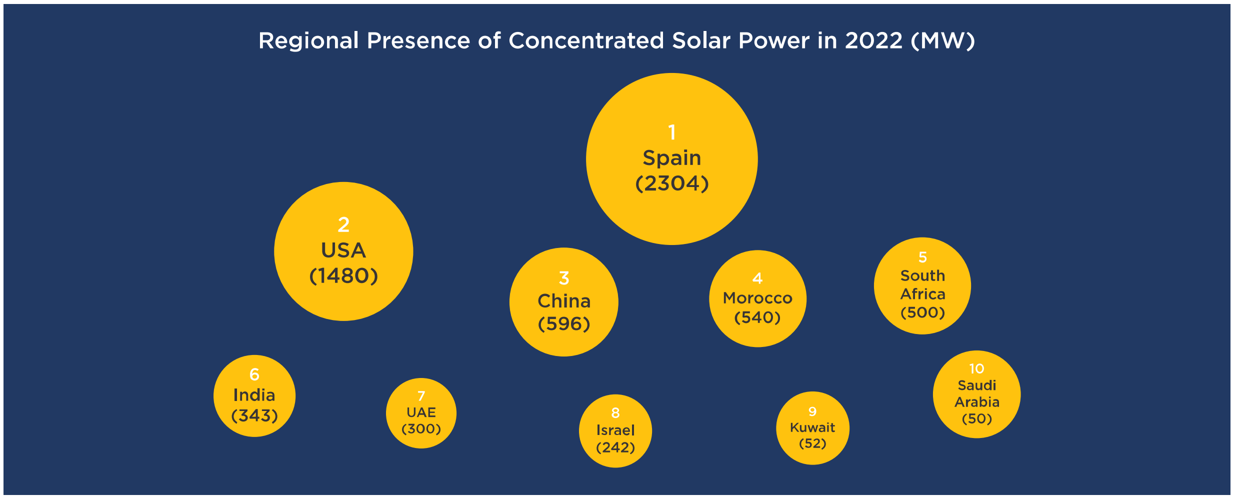


Figure 64: Regional Presence of Concentrated Solar Power (MW)

Source: IRENA - Renewable Energy Statistics 2023

Spain and the United States have been the main markets in the past but have not added significant capacity in recent years. Newer projects utilizing the technology have typically been in a Hybrid format alongside solar PV to provide round-the-clock power.

Despite the global preference for PV, CSP has its benefits and has made a compelling use case through various projects. Further, they can increase resilience against rising energy prices, because CAPEX for the system forms the majority of the investment, with minimalistic OPEX required, and there is almost no exposure to the volatility of oil, gas or electricity prices. In addition, the CSP has significant potential in the repurposing of coal power plants. Due to similarities between the electricity production process of CSP and the coal power plant, CSP would play a key role while repurposing the coal power plant. The existing infrastructure of the coal power plant can be utilized easily by CSP with minimum modification. Moreover, the bare land associated with coal power plants can be deployed for the installation of concentrators and solar PV systems. Therefore, CSP is expected to emerge as a demanding technology in the near future.

3.8. Achieving Net Zero Goal with Solar Energy

As we discussed in Chapter 2, industry being largest energy consuming sector, responsible for 36% of the total final energy consumption, out of which 34% met from electricity, and accountable for 40% of the global emissions. Therefore, moving to net zero goal and decarbonizing electrical power sector, we must consider the energy requirement for industrial process and manufacturing which is presently met by fossil fuel and replace it with an appropriate renewable energy resource. Simultaneously, it is also expected a surge in the energy demand of industrial sector in the coming years, since the industrial material demand not at the peak yet[12].

The share of solar energy is less than 1% of the total final energy use, according to IEA[13], which will generate opportunity as well as need of utilization of solar energy system to meet the energy demand in industrial segment. The analysis of IRENA[14] projects, the solar energy could meet 30% of the energy demand for industrial process by 2030. This can achieve in two ways, generation of electricity by means of solar PV system and generation of heat which can be utilized for the industrial process by solar

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[12] *ELSEVIER - Editorial Solar Compass, Decarbonizing industrial process heat is essential to achieve net-zero goal.*

[13] *IEA World Energy Outlook 2021*

[14] *IRENA (2021), World Energy Transitions Outlook: 1.5oC Pathway, IRENA, Abu Dhabi*

thermal systems or CSP. Since heat in the form of steam or hot air, for industrial process and manufacturing, is the major form of energy in industry segment, it can be easily produced from solar thermal systems at an efficiency of 65%[9] because of two reasons; firstly, different well developed solar thermal technologies with several GW capacity on line, from evacuated tubes to solar power towers (central receiver solar concentrators), are capable to supply steam or hot air for IPH at a temperature ranging from less than 100°C to above 1000°C, secondly, the diminishing trend in the cost of high efficiency solar thermal technologies, on the flip side the increasing cost of fossil fuels.

Various solar energy technologies and achievable temperature is given in Table 3.

Table 3: Solar Thermal Technologies and Achievable Temperature

Solar Thermal Technology	Temperature in °C
Solar ponds and flat plate solar collectors	Less than 70
Evacuated tube collectors	Less than 150
Parabolic troughs	150 – 450
Parabolic dishes	100 – 700
Solar power tower / Central receiver tower	300 -1000

Source: ELSEVIER -Editorial Solar Compass, Decarbonizing industrial process heat is essential to achieve net-zero goal.

There are different successfully operating systems globally and it is clear that decarbonizing industrial sector implementing solar energy systems to generate electricity and heat are essential in which the solar thermal systems to produce IPH is expected to be popular in the near future.