INTERNATIONAL SOLAR ALLIANCE

WORLD SOLAR TECHNOLOGY REPORT 2023

Foreword

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Rapid advancement in renewable energy technologies is crucial for mitigating climate change, and solar offers sustainable alternatives with an unprecedented growth potential. The increasing solar deployment is emphasized by the rapid research and development of solar technologies in various aspects like module efficiency, which has shown a significant increase from 15% to 24% in the last decade, and power output with more than 600W available in the market; poised to reach 32% cell efficiency by 2033. The advancement in technology options caused an overall reduction in cost, material usage, and barriers to deployment. Technical and financial maturity, modularity, and scalability have made solar technologies viable.

While PERC remains the proverbial working horse of the global PV industry, in 2022, new cell and module production capacities shifted from PERC to n-type-based tunneling oxide passivated contacts (TOPCon) and silicon heterojunction (SHJ) technologies. Several promising next-generation solar technologies such as perovskite-silicon tandem solar cells with power conversion efficiencies exceeding 30% are currently developing or approaching large-scale commercial manufacturing. These technologies offer significant benefits and potentially drive future capacity installations. Further research and development activities are required to ensure that they achieve their potential. Recent advancements in solar technologies include not only the developments in the solar module but also the innovations in the balance of systems such as inverters and trackers, plant design, construction activities operations, and maintenance, making solar deployment attractive for a wide range of consumers.

The solar manufacturing supply chain continues to witness significant capacity growth and process improvements in material, technology, and energy efficiency. However, the geographically concentrated manufacturing supply chain needs to be diversified to ensure a laminar material supply. Furthermore, the annual growth of production needs to be pushed at least by 5% to attain the required pace of production to move towards the net zero scenario.

Integration to the grid infrastructure is a barrier to the high penetration of intermittent sources like solar, which is being addressed by coupling with suitable technologies such as battery energy storage systems, green hydrogen, etc. Similarly, combining solar thermal technologies with other technologies opens new avenues in sectors like power generation and industry. Integrating concentrated solar power plants with coal power plants can support repurposing coal power plants. Moreover, advancements in solar thermal technology and diminishing cost trends enable them to be utilized to produce industrial process heat, which will significantly reduce greenhouse gas emissions from the industrial segment, the dominant emitter of greenhouse gases.

While solar energy has come a long way, there remains work to be done to explore the full potential of technology. Research and development activities must continue to drive technology innovation, while the global manufacturing supply chain must be more diversified and resilient.

Through this flagship annual World Solar Technology report, ISA aims to track solar technology developments and sectoral data trends, review the status of solar manufacturing worldwide, highlight gaps to be addressed, and shine a spotlight on the multiple benefits solar technologies can provide to different sectors.

I congratulate the ISA team and all the stakeholders involved for their work and support, and I look forward to sharing the ISA World Solar Technology Report 2023 with the global solar community.

Table of Contents

Abbreviations

AC	Alternating Current
AI	Artificial Intelligence
AR6	Sixth Assessment Report
BESS	Battery Energy Storage System
BNEF	Bloomberg New Energy Finance
BoM	Bill of Materials
BoS	Balance of System
BSF	Back Surface Field
CAES	Compressed Air Energy Storage
CAISO	California Independent System Operator
CAPEX	Capital Expenditure
CGS	Copper Gallium Diselenide
CIGS	Copper Indium Gallium Selenide
CIS	Copper Indium Diselenide
CPV	Concentrator Photovoltaics
c-Si	Crystalline Silicon
CSP	Concentrated Solar Power
CSS	Close Space Sublimation
CTM	Cell to Module
CUF	Capacity Utilisation Factor
CVD	Chemical Vapor Deposition
CVD	Chemical Vapor Deposition
DC	Direct Current
DW	Diamond Wire
EIM	Energy Imbalance Market
EoL	End of Life
EPC	Engineering Procurement and Construction
eV	Electron Volt
EV	Electric Vehicle
EVA	Ethyl Vinyl Acetate

FBR	Fluidized Bed Reactor
GHG	Greenhouse Gas
GW	Giga Watt
HJ	Hetero-Junction
HVRT	High Voltage Ride-Through
IBC	Interdigitated Back Contact
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPH	Industrial Process Heat
IRENA	International Renewable Energy Agency
ISA	International Solar Allience
ITRPV	International Technology Roadmap for Photovoltaic
kWh	kilowatt hour
kWp	kilowatt peak
LCOE	Levelized Cost of Energy
LID	Light Induced Degradation
LVRT	Low Voltage Ride-Through
MBB	Multi Busbar
MPP	Maximum Power Point
MtCO2	Million Tons of Carbon Dioxide
MW	Megawatt
MWT	Metal Wrap Through
NDC	Nationally Determined Contributions
NREL	National Renewable Energy Laboratory
NZS	Net Zero Scenario
OPEX	Operational Expenditure
PERC	Passivated Emitter Rear Contact
PHS	Pumped Hydro Storage
PID	Potential Induced Degradation
PV	Photovoltaic

RE	Renewable Energy
SMES	Superconducting Magnetic Energy Storage
SWCT	Smart Wire Connection Technology
TCS	Trichloro Silane
ToD	Time of Day
TOPCon	Tunnel Oxide Passivated Contact
TR	Tiling Ribbon
TW	Terrawatt
TWh	Terrawatt hour
UAE	United Arab Emirates
UHV	Ultra-High Voltage
UMG-Si	Upgraded Metallurgical Grade Silicon
USA	United States of America
VPP	Virtual Power Plants

Executive Summary

The world has embarked on a significant transition by moving towards cleaner sources of energy. According to the 2022 Global Climate Stocktake report by the UN, the average global temperature is expected to reach or exceed 1.5°C of warming over the next 20 years. The report has also attributed over 1°C of warming to greenhouse gas emissions from human activities since the late 19th century. The effects of climate change are becoming increasingly apparent, with heat waves, cold snaps, forest fires, floods, and other such national disasters becoming increasingly common.

The industrial sector consumes the biggest chunk of energy accounting for 36% of the total energy consumption followed by the building (33%) and transportation (31%) sectors. The key emitting sub-sectors include power, road transportation, residential building, steel industries etc. while the major chunk of electricity generated in the power sector is being utilized by the industrial sector. The CO_2 emissions have increased in 2022 by 45% over the last 20 years and the total GHG emissions in 2022 were recorded as 39.3 billion tonnes ($BTCO_2e$) of carbon dioxide (CO_2) equivalent out of which 34.6 $BtCO_2e$ (88%) was contributed by carbon dioxide which is the primary greenhouse gas.

There are several pathways to achieve greenhouse gas abatements required to limit climate change, but all require significant deployment of renewable energy sources. While multiple renewable energy technologies are available, the last decade has seen solar energy emerge as the leading RE technology, with cumulative installations growing sixfold to reach ~1100 GW in 2023. This rapid growth is set to continue for years to come, fueled by technical and financial maturity as well as scalability. The future of solar also looks bright due to its potential to enable or link with other technologies to abate sectors that pose complex decarbonization challenges, such as transport, building, agriculture, and manufacturing, among others.

Solar technologies encompass a broad and ever-growing array of options and are primarily divided into two major groups. Solar photovoltaic (PV) technologies convert light into usable electricity, while Solar Thermal technologies convert light into usable thermal energy. Solar PV technologies have emerged as the dominant technology, while solar thermal remains relevant for certain specific applications. The solar PV technology family is dominated by crystalline silicon technologies, which have seen significant research and development (R&D) investments leading to average module efficiencies increasing from around 15% in 2010 to around 23% in 2023. Additionally, average module power ratings have gone from under 250 W in 2010 to around 440 W by 2022, with 700 W commercial modules now available in the market. A rapid technology development cycle and significant R&D expenditure promise further innovations that will drive future improvements. Over the last 15 years, solar PV prices have seen a dramatic fall from around 5 USD per watt in 2009 to under 0.24 USD per watt in 2022. The same period has seen cumulative capacity grow by two orders of magnitude. Non-silicon-based technologies are promising but are unlikely to replace crystalline silicon technologies and will likely remain more relevant for niche applications such as space-based deployment. The Balance of System (BoS) components, including inverters, mounting and racking systems, and trackers, have seen their own cost and technology improvements to help lower the solar lifetime cost of electricity (LCOE).

Solar benefits extend to the wider system in which the technology is deployed. Solar PV systems utilize far fewer materials than equivalent capacities of wind power and are unique such that glass makes up a significant portion of their material usage by weight. The land usage (3-10 acres per MW) and lifetime GHG emissions (under 50-60 gCO2e/kWh) remain low as well. Solar PV systems fall under three main categories: Residential, Commercial and

Industrial), each with its own technical and financial considerations that help maximize generation and minimize cost. The design, construction, and operations and maintenance (O&M) activities of a solar PV system also play a role in maximizing generation and minimizing deployment costs.

Despite seeing widespread global deployment, solar remains a source of untapped opportunities. The coupling of solar energy with other technologies can help address sector-specific needs. Solar may be -

- Deployed with energy storage to improve the flexibility of generation
- Generate green hydrogen for industrial decarbonization
- Deployed on agricultural land to improve land use efficiency
- Power heating and cooling
- Charge electric vehicles to help decarbonize transportation
- Integrated into buildings or vehicles for electricity generation
- Deployed on water bodies to minimize land usage

These innovative applications and sectoral linkages are already seeing traction and are expected to be a key source of solar energy growth.

As per an average of various expert predictions, cumulative solar deployment is expected to reach nearly ~5 terawatt by 2030, having crossed 1 terawatt in April 2022. The likelihood of this target being achieved is inextricably linked with the strength of the manufacturing supply chain. This supply chain involves not just the components of solar modules, but also includes the BoS components that comprise a complete PV system. The crystalline silicon PV supply chain is by far the largest worldwide, consisting of four key stages: polysilicon, ingots/wafers, cells, and modules. Manufacturing capacity across these stages is geographically concentrated in China, with at least 75% of manufacturing capacity at each stage located in the country. In contrast, the manufacturing of BoS components is disaggregated.

The supply of polysilicon has been constrained after a long period of supply glut despite over 950,000 MT of manufacturing capacity worldwide. These undersupply situations have in turn seen prices increase multi-fold, affecting the supply chain. While China has a significant share of polysilicon manufacturing, it has a near monopoly for the next stage, ingot/wafer production, with around 96% of the 400+ GW global manufacturing capacity located there. However, this geographic concentration of manufacturing is dispersed slightly for the downstream stages of cell and module manufacturing.

Solar cells are the heart of a PV system, and production varies significantly based on the specific cell architecture used. Around 470 GW of cell manufacturing capacity is present worldwide. Module manufacturing, by contrast, is a relatively low-skilled process, and is present in several countries, resulting in over 600 GW of module manufacturing capacity. Across all the supply chain stages, constant innovations and process improvements have led to increased material efficiency, lower costs, and improved module performance. Thin film PV manufacturing capacity is significantly smaller than crystalline silicon PV and growth has been stagnant in most countries. However, it is being explored as an opportunity by some countries to minimize external dependencies while meeting solar demand.

The solar manufacturing supply chain must address a few key concerns in the coming years. The geographic concentration of manufacturing capacity leaves the supply chain open to shocks. Additionally, current manufacturing capacity is much larger compared to demand for all stages except polysilicon and is expected to grow further in coming years. This oversizing is due to large-scale capacity expansion in China. However, other regions face a huge manufacturing capacity deficit and thus are heavily reliant on imports. The sustainability of manufacturing operations also needs to be addressed, with energy-hungry processes being fueled primarily by coal-fired electricity generation in China. Solar recycling, currently a nascent field, will also become increasingly important as deployed modules reach the end of their lifecycle in the coming decades.

As solar generation is set to increase with the acceleration of global capacity deployment, it is important to consider the impact of Variable Renewable Energy (VRE) sources on the electrical grid of a region. High penetration of VRE often leads to grid instability due to loss of power flexibility, frequency mismatch, nonsynchronous generation etc. Thus, integrating sufficiently high shares of solar in the electricity mix can run the risk of causing blackouts and damaging electrical equipment. To avoid this outcome, some grids have turned to curtailment, which is essentially a waste of potential generation, and an undesirable outcome.

To address the challenges posed by solar generation and support grid integration, a variety of tools are available. These include both demand-side and supply-side initiatives and can involve the usage of energy storage, demand-side management, energy markets, grid interconnections, flexible generation assets, and grid digitalization activities. It is important to note that there is no 'one size fits all' solution-Instead, it is important to utilize the appropriate solution to tackle a specific grid integration challenge effectively. A number of countries, such as Germany, USA, China, India, and Japan, are at various stages of deployment of these solutions for grid integration.

Solar PV has the potential to be a key technology for the energy transition, but barriers and gaps remain to be addressed across the ecosystem. These include:

- Improvement of supply chain resilience through a diversified and vertically integrated manufacturing
- Appropriate disposal and/or recycling of solar waste, including through minimization of toxic components and clear policy initiatives
- Improved project development through design optimization, skill development, and market support for advanced technologies
- Standardization of quality across manufacturing locations and companies, with frequent updating of benchmarks and improved testing infrastructure
- Optimization of module bill of materials and greening of supply chains to minimize industry footprint

This will help pave the way for terawatt scale installations and unlock significant socio-economic benefits. The sector can generate significant employment, with 1 GW of vertically integrated manufacturing capacity creating anywhere from 1000-2000 direct manufacturing jobs. Distributed generation through solar devices can improve energy access for remote communities, and benefit users in impoverished areas. Additionally, the environmental benefits of solar are clear, with a 100 MW solar plant estimated to avoid the emission of 139,000 MT of CO_2, 90 MT of NOx, 80 MT of SOx, and 6 MT of PM2.5 particles each year. Solar has the potential to provide far more than energy.

This report is divided into seven sections. The first section outlines the approach and methodology used to prepare the report. The second section introduces the energy transition and the central role that renewable energy, specifically solar energy, can play a key role to help drive the transition. The third section discusses the wide array of solar technologies available such as solar PV and solar thermal technologies, as well as the additional components that make up a solar energy system. This section also highlights solar energy's flexibility to address clean energy demands in multiple sectors, and the significant potential for sectoral linkages that arise from this flexibility. The fourth section provides an overview of the solar manufacturing supply chain, including the manufacturing of additional components. This section also underlines the need for solar recycling. The fifth section showcases the various demand and supply side measures available to assist with grid integration of rising shares of solar generation. The sixth section highlights the key gaps and considerations across the solar technology ecosystem and provides recommendations to help address the same. The seventh and final section concludes the report.

The ISA World Solar Technology Report is an annual publication that aims to track solar technology developments and data trends year on year. Subsequent reports will build on the work done in previous editions to provide a clear overview of the global solar technology ecosystem.

Approach & Methodology

Approach

The solar technology ecosystem is diverse, with a wide variety of components, technologies, manufacturing stages, applications, and enabling technologies involved. Additionally, the technology development cycle is rapid, with the industry shifting radically in the space of a few years to adopt new technologies and processes. Thus, while preparing a comprehensive overview of the global solar technology ecosystem, it is important to have a clear approach and methodology in place to ensure that all key topics are covered in requisite detail and that the data and insights represented are accurate.

While the solar sector has seen significant growth over the past decade, there remain areas to be addressed to ensure that the technology achieves its potential. In its efforts to ensure large-scale solar adoption globally, ISA has undertaken the development of the World Solar Technology Report to provide a sustainable knowledge base for policymakers, manufacturers, developers, and other key sectoral stakeholders to monitor the current situation of solar technologies and have greater clarity on future trends. ISA aims to ensure the utilization of the report for the dissemination of knowledge on the solar technological situation, including the main trends in PV modules and designs, the various applications and sectoral linkages, the manufacturing supply chain, grid integration technologies, and circularity and sustainability considerations.

An overall architecture approach, consisting of 4 broader steps, viz. review, collect, analyze, and report, has been adopted to prepare the report. The steps adopted under the approach were mainly focused on 2 broad aspects, namely secondary research and data analysis. The approach was aimed at ensuring that key solar technology and manufacturing indicators are covered under the report.

Methodology

For the development of the report, a detailed methodology was prepared under the adopted approach. It was focused on gathering relevant data points and presenting it in order to derive key insights on the solar technology ecosystem around the world.

The primary activity undertaken involved reviewing the present scenarios as well as gathering relevant data on technologies in the solar energy sector. **Secondary research** was conducted to understand the key developments around the solar sector, with a focus on solar technologies, manufacturing, and grid integration. Additionally, a review of existing reports on similar topics, with global and regional scopes, was carried out. A review of the solar manufacturing ecosystem, grid integration challenges and solutions, and system level considerations was conducted. Relevant case studies were also identified and shortlisted, with key case studies developed with information captured during the secondary research. To carry out the secondary research activities, a range of reputed databases and reports were reviewed and scrutinized; these include ISA, BloombergNEF (BNEF), IRENA, IEA, and NREL, among others. Thus, through secondary research, activities on **review of information and collection of data** were completed.

After data collection, **data analysis** was carried out to identify the key trends in terms of improvements in solar technologies, including efficiency improvements, cost and material usage reductions, and power output increases. Improvements at the system level, including design, construction, and operations and maintenance were also covered. The geographical distribution of the manufacturing supply chain, manufacturing process trends, as well as key players in the sector, were identified. These analyses extended to balance of system components such as inverters, racking systems, and solar trackers. The projected requirements for recycling and circularity were also analyzed. The varied sector linkages made possible by solar technologies were showcased through case studies. Additionally, the gaps across the ecosystem were highlighted, with recommendations for possible solutions.

Energy Transition: Solar Technologies are at the forefront

In achieving the net-zero GHG emission scenario thereby mitigating the impact of climate change, energy transition and decarbonization is imperative. The recent abnormal weather patterns across the world substantiate the threat of climate change and a need to shift to renewable energy resources which would play a key role in the abatement of GHG emissions.

Reducing greenhouse gas (GHG) emissions is crucial to combat climate change and its adverse impacts. The total GHG emissions in 2020 were recorded as 39.3 billion tonnes of carbon dioxide (CO_2) equivalent[1] (BTCO2e) out of which 34.6 BtCO_2e (88%) contributed by CO_2,[2] the primary greenhouse gas.

The other greenhouse gases include methane, nitrous oxide, fluorinated gases etc. Global warming, the phenomenon of increasing the average surface temperature of the earth, is expected to continue until 2040 mainly due to the increased cumulative emissions of CO_2[3]. Being the primary greenhouse gas, energy utilized by the end-use sectors such as industry, buildings, and transportation have a footprint of CO_2 either directly and/or indirectly. For instance, industries emit CO_2 and other GHGs directly as a part of different industrial processes whereas the electricity consumed from the grid, which has been generated from power plants with feedstock such as coal, oil and/or gas, is also responsible for the indirect CO_2 emissions. The share of the end-use sector in CO_2 emission is given in Figure 1.

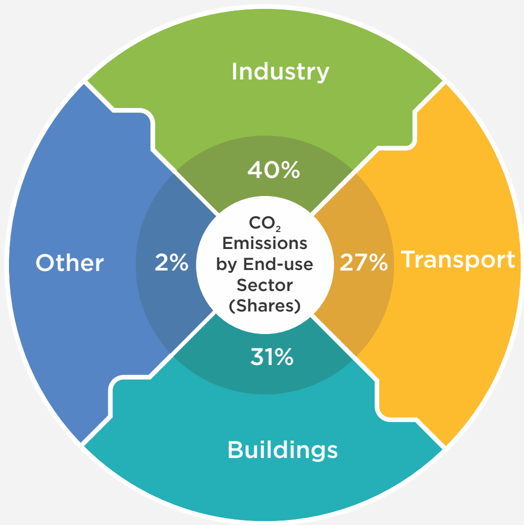

Figure 1: CO_2 Emissions by End-use Sector (Shares)

Source: BNEF- New Energy Outlook 2022

As an end user, industry (40%) accounts for the major share of emissions of CO_2 followed by the buildings (31%) and transportation segment.

Progressing on, the end-user segments are elaborated into various sub-sectors to get better visibility on CO_2 emissions. The sub-sectors accounting for emissions and their respective emissions are highlighted in Figure 2.

[1] *Our World in Data - emissions?breakBy=sector&chartType=area&end_year=2020&sectors=bunker-fuels&start_year=2000*

[2] *BNEF- New energy outlook 2022.*

[3] *IPCC- Sixth assessment report (Ar6)*

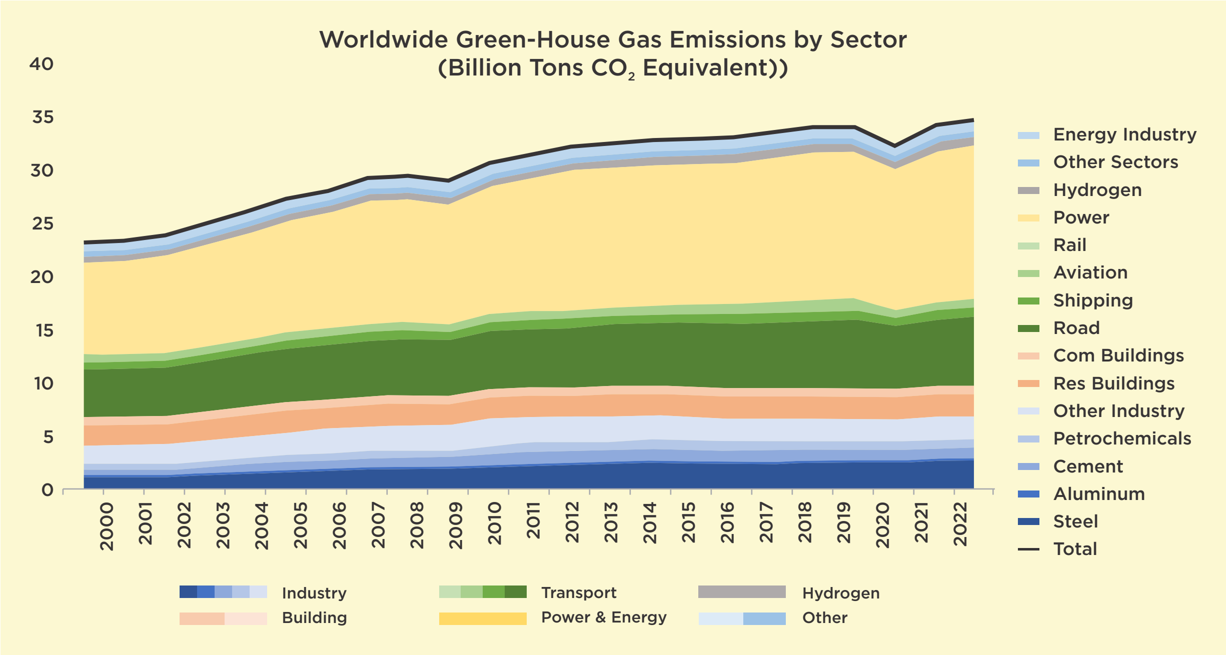

Figure 2: Worldwide Green-House Gas Emissions by Sector (Billion Tons CO_2 Equivalent)

Source: BNEF- New Energy Outlook 2022

Notably, the indirect CO_2 emissions of the end-users, industrial, transportation and building segments, majorly associated with the electricity consumed, are categorized under the CO_2 emissions of the power sector, where it would be direct emissions. Therefore, the emissions under the power segment comprised of CO_2 emissions associated with the production of electricity and heat which might be used in industry, transportation, and buildings as an end-user. While the CO_2 emitted by different processes in the industry sector is expressed as a combination of various individual emission-intensive industries like steel, aluminium etc. Similarly, the direct CO_2 emissions in the transport and buildings segments are also plotted in the Figure.

Considering the data for the last two decades, because of the increasing industrial and non-industrial activities, CO_2 emissions have seen an average yearly increase of 1.9% to hit 34.6 BtCO2 by 2022, an increase of 49.7% compared to the emissions in 2000. In 2020, amid the Covid-19 pandemic, CO2 emissions witnessed a slight dip, however, it inched up in successive years.

Based on the assumptions of BNEF as mentioned above, in 2022, the major share of CO_2 emission primarily accounts for the power sector (41.1%) followed by transportation (23.7%) and industrial processes (19.6%). Note that, major chunks of electricity generated in the power sector are further utilized in the industry segment, consequently, it becomes responsible for the highest CO_2 emissions as an end-user as demonstrated in Figure 1. While in the transportation sector, road transport retains the highest share of CO_2 emissions for the last two decades, accountable for 78.0% of the emissions from the transport sector alone and 18.5% of total emissions in the year 2022. Similarly, steel industries release 40.3% of the total CO_2 emitted from the industrial sector because of various industrial processes, responsible for 7.9% of the total Co_2 emissions.

The final energy consumption of different end-user is also estimated and illustrated in Figure 3.

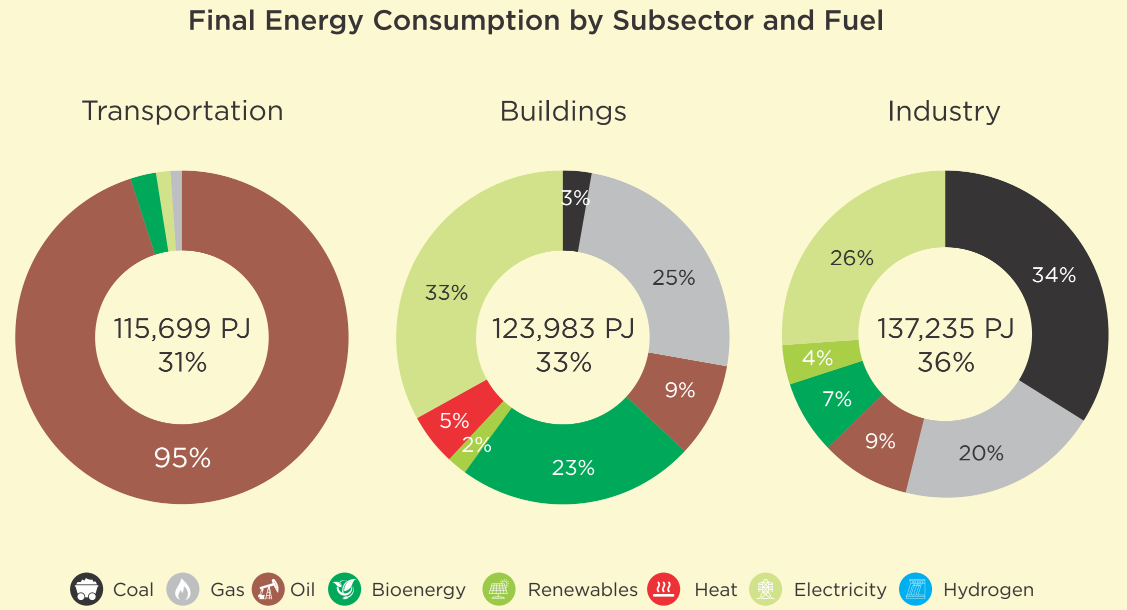

Figure 3: World Total Energy Consumption

Source: BNEF- New Energy Outlook 2022

As per the Figure, the energy demand in three major segments is slightly dominated by the industrial segment (36%). In the industrial segment, the major share of energy demand is met by coal (34%) and electricity (26%). While in the buildings sector, the second largest energy consuming sector, the major share of energy requirement is satisfied by electricity (33%) followed by gas (25%) and bioenergy (23%) whereas in the transportation sector, 95% of energy demand is met by oil.

The electricity, being the second largest form of final energy source succeeding that behind oil, attract attention. The various sources of electricity and patten of generation is plotted in Figure 4.

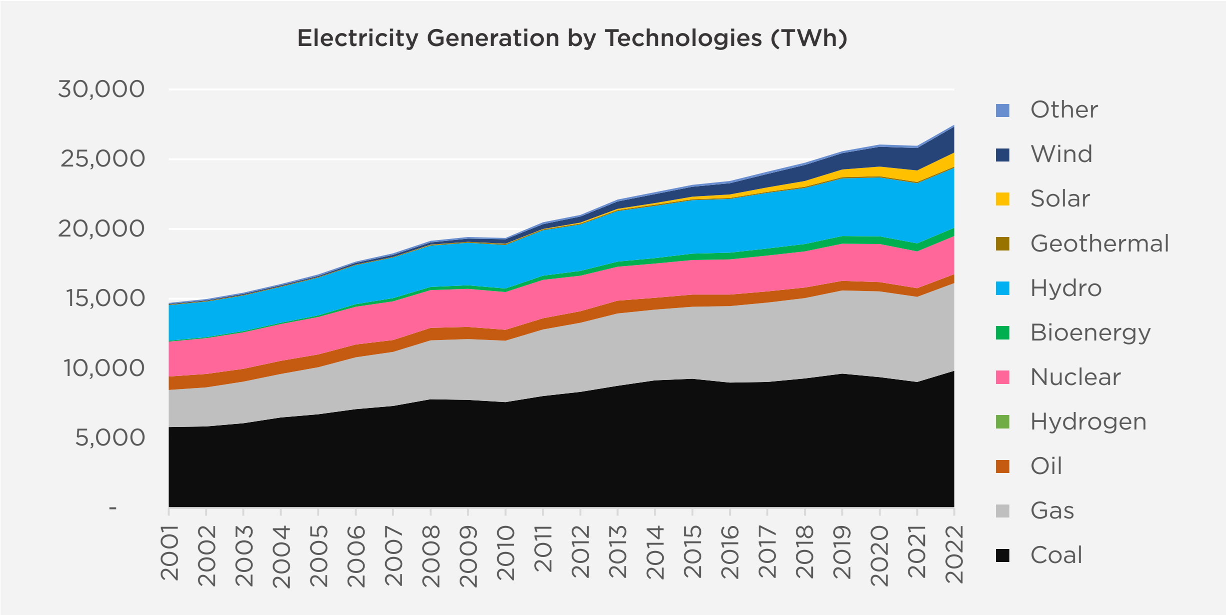

Figure 4: Electricity Generation by Technologies (Twh)

Source: BNEF- New Energy Outlook 2022

Figure depicts the gradual increase of electricity consumption over the last twenty years reaching 28,403 TWh in 2022, a 93% increase of consumption in comparison with that of 2000. Though, in 2022, major share of electricity is generated (38%) from coal, a fuel which accountable for the 48% of the total CO_2 emission. Therefore, as a deduction, reduction of consumption of coal to generate electricity and oil for the transportation is necessary to reduce the overall Co_2 emission thereby decreasing concentration of GHGs in the atmosphere.

Greening electricity through faster adoption of renewables can abate GHG emissions significantly - have been detailed in the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) published on 20th March 2023 has detailed the Devastating consequences of GHG emissions around the world, resulting in the destruction of homes, loss of livelihoods and fragmentation of the communities. One of the key findings of the report is that the earth's climate is experiencing unprecedented changes in recent human history due to human-induced global warming, with a rise of global surface temperature by 1.1°C. Furthermore, the global temperature is on an upward trajectory, with the global temperature rising more than 1.5°C during the 21st century, making it harder to limit it below 2°C under high-emission pathways. Such high global temperature rise is expected to have severe and widespread consequences on humankind, and flora and fauna.

The resilient adaptation measures are also described in the AR6 synthesis report with aligned pathways to reduce GHG emissions. The report describes modelled pathways to achieve the goal of limiting global warming to 1.5 oC, and to reduce GHG emissions to 33.7 giga tonnes CO_2 equivalent ($GtCO_2e$) by 2030 and 18.3 $GtCO_2e$ by 2040 compared to the 59.1 $GtCO_2e$ emissions in 2019. To limit global warming to the set goal, the world must shift from fossil fuels, the key sources of GHG emission and climate crisis, to renewable energy resources. Additionally, a clear strategy has to be formulated and implemented to secure net-zero emissions at the earliest.

2.1 Renewable Energy Addition; Keep an Upward Trajectory

The transition from fossil fuels to renewable energy is essential to achieve the net-zero emissions scenario, particularly in the electricity sector which accounts for the second largest energy consumed but contributes the highest GHG emissions. The total global electricity requirement and the share of renewable energy generation are represented in Figure 5.

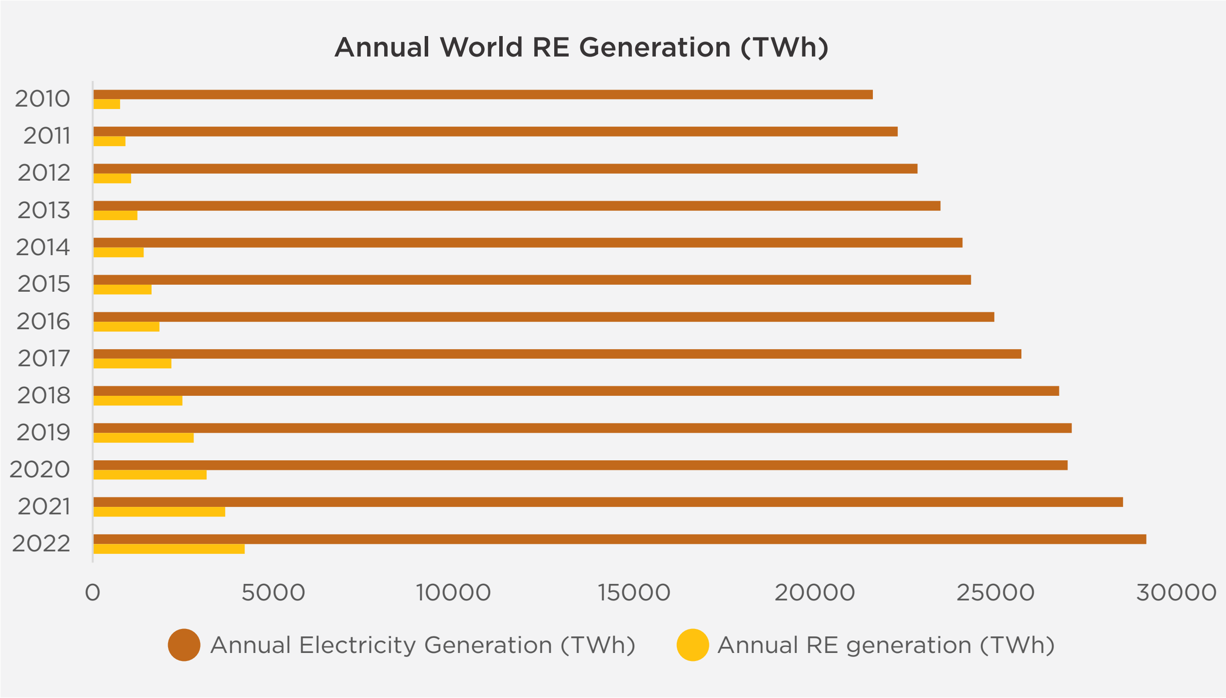

Figure 5: Annual World Electricity Generation and RE Generation
Source: BNEF - New Energy Outlook 2022

Both electricity and RE generation have seen steady growth over the last decade. Nevertheless, RE contributes 12.6% of the total energy requirements as of 2022, up from 3% in 2010. This upward trajectory is set to continue for years to come. Several renewable energy sources are being deployed at scale, including hydropower, wind, solar, and biofuels as depicted in Figure 6.

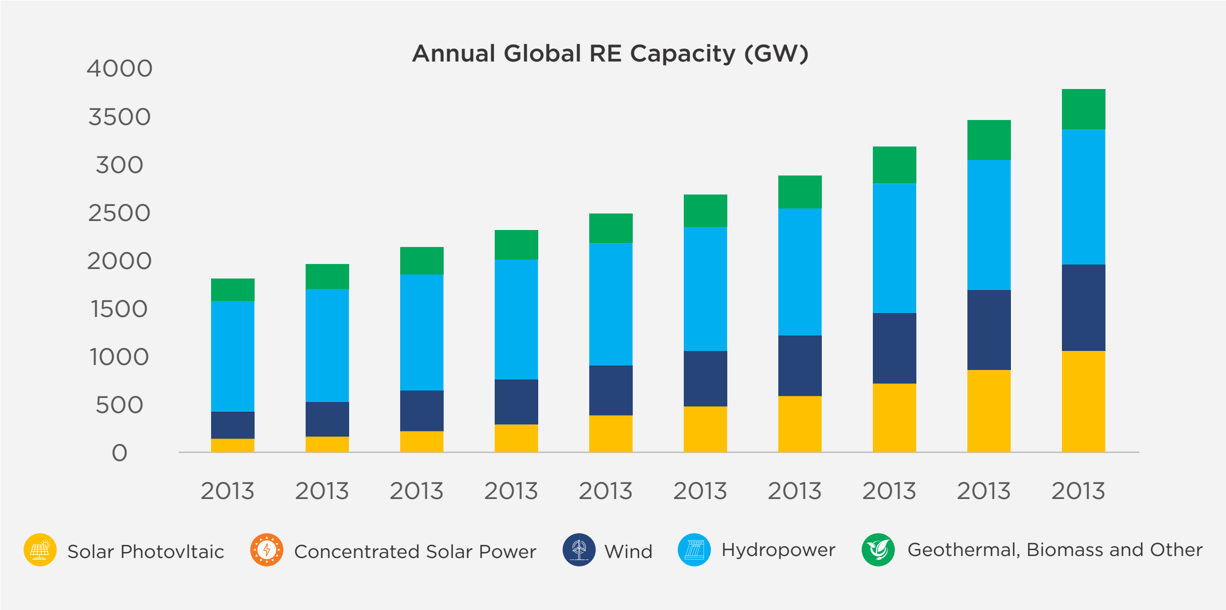

Figure 6: Global Renewable Energy Deployment

Source: IRENA Renewable Energy Statistics 2023

Hydropower has been the dominant fraction of RE for several decades, while wind power has also contributed a significant part including both off-shore and on-shore projects. Remarkably, in recent years, solar power especially solar photovoltaic (PV) power has seen a steady growth in the past decade, leap-frogging biofuels and wind and becoming the second largest renewable energy source after hydropower. A detailed analysis is summarized in Table 1.

Figure 6: Global Renewable Energy Deployment

	Solar Photovoltaics	Concentrated Solar Power	Wind	Hydropower	Biofuels
Absolute growth over the Last Decade	667%	67%	200%	22%	79%
Absolute growth over the last 2 years	46%	1%	23%	4%	12%
Growth over last year	22%	4%	9%	2%	6%

Solar has grown over six-fold in the past decade and climbed to 1055 GW of installed capacity in 2022. Wind power attained a two-fold growth over the last decade and hydropower has grown by 22%. With an annual growth rate of 25% for solar power, compared to 13% for wind and 6.7% for biofuels, it is not difficult to imagine that solar will eventually become the largest renewable energy source in terms of installed capacity worldwide.

Share of Global Capacity Additions by Technology

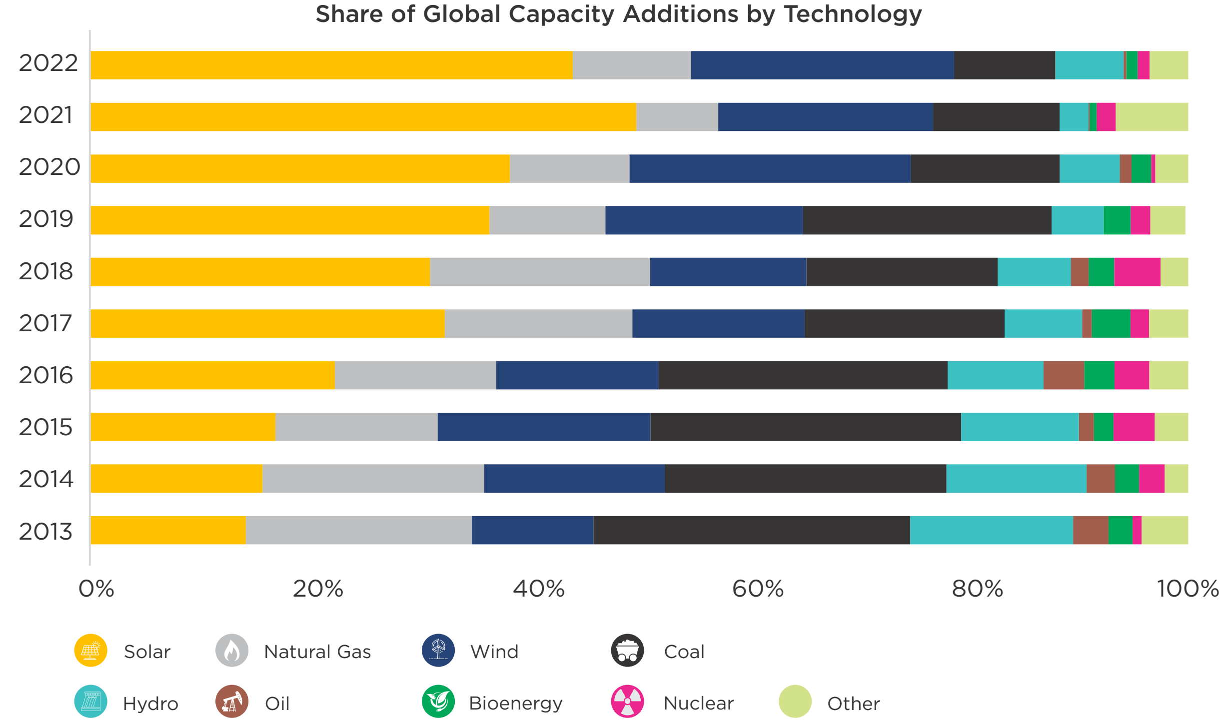

Figure 7: Share of Global Capacity Additions by Technology

Source: BNEF- New Energy Outlook 2022

As illustrated in Figure 7, the global capacity additions by technology highlight the dominance of solar power (44%) among the RE resources followed by wind (24%) in 2022. Although hydropower contributes the largest share of RE electricity, solar has shown remarkable growth to hit a 15.5 % share of the RE power as of 2022, up from 1% in 2010, as depicted in Figure 8.

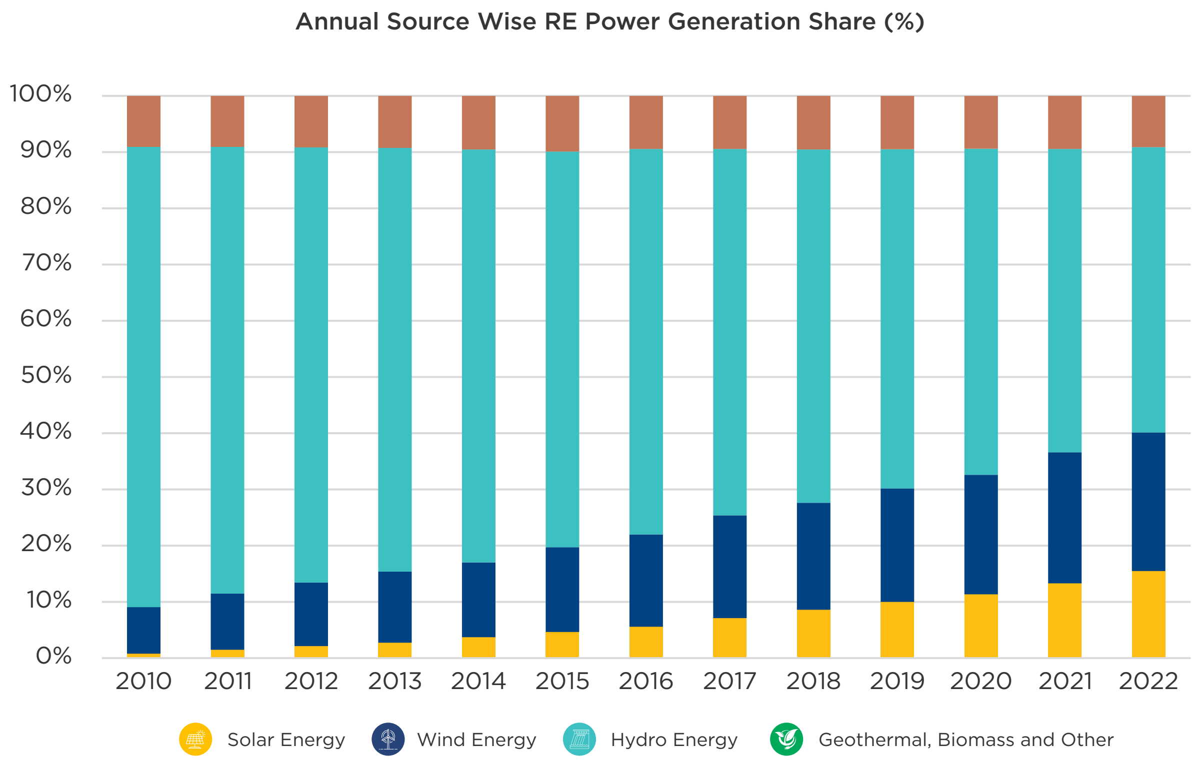

Figure 8: Annual Source-wise RE Power Generation Share

Source: Energy Institute Statistical Review of World Energy - 2023

Solar has grown over six-fold in the past decade and climbed to 1055 GW of installed capacity in 2022. Wind power attained a two-fold growth over the last decade and hydropower has grown by 22%. With an annual growth rate of 25% for solar power, compared to 13% for wind and 6.7% for biofuels, it is not difficult to imagine that solar will eventually become the largest renewable energy source in terms of installed capacity worldwide.

Fast-paced growth in technological advancements

Years of research and developments in the field have led solar energy systems to achieve a robust technological foundation as an energy-generating system. Though solar PV dominates as a technology, solar thermal technology has also been developed and installed significantly. Solar PV has seen the development of multiple technologies that have increased the efficiency and reliability of solar modules.

Commercial viability and grid parity

Improvement in technologies resulted in a steady decrease in the levelized cost of energy (LCOE) for solar resulting in financial benefits for the private sector. Furthermore, the declining cost of solar PV equipment such as solar panels, inverters and other components has made solar energy increasingly cost-competitive with traditional fossil fuel-based power generation methods. Additionally, the development of a strong supply chain for solar PV components has further helped drive down equipment costs while ensuring high quality and durability to increase the solar plant's operational lifespans.

Ease of deployment including modularity to meet various applications

The modularity and flexibility of solar lends itself to ease of deployment, which in turn has led to increased generation. The extensive deployment of solar systems worldwide has provided valuable data and operational experience, leading to a better understanding and optimization of solar power systems. The large portfolio of options, solutions, and applications offered by solar allows it to address all sectors, with systems ranging from the kW size to the GW size.

Grid Integration

The successful integration of solar power into the electricity grid through advanced grid management techniques and smart grid technologies has enhanced its reliability and stability. Additionally, ongoing research and innovation in the field of storage have led to substantial integration of solar energy systems into the grid ensuring a stable operation.

2.2 Renewable Energy; Quintessential on Energy Transition Pathways

Immediate and systemwide transformation strategy and pathways to reduce GHG emissions and secure net zero is an absolute necessity. However, there is no single approach or technology that can claim to cover all aspects required for a successful transition. There are multiple opportunities for scaling up technologies which are assessed and found to be feasible and able to contribute to net emissions reduction. Some of the potential mitigation options related to the energy sector are:

- Renewable energy and energy generation diversification
- Energy efficiency and conservation
- Demand-side management (higher efficiency appliances and peak shifting using storage)
- Substantial reduction in overall fossil fuel use, methane emission reductions – Retirement and/or repurposing of coal power plants to Concentrating Solar Power (CSP).
- Biofuels/Bio Energy
- Using Green Hydrogen and derivatives as fuel as well as storage
- Electric transportation powered by low-GHG emissions electricity

According to the AR6 synthesis report, the electricity sector will be the second largest source of GHG emissions in 2050 with the highest potential of reduction of emissions (73%) among the sectors - food, transport, buildings and industry. Rapid integration of renewable energy resources in the electricity sector is essential to achieve the required emissions abatement where solar energy will provide the largest share as depicted in Figure 9.

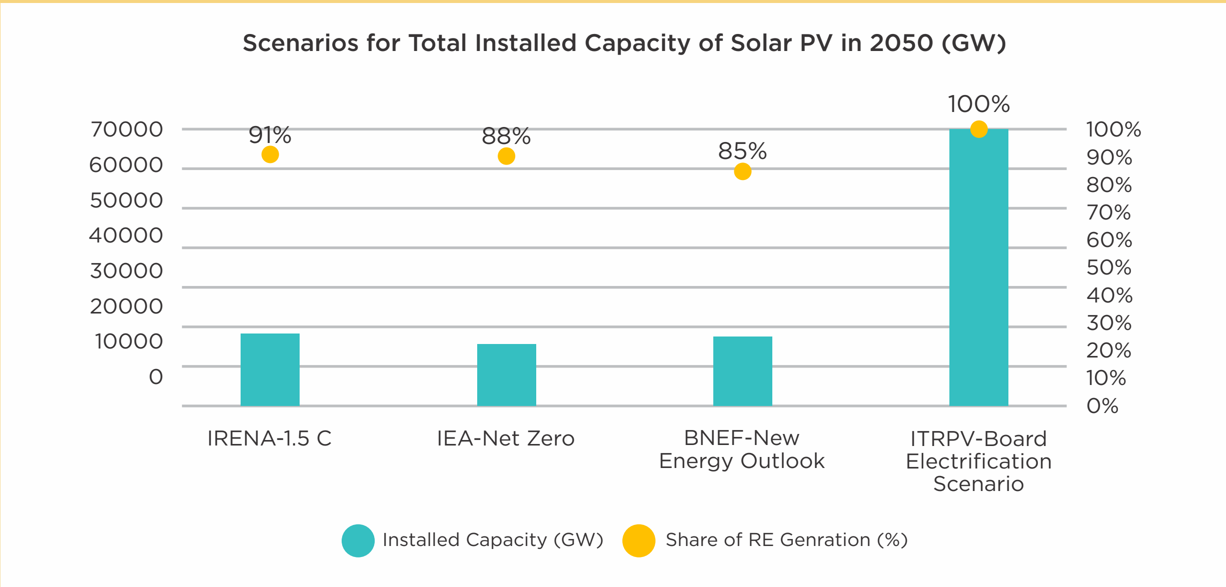

Figure 9: Solar PV installation Scenario in 2050

Source: ISA Analysis

Based on the reports and findings of different organizations, renewable energy resources, especially solar are at the center stage of the energy transition in achieving net-zero GHG emissions by 2050. Quoting the studies on the topic, a minimum capacity deployment of 15500 GW of solar and at least 85% renewable energy share is necessary to achieve the net-zero GHG emission target.

2.3 Solar Energy: Accelerating the path towards net zero

While solar energy's strong historical growth has been driven by a combination of technological and financial considerations highlighted above, the future of solar remains bright due to the technology's modularity and capability for usage in different applications. The global emissions are expected to fall from 2024 and reach net zero in 2050, according to the Net Zero Scenario (NZS) of BNEF, aligned to the target of the Paris Agreement to keep the temperature below 2°C above the pre-industrial level. The expected RE installations to be achieved is illustrated in Figure 10.

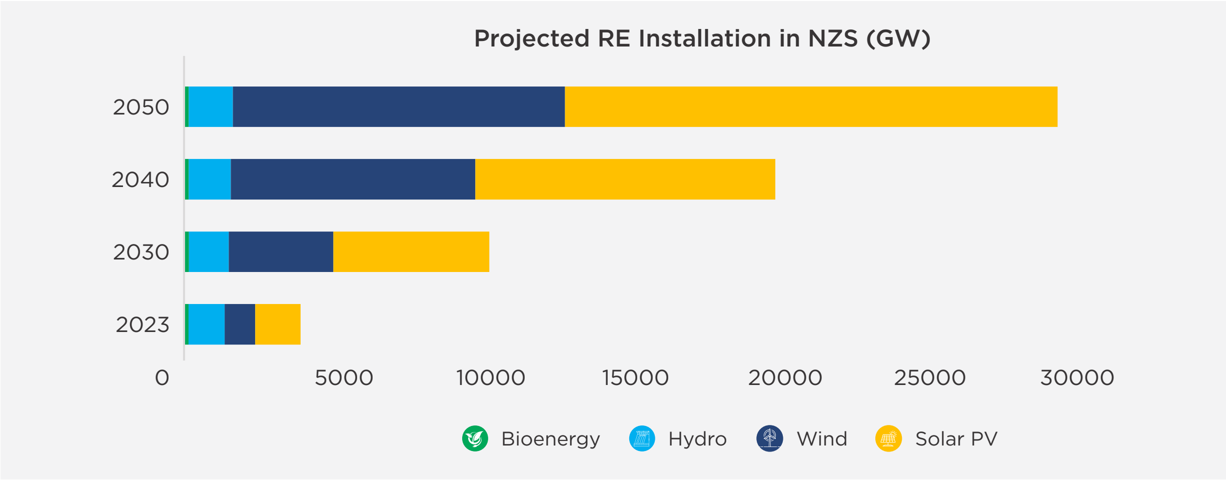

Figure 10: Projected RE Installation in NZS (GW)

Source: BNEF-New Energy Outlook 2022

Evidently, solar projected to be at the center stage by 2030 with an installed capacity of 5345 GW, contributing 51.0% of the total RE share. Furthermore, solar share is also expected to reach an installed capacity of 16887 GW in 2050, 56.5% of the total RE capacity. Solar is uniquely placed due to its potential to directly generate clean energy as well as in combination with other technologies to abate sectors that pose complex decarbonization challenges.

These linkages mean that solar energy has the potential to help decarbonize not just the power and heat sector, but also tackle decarbonization challenges in transportation, agriculture, manufacturing, and buildings, among other sectors. The use of solar energy ties in well with the electrification of end uses of energy, a trend that is already underway in certain sectors and will continue to grow. Some of the areas where Solar energy can be utilized, apart from direct electrification are:

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Energy storage systems

Utilization of solar energy integrated with energy storage systems, such as batteries, ensures the energy supply round-the-clock. The battery energy storage systems can also support the utilities to improve the stability and reliability of the grid with a high penetration of solar energy systems.

Building integrated photovoltaics

The use of building integrated PV to develop solar facades and other architectural solutions can help to improve building energy efficiency while also generating clean energy for self-consumption.

Electric Vehicle

Solar power has a significant potential in the charging of electric vehicles which is set to be vital for the decarbonization in the transportation sector.

Green hydrogen

Solar energy can power electrolysis to produce green hydrogen, a clean fuel with various industrial and transportation applications which can reduce the GHG emission tremendously.

Solar water heating system

Integrating solar thermal collectors with water heating systems can reduce the energy consumption associated with heating water for domestic and commercial purposes.

Hybrid and round-the-clock renewable energy systems

Solar energy can be combined with other renewable energy resources or even with fossil fuel plants like to reduce carbon footprints. This approach takes advantage of the complementary nature of resources, ensuring an uninterrupted power supply across different weather conditions.

Solar PV is a versatile technology that can be deployed from Watts to GW scale depending upon the application. Solar can also be deployed in remote regions with no or limited grid connectivity, providing clean energy in regions that would otherwise continue to rely on traditional non-renewable sources. The versatility, mature ecosystem, and sector coupling opportunities associated with solar energy underline its credentials as the go-to technology for the energy transition.

Various details concerning the evolution of solar energy technologies, manufacturing processes and utilization of solar energy for various purposes, advancement in recent years and the future of technologies shall be discussed in the later chapters.

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.

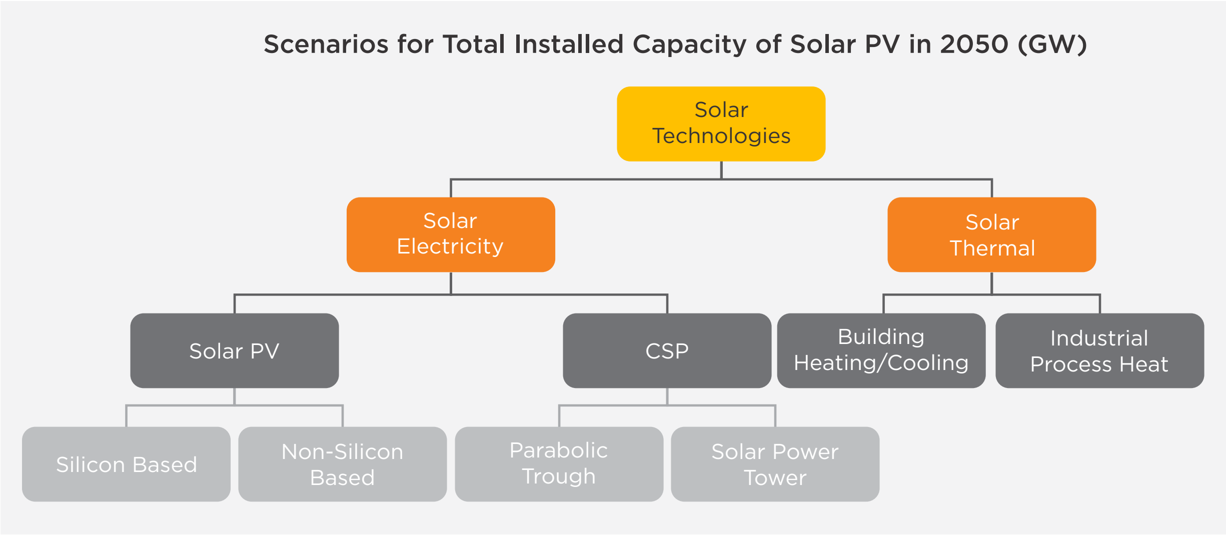


Figure 11: Different Solar Technologies

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.

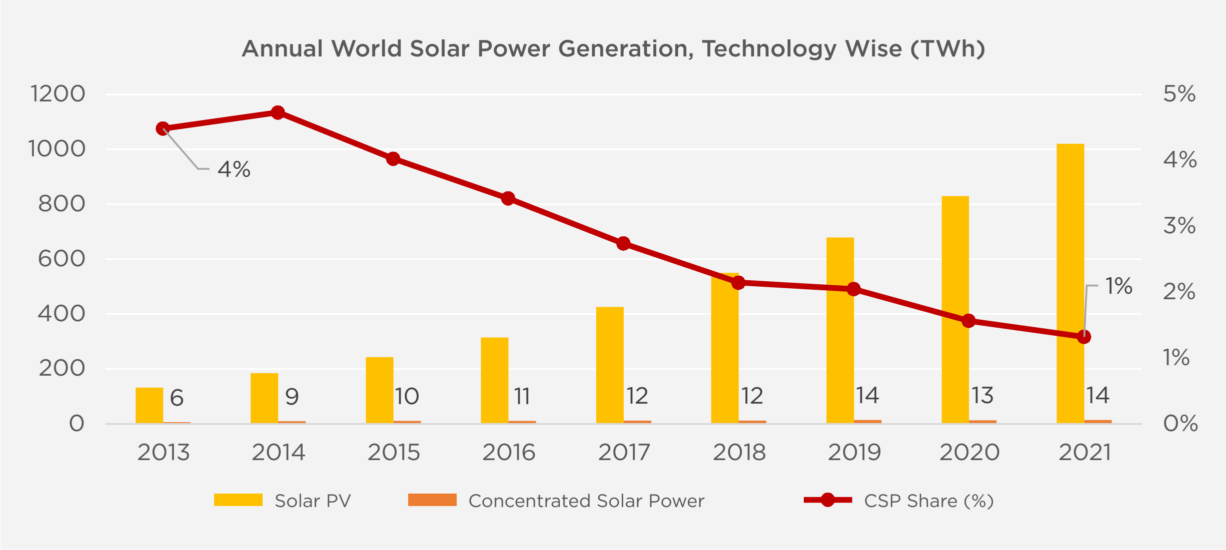


Figure 12: Annual Solar Power Generation Technologies

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.

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

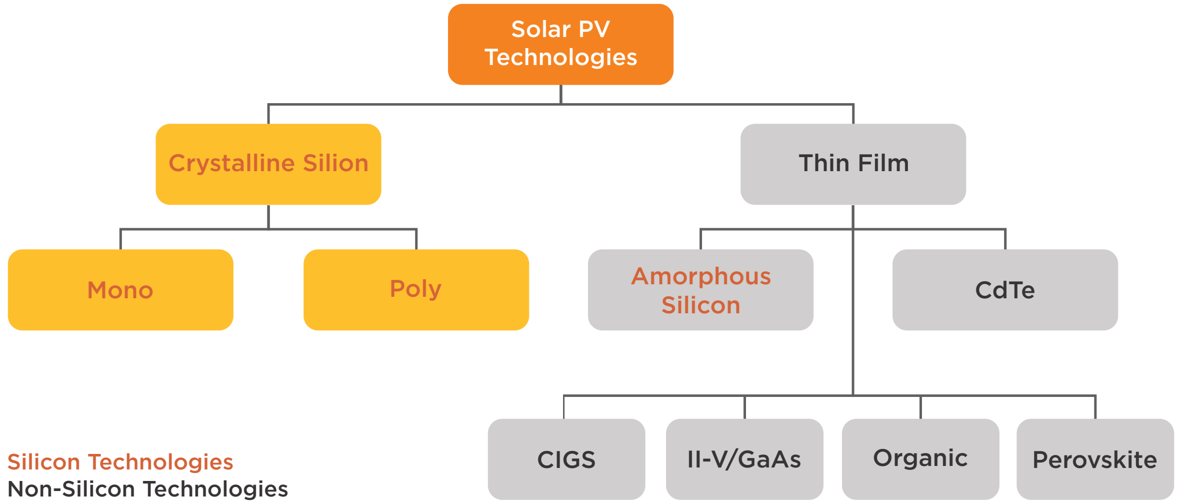


Figure 13: Different PV Technologies

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.

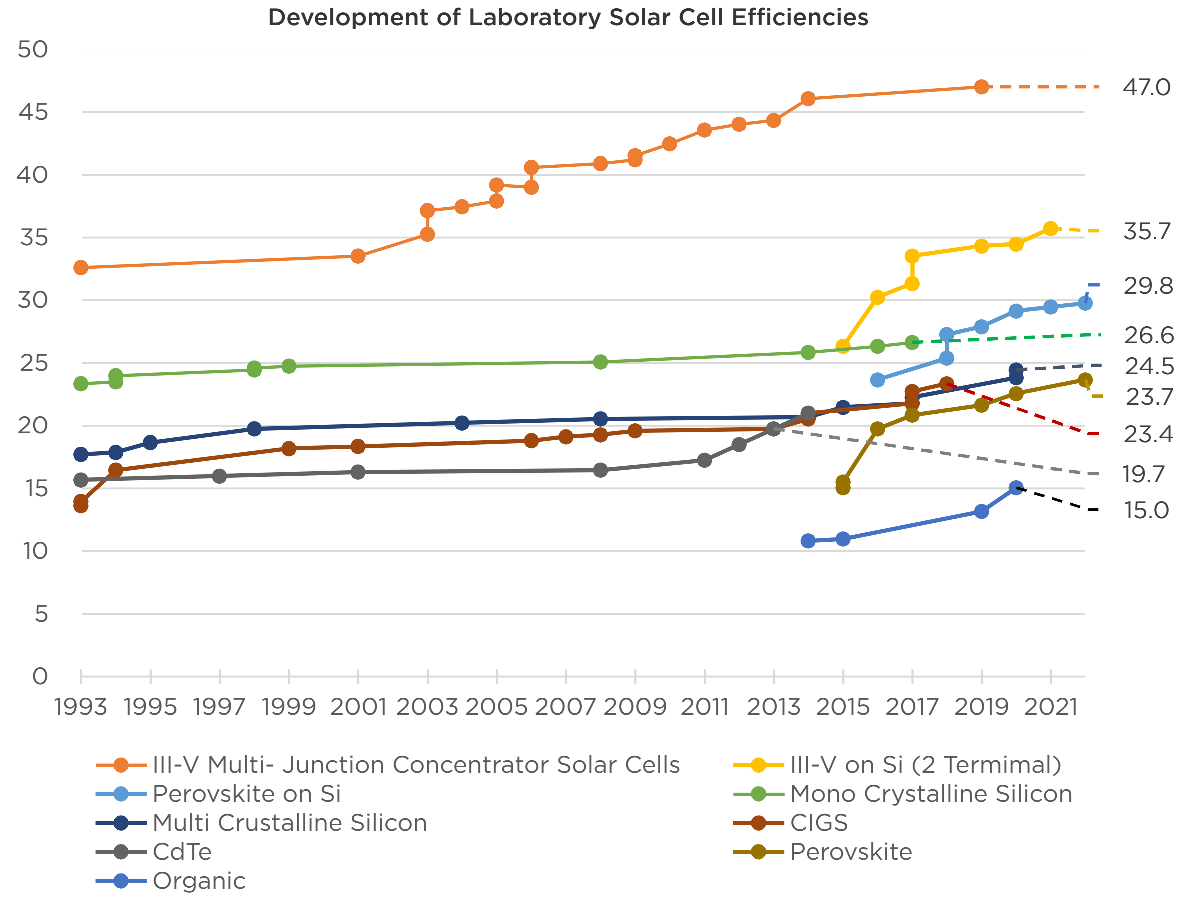


Figure 14: Solar Cell Efficiency at Laboratory Level

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.

[5] *Delft University- Database*

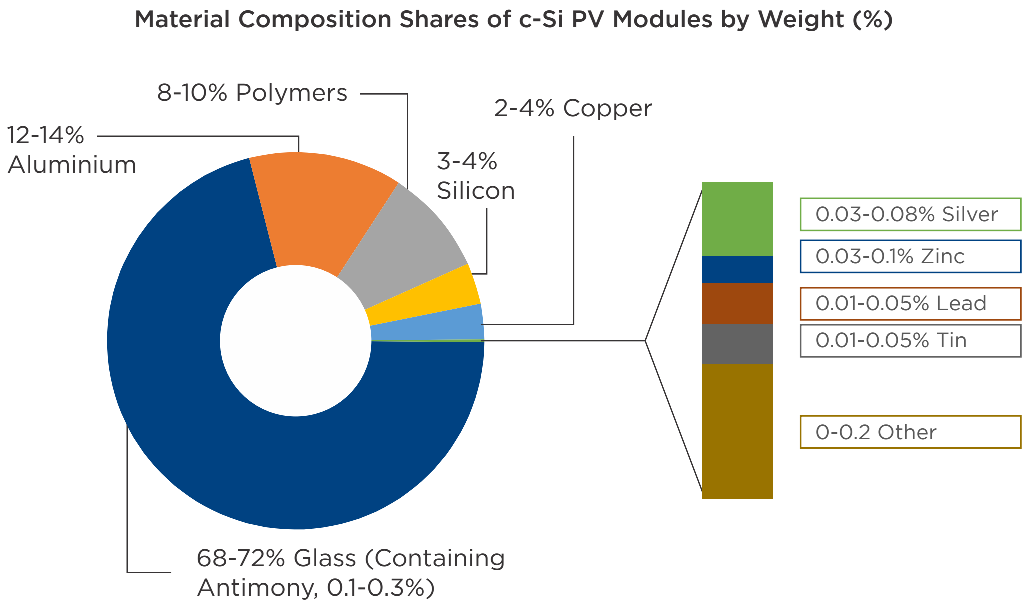


Figure 15: Material Composition Shares of c-Si PV Modules by Weight (%)

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.

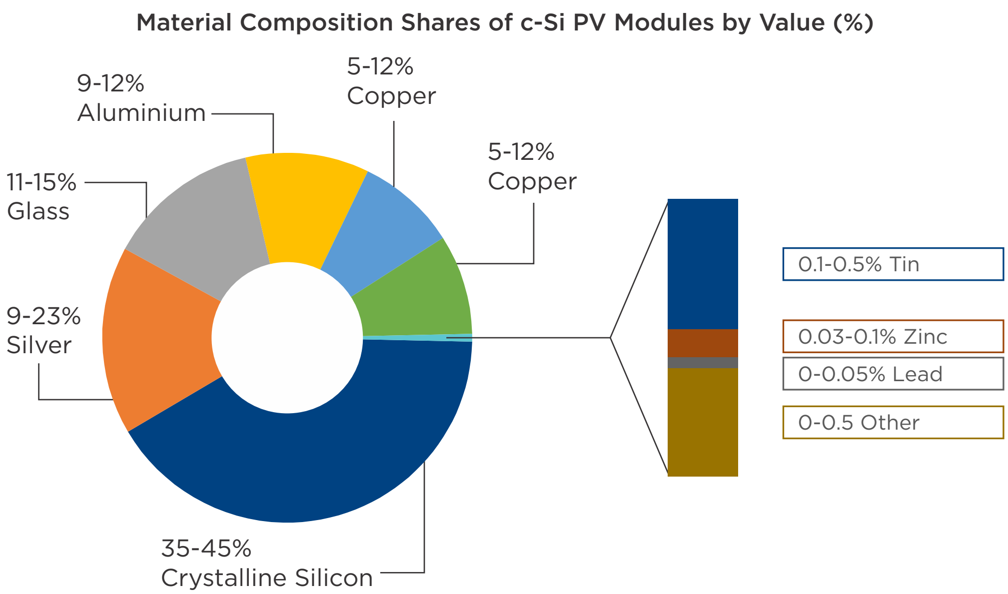


Figure 16: Material Composition Shares of c-Si PV Modules by Value (%)

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.

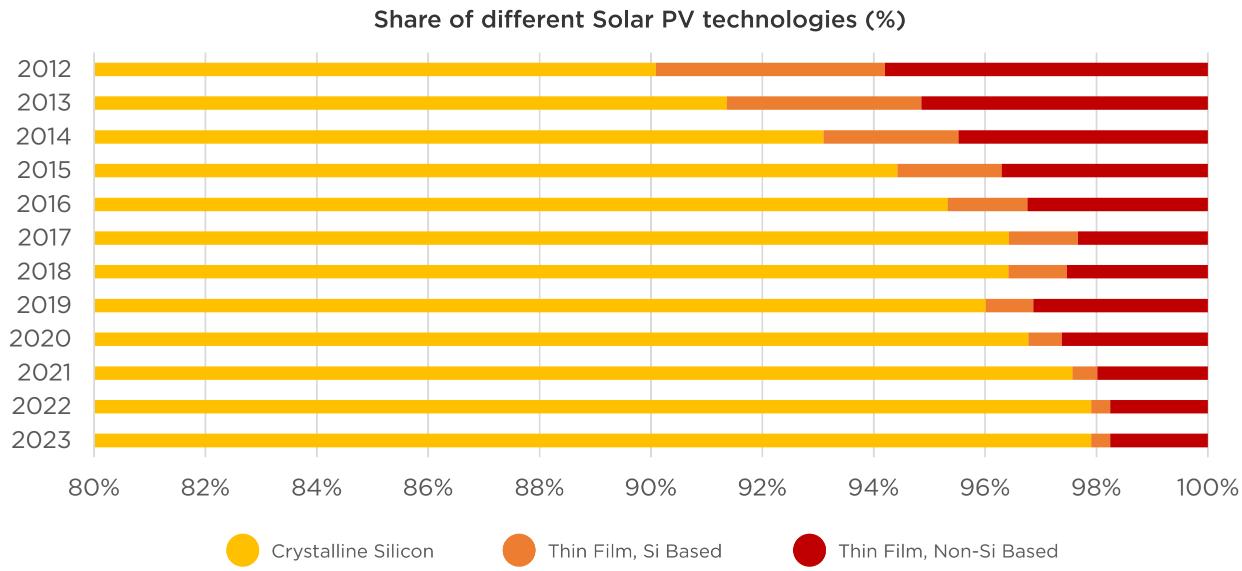


Figure 17: Share of Different Solar PV Technologies (%)

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.

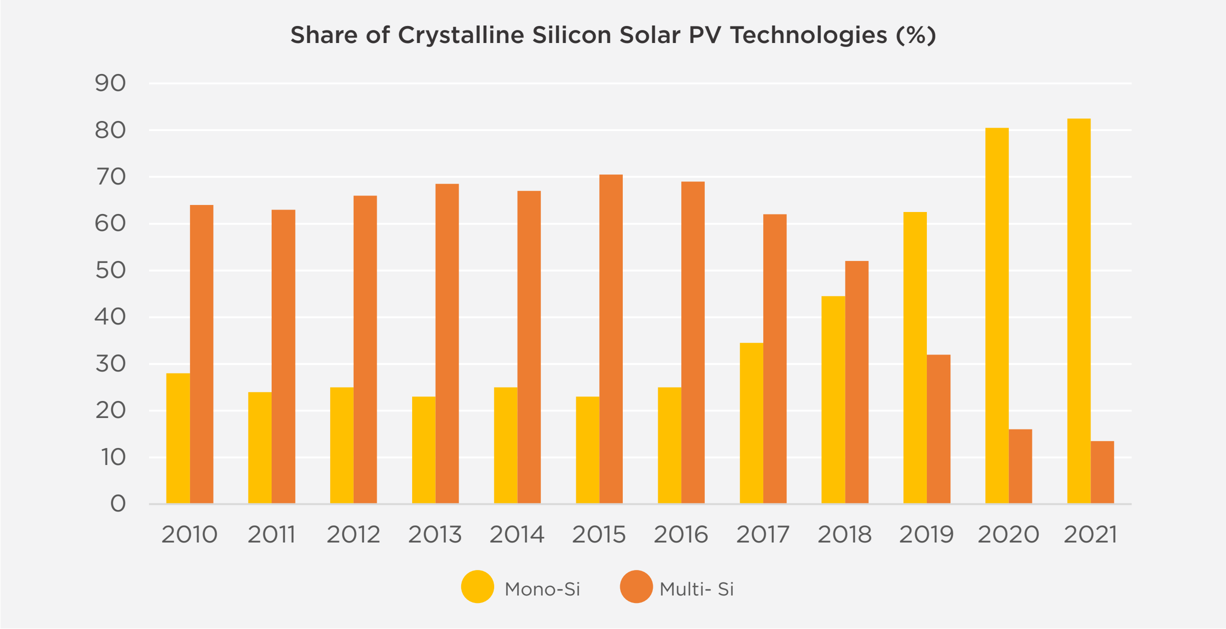


Figure 18: Share of Crystalline Silicon Solar PV Technologies

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.

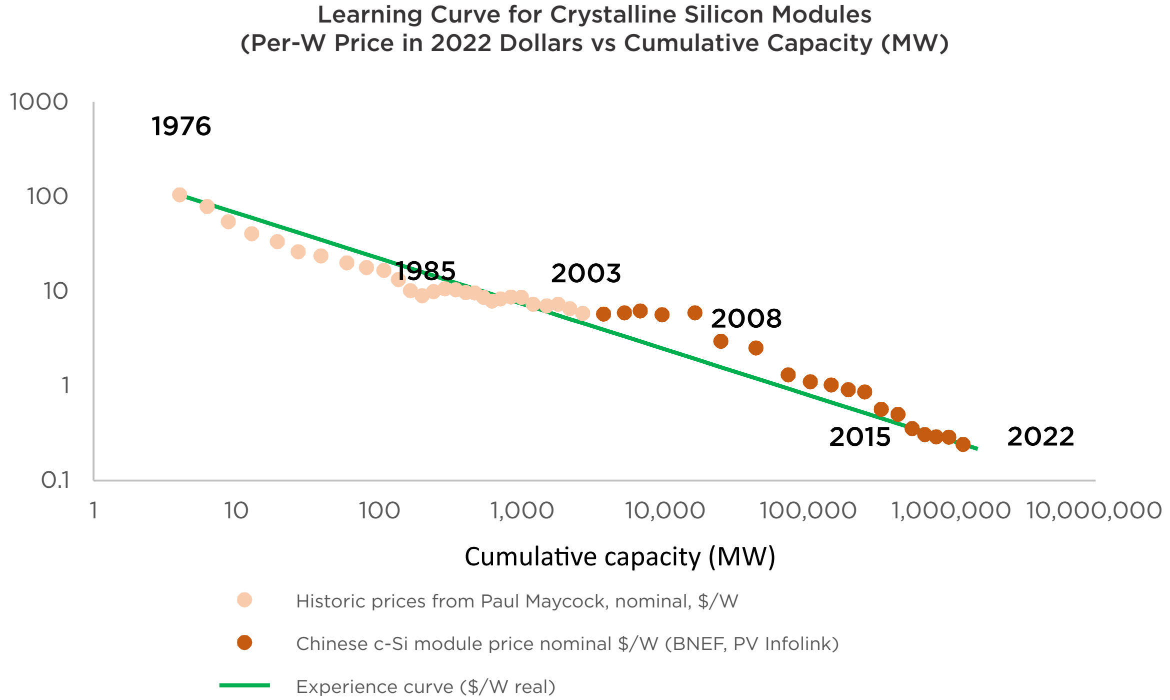


Figure 19: Learning Cure

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.

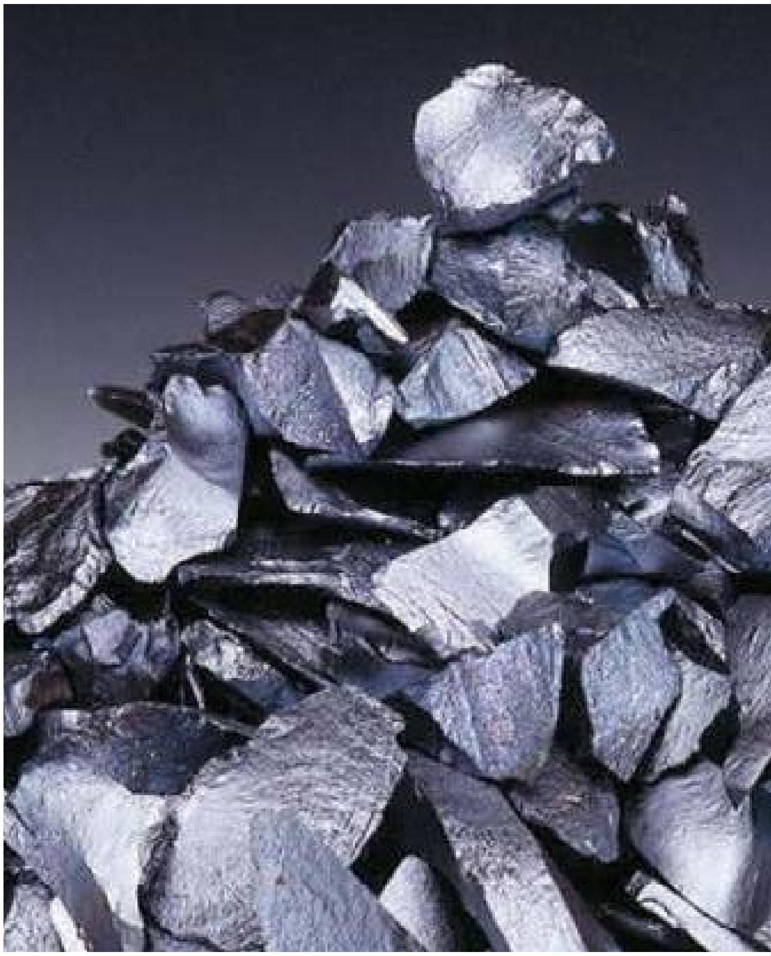
3.2. Crystalline Silicon Solar PV Technologies

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.

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

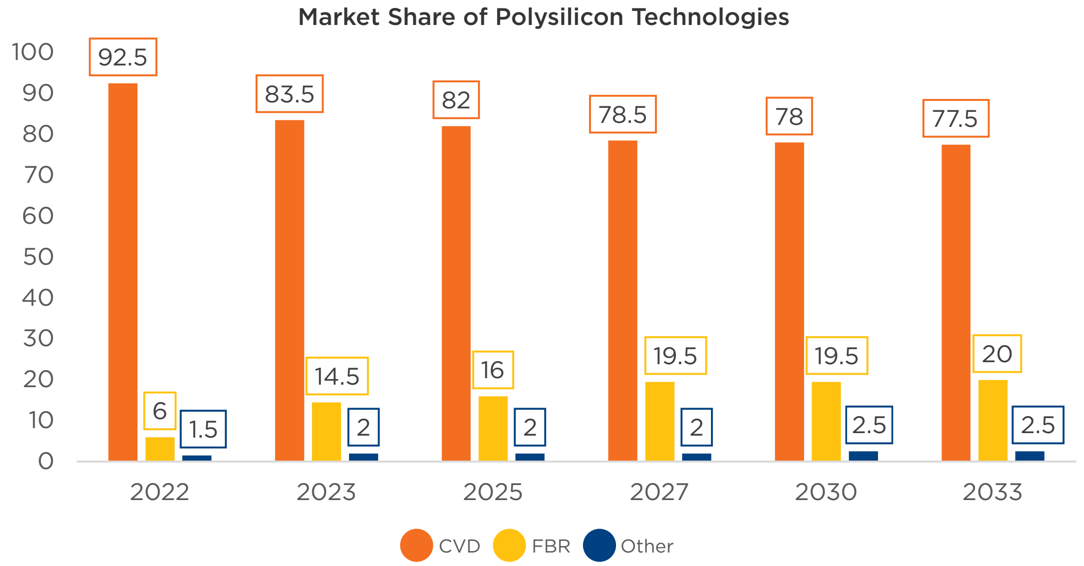


Figure 20: Market Share of Polysilicon Manufacturing Technologies

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.

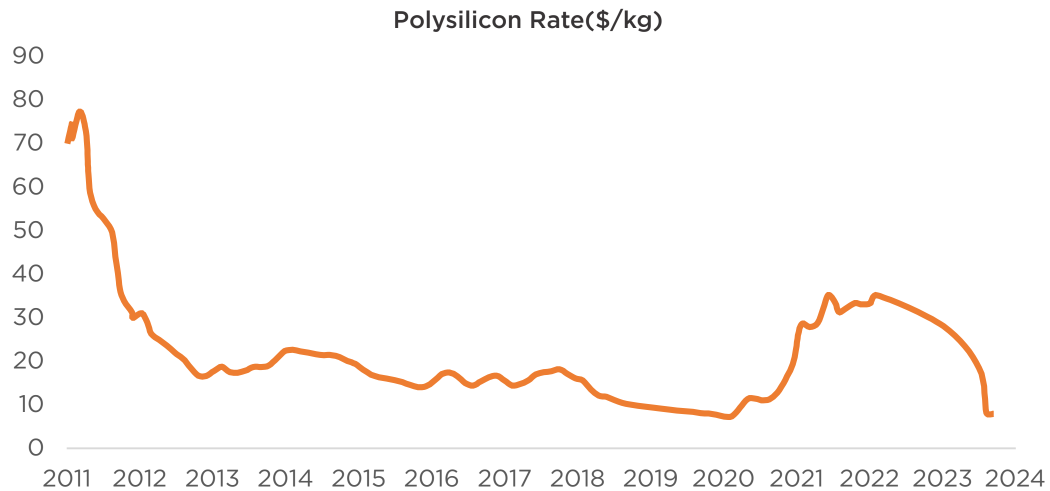


Figure 21: Polysilicon Rate

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.

[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.*

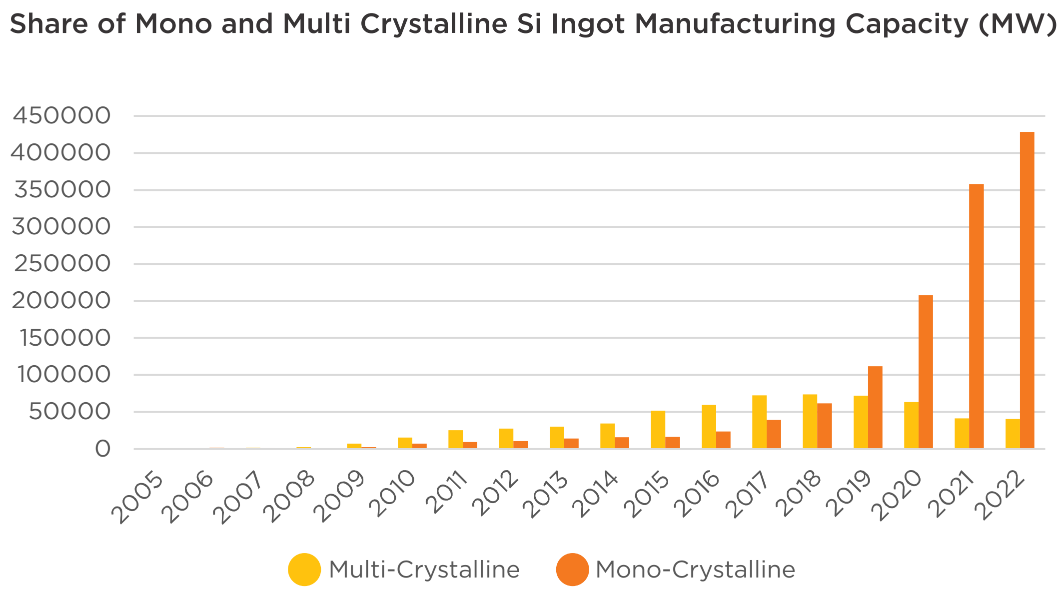


Figure 22: Share of Mono and Multi Crystalline Si Ingot Manufacturing Capacity (MW)

Source: BNEF Database- ISA Analysis

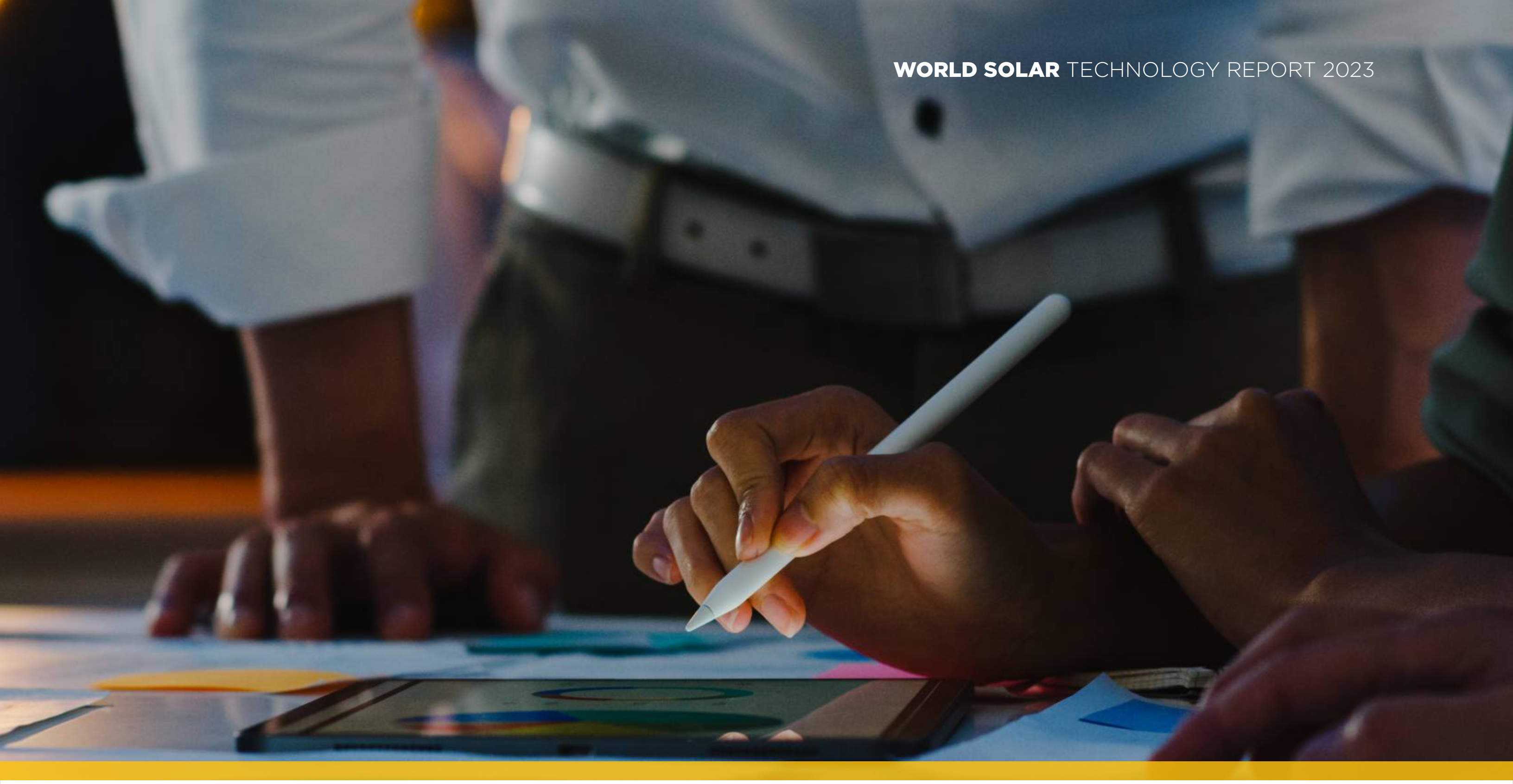
As shown in the graph, monocrystalline silicon is now by far the dominant technology being utilized for solar cell production, while multi crystalline silicon manufacturing capacity has stagnated and started to fall as the technology which is no longer the preferred material for crystalline silicon cells. 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

[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.

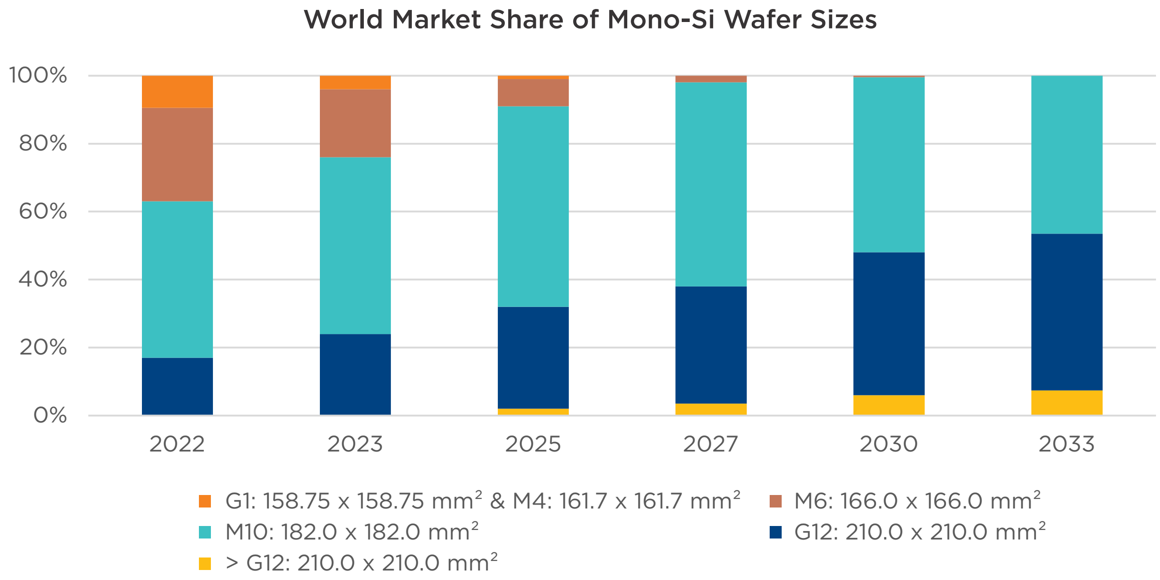


Figure 23: World Market Share of Mono-Si Wafer Sizes

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.

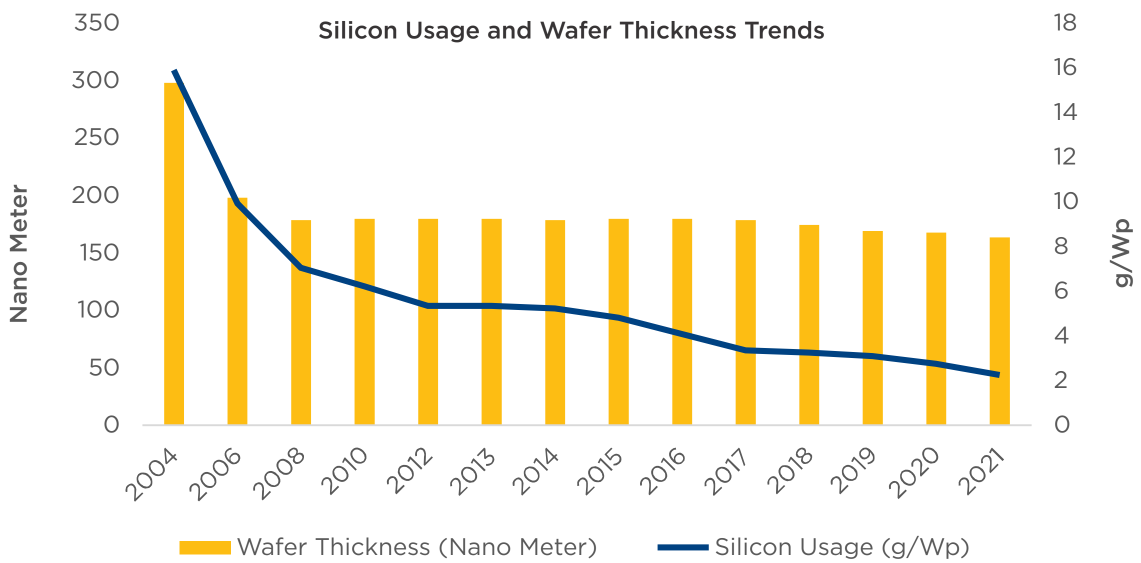


Figure 24: Silicon Usage and Wafer Thickness Trends

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.

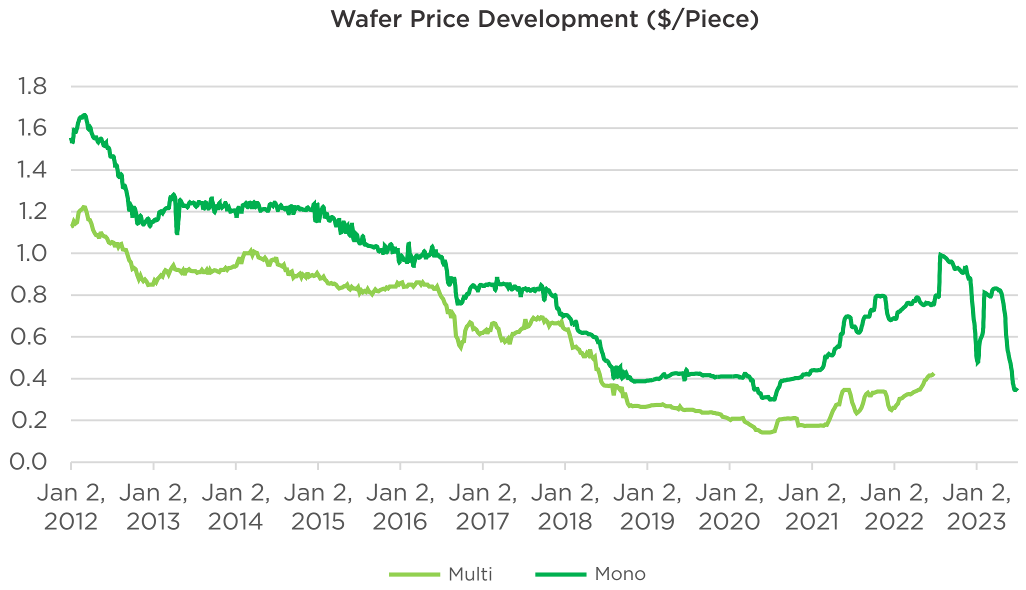


Figure 25: Wafer Price Development ($/Piece)

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.

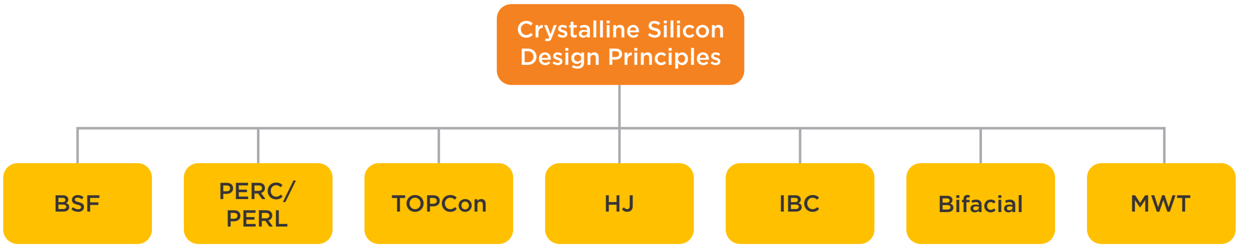


Figure 26: Various Crystalline Silicon Design Principles

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.

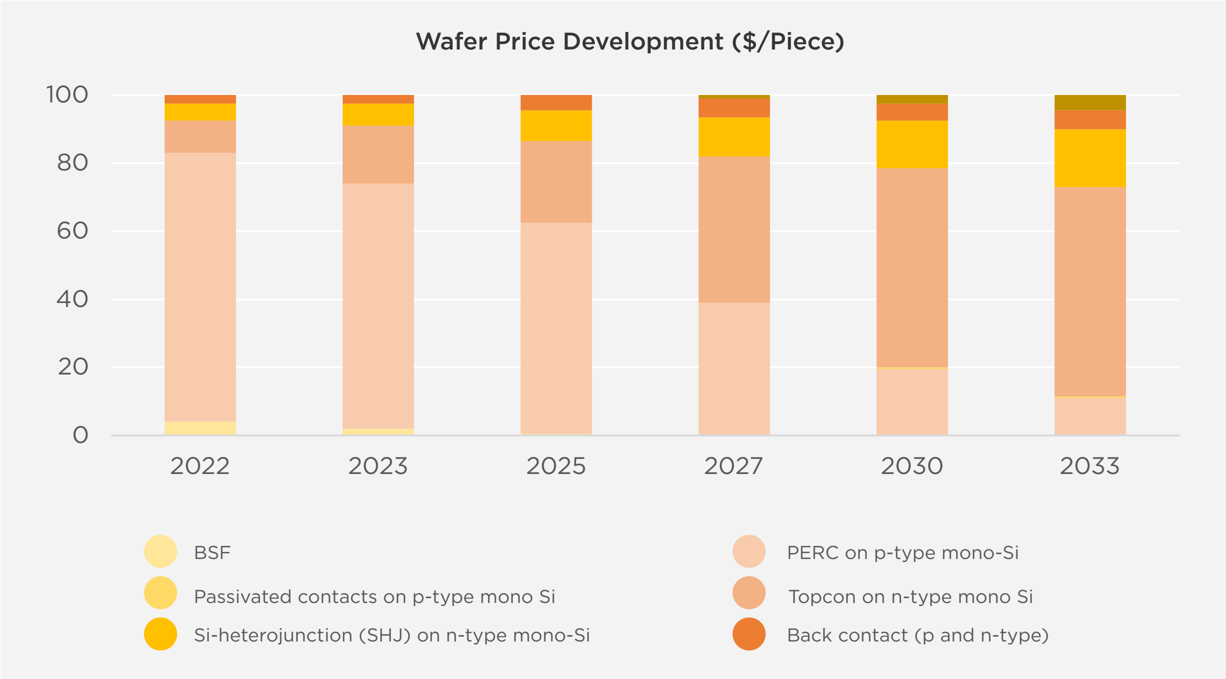


Figure 27: World Market Share of c-Si Cell Architecture (%)

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.

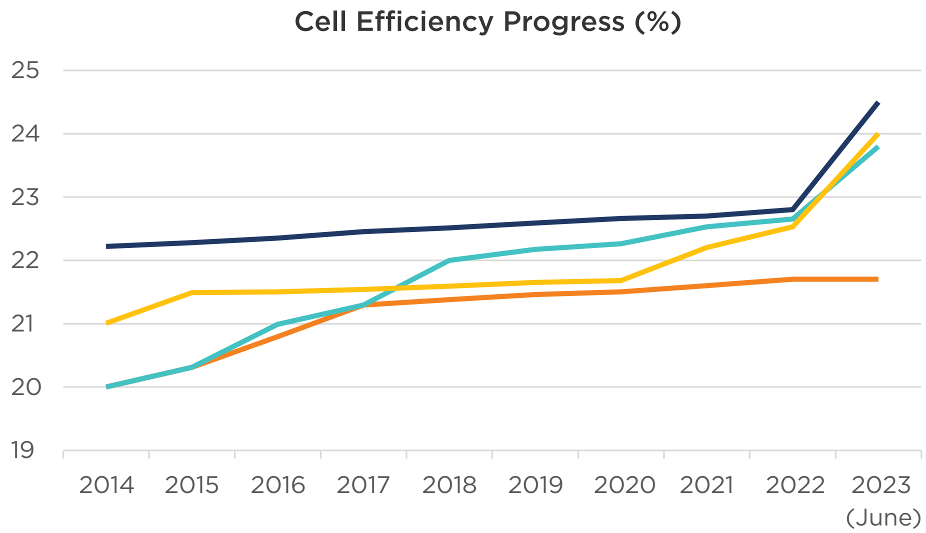


Figure 28: Cell Efficiency Progress

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.

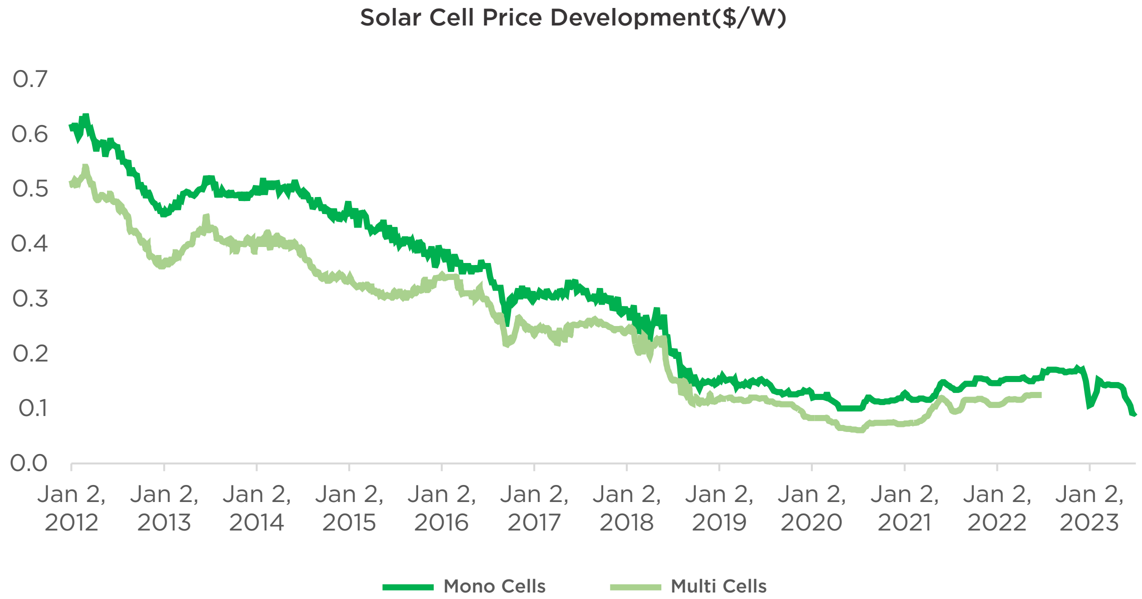


Figure 29: Solar Cell Price Development

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.

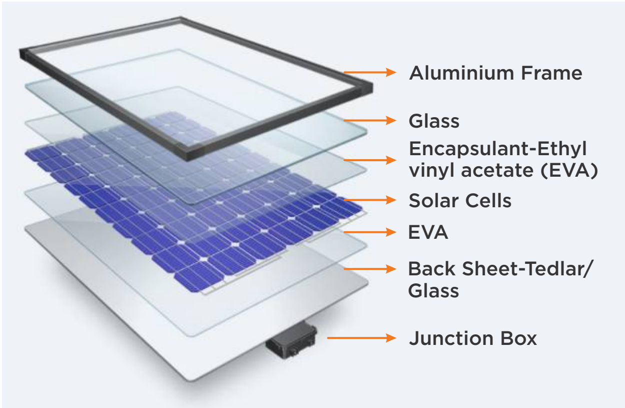


Figure 30: Crystalline Silicon PV Module Evolution

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.

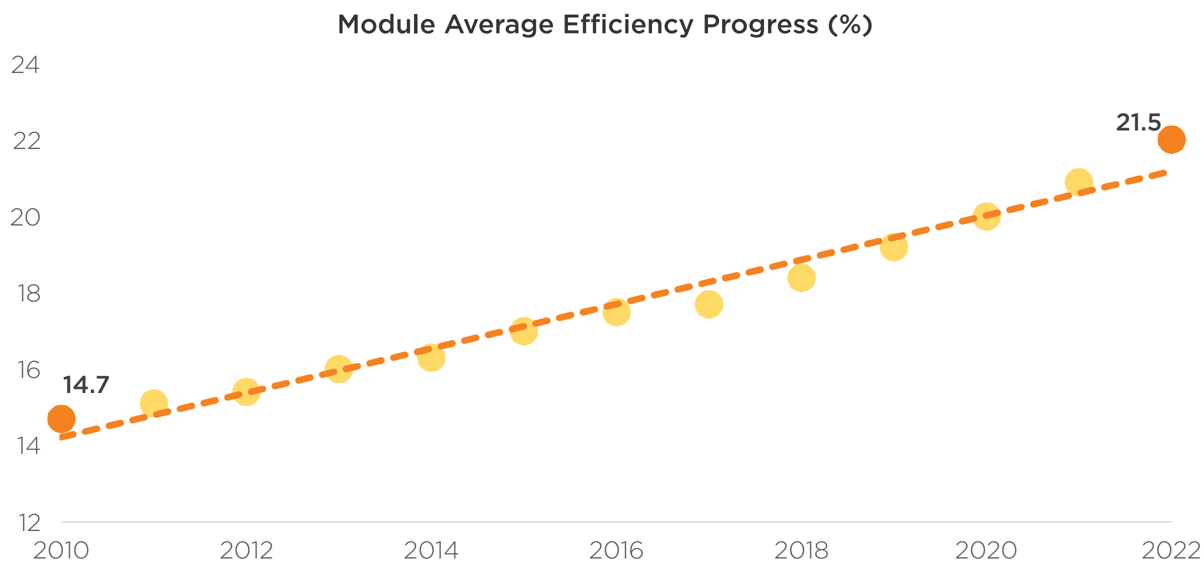


Figure 31: PV Module Average Efficiency Progress

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.

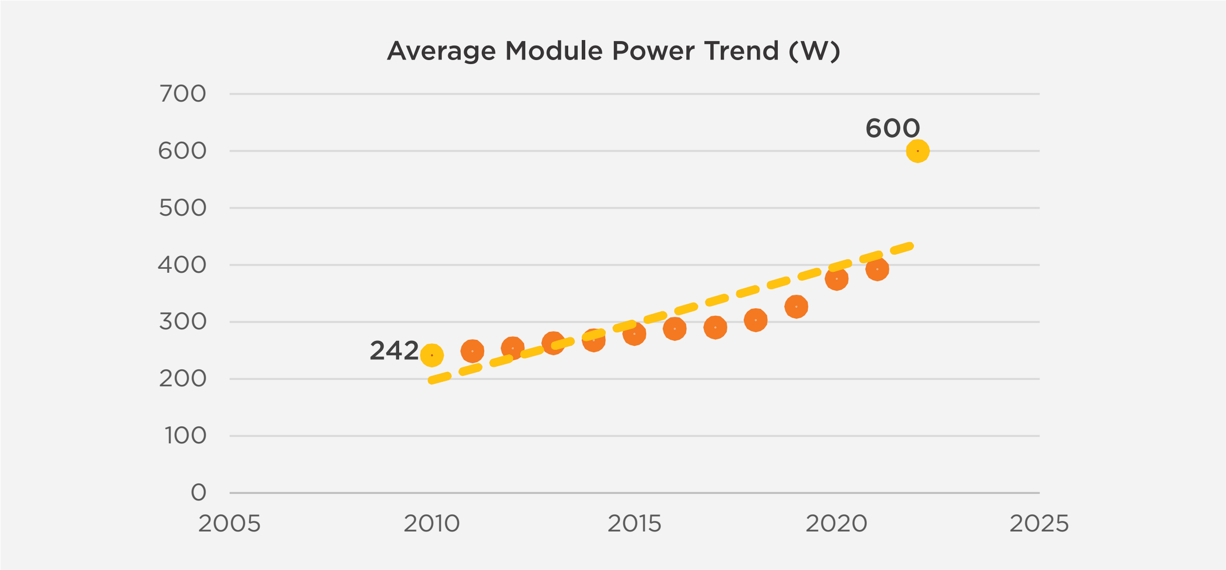


Figure 32: Average Module Power Trend

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.

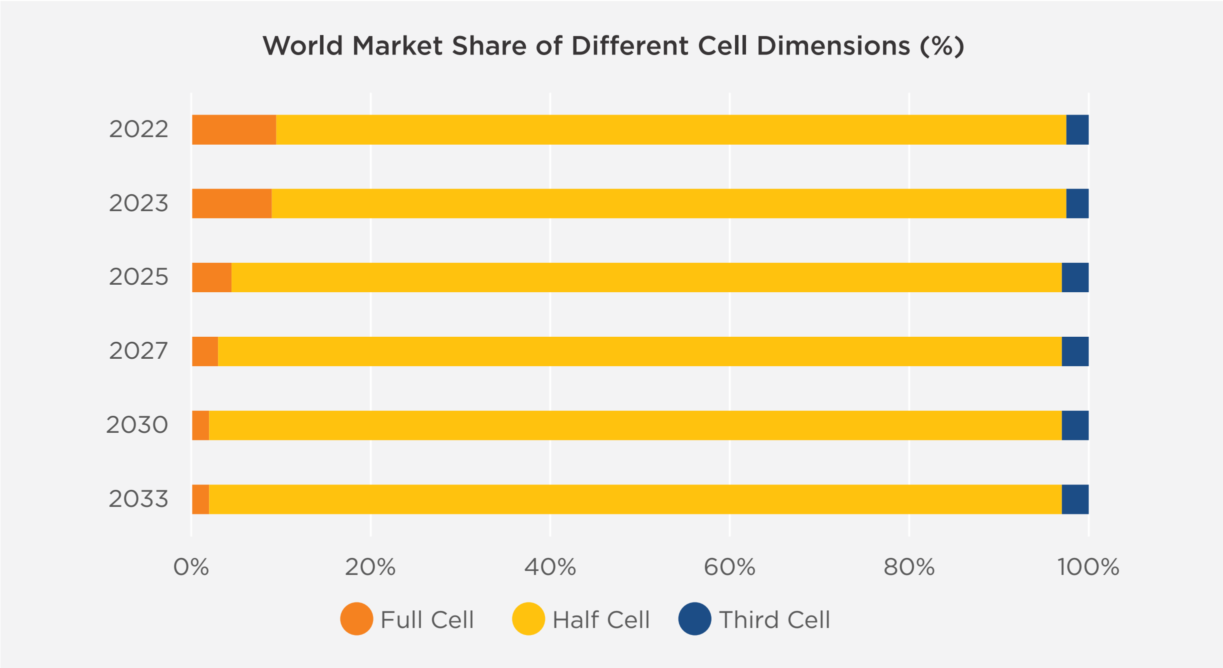


Figure 33: World Market Share of Sliced Cells

Source: ITRPV- 2023

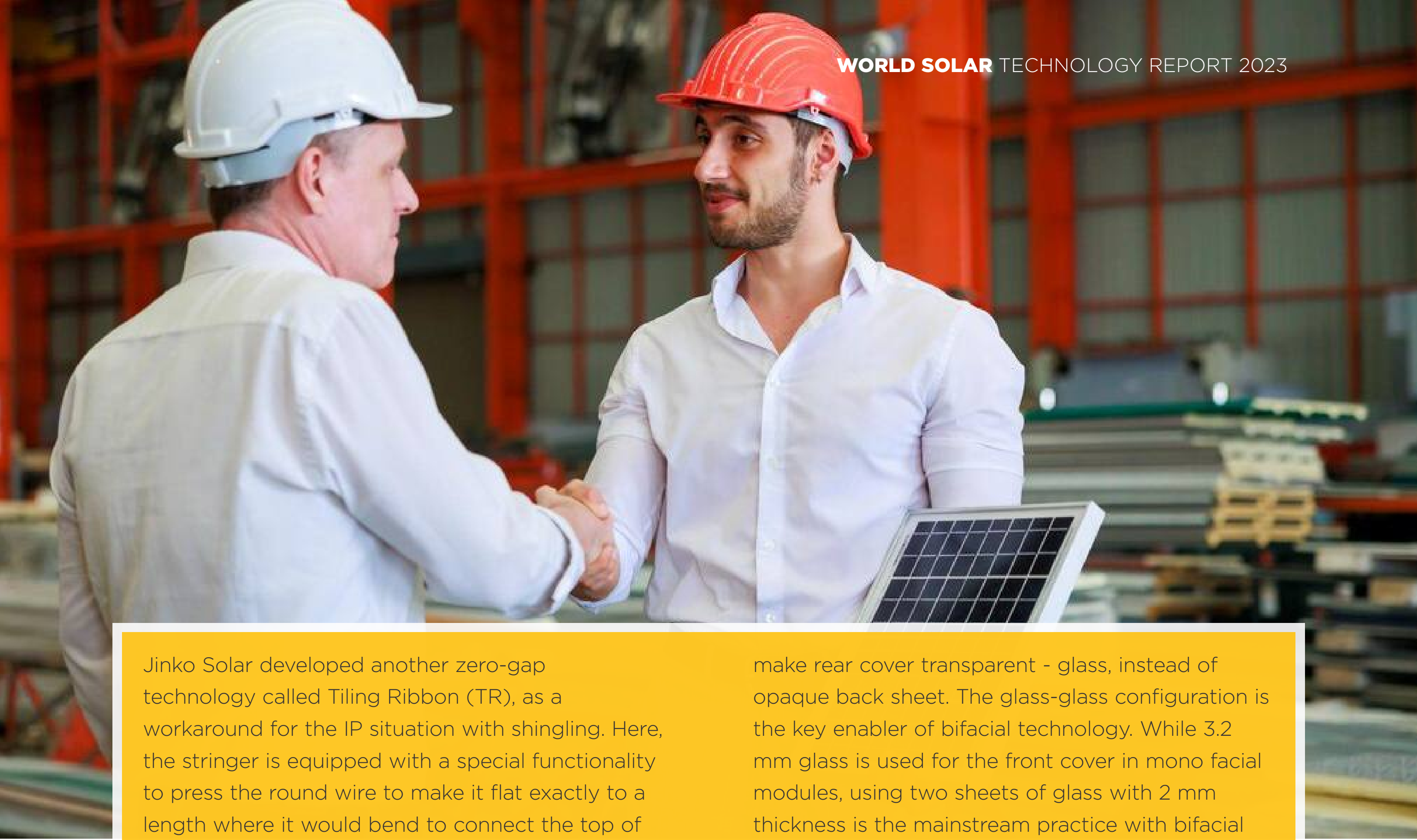
As displayed in the figure, the half-cells modules are the dominating mainstream today for cells < M10 and expected to continue for the next 10 years. Market share of full cell technology will be reduced to below 2% in 2023 which will be used for IBC and in special module applications. Third and quarter 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.

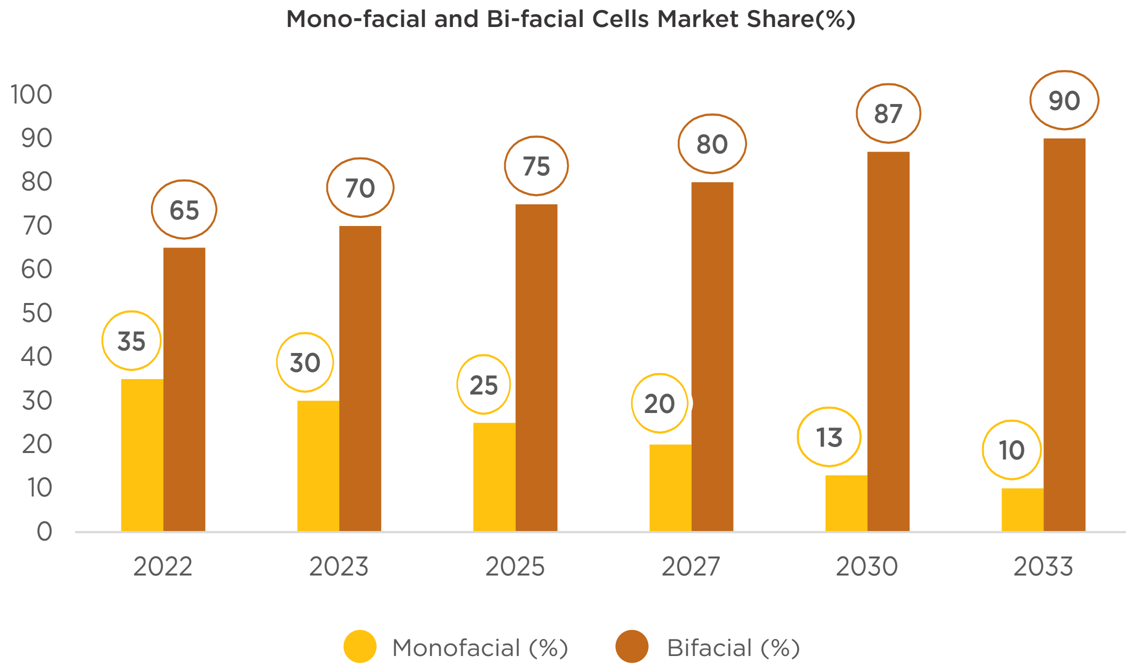


Figure 34: Mono-facial and Bi-facial Cells Market Share

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.

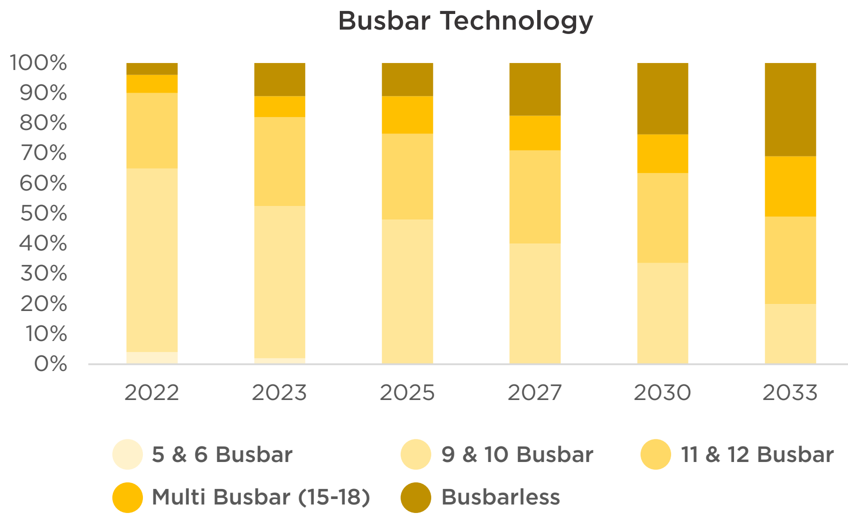


Figure 35: Busbar Technology

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.

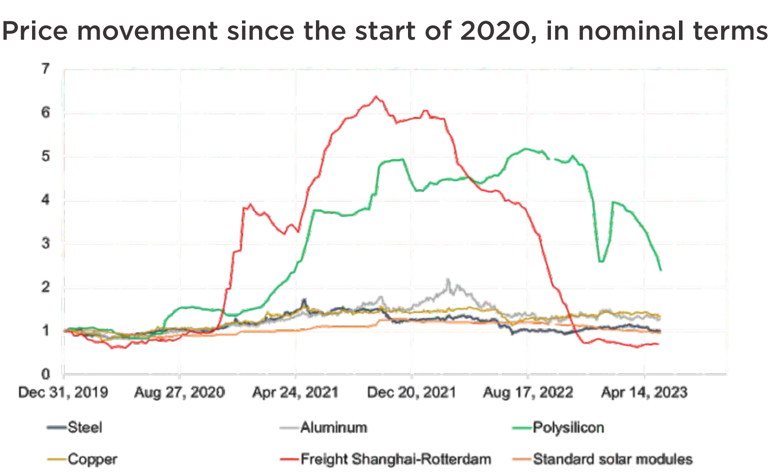


Figure 36: Price Movement of Solar Modules

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.

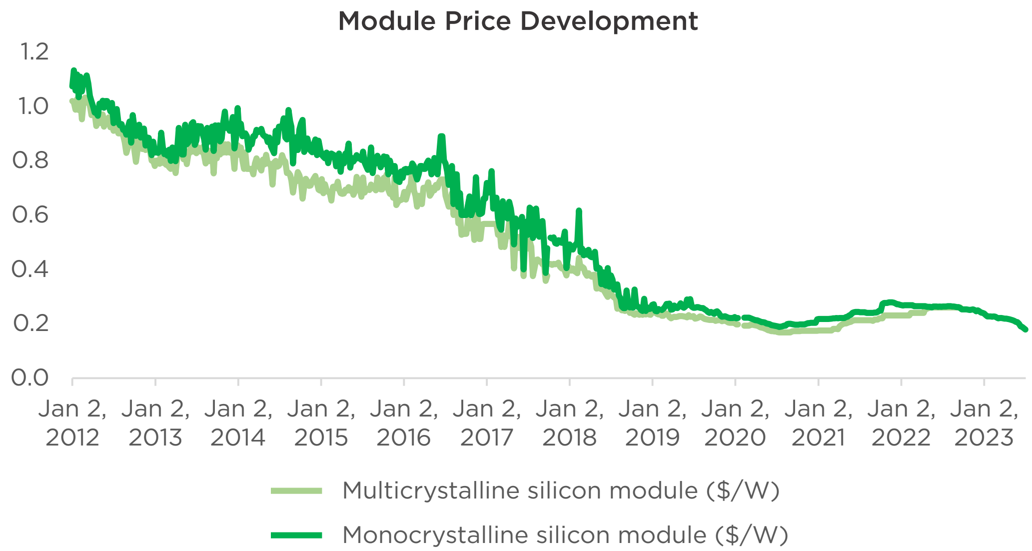


Figure 37: Module Price Development

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

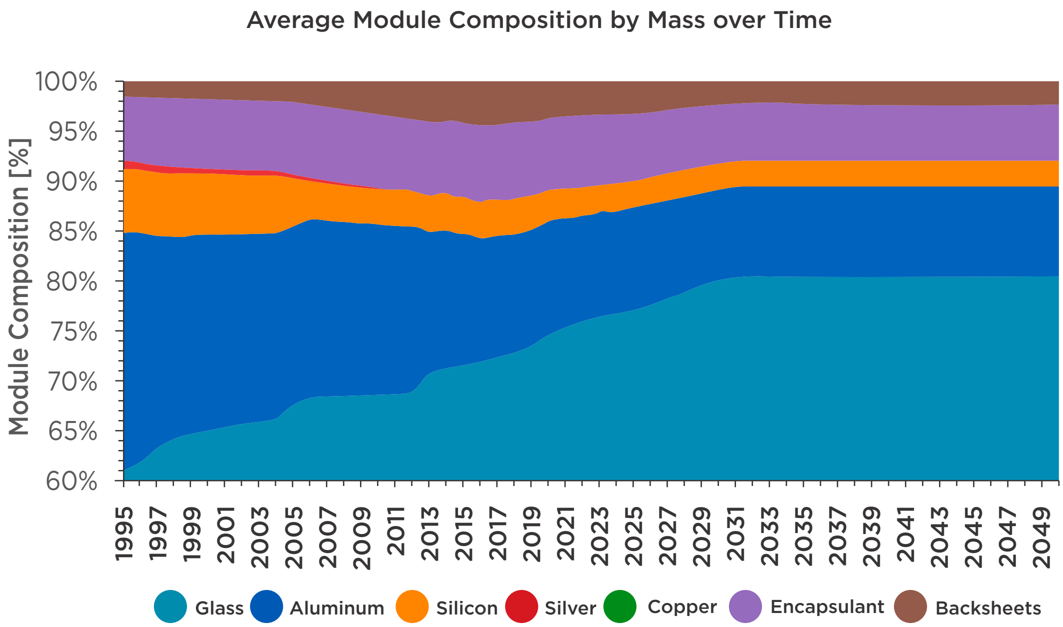


Figure 38: Average Module Composition by Mass over Time

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.

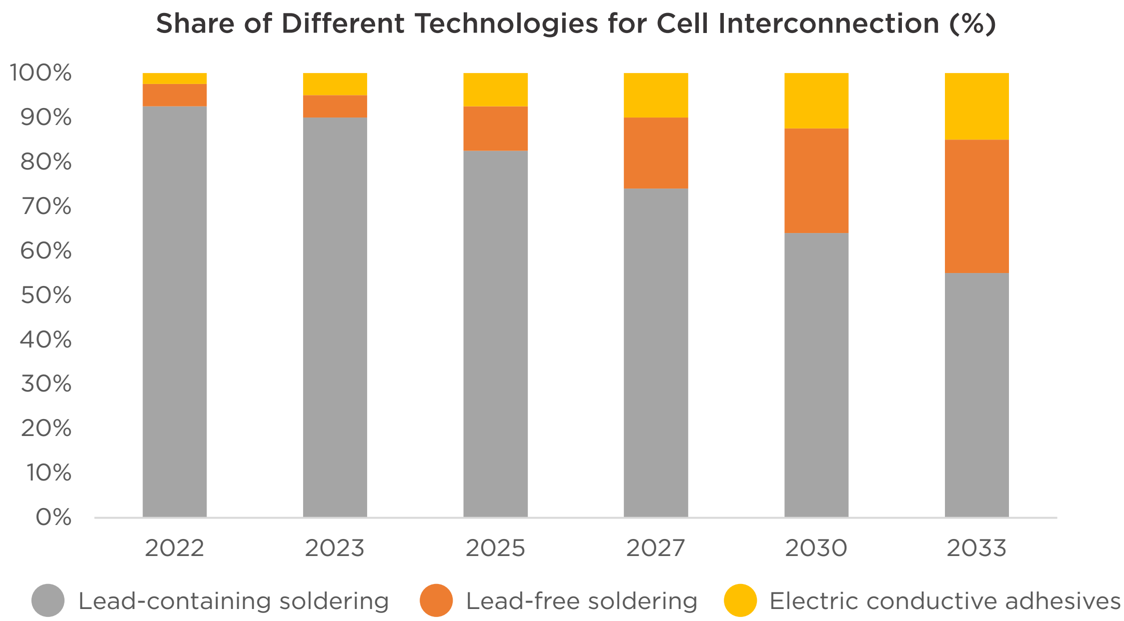


Figure 39: Share of Different Technologies for Cell Interconnection

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.

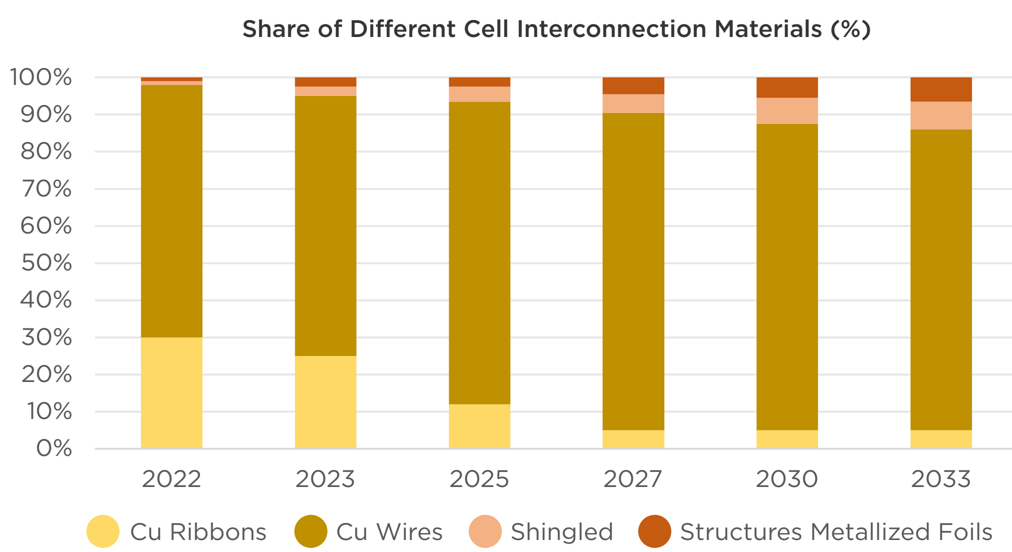


Figure 40: Share of Different Cell Interconnection Materials

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.

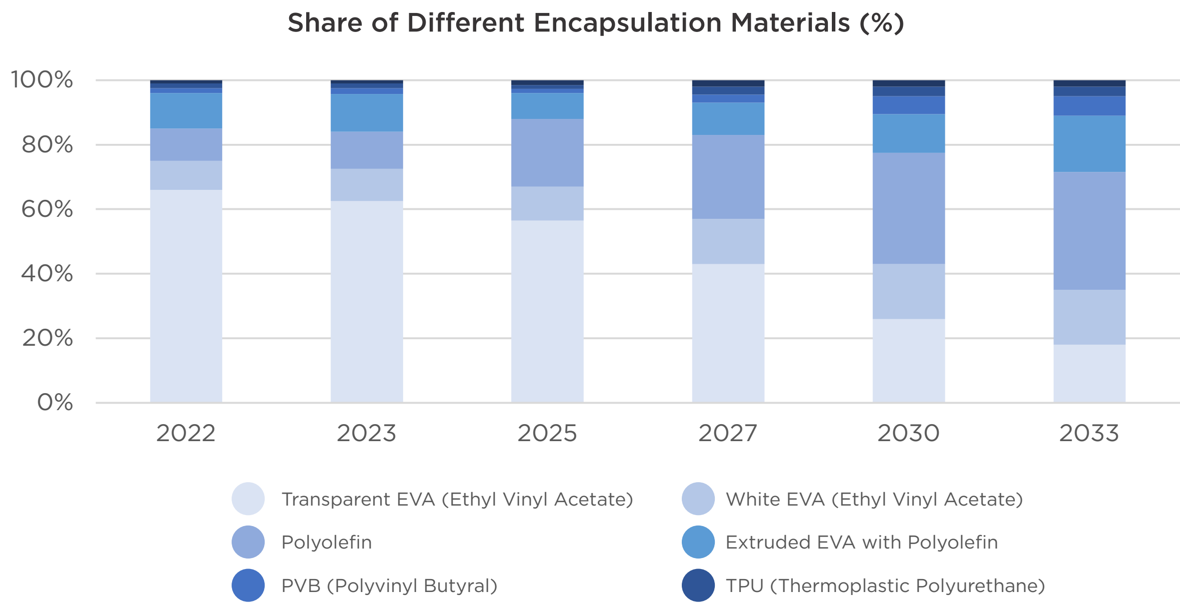


Figure 41: Share of Different Encapsulation Materials

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.

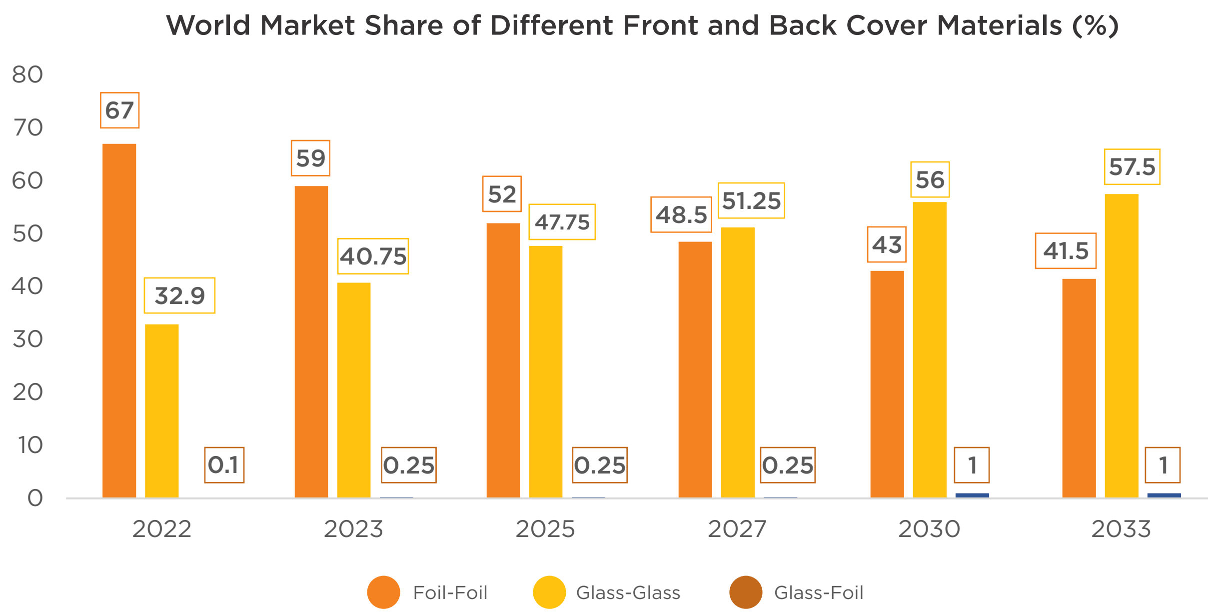


Figure 42: World Market Share of Different Front and Back Cover Materials

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.

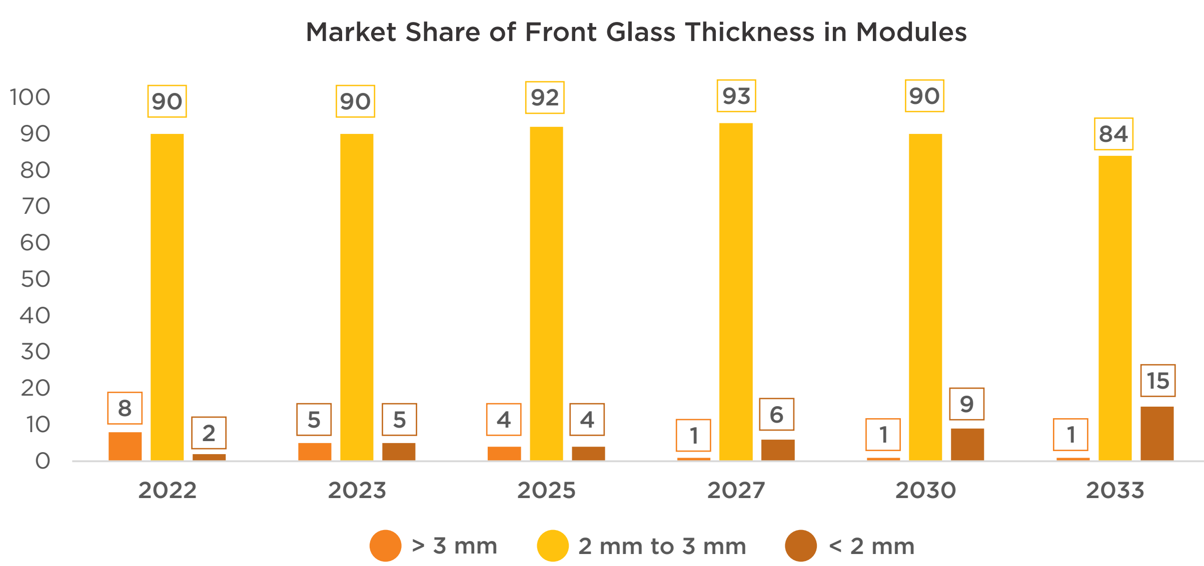


Figure 43: Market Share of Front Glass Thickness in Modules

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.

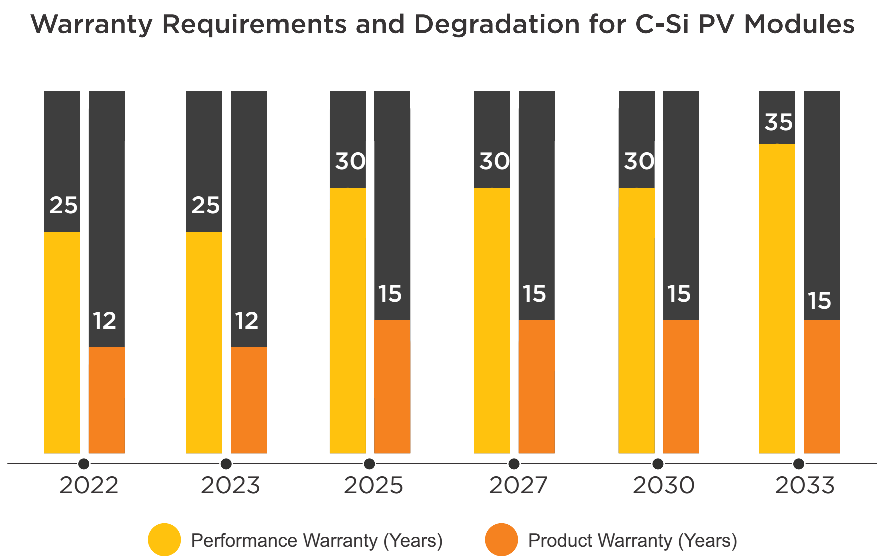


Figure 44: Warranty Details

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.

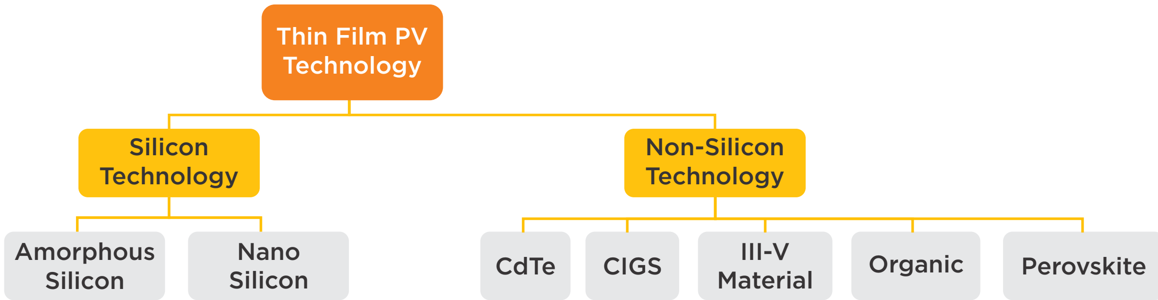


Figure 45: Overview of Thin Film Technology

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.

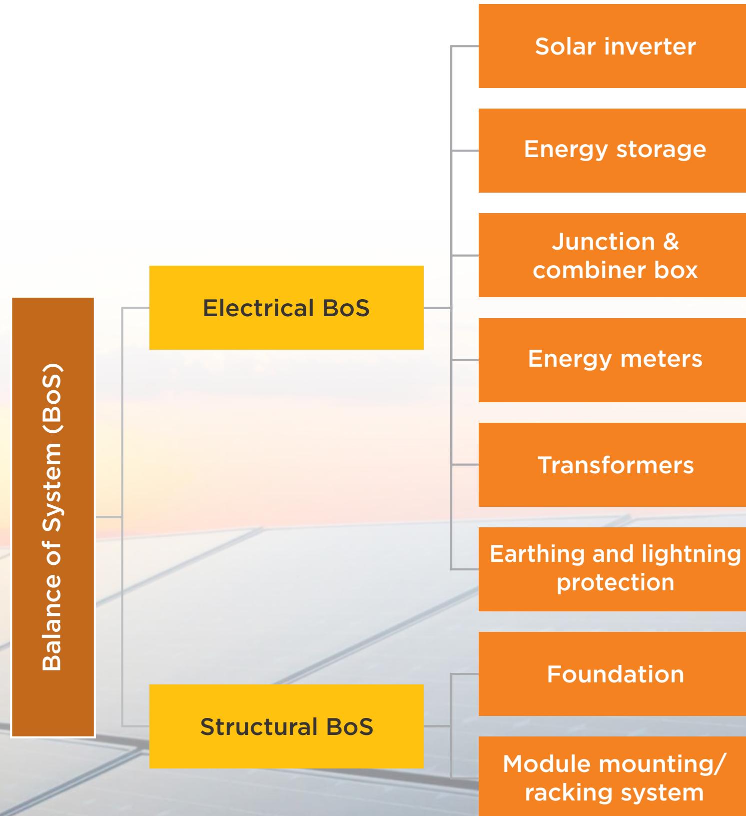


Figure 46: Balance of System

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.

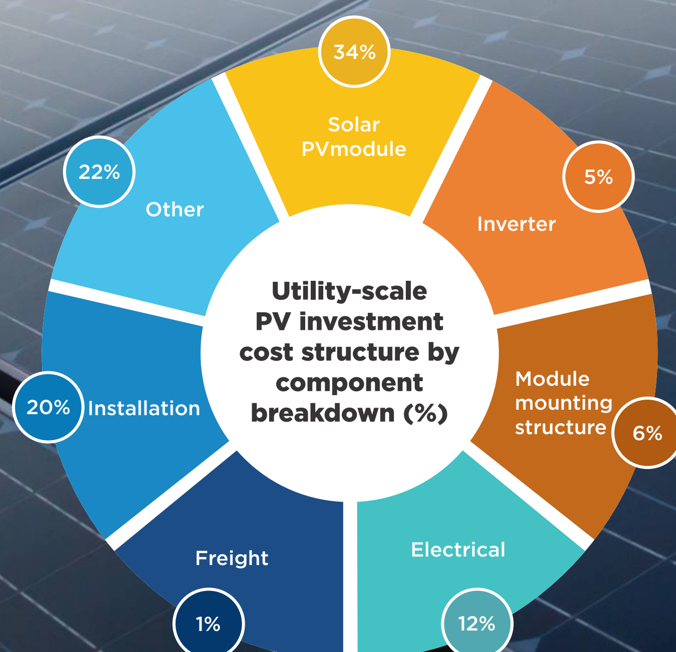


Figure 47: Utility-scale PV investment cost structure by component breakdown (%)

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.

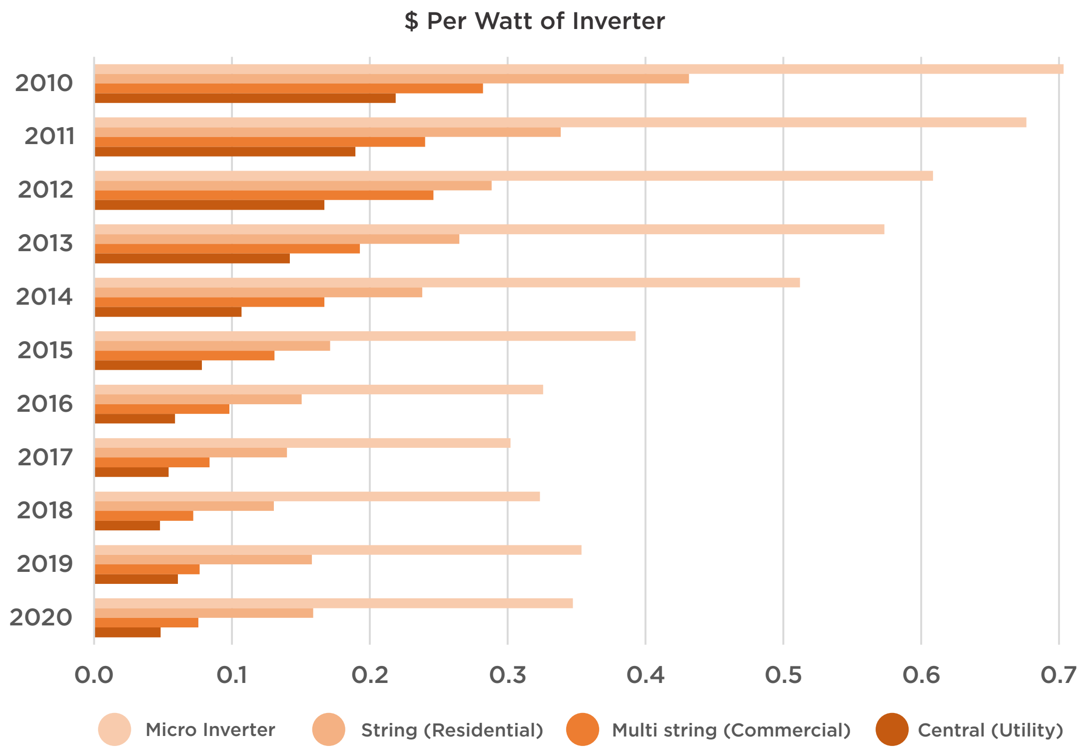


Figure 48: Cost of Inverter ($/W)

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.

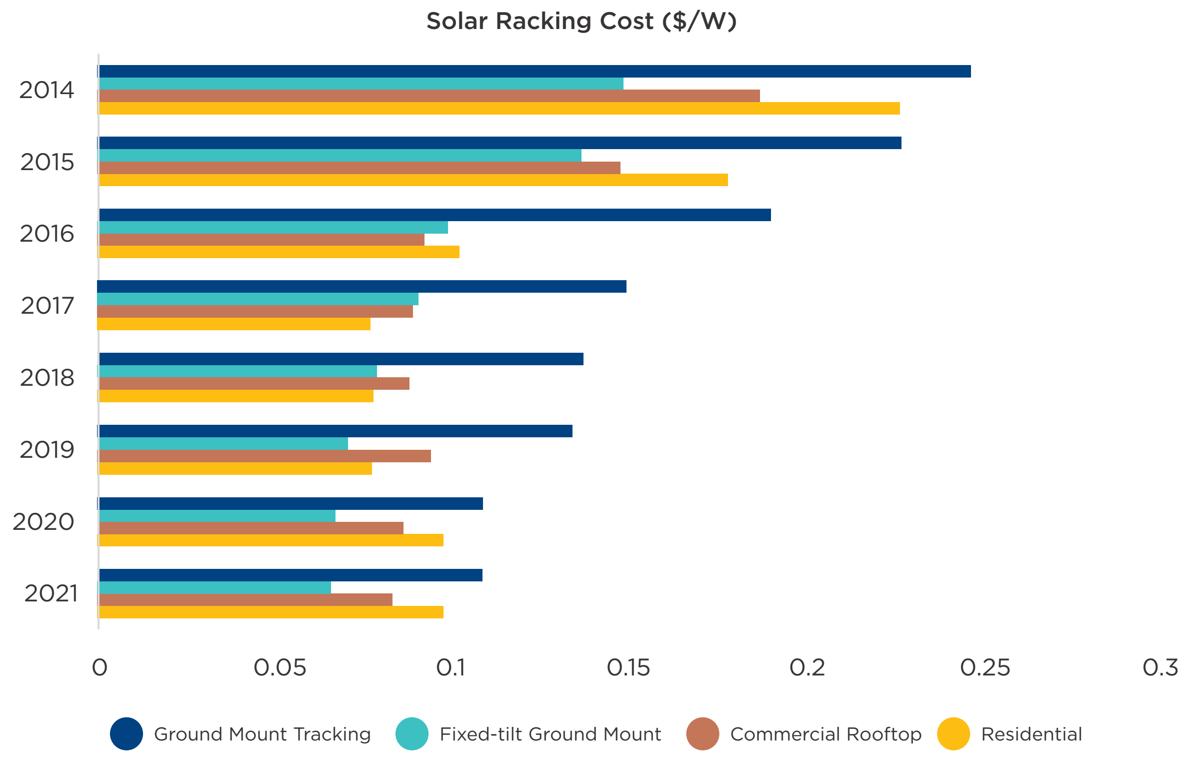


Figure 49: Solar Racking Cost ($/W)

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.

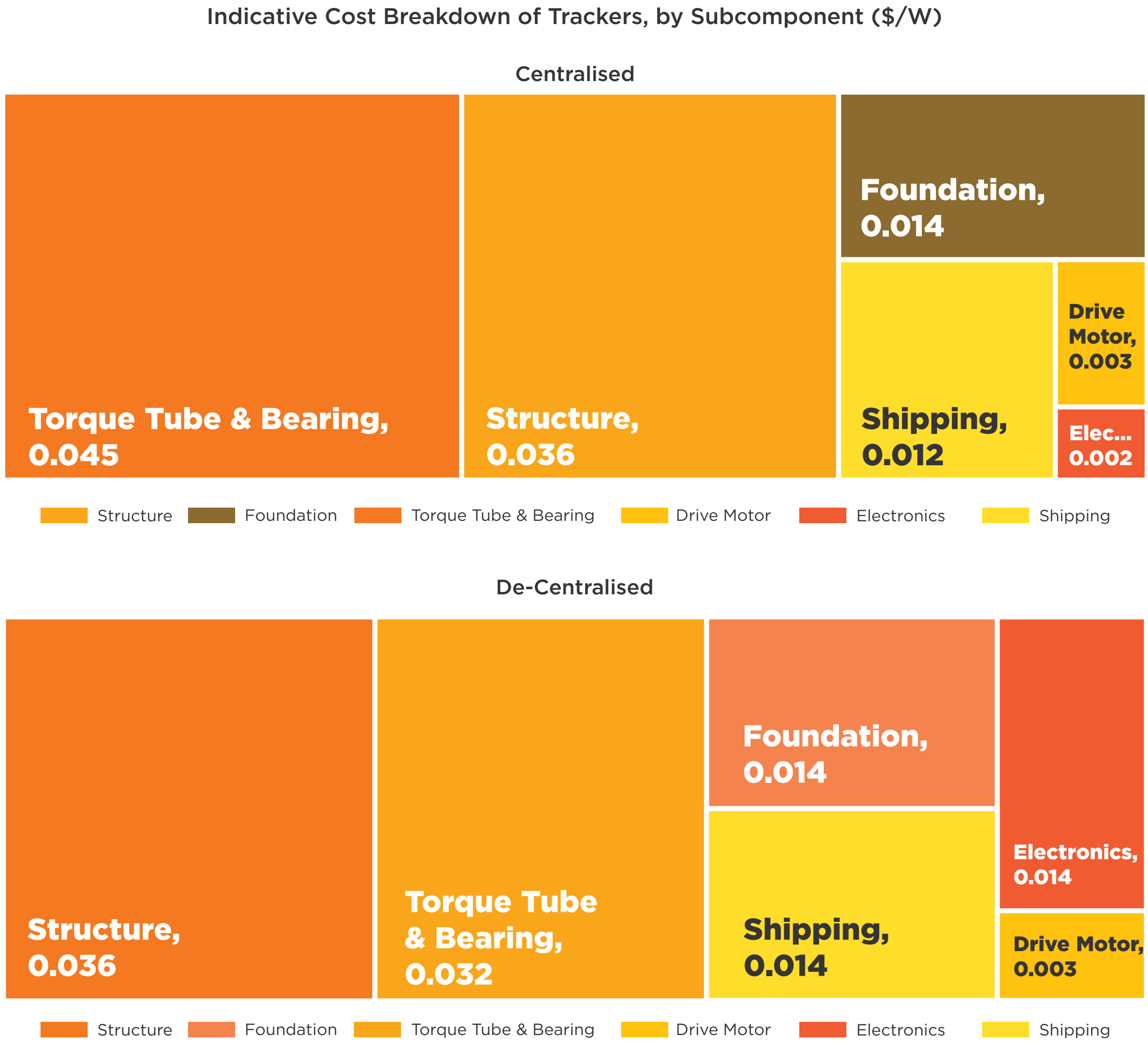


Figure 50: Indicative Cost Breakdown of Trackers, by Subcomponent ($/W)

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.

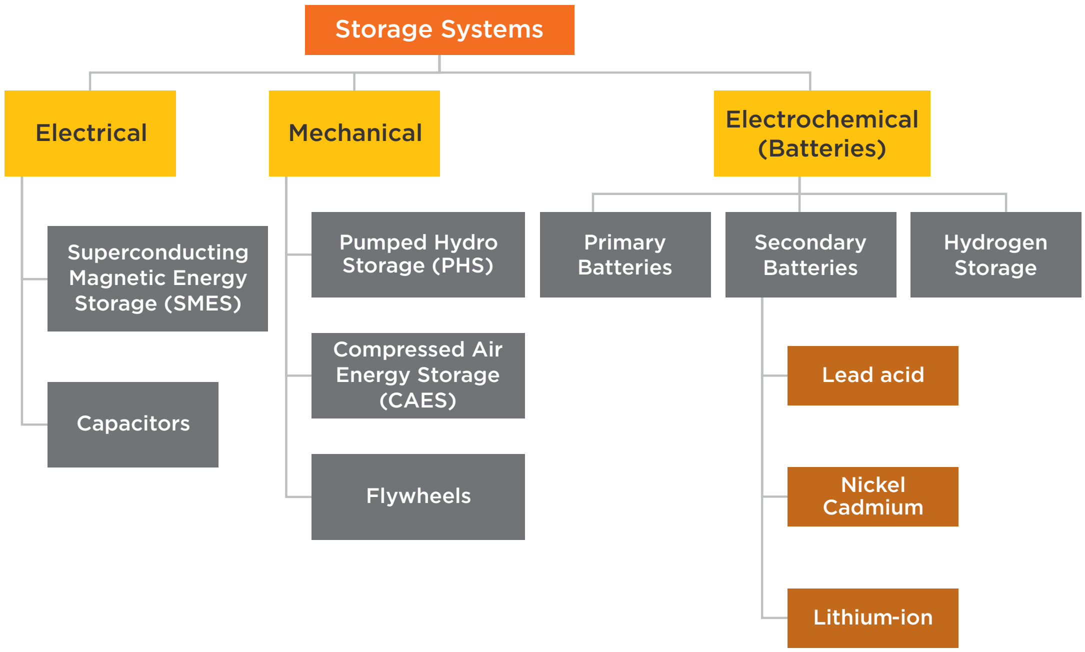


Figure 51: Energy Storage Technologies

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.

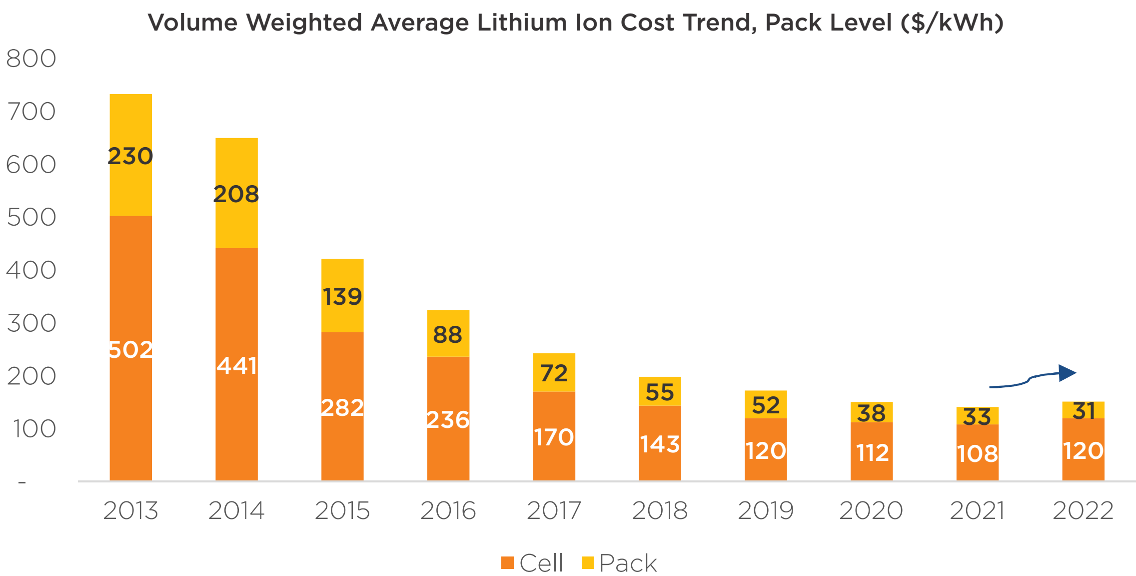


Figure 52: Volume Weighted Average Lithium Ion Cost Trend, Pack Level ($/kWh)

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.

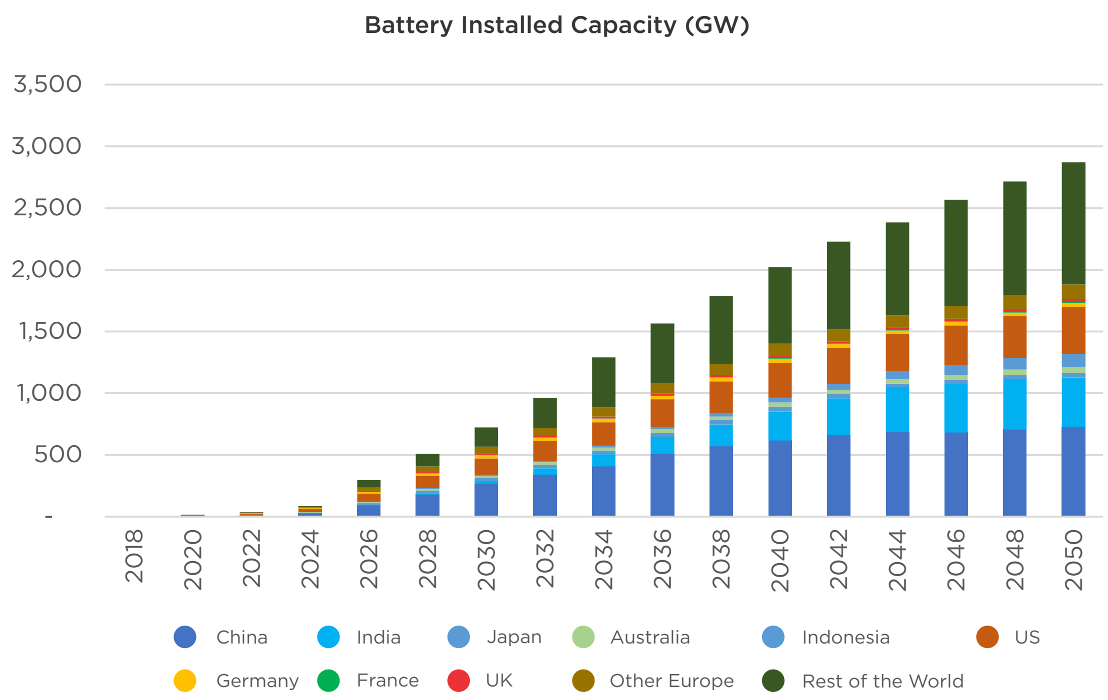


Figure 53: Projected Installed Capacity of Battery

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.

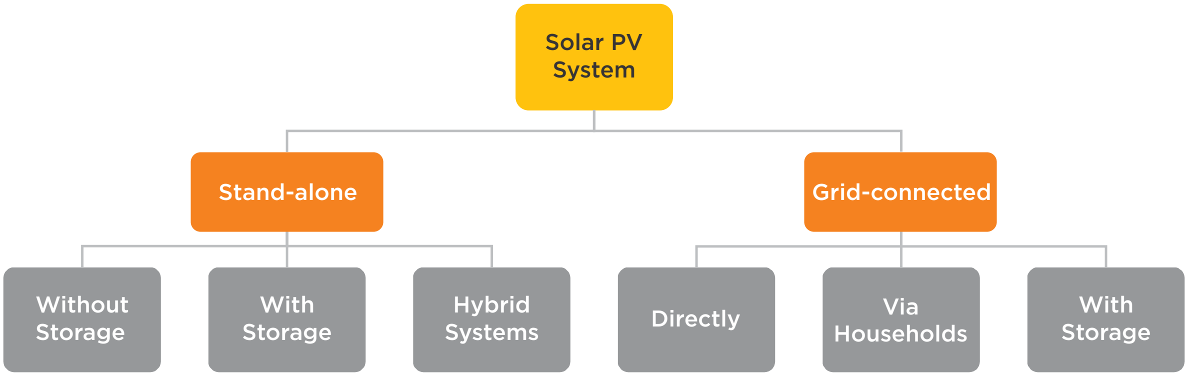


Figure 54: Classification of Solar PV System

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.

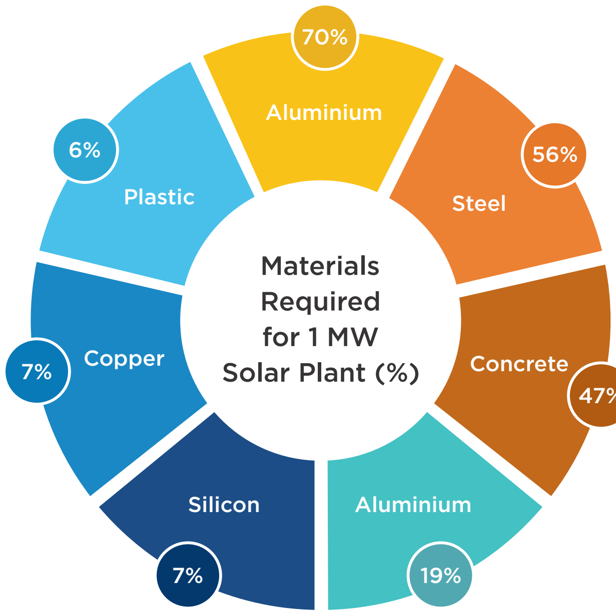


Figure 55: Materials Required for 1 MW Solar Plant (%)

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.

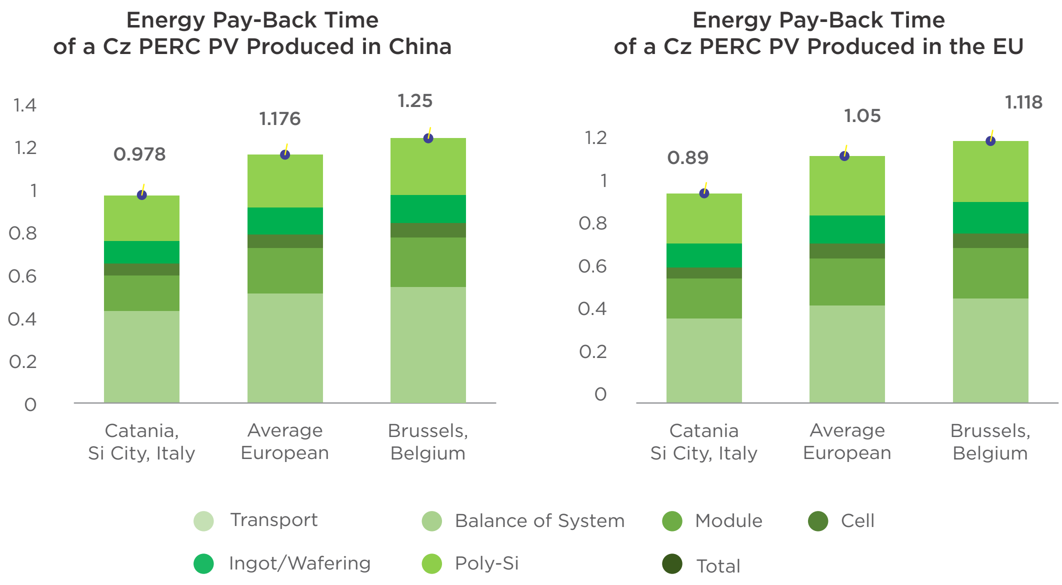


Figure 56: Energy Payback Time

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.

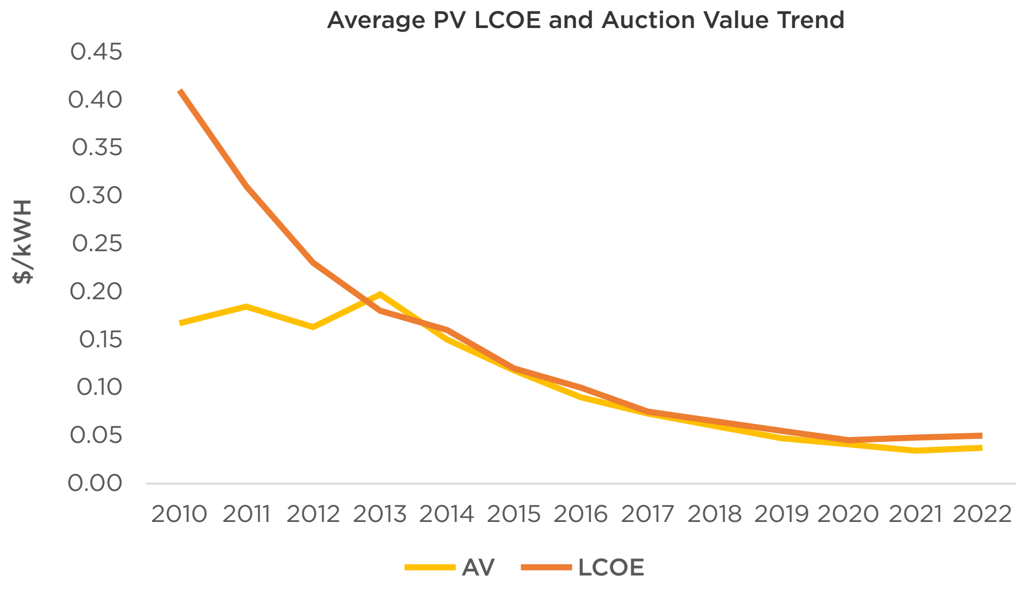


Figure 57: Average PV LCOE and Auction Value Trend

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.

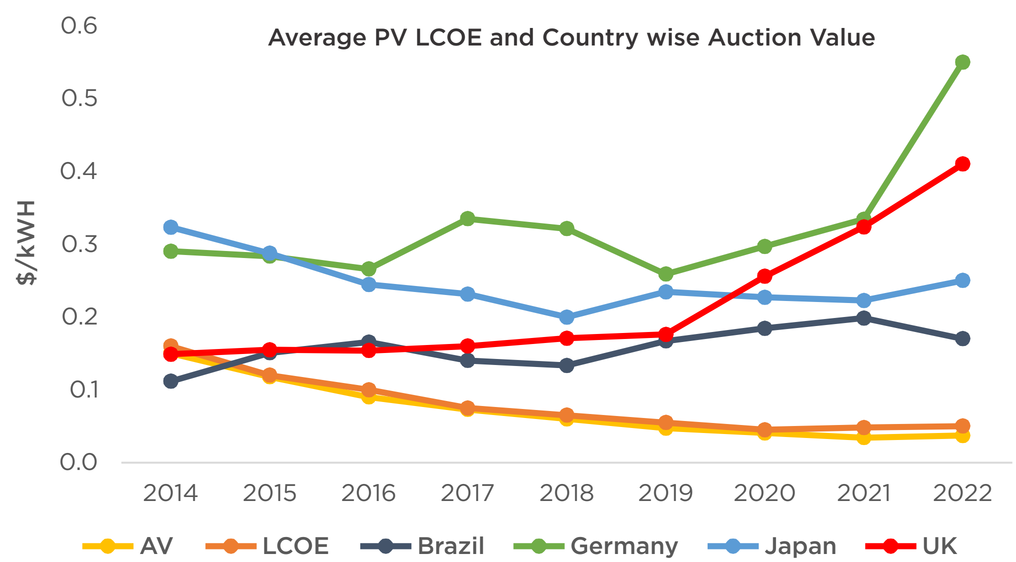


Figure 58: Average PV LCOE and Country wise Auction Value

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.

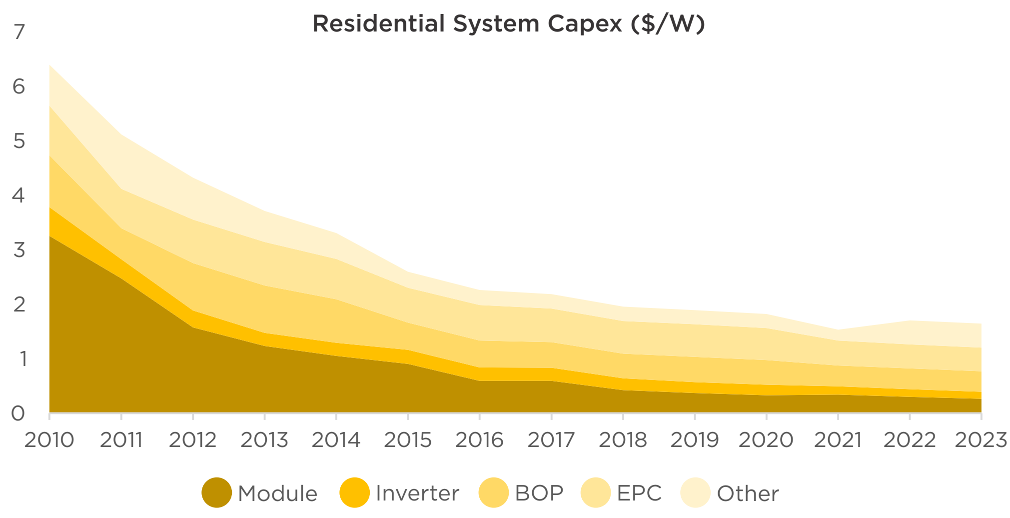


Figure 59: Residential System Capex ($/W)

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.

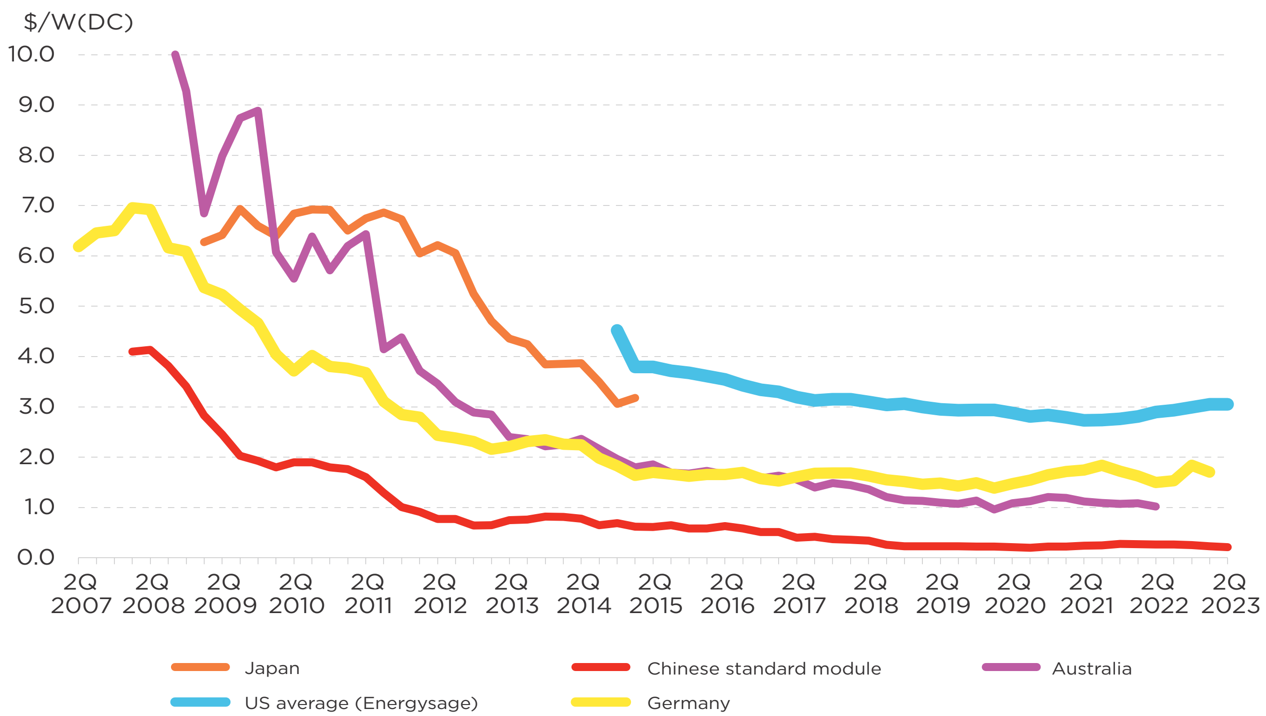


Figure 60: Residential PV Capex Around the World, $/W (DC)

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.

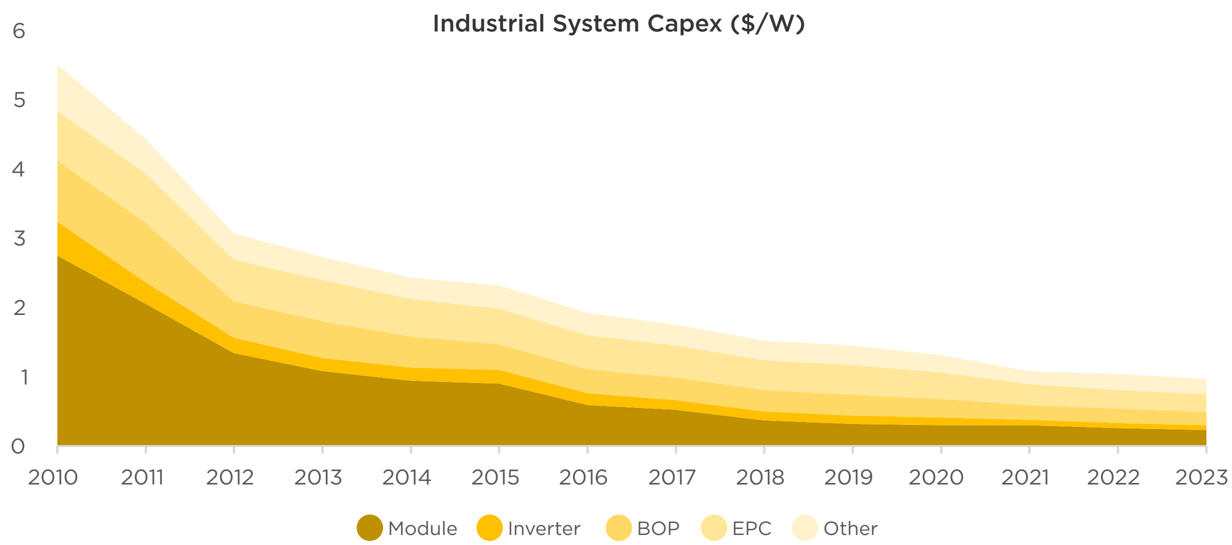


Figure 61: Commercial and Industrial System Capex ($/W)

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.

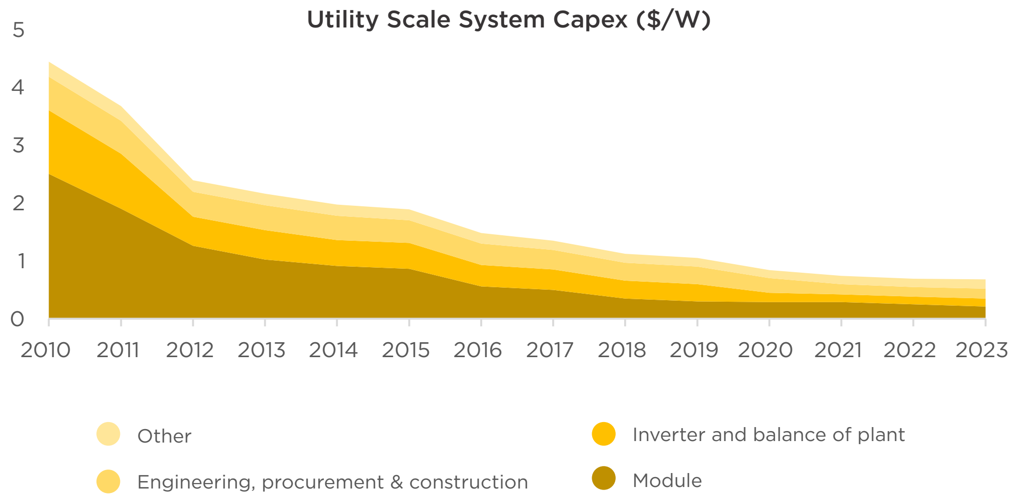


Figure 62: Utility Scale System Capex ($/W)

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.

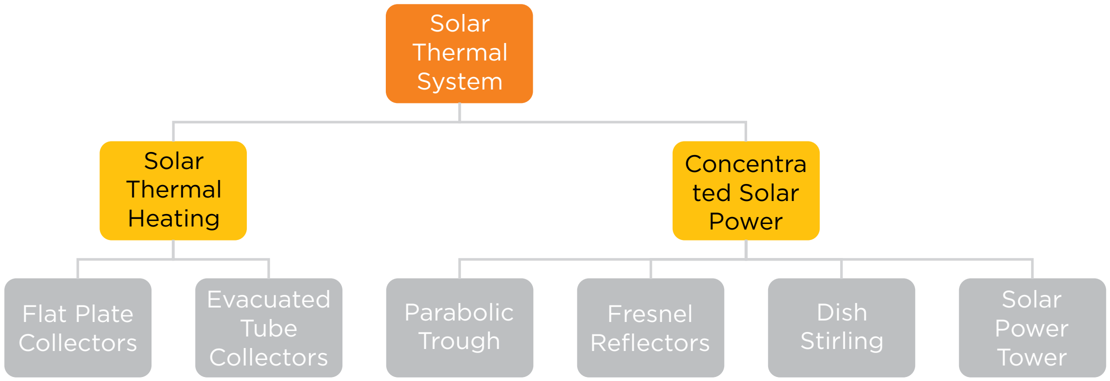


Figure 63: Solar Thermal Technologies

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.

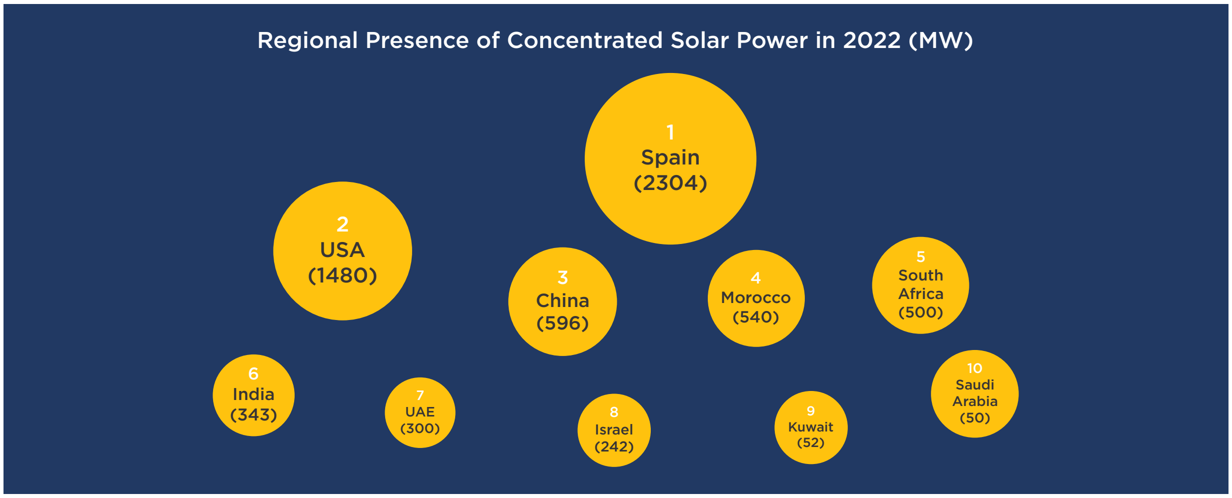


Figure 64: Regional Presence of Concentrated Solar Power (MW)

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

[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.

Technological solutions and Innovations to integrate rising shares of solar power generation

In recent years, countries have been adopting more and more green policies to enhance production from renewable energy sources. It is, therefore, crucial to combine the variable renewable energy sources, with the energy demand of modern society.

Also, PV production is believed to grow exponentially in the coming years due to techno commercial feasibility. The share of electricity generated from solar PV systems and total electricity demand have been analyzed and observation is plotted in Figure 65.

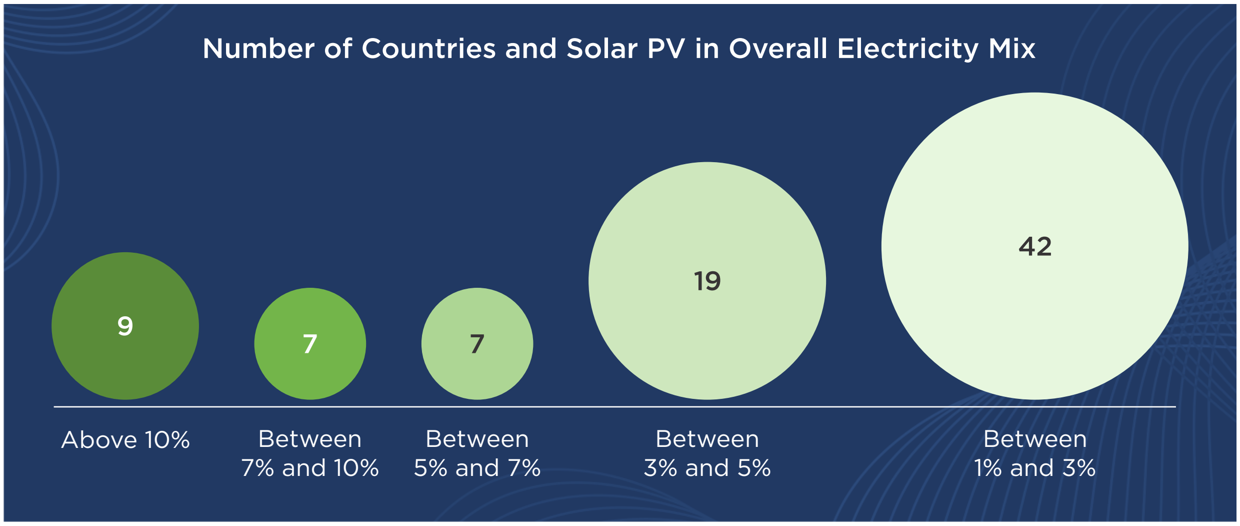


Figure 65: Number of Countries and Solar PV in Overall Electricity Mix

Source: Energy Institute Statistical Review of World Energy - 2023

In 2022, nine countries met more than 10% of their electricity demand from solar PV systems, addition of three more countries in comparison with the data in 2021. Thanks to the capability of solar PV systems, they can often compete with and even beat fossil fuel-powered sources of electricity based on economic considerations. Additionally, several countries have announced a freeze on developing new fossil fuel capacity and the possibility of phasing out existing capacity. These factors, alongside solar energy's popularity as a renewable energy source, make it clear that the technology will garner a larger share of the global generation mix in the years to come. The solar PV installed capacity and the share with the total installed capacity for the top five countries are plotted in Figure 66.

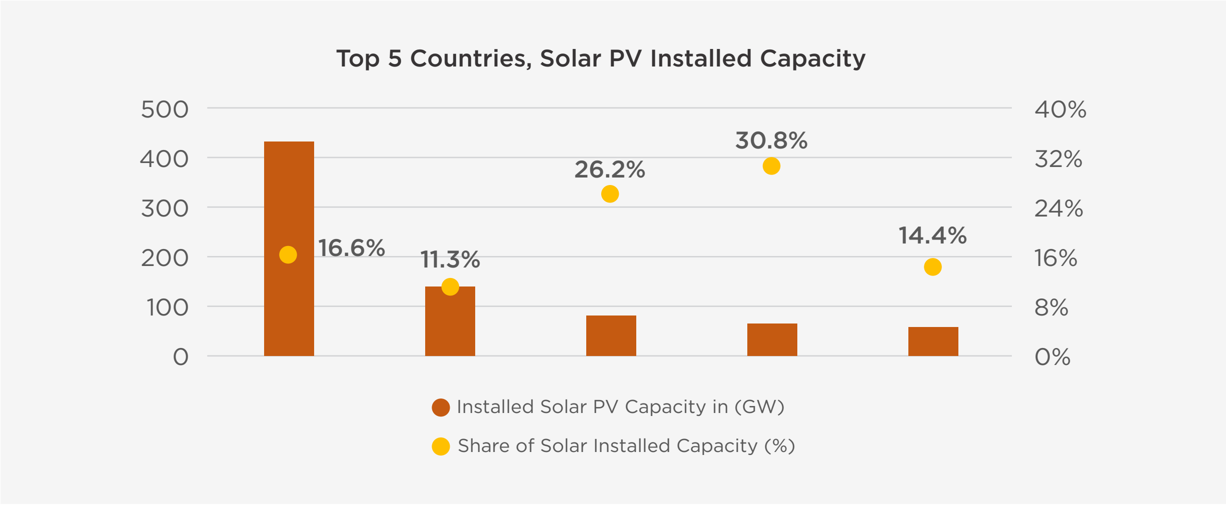


Figure 66: Top 5 Countries, Solar PV Installed Capacity

Source: IRENA - Country Rankings

All these countries have a share of 10% or above in the total installed capacity of Solar PV systems and Germany has the highest share (31%) among them.

Although the world must move towards renewable energy sources, it is not sufficient to simply increase their capacity. Intermittent sources such as solar PV and wind are different from the existing conventional power plants. Some of the key characteristics of solar and wind energy systms are listed below.

Variable

The generation depends on the sun shining or the wind blowing, which are intermittent; Energy generated may not be available on demand, variable in nature.

Uncertain

Prediction of generation is challenging, though weather-forecasting tools are at the edge of development.

Electronic devices

Inverters and electronic devices are crucial in solar PV and wind energy which act as generating sources instead of synchronous generators as in conventional power plants.

Distributed

Solar and wind power plants are typically small in scale and installed distributed compared to the large scale, central conventional power plants.

These features of intermittent sources lead to various challenges at the time of integration with the grid which get amplified as the variable renewable share in the grid system increases and must be suitably addressed to achieve terawatt-scale solar installations.

4.1. Managing High Share of Solar PV Systems

Due to the peculiar characteristics along with growing generation, the rising share of solar PV and wind in the grid poses several challenges to the grid related to the stability of voltage, power, and frequency, and the adequacy of networks that affect the reliability of the grid. Different challenges and mitigating measures in high penetration to the grid, specific to solar PV, are discussed below.

4.1.1. Voltage Issues

In a conventional system, during load conditions, the voltage in distribution networks decreases along the network right from the substation to the consumer. A flat voltage profile with minimal variations requires a constant generation source that can adapt to grid demands. As the capacity of solar PV systems connected to the network increases, there are concerns about the voltage profile which includes voltage fluctuations, grid-derived voltage fluctuations, and voltage imbalance.

Voltage fluctuations: Solar PV generation varies depending on the position of the sun, with peak sun hours lasting anywhere from 3 to 6 hours. Thus, high PV penetration may cause significant voltage variation, especially in low-voltage distribution grids. This can cause over-voltage or voltage dip situations in the low voltage distribution system, which can have effects on the performance of different loads.

BESS can be integrated with the grid as one of the solutions to cope with voltage fluctuations which can act as a sink in the event of excess generation from solar PV systems and as an energy source in deficient generation. The details of BESS will be discussed separately in successive sections. On the other hand, synchronous condensers or synchronous motors are used to inject or absorb reactive power, contributing to voltage stability. Currently, grid-connected inverters are capable of supplying and absorbing reactive power to a particular extent which will lead to the stabilization of voltages.

Grid-derived voltage fluctuations: In grid-connected solar PV systems, voltage fluctuations may occur also outside of the PV systems, depending on the stability of the grid. In these situations, inverters normally feature a disconnecting system that is set to avoid that grid- derived voltage fluctuations may being transmitted to the PV system. If the voltage of the grid is higher or lower than a pre-set threshold, the disconnector will shut off the PV system from the grid. This means that the PV power generated during this period of grid instability will be wasted. Such a failure may potentially result in a major blackout.

Grid-forming inverters are becoming popular in the market with improved tolerance to voltage fluctuations due to the incorporation of low voltage ride-through (LVRT) or high voltage ride-through (HVRT) capabilities. These terms referred to the ability of electric generators to stay connected to the grid for a shorter period during a dip or hike in the network voltage.

Voltage imbalances: Voltage imbalances are another issue for system stability that arises due to the increasing installation of single-phase grid-connected inverters into a three-phase system. Single-phase systems installed disproportionally on the three-phase network may cause a severely unbalanced network and damage to the control system and transformers.

At high PV penetrations, the cumulative size of all systems connected to each phase should be as equal to as possible. Generally, all systems with installed power above 5 kW should be connected to an inverter, which can guarantee a balanced three-phase output.

4.1.2. Power Issues

In traditional power systems, the power is injected constantly by power plants into the grid, making management of power generation according to the system load relatively simple. Now, with the widespread diffusion of solar and wind energy systems, grid management has become more complex. The associated challenges are explained below.

Power fluctuations: Solar PV systems show a peak when the irradiance is at its maximum over the panels, which usually occurs at noon, while during the night no electricity is delivered. Weather conditions such as cloud cover can also cause power fluctuations, short term, in the daytime whereas seasonal variations are responsible for long-term fluctuations. This short-term and long-term fluctuation can cause a problem with the quality of the power that a load receive.

To confront short-term and longer-term fluctuations, backup generation or storage is required to maintain a stable power supply, which can be effectively achieved using BESS.

Another good way of managing intermittent power inputs into the grid is to forecast the probable PV production in selected areas. Grid operators make intensive use of forecast algorithms to control the power flows and guarantee a constant feed to the loads.

Nevertheless, these forecasts may predict less power than a PV system can produce. In this case, traditional power plants are shut off to avoid a surplus of energy in the system that could cause faults or could end in a waste of power produced. Alternatively, this excess can be stored if storage is integrated into the grid. On the other hand, the forecast might also be higher than the actual PV production: in this case, backup power generation is needed to cover the energy demand.

Reverse power flow: When a consumer becomes a prosumer (customer who installs a solar PV system and generates electricity for their use in the daytime along with the electricity consumed from the grid to meet the demand in non-sun shine hours), using solar PV system which provides power at low voltage to the substation, the linearity of traditional distribution system change into a decentralized bidirectional distribution system and it also result in elevation of voltages at load point. Bigger solar PV farms also play a role at the transmission level. In this more complicated scenario, protection devices on the low-voltage side of the network are designed to detect and stop upstream current flow towards the transformer.

BESS can help to reduce the reverse power flow by storing excess electricity during periods of low residual demand and discharging it during periods of high demand, while pumped hydro storage (PHS) are suitable to manage seasonal imbalances[15]. Demand-side management (DSM) also enables the grid operators to smoothen the difference in the demand and supply pattern. For instance, curtailing the output of solar PV during periods of excess generation, limiting shifts in the demand and ramping up dispatchable plants during a shortage of generation from sources like solar and wind.

Poor power quality: The electronic converters employed to integrate PV into the grids introduce various quality distortions such as harmonics, current distortion, etc. that can damage the equipment connected to the network and reduce their efficiency and lifetime.

Filters use capacitances and inductances either in parallel or in series to cancel out the lower or higher harmonics from the output power. Apart from passive filter circuits, some more expensive active harmonic filters can be used. An active filter injects into the grid a harmonic compensation wave that evens out the distortion. This way, a filtered wave can be delivered to the grid.

4.1.3. Frequency Issues

Disruptions in the balance between supply and demand lead to frequency fluctuations. In particular, the frequency of a system falls when demand exceeds supply. The other way around, the frequency rises when supply exceeds demand. With less controlled energy sources like PV, the grid becomes increasingly difficult to control and monitor. Lower availability of operating reserves which are traditionally provided by controllable conventional generators, reduced inertia due to the replacement of rotating machines, which decelerates the effect of frequency changes, with electronic devices like inverters are some of the driving factors of frequency distortions.

DSM and coordinating with the neighbouring region, storing electricity using BESS, curtailing the generation of solar PV, improving the forecasting techniques and incorporation advanced technology (low/high-frequency ride through) in grid-connected inverters can mitigate the challenges on frequency due to increased share of solar PV in the grid.

4.1.4. Network Adequacy

The shift in power flow from conventional centralized power plants to intermittent sources leads to network congestion and thermal violations due to overloading. The distributed solar PV systems generate most of the electricity, but in an area with weaker connections to the main electricity grid, resulting in congestion issues. Loading solar PV beyond the thermal limits of distribution or transmission lines may lead to permanent damage or even initiate a fire or explosion. In most cases, the most convenient connection may also lead to higher currents at some part of the distribution or transmission system which can cause loading issues during higher generation and minimum load.

[15] *Rising to the Challenges of Integrating Solar and Wind at Scale, BCG Henderson Institute*

One of the solutions is the selection of optimal sites for the installation of solar PV systems, considering the available network capacity and possible power flow apart from the best obtainable yield from the system. However, increasing grid capacity by augmenting distribution and transmission networks is essential to accommodate the growing share of not only solar PV but other variable distributed energy sources also. Integration of BESS with the network can regulate power flow and congestion in the network by storing and discharging the electricity as necessary. Generation curtailment of solar and wind energy systems also supports the grid operators in managing the violation of the thermal capacity of distribution and transmission lines.

4.2. Enabling Measures and Technologies to Enhance Solar PV Penetration in Electric Grids

Solar energy, with all its potential upsides, has certain limiting factors to be the major mode of electricity generation. Some of the key enabling strategies and technologies that support to mitigate of the challenges of a growing share of solar PV, ensuring the stability and reliability of the grid are discussed below.

Battery Energy Storage System (BESS): Energy storage devices can store and shift PV output according to grid needs. Storage technologies can provide a variety of grid flexibility services across both short- and long-term timescales, depending on the specific storage type deployed. A wide variety of storage solutions are available at different price points, with BESS emerging as a key technology, with potential for both utility-scale and distributed deployment. However, many storage technologies, currently entail high up-front costs. The installed capacity of BESS globally reached 36.2 GW in 2022 and the trend in the installation is plotted in Figure 67.

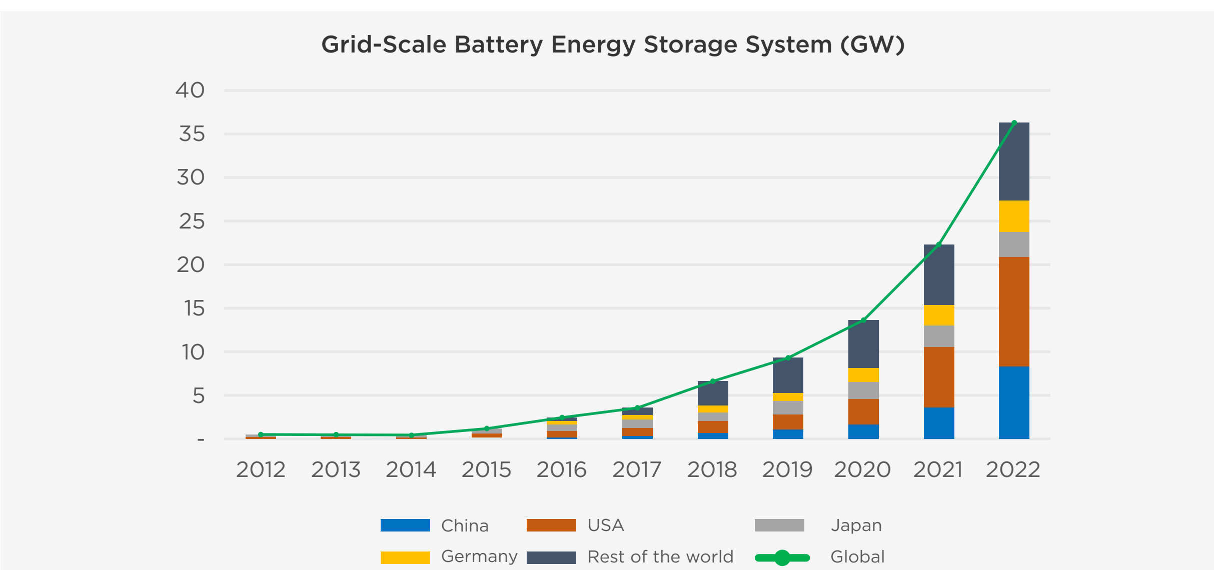


Figure 67: Grid-Scale Battery Energy Storage System (GW)

Source: BNEF - New Energy Outlook 2022

Storage additions are being driven by a few key countries, including the USA, China, Germany, and Japan. Utility-scale installations in the four countries dominate the market and account for two-thirds of the total installed capacity all over the world.

Renewable Energy curtailment: Most modern grids operate under some form of constrained economic dispatch, maintaining system reliability and flexibility at the lowest possible cost. To decrease the instability a grid might face due to the above-mentioned factors, curtailment of power is expected to increase. RE curtailment can be defined as the reduction of renewable energy delivered due to oversupply or lack of system flexibility. PV curtailment is often framed as a loss given that generated clean electricity goes unused. Because of its zero-cost attributes, PV output is almost always accepted in a constrained economic dispatch and only curtailed when additional PV output could compromise system reliability. Curtailment may also undermine PV project economics and could hinder future PV deployment. As a result of these negative effects, the widespread adoption of solar relies on minimizing curtailment. The trend in curtailment of energy from solar and wind energy system for the top four countries with PV installed capacity is plotted in Figure 68.

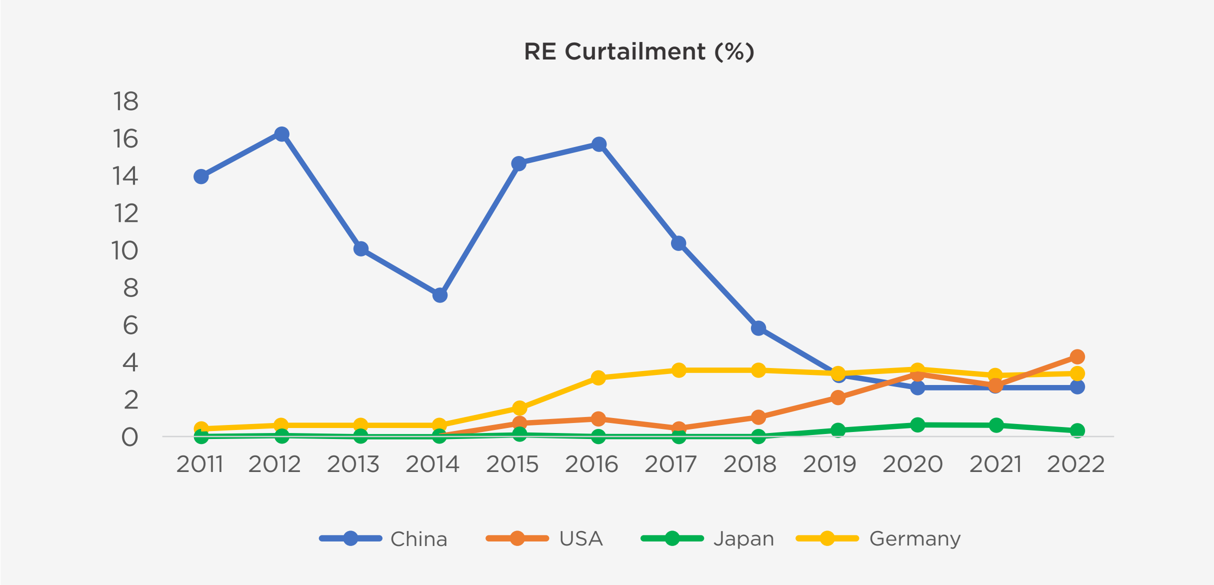


Figure 68: RE Curtailment (%)

Source: IEA- Renewable Energy Market Update - June 2023

The figure depicts, the trend in curtailment of energy from solar PV and wind energy systems. Although an increasing energy curtailment is observed overall, the share of curtailed wind and solar PV is relatively low with a maximum of 4% in 2022. This implied that the higher installed capacity of RE does not necessitate the curtailment of energy as the countries can manage the challenges related to the high penetration of RE.

Expansion of grid infrastructure and interconnections: Improving inter and intraregional grid interconnections help improve supply security, system efficiency, and integration of RE such as solar PV system. Interconnections help improve system flexibility by allowing different grids to share resources across regions. Additionally, the development of long-distance transmission infrastructure can help move solar energy (that is often deployed at scale at remote locations with low electricity requirements) to areas with high loads that most require it. As a result, curtailment of renewable energy generation can be minimized as the generated energy can be utilized. Regional coordination has already proven effective in reducing curtailment, such as in Germany. However, it is limited by transmission constraints and challenges associated with building expensive new transmission infrastructure. The expansions in grid length and expected trend are analyzed and plotted in Figure 69.

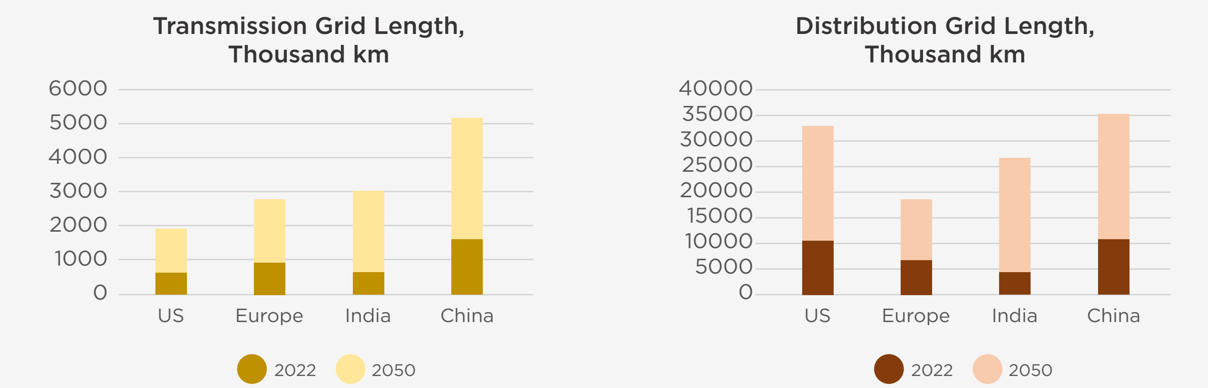


Figure 69: Length of Power Grid

Source: BNEF - New Energy Outlook: Grids

India and China are expected to lead transmission and grid infrastructure growth in the coming decades whereas the US is also expected to expand the distribution network significantly along with China and India.

4.3. Country Specific Case Studies

The integration of significant amounts of solar generation has already been seen in select countries and regions. These may be studied to evaluate the measures taken by them to ensure grid integration of renewables, and thus guide other countries in how to best manage their own grid integration challenges.

4.3.1. China

China has seen significant solar capacity additions in the last decade, culminating in a record 101.4 GW of additional installed solar capacity in 2022. This annual installation took the country's overall solar capacity to 434.2 GW by the end of 2022 which bears a share of 16.6% of the overall installed electric capacity and is responsible for the generation of 481.4 TWh electricity in 2022, 5.6% of the total electricity demand[16].

The Gobi Desert and other desert regions are key to China's renewable energy strategy, and the country plans 450 GW of wind and solar generation capacity in such regions. However, these regions are relatively underdeveloped and sparsely populated. Thus, local generation is unable to match local consumption, resulting in increased curtailment of excess power that cannot be transported across the country. The country also lacks sufficient peak shaving capacity within its power system, further increasing the likelihood of curtailment.

[16] *BNEF- Energy Outlook- 2022*

The country's renewable energy curtailment rates over the last decade were very high, prompting the government to introduce a quota system to force regions to slow new projects until all their power was being used. This quota system led to an initial drop in wind and solar additions in 2018 and 2019 before deployment again increasing in 2020 and 2021[17]. Subsequently, China's curtailment rates for solar and wind power fell. However, the recent record installation of variable renewable energy capacity has again led to curtailment challenges, with recent figures indicating that solar and wind curtailment in renewable energy rich provinces is exceeding 10%[18]. The trend in curtailment of solar PV and wind in China is depicted in Figure 70.

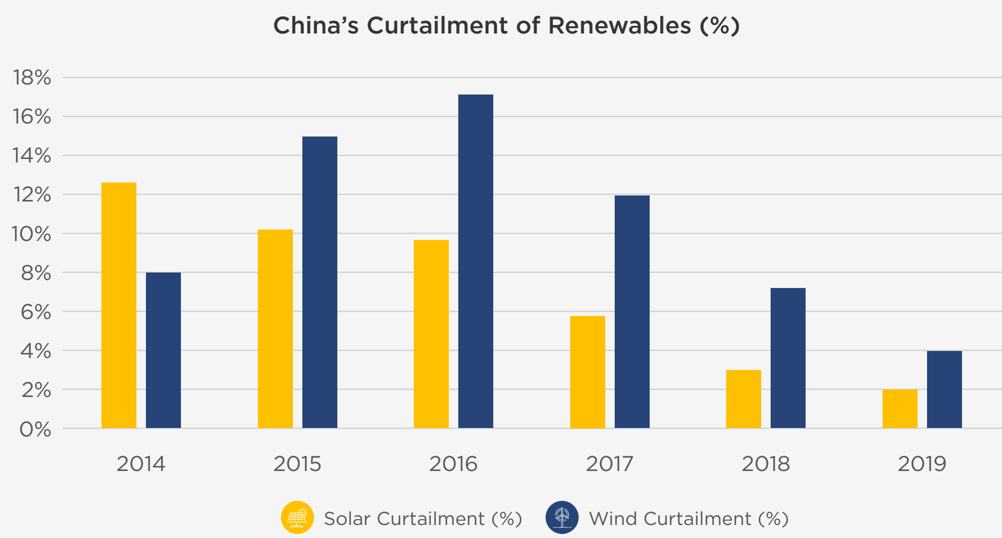


Figure 70: China's Curtailment of Renewables (%)

Source: BNEF Power Grid Long-Term Outlook 2021

The share of curtailment in China has reduced drastically and achieved a minimum of 2% and 4% for solar PV and wind respectively in 2019, achieved due to the adequate expansion of grid infrastructure[19].

China faces the challenge that its wind and solar resource-rich provinces are in the far north-west region of the country such as Xinjiang and Gansu, while higher electricity demand provinces like Shanghai, Jiangsu, Zhejiang, Shandong, and Guangdong are at the south-east region and the generated power need to be transmitted from north-west to south-east. The large-scale investment by China improved the interconnection capacity between the northwestern region, wind and solar resource-abundant area, and the load centers in the south and eastern regions which reduced the curtailment significantly. The ultra-high voltage (UHV) power lines capacity in China for the last decade is illustrated in Figure 71.

[17] *https://www.bloomberg.com/news/articles/2022-06-06/china-s-renewable-energy-fleet-is-growing-too-fast-for-its-grid-l425v47z*
[18] *https://www.solarpaces.org/chinas-curtailments-go-up-as-renewables-growth-explodes/*
[17] *IEA- Renewable Energy Market Update - June 2023- Will more wind and solar PV capacity lead to more generation curtailment? – Renewable Energy Market Update - June 2023 – Analysis - IEA.*

China's UHV Transmission line Capacity

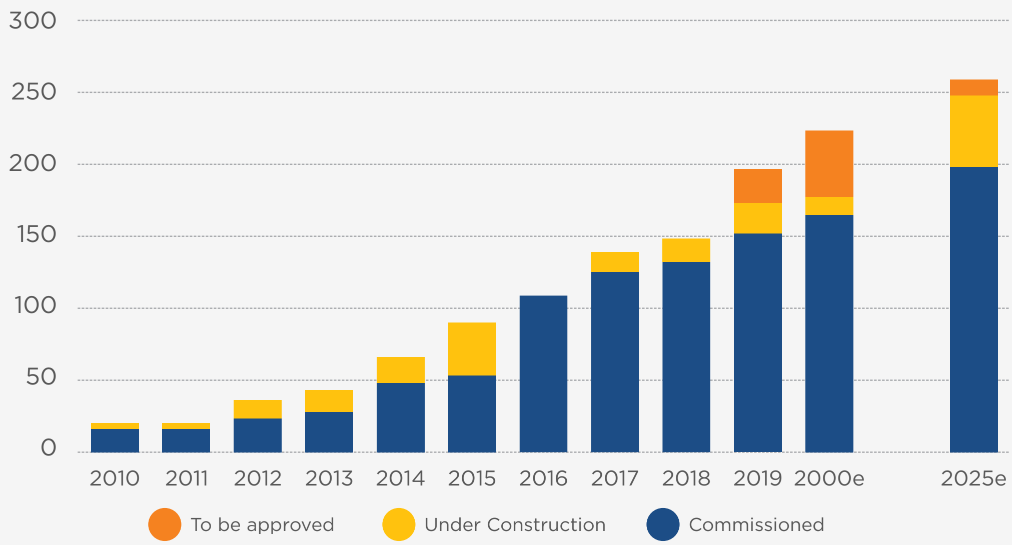


Figure 71: China's UHV Transmission Line Capacity

Source: BNEF- Power Grid Long-Term Outlook- 2021

The country expanded UHV transmission lines, approximately by 15 GW in each year and expected to reach a cumulative capacity of 200 GW in 2025 with an average growth rate of 6.6 GW per year.

4.3.2. United States (California)

The USA has seen significant solar capacity additions in the last decade, reaching an installed capacity of 141.9 GW in 2022 from 6.7 GW in 2012. In 2022, solar accounted for 11.3% of the total installed capacity, generating 270.2 TWh electricity in that year, which was 6.2% of the total electricity demand[20]. For the USA the state of California will be considered due to various aspects related to RE making California a good international example. California has the largest solar PV capacity of any state in the country, estimated to be almost 5 times as large as the next biggest state. A significant share of this capacity is utility scale, and thus subject to curtailment. The constrained economic dispatch in California is carried out by a wholesale market administered by the California Independent System Operator (CAISO). The electricity demand and supply on April 23, 2023 of CAISO is given in Figure 72.

[20] *BNEF- Energy Outlook- 2022*

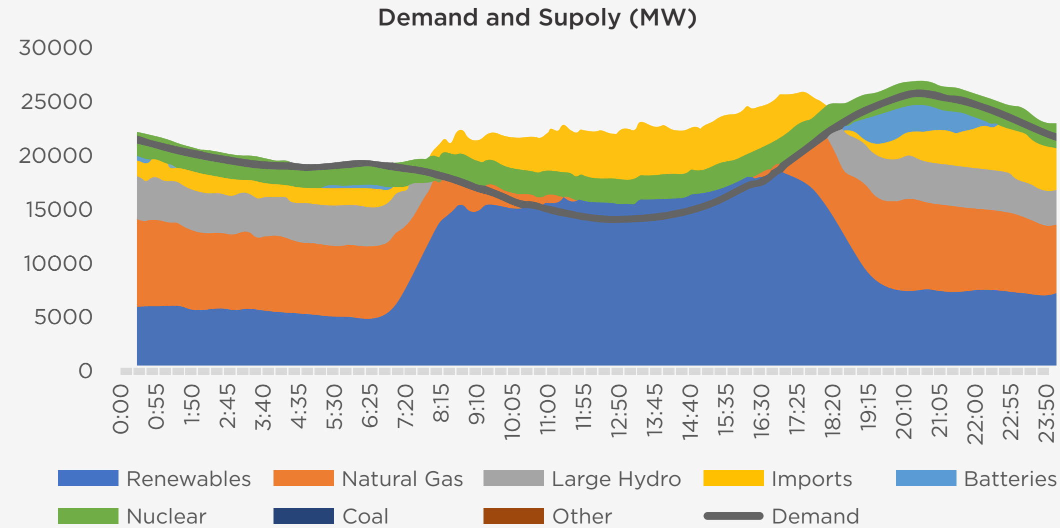


Figure 72: Demand and Supply, California

Source: CAISO

Evidently, the supply from renewable energy sources is surplus in the noontime which is either curtailed or utilized to charge the BESS installed. The state witnessed a curtailment of 2449.2 GWhin solar and wind generation[21]. The curtailed electricity from wind and solar PV systems are demonstrated in Figure 73.

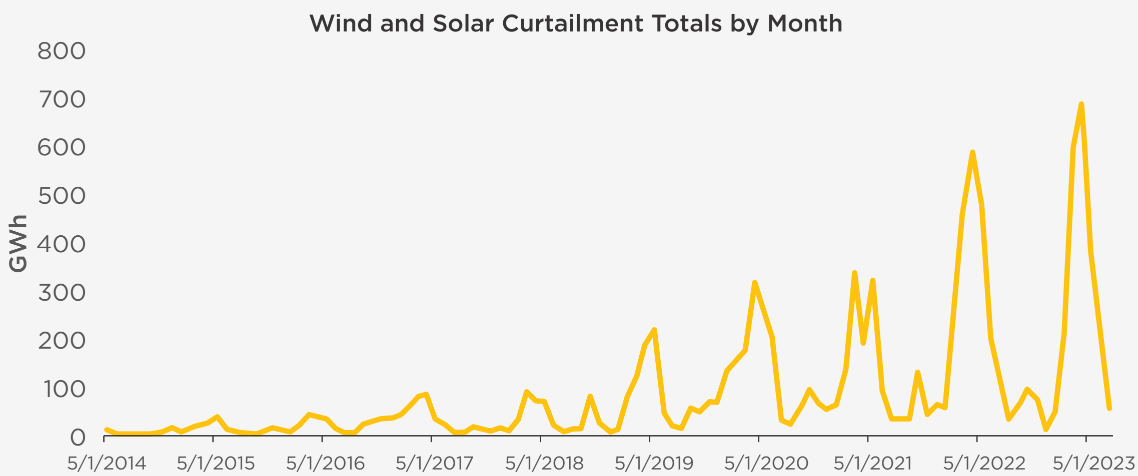


Figure 73: Wind and Solar Curtailment Totals by Month

Source: CAISO

[21]*CAISO - http://www.caiso.com/informed/Pages/ManagingOversupply.aspx*

PV curtailment in CAISO peaks in the spring and fall seasons and is relatively lower in the summer and winter. This is due to a mismatch between the peak of annual PV outputs, and the peak demand load seen in the state. Curtailment in the state is typically system wide, and not purely in areas with transmission constraints.

Despite this high solar PV capacity and slight mismatch of peak loads and demand, California can keep curtailment levels relatively low. This is partially due to the large size of the CAISO balancing area, and the creation of a regional Energy Imbalance Market (EIM). The EIM allows balancing areas outside of CAISO to voluntarily trade in the CAISO real-time market. This allows the state to import power to meet electricity peaks for the morning and evening demand peaks, while the midday solar PV peak leads to a fall in imports. Different strategies to manage the oversupply followed by CAISO are listed in Table 4.

Table 4: Strategies to Manage Oversupply

Storage	Increase the effective participation by energy storage resources.
Demand response	Enhance DR initiatives to enable adjustments in consumer demand, both up and down, when warranted by grid conditions.
Time-of-use rates	Implement time-of-use rates that match consumption with efficient use of clean energy supplies
Minimum generation	Explore policies to reduce minimum operating levels for existing generators, thus making room for more renewable production.
Western EIM expansion	Expand the Western Energy Imbalance Market.
Regional coordination	Offers a more diversified set of clean energy resources through a cost-effective and reliable regional market.
Electric vehicles	Incorporate electric vehicle charging systems that are responsive to changing grid conditions.
Flexible resources	nvest in modern, fast-responding resources that can follow sudden increases and decreases in demand.

Source: CAISO[22]

4.3.3. Japan

Japan was an early mover into the Solar PV market and achieved 1 GW of total installed capacity by 2004[23]. Japan has an installed solar PV capacity of 83.0 GW, as of 2022, 26.2% of the total installed capacity, generates 96.3 TWh to meet 9.6% of the electricity demand. In Japan, uneven distribution of installed solar capacity, such as in the Kyushu region, is a key cause of increased curtailment. The first instance of solar curtailment in the country took place in October 2018 in Kyushu[24]. Additionally, limited transmission capacity within and between regions leads to bottlenecks when attempting to transmit power from supply locations to load centres. In addition, the curtailment rates of wind and solar PV plants are announced one day ahead of delivery based on day-ahead weather forecasts, because curtailment requires physical presence at the plant site in many cases.

[22] *CAISOs ManagingOversupply-Solutions.pdf (caiso.com)*
[23] *BNEF- New Energy Outlook 2022*
[24] *https://iea.blob.core.windows.net/assets/3470b395-cfdd-44a9-9184-0537cf069c3d/Japan2021_EnergyPolicyReview.pdf*

Solar manufacturing: Moving towards terawatt scale

Solar PV manufacturing is a very dynamic sector, comprised of two types of technological processes, crystalline silicon PV and thin film PV technologies. Crystalline silicon PV and thin film PV, have entirely different manufacturing processes, and considerations.

Crystalline silicon accounts for most of the manufacturing capacity worldwide with a share of 95% of total installed capacity[25]. Thin film technology manufacturing peaked in 2009, accounting for 14.2% of module manufacturing capacity. Since then, crystalline silicon PV has been the dominant technology for solar modules. The share of different manufacturing technologies is demonstrated in Figure 74.

[25] *Special Report on Solar PV Global Supply Chains*

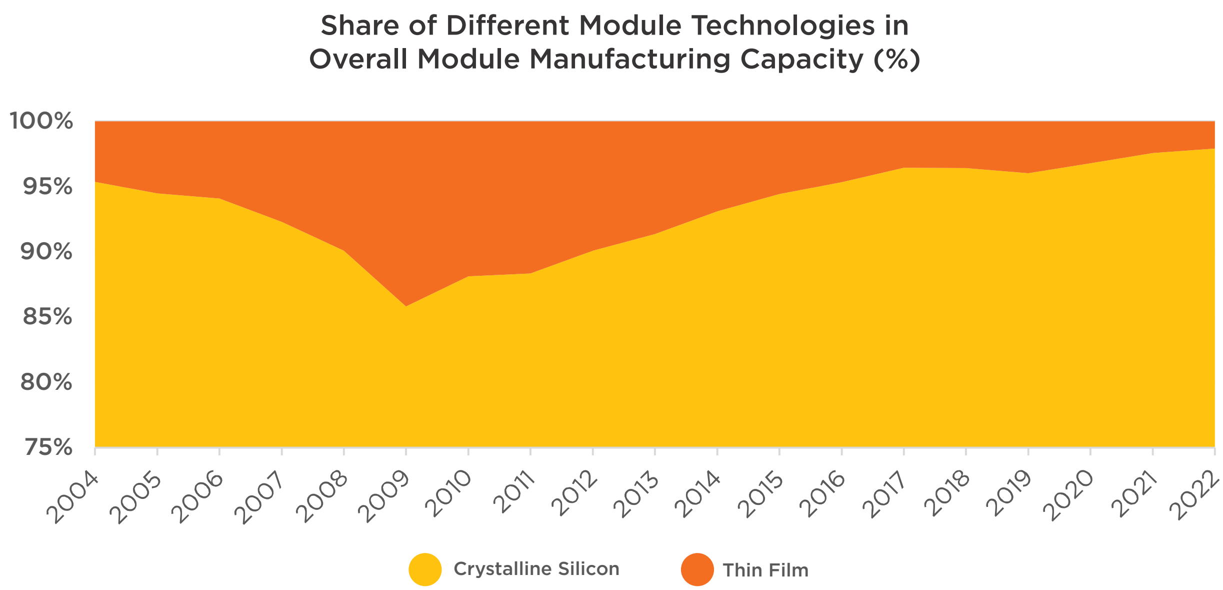


Figure 74: Share of Different Module Technologies in Overall Module Manufacturing Capacity (%)

Source: BNEF Database

Besides solar modules, scaling up the balance of the system (BoS), including inverter, module mounting structure etc., for a solar power plant is essential for achieving economies of scale, maximizing energy production, improving grid integration, and optimizing the overall efficiency and financial viability of the project. Several technology and process trends have emerged in BOS components which have increased efficiency/power, reduced material usage, or simply opened new avenues for PV deployment. Additionally, solar panel recycling, a new segment in the value chain, becoming increasingly important as the number of solar panels reaches the end of their operational life. As the solar industry continues to grow, effective recycling practices will be crucial to minimize waste and maximize the environmental and economic benefits of solar energy, although solar has a smaller footprint than most energy-generating technologies.

5.1. Crystalline Silicon Based PV Technologies

For a long time, crystalline silicon PV technology has used two types of silicon wafers: monocrystalline and multicrystalline silicon. Monocrystalline silicon is a single crystal, having the same lattice orientation throughout the entire wafer. For multi-crystalline silicon, grains of a single crystalline material with different lattice orientations are side by side, having dimensions in the order of millimeters to nearly a centimeter. As a result, many defects or impurities reside at the grain boundaries. Consequently, solar cells made from multi-crystalline silicon wafers have a lower conversion efficiency in comparison with monocrystalline wafer-based solar cells. For a long time, the much cheaper production process of the multi-crystalline silicon wafers allowed the production of silicon solar cells with lower performance than the expensive monocrystalline. However, due to upscaling of the monocrystalline silicon production, this wafer type has become much cheaper as well. In recent years multi-crystalline silicon production phased out quickly and mono-crystalline silicon solar cell production has taken over the market. Therefore, the production of crystalline silicon wafers with a focus on mono-crystalline silicon is explained in the successive sections. The different process in the monocrystalline silicon is illustrated in Figure 75.

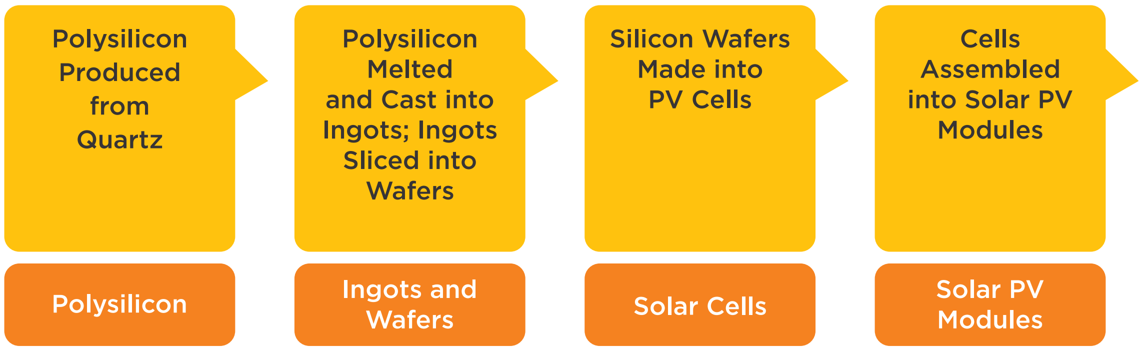


Figure 75: Main Stages in the Supply Chain of Crystalline Silicon PV Modules

Source: ISA Analysis

The crystalline silicon supply chain is heavily concentrated in a single country: China. Due to several reasons, including government support and initiatives, significant investments, and subsequent economies of scale, Chinese PV manufacturing accounts for a lion's share of polysilicon, silicon cell, and crystalline silicon module manufacturing capacity. The share of China in different supply chains is depicted in Table 5.

Table 5: Share of China in Production of Different Supply Value Chain

Stage	Polysilicon	Ingots	Wafer	Crystalline Silicon Cells	Crystalline Silicon PV Modules
China's share in installed manufacturing capacity	94.4%	96.5%	95.2%	87.4%	82.6%

Source: BNEF -Solar PV Equipment Manufacturers

China has a near monopoly on polysilicon, silicon ingot and wafer production bearing above 80% of the share in all segments. The geographical concentration of manufacturing of an energy source that will play a crucial role in the energy transition has the potential to leave certain countries open to supply chain disruptions. With geopolitical concerns and recent global disruptions like the COVID-19 pandemic fresh in the memory, several countries are attempting to promote localized manufacturing across the solar PV value chain.

Solar PV installations are expected to ramp up in the coming decade, with estimates for required average annual capacity additions ranging from 500 GW to upwards of 1 TW. This scale-up will require a robust manufacturing supply chain that can scale anywhere from 600 GW to 1 TW of manufacturing capacity. The following subsections will cover the significant processes for crystalline silicon manufacturing in detail, along with the critical manufacturing locations and other features observed in each stage.

5.1.1. Polysilicon

Silicon is the second most abundant material on Earth, right behind oxygen, as the crust of the Earth consists of 90% of silicon-based compounds. Silicon dioxide or silica is found in forms: sand, sandstone, and quartzite. High-efficiency solar cells require a high level of purity of the silicon base material. Quartzite is a rock of almost pure silicon dioxide (quartz). The oxygen should be removed from this compound to obtain so-called metallurgical silicon (MGS), the lowest quality processed silicon. This metallurgical-grade silicon is further purified, and the result is solar-grade polysilicon. Therefore, the production of polysilicon from quartzite consists of two main processes as explained below.

Step 1- Quartzite to Metallurgical Silicon

During the production process, the silicon is purified by removing the oxide. This happens in a submerged electrode arc furnace. The quartzite is moved into the furnace, where it's melted. Using an electrode, the quartzite is heated up to a temperature of around 1900 °C. The molten quartzite is mixed with carbon. The carbon source is a mixture of coal, cokes, and wood chips. The carbon reacts with the silicon oxide leaving the furnace as carbon monoxide. The molten silicon that is formed is drawn to the furnace and solidified. The purity of the MGS is around 98 up to 99%.

The quartzite required to produce MGS, and subsequently polysilicon, needs to be of sufficiently good quality. This high-purity quartz is typically not prospected for directly, as quartzite is relatively inexpensive and accounts for a small share of the cost. Thus, the amount of high-quality quartz reserves worldwide is unknown, and the material is typically found co-located with gold deposits. China, the leading MGS producer in the world, does not have abundant quartz resources and relies on quartz imports. Conversely, Spain and Brazil are among the key countries supplying quartz for PV applications[26]. As most silicon production is ferrosilicon production, capacity could be switched over, and even brownfield existing sites could pick up solar demand.

About 2.7 tons of quartz is required to produce 1 ton of MGS[27]. The processing and purification stages involved in converting quartz sand to MGS entail a large amount of energy consumption which is 10-15 MWh per ton[2]. The energy consumption per ton of alloy is reduced significantly with increasing iron content in the silicon alloy product.

Step 2- Metallurgical Silicon to Polysilicon

The silicon material with the next level of purity is called polysilicon produced from powdered MGS, the source material, by three popular processes- chemical vapour deposition (CVD) or Siemens process, fluidized bed reactor (FBR), and upgraded metallurgical grade silicon (UMG-Si). The first two methods are discussed in detail. Compared to the first two methods, UMG-Si is a low-cost method alternative, but the purity of its silicon produced is low the technology is not very successful.

Chemical vapour deposition (CVD) or Siemens process: The metallurgical silicon is exposed in a reactor with hydrogen chloride at elevated temperatures in the presence of a catalyst. The silicon reacts with the hydrogen chloride and starts to form trichlorosilane (TCS). The TCS gas is cooled and liquified. Impurities with higher or lower boiling points are then removed using distillation. The purified trichlorosilane is vaporized again in a different reactor and mixed with hydrogen gas. Trichlorosilane reacts with the hot rods which are at a high temperature of 850 up to 1050oC. The silicon atoms are deposited on the rod whereas the chlorine and hydrogen atoms are desorbed from the surface of the rod back into the gas phase. As a result, pure silicon material is grown as a rod or chunks, and this deposition method is called chemical vapour deposition or Siemens process.

Fluidized bed reactor (FBR): In this method, metallurgical silicon is fed into the reactor as silane gas, which has the chemical formula SiH_4, while small crystalline silicon seed particles are fed from above. This forms a fluidized bed, and the silane will decompose into crystalline silicon particles that will start to grow in size and which will eventually fall to the bottom of the reactor, as granules, when they are large enough. Overall, this process consumes about 90% less energy than is required for the Siemens process and it can run continuously. However, the purity of the obtained polysilicon is slightly lower than the Siemens process.

The granular form of silicon is better suited to the next ingot-pulling process, because of its shape and it fills the ingot crucible quickly and effectively and leads to cost savings, compared to the polysilicon chunks prepared from the Siemens process. However, the decision on the two processes is determined by various considerations such as impurity differences between the suppliers and the processing capabilities of the ingot production equipment. GCL Tech, the second-largest producer of polysilicon, produced 26.9% of its total production via the FBR method, which is 74% of the total polysilicon manufactured from the FBR process.

[26] *Solar Photovoltaics: Supply Chain Deep Dive Assessment – US Department of Energy*
[27] *Silicon Metal | CRM Alliance*

Manufacturing Status and Key Suppliers

Global polysilicon manufacturing capacity crossed a capacity of 1,000,000 tons in 2022 and it has reached a capacity of 1,128,385 tons in 2022 with production highly concentrated in a few countries worldwide, according to the database of BNEF. The polysilicon production capacity in key countries is depicted in Figure 76.

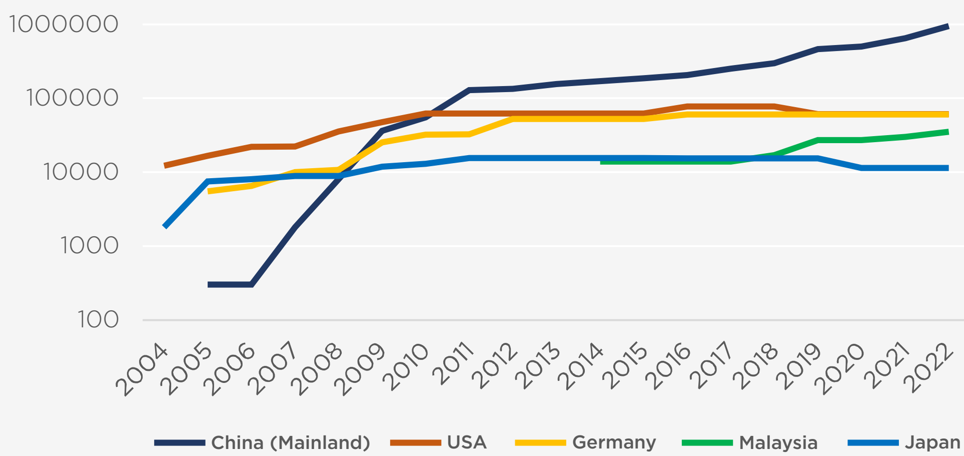


Figure 76: Polysilicon Manufacturing Capacities of Key Countries (Tonnes/Year)

Source: BNEF Database

China has become the market leader over the past decade. Chinese polysilicon manufacturing capacity has grown nearly six-fold since 2012, and nearly 89% between 2020 and 2022 alone. Outside China, countries such as the USA, Germany, and South Korea once had significant production capacity, with the USA being the leader until 2010. The top 5 countries in terms of polysilicon manufacturing capacity accounted for over 98% of the global manufacturing capacity for the sector. Rising prices of electricity in other countries have often made polysilicon manufactured outside China uncompetitive. The country-wide share of polysilicon production in 2022 is illustrated in Figure 77.

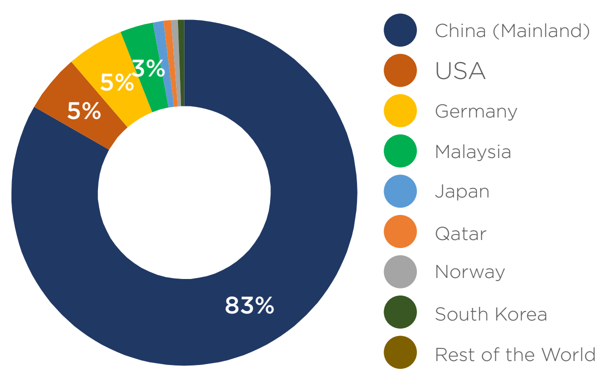


Figure 77: Polysilicon Manufacturing Capacity (2022)

Source: BNEF-Database

China has a share of 83% of global polysilicon production capacity. However, several countries such as Thailand, India, and Japan are exploring vertically integrated solar manufacturing to reduce import dependence and improve energy security as solar power becomes a key component of their decarbonization plans.

Setting up a production unit for polysilicon demands significant capital investments to build plants, learn and refine the production process, and meet the requirement of highly skilled labour to operate the plant. Furthermore, low electricity cost is preferable due to the high energy-intensive processes to produce polysilicon. Therefore, a few geographical locations are best suitable for polysilicon manufacturing. The shortfall in supply and strong demand for polysilicon boosted the spot price of polysilicon which led the Chinese manufacturers to increase their production in 2022.

According to the data from BENE-Solar manufactures production in 2022, global solar-grade polysilicon supply reached 978,268 tons in 2022, 52% higher than in 2021. The trend of total polysilicon production for key countries is demonstrated in Figure 78.

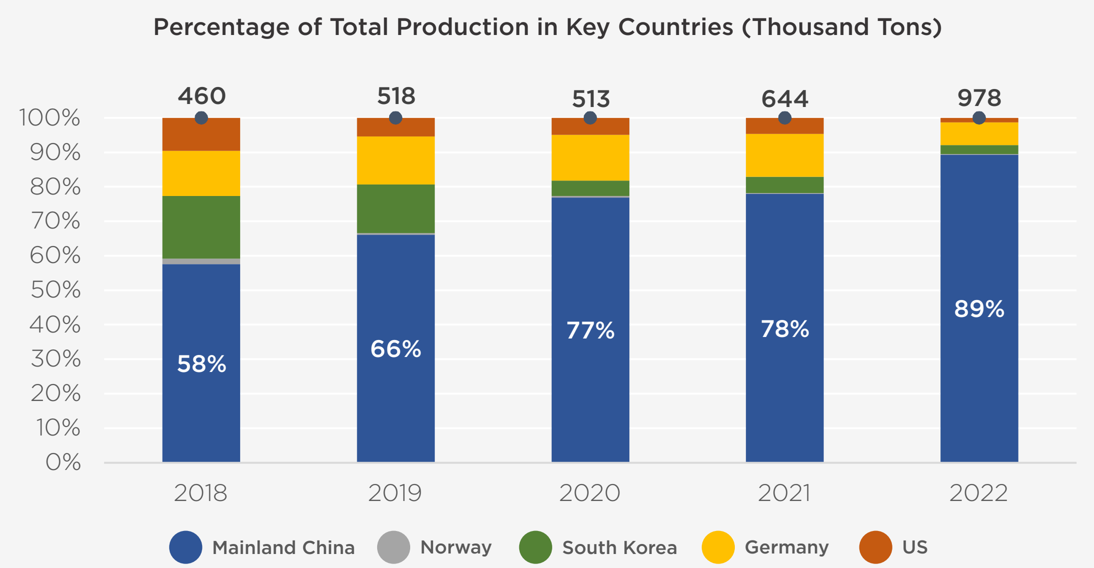


Figure 78: Percentage of Total Production in Key Countries (Thousand Tons)

China produced 89% of the total polysilicon manufactured in 2022. Considering a requirement of 2.7g[28] average polysilicon consumption to produce each watt of PV, total production in 2022 is sufficient to manufacture 362.3 GW of PV modules. The production of polysilicon in 2023 is estimated to be 1,570,000 tons which would be sufficient to produce 581.4 GW solar PV modules. Furthermore, to meet the projected installed capacity of solar PV in 2030 (5345 GW), according to the NZS of BNEF, the production of polysilicon must surge to 14,431,500 tons. The total capacity of the announced and under-construction polysilicon plant adds up to 3,375,500 tons per year in China which will be enough to produce 1250 GW of silicon solar PV module production. However, the capacity expansion outside China keeps a slow pace[29]. The polysilicon produced by the top ten companies is illustrated in Figure 79.

[28] *BNEF- Solar Manufactures' 2022 Production*

[29] *BNEF-2Q 2023 Global PV Market Outlook*

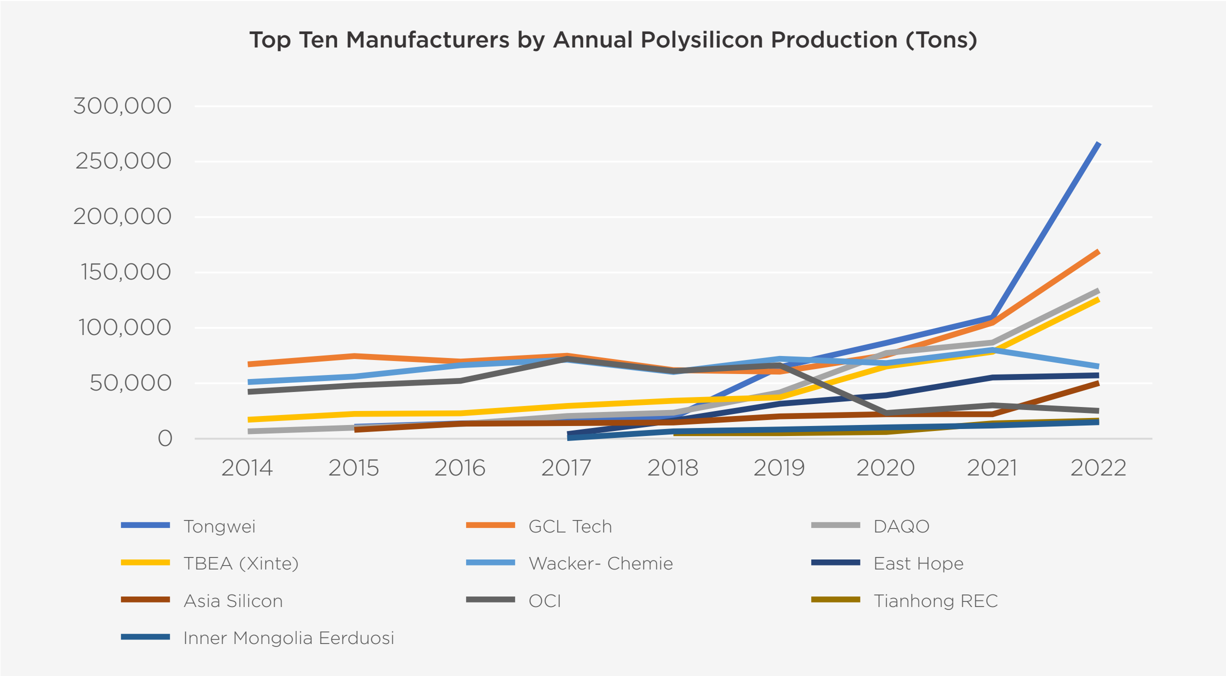
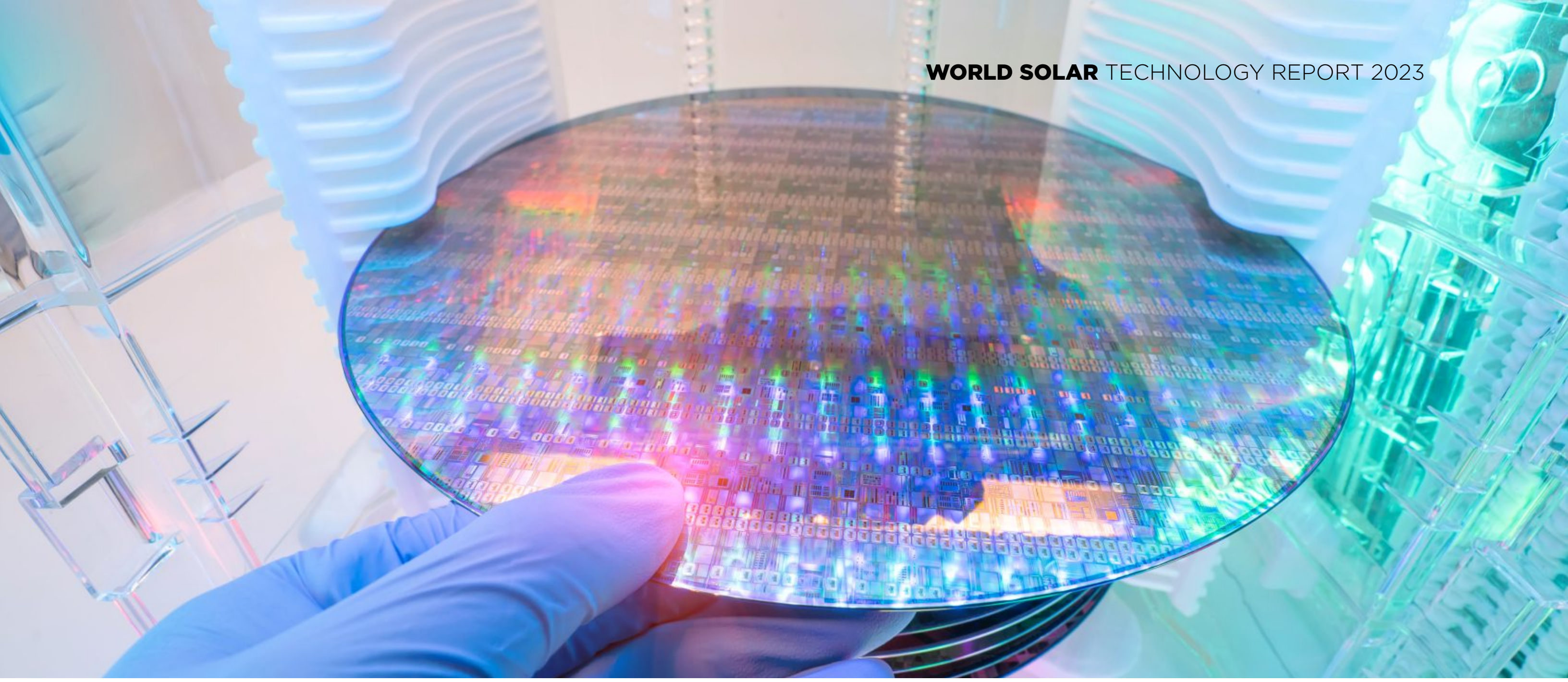


Figure 79: Top Ten Manufacturers by Annual Polysilicon Production (Tons)

Source: BNEF - Solar PV Equipment Manufacturers

Tongwei, GCL Technology and DAQO are now the top 3 suppliers of polysilicon and all of them are from China. The world's largest polysilicon manufacturer, Tongwei, increased their production by 144% compared to 2021 and produced 266,900 tons in 2022. GCL Technology has also witnessed a ramp-up in polysilicon production to achieve an output of 169,224 tons in 2022, a 537% rise in production in comparison with the year 2021. Also, except for three manufacturers, Wacker-Chemie, OCI and Tianhong REC, all other manufacturers belong to China.

The manufacturing capacity of polysilicon is expected to scale up in recent future with a capacity of 583,350 tons/year which is under construction and noted that 99% of the ongoing construction is in China. Furthermore, China and Iceland also announced an addition in the capacity of 1,850,000 and 16, 000 tons per year respectively, according to the BNEF database. To meet the demand for polysilicon in 2030, as per the projection of NZS of BNEF, the expansion of polysilicon manufacturing must maintain at least a 40% annual growth rate in the next five-year whereas the annual growth rate of the previous five-year was 21%. However, manufacturing process improvements and the development of innovative technologies may reduce specific silicon consumption in the coming years.



5.1.2. Ingots and Wafer

Ingot and wafering are the second stage of the PV value chain. Though ingot growth and wafering are two completely different processes, the general practice is to combine these two steps when discussing the PV supply chain. As a result, they can be considered jointly for analysis.

Ingots are large blocks of crystalline silicon. The monocrystalline ingots are solids that consist of one big crystal, being produced by two different methods, Czochralski and float zone processes whereas the multi-crystalline ingots are manufactured by silicon casting, which are explained and discussed below.

Czochralski Process: In this method, highly purified silicon is melted in a crucible at typical temperatures of 1500°C. Intentionally boron or phosphorous can be added to make p- doped or n-doped silicon, respectively. A seed crystal that is mounted on a rotating shaft is dipped into the molten silicon. The orientation of this seed crystal is well-defined. The molten silicon solidifies at the seed crystal and adopts the orientation of the crystal. The crystal is rotating and pulled upwards, allowing the formation of a large, single-crystal cylindrical column from the melt. This big single crystalline silicon block is called an ingot.

In this process, the temperature gradients, rate of pulling up and speed of rotations are precisely controlled. This process is further developed through years of advances and nowadays crystal ingots of diameters of 200 to 300 mm with lengths of 2 meters can be processed. To prevent the incorporation of impurities this process takes place in an inert atmosphere, like argon gas. The crucible is made from quartz, which partly dissolves in the melt as well. Consequently, Czochralski monocrystalline silicon has a relatively high oxygen level.

Float zone process: This is a process which results in monocrystalline silicon ingots with extremely low densities of impurities like oxygen and carbon. The source material is a polycrystalline rod as processed in the earlier mentioned Siemens process. The end of the rod is heated up and melted using a radio-frequent heating coil. The melted part is put in contact with seed crystals. Here it solidifies again and adopts the orientation of the seed crystal. As the molten zone is moved along the polysilicon rod, the single crystal ingot is growing as well. Many impurities remain in and move along with the molten zone. During the process nowadays, intentionally, nitrogen is added which improves the control of the micro defects and improves the mechanical strength of the wafers. The advantage of the float-zone technique is that the molten silicon is not in contact with other materials like quartz as in the Czochralski method. In the float-zone process, the molten silicon is only in contact with the inert gas like argon. The silicon can be doped by adding doping gasses like diborane and phosphine to the inert gas to get p-doped and n-doped silicon, respectively. The diameter of float-zone ingot is generally not larger than 150 mm, as the size is limited by the surface tensions during the growth.

Directional Solidification: Multi-crystalline or polycrystalline silicon consists of many small crystalline grains. Highly purified silicon is meted in a dedicated crucible and the molten silicon is poured into a cubic-shaped growth crucible where the molten silicon solidifies into multi-crystalline ingots, termed as silicon casting. If the melting and solidification occur in the same crucible it is referred to as directional solidification. The cross-section of a multi-crystalline ingot can go up to 70 x 70 cm and the height is typically 25 cm.

Irrespective of the process used, the resulting polysilicon ingot must be sliced into thin wafers, with thickness in the order of tens or hundreds of micrometers. Two different methods are employed for the wafering process - sawing and silicon ribbon method.

Sawing is a process in which silicon ingots are sliced into thin wafers using thin wires. Diamond-coated wires are typically used for wafering. The wires are wrapped around the ingot multiple times for all the wafers to be cut in parallel, simultaneously. The disadvantage of the sawing step is that a significant portion of the ingot is wasted as sawdust in the sawing process, an occurrence known as kerf loss. The kerf loss is usually determined by the thickness of the wire or saw used for sawing and is in the order of 100 microns of silicon. Minimizing these losses is key to the optimization of the wafering process. Sawing will logically damage the surface of the wafers, so this processing step is followed by a polishing step.

Silicon ribbon is a completely different approach to making wafers that do not face the problem of kerf losses because it does not include a sawing step. Silicon ribbon is based on a high-temperature resistant string, which is pulled up from a silicon melt. The silicon solidifies on the string and a sheet of crystalline silicon is pulled out of the melt. The ribbon is then cut into wafers. The surface is further treated before they are further processed into solar cells.

Manufacturing Status and Key Suppliers

Global ingot manufacturing capacity has reached 428.31 GW in 2022, according to the BNEF database. Global ingot manufacturing capacity witnessed a substantial spur in the last decade which marks a 39 times increase in the manufacturing capacity of ingots. Similarly, ingot manufacturing capacity has seen an increase of 106% from 2020 to 2022. The developments in the manufacturing capacity of ingots in key countries are illustrated in Figure 80.

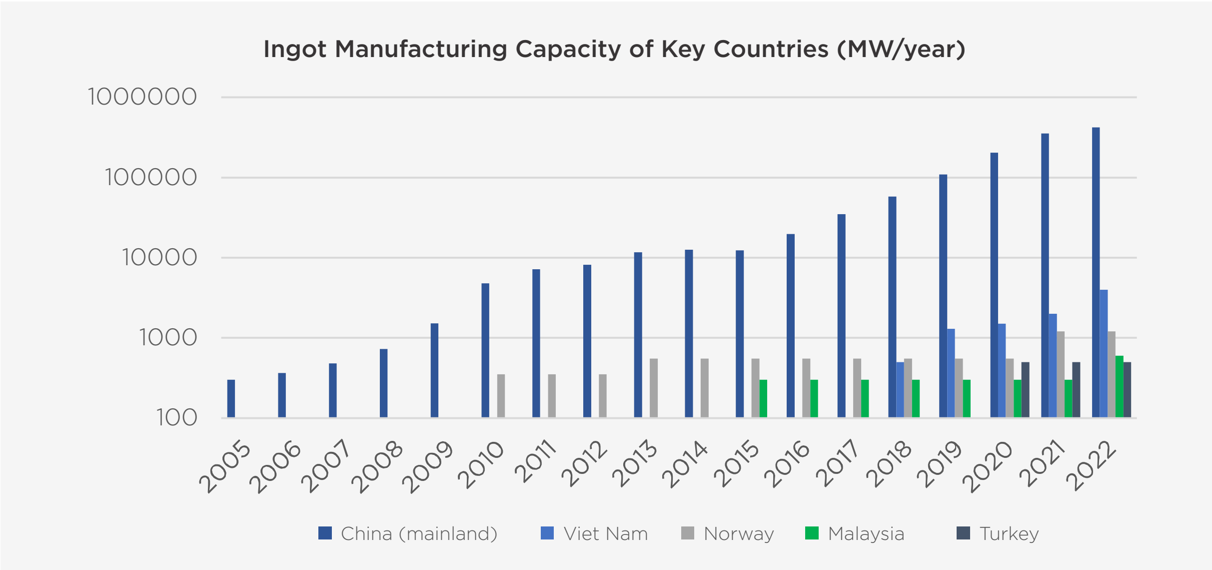


Figure 80: Ingot Manufacturing Capacity of Key Countries (MW)

Source: BNEF Database

China has developed as the hub of crystalline silicon manufacturing across the value chain, and at no stage is this fact more apparent than for the ingot and wafering processes. The capacity of ingot manufacturing has increased by a factor of 50 in the last decade. The details of the present installation capacity in key countries are depicted in Figure 81.

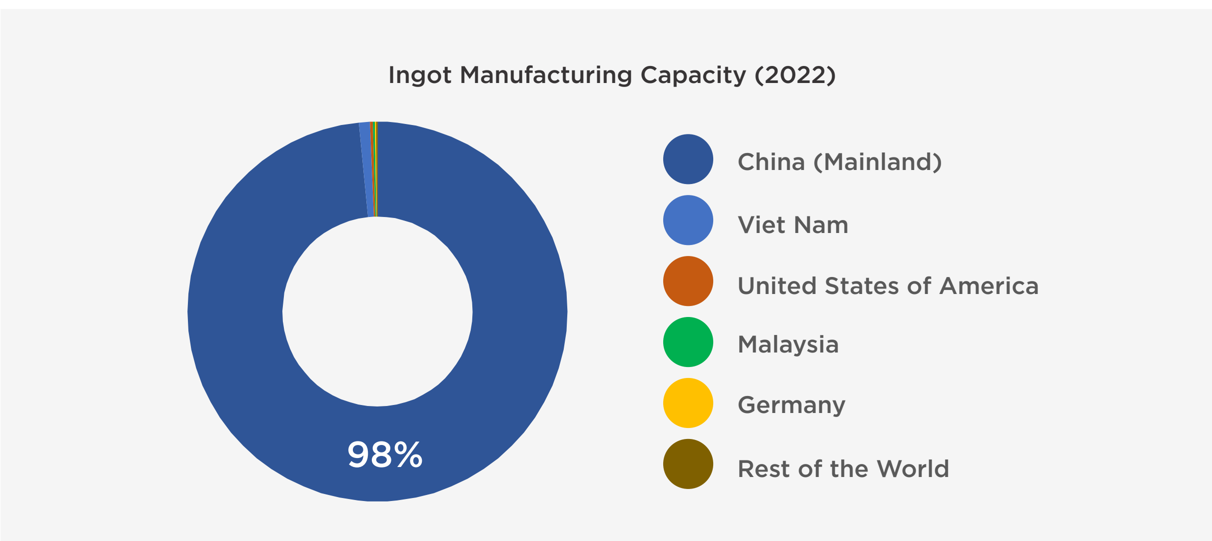


Figure 81: Ingot Manufacturing Capacity (2022)

Source: BNEF Database

China hosts approximately 98% of global ingot manufacturing capacity followed by Viet Nam. Additionally, most of the announced expansion plans with ingot and wafer production are also China-centric, implying that the country will continue to dominate these segments in the upcoming years too.

Ingots will be directly fed into the manufacturing process of wafers. The manufacturing capacity of wafers has reached 491.7 GW globally in 2022 from 54.5 GW in 2012. The trend in the wafer manufacturing capacity of key countries is demonstrated in Figure 82.

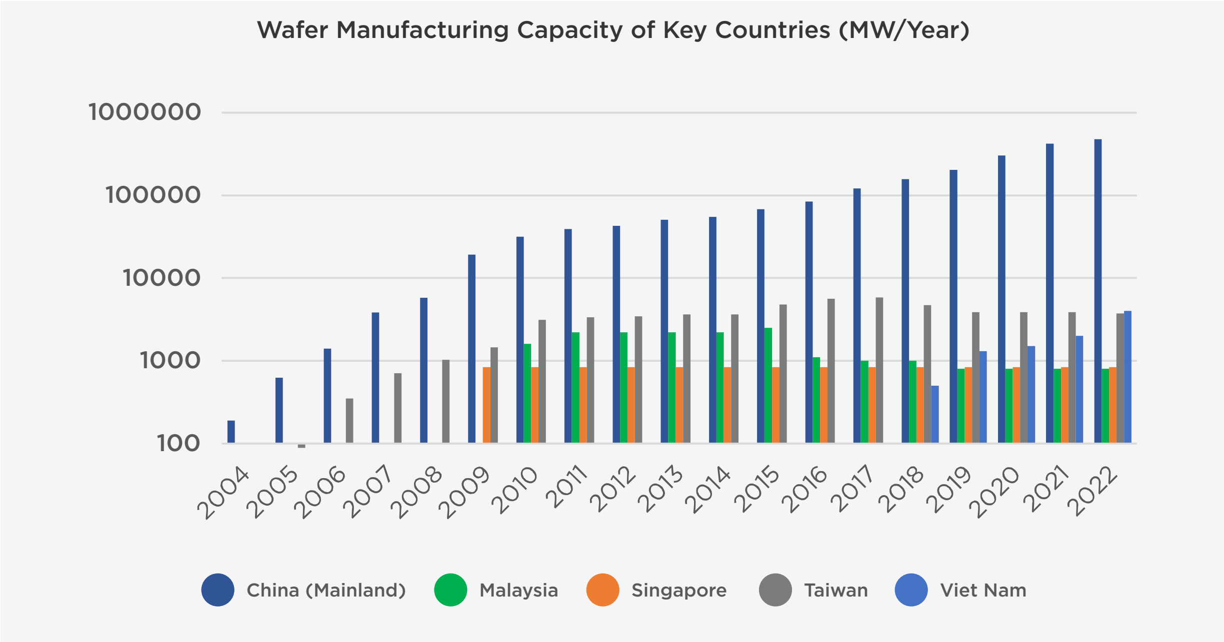


Figure 82: Wafer Manufacturing Capacity of Key Countries (MW/Year)

Source: BNEF Database

Chinese wafer manufacturing capacity grew nearly tenfold in the last ten years and approximately 58% in the last year. Amongst the other top countries with ingot and wafer manufacturing, Vietnam has seen significant growth, with capacity growing twofold in the last year. The wafer manufacturing capacity of key countries in the 2022 are illustrated in Figure 83.

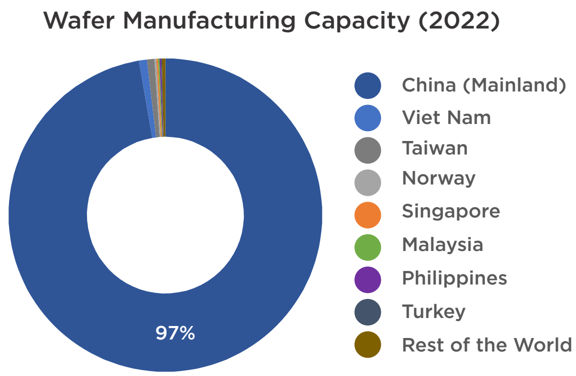


Figure 83: Wafer Manufacturing Capacity (2022)

Source: BNEF Database

China has a share of 97% of the total manufacturing capacity of wafers followed by Vietnam (1%) and Taiwan (1%).

The increased preference for monocrystalline silicon-based PV due to their higher efficiencies has resulted in significant growth of manufacturing capacity for monocrystalline ingots and wafers. The shared monocrystalline and multi-crystalline ingot and wafers are shown in Figure 84.

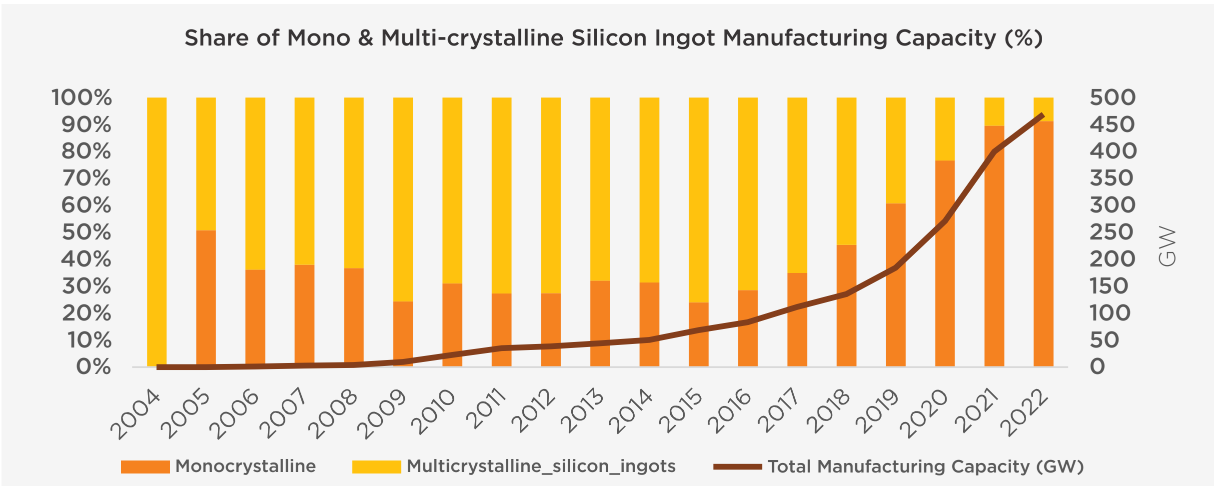


Figure 84: Share of Mono & Multi-crystalline Silicon Ingot Manufacturing Capacity (%)

Source: BNEF Database

Monocrystalline ingot manufacturing capacity accounted for 27.4% of ingot manufacturing capacity in 2012. Since then, coinciding with the development of mono silicon PERC architecture, monocrystalline ingot manufacturing capacity has increased rapidly to account for around 91.3% of global ingot manufacturing capacity.

BNEF estimated that nearly 369 GW wafers were produced in 2022 which implied that 75% of the manufacturing capacity has been utilized. More than 95% of global wafer production in 2022 was accounted for by the top 10 companies, as depicted in Figure 85.

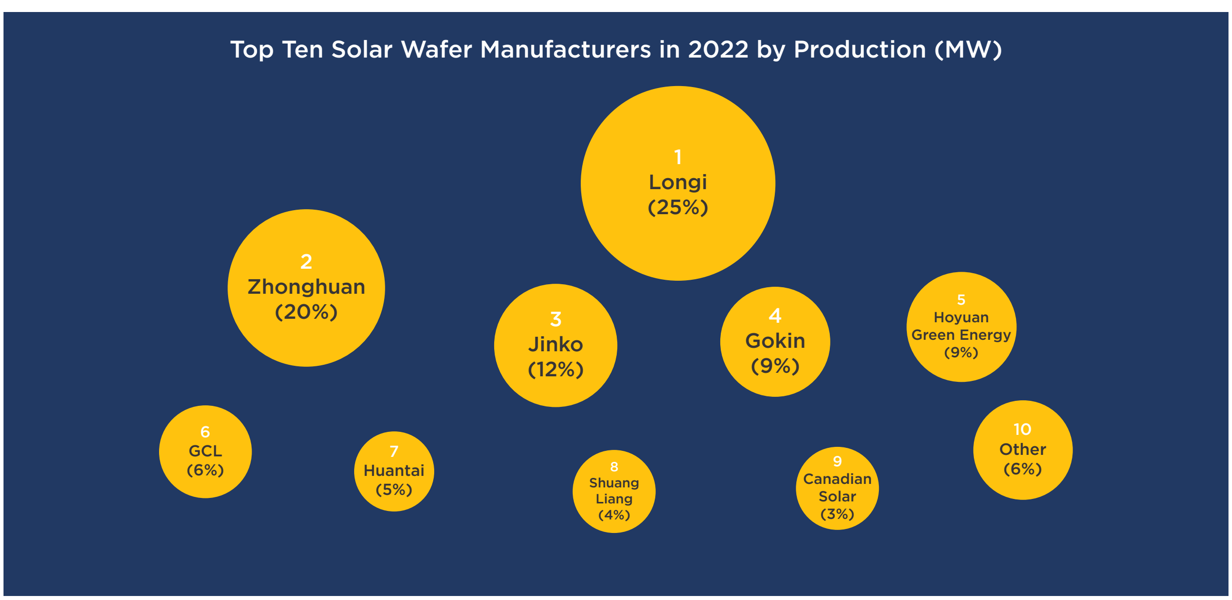


Figure 85: Top Ten Solar Wafer Manufacturers in 2022 by Production (MW)

Source: BNEF database

LONGi and Zhonghuan are the two leading wafer suppliers, which cover 45% of the total production in the leading manufacturers.

To meet the targeted installed capacity of solar PV in 2030 (5345 GW), according to the NZS of BNEF, the manufacturing capacity of wafers must be increased annually with a growth rate of 35% in the coming years, considering the cent per cent utilization of manufacturing capacity, wherein the present annual growth rate for the last 6 year 30%.

5.1.3. Cells

A wafer-based device is usually referred to as a solar cell. The dimensions of c-Si wafer-based solar cells in industry have been increasing rapidly during the last years due to advancements in ingot manufacturing. Currently, wafer sizes of 21.0 cm x 21 cm are becoming the mainstream size. During the cell manufacturing process, silicon wafers are converted into cells through a series of wet chemical treatments, high-temperature gaseous diffusions, coating depositions, and metallization steps. The steps and the tools used for these procedures vary based on cell architecture. Different architectures may require different numbers of steps, each with differing complexities. These architectures may vary depending on the type of wafer utilized (p-type vs. n-type), the passivation technique used to increase cell efficiency or changes in cell architecture (such as positioning of all electrical contacts on the back side of the cell). There is a plethora of options available, catering to various price points, efficiency requirements, and other potential benefits that are inherent to each architecture.

Regardless of the architecture, inspections at the start of the manufacturing line and electrical testing at the end of the line are used to identify cells that must be discarded. The tools and expertise needed to manufacture standard and PERC cells at high volume with guaranteed efficiencies are now widely available.

The process for manufacturing a PERC cell, the dominant cell technology in the market today, is highlighted below for reference:

1. **Wafer Scanning**
2. **Saw damage removal, surface texturization, and pre-diffusion clean**
3. **Phosphoryl Chloride (POCl3) Diffusion**
4. **Laser-driven selective emitter formation**
5. **Wet chemical PSG etch, rear side planarization and isolation etch by the rear side Phosphorous removal Z**
6. **High-temperature Silicon Oxide formation and Plasma Enhanced Chemical Vapor Deposition (PECVD) or Atomic Layer Deposition (ALD) of Aluminum Oxide for rear side silicon-aluminium surface passivation**
7. **PECVD of Silicon Nitride on the front and back for frontside anti-reflection, backside reflection, and surface passivation for the solar cell**
8. **Laser opening of dielectric layers for ohmic contact between Si and Al BSF**
9. **Screen-print Ag and Al pastes for tabbing and BSF formation respectively. Screen-print Ag pastes for fingers and optional busbars on front.**
10. **Optional hydrogenation step under illumination (or bias) that improves efficiency and passivates and stabilizes defects responsible for light-induced degradation**
11. **J-V measurement, visual inspection, and cell binning**

The 11-step standardized PERC process has 4 additional steps over the process used to produce Al-BSF cells. Certain newer cell technologies such as TOPCon build on the PERC architecture, whereas others, such as Heterojunction cells, have fewer processing steps but may require greater process variation due to the broad range of cells available.

Manufacturing Status and Key Suppliers

Solar cell fabrication has become a highly automated and technologically intensive process. As a result, cell fabrication typically thrives in locations with a few key advantages such as a sufficient labour pool of manufacturing engineers and machine labourers, government support of manufacturing through cheap land, electricity, and tax breaks to incentivize companies with sufficient access to capital to procure the equipment and land, access to the supply chain of affordable machines.

Global cell manufacturing capacity has gone up by 103.0 GW as compared with the installed capacity of 2021 and stood at 538.4 GW in 2022. The development of cell manufacturing capacity for key countries is demonstrated in Figure 86.

Cell Manufacturing Capacity of Key Countries (MW/Year)

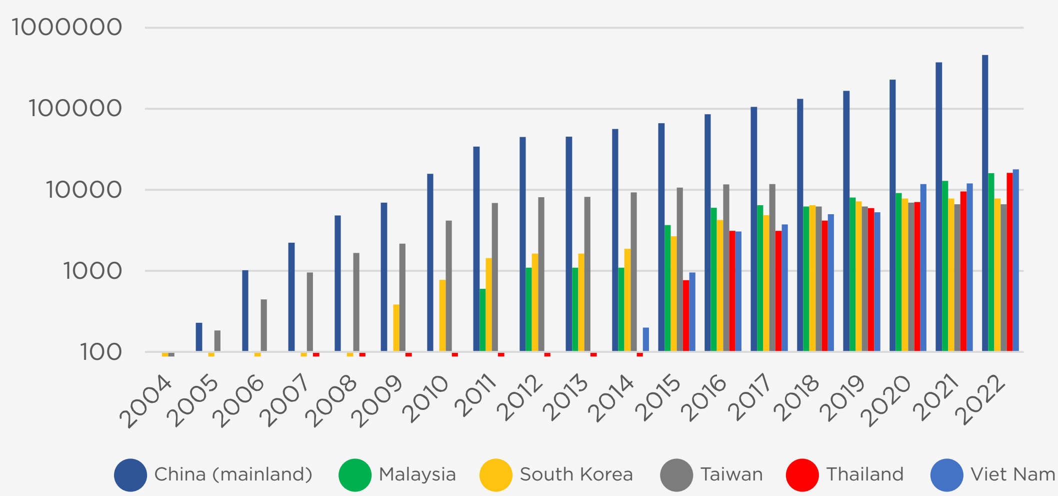


Figure 86: Cell Manufacturing Capacity of Key Countries (MW/Year)

Source: BNEF Database

The top five countries accounted for 96.4% of the total global cell production. China is dominant in terms of cell manufacturing capacity and is ahead of the other countries with cell manufacturing capabilities by over an order of magnitude. Chinese cell manufacturing capacity has grown ninefold since 2012. Despite their small installed capacity as compared with China, other countries like Thailand, and Vietnam have also seen significant surges in installation growth in the last five years by a factor of four like China. The manufacturing capacity of different countries in 2022 is illustrated in Figure 87.

Cell Manufacturing Capacity (MW),2022

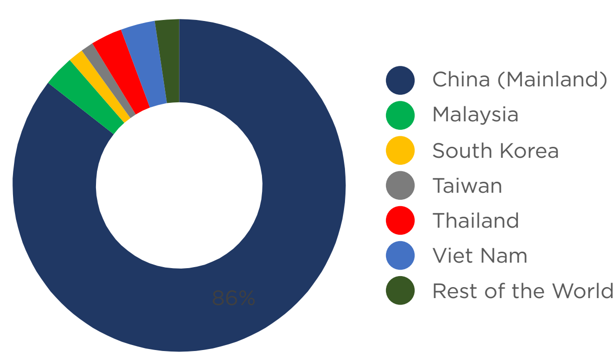


Figure 87: Cell Manufacturing Capacity (MW)-2022

Source: BNEF Database

Chinese cell manufacturing capacity has a share of 86% of the global installed capacity and has grown ninefold since 2012. Chinese manufacturers make significant R&D investments to drive process improvement and will likely remain a vital player in the PV cell supply chain for the coming years. The production trend in key countries is shown in Figure 88.

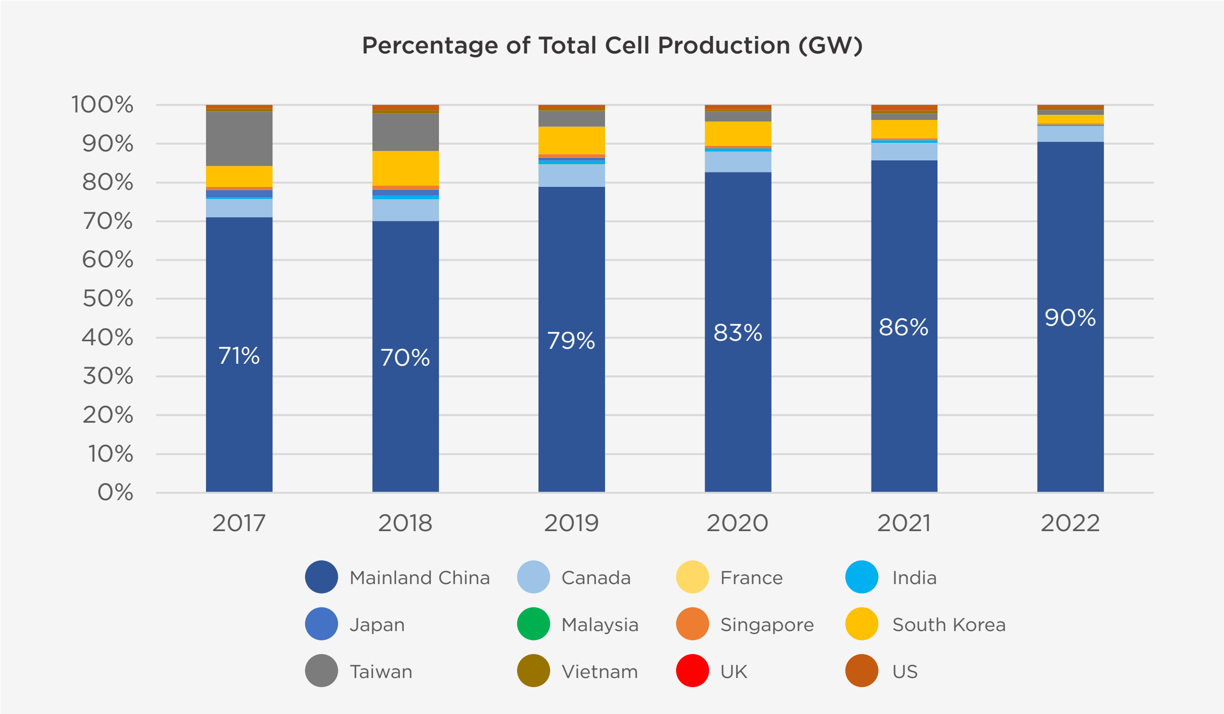


Figure 88: Percentage of Total Cell Production (GW)

Source: BNEF -Solar PV Equipment Manufacturers 2022

With an increase of 133 GW production in 2022 compared with the preceding year, total cell production in 2022 is estimated to be 361 GW, according to BNEF, indicating 67% of the utilization of installed capacity. The key manufacturing units headquartered in China increased their market share to 90% of the total market supply.

Cell makers compete in the market with both at specialized cell suppliers and integrated module manufacturers. Consequently, multiple cell makers are entering the module business, for instance, manufacturers like Tongwei, and Aiko Solar now, enter the module business[30]. The cell produced by key companies, as per the latest data in 2022, is depicted in Figure 89.

[30] *BNEF-2Q 2023 Global PV Market Outlook*

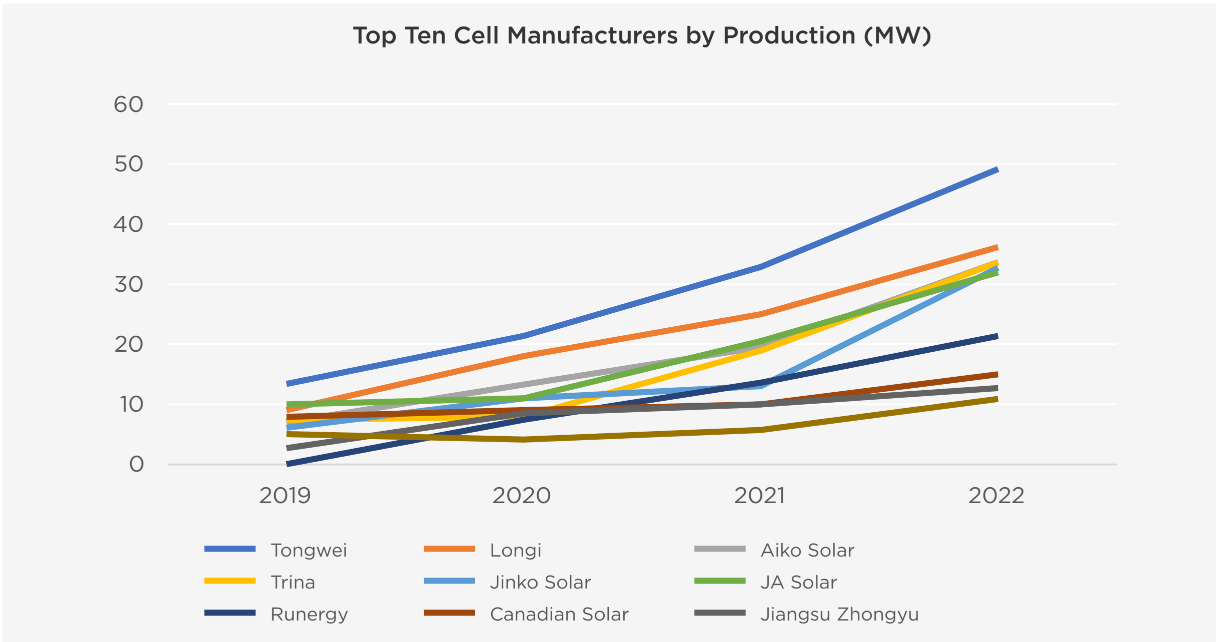


Figure 89: Top Ten Cell Manufacturers by Production (MW)

Source: BNEF -Solar PV Equipment Manufacturers 2022

Tongwei retained the top place in cell production over the last four years with an increased cell production from 33 GW in 2021 to 49 GW in 2022, a 59% increase in comparison with 2021. Now the cell markets are relatively diversified, with a significant portion supplied by manufacturers like Tongwei (13.6% with global production), Longi (10%), Aiko Solar (9%), Trina (9%) etc. However, it is observed that newly built manufacturing units are mainly for TOPCon production, led by integrated module makers. Jinko Solar has commissioned a cumulative capacity of 35 GW/year as of 2022. Similarly, other factories have also expanded their production capacity to TOPCon technology as shown in Figure 90.

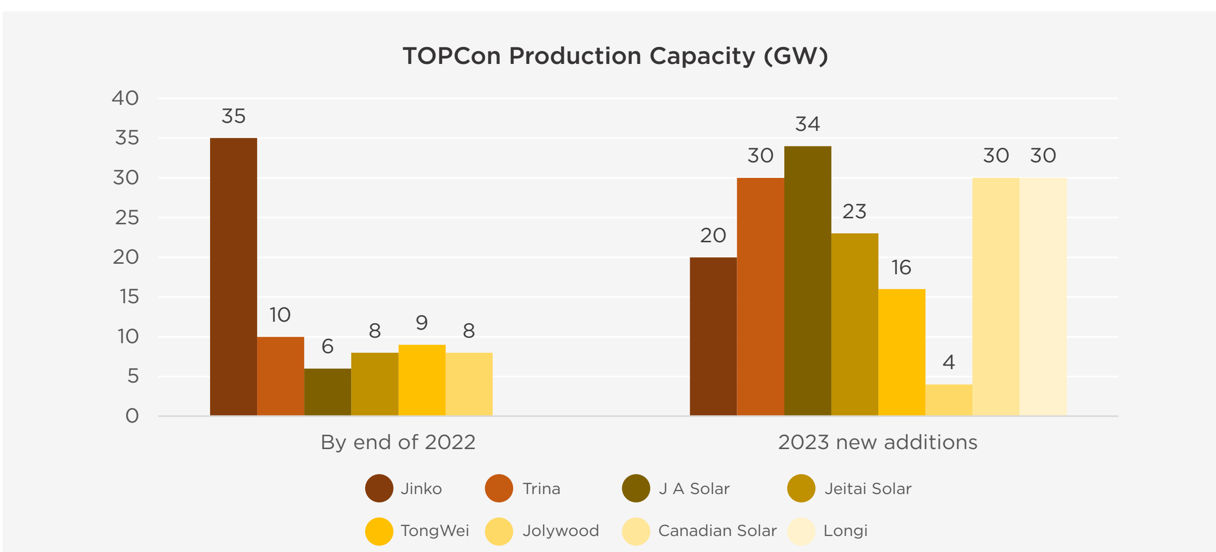


Figure 90: TOPCon Production Capacity (GW)

Source: BNEF-2Q 2023 Global PV Market Outlook

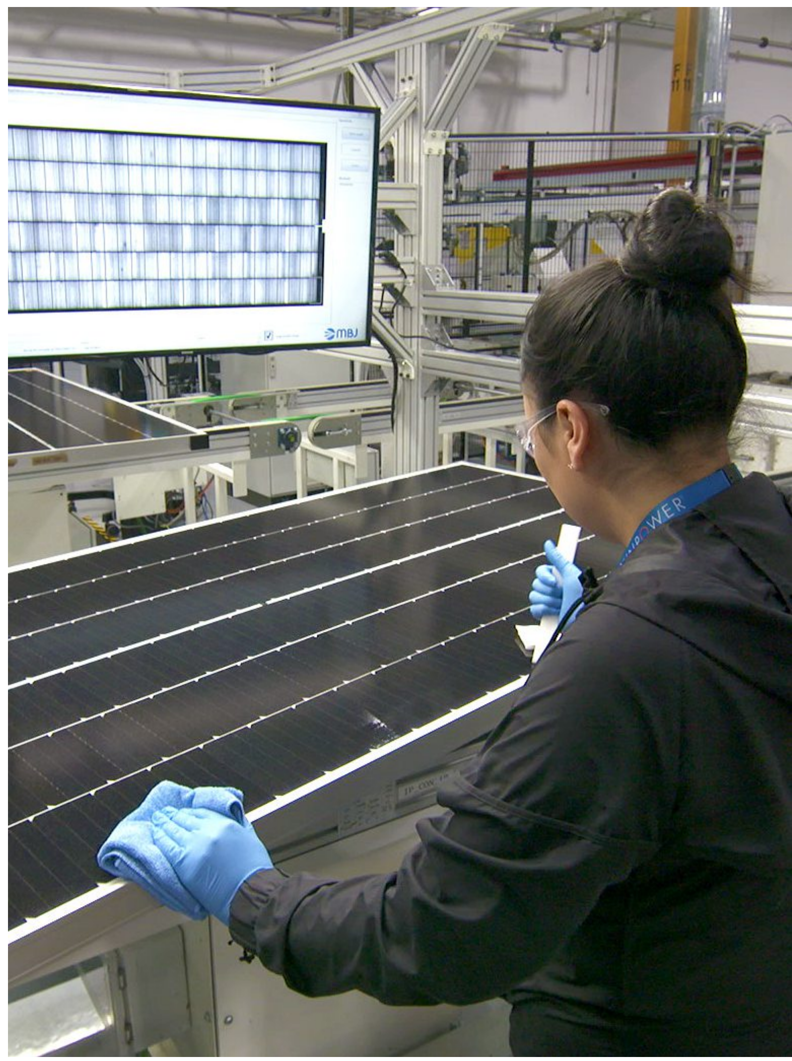
At the end of 2022, TOPCon technology has an installed capacity of 76 GW and it is expected to increase the capacity by 187 GW in 2023, led by primarily cell makers like Jinko (55 GW by the end of 2023), Trina (40 GW) and JA solar (40 GW). Capacity development of hetero junction cells also expands, which requires a significant investment, but is slower in comparison with TOPCon.

Apart from the present global cell manufacturing capacity (538.4 GW), an additional capacity of 111.8 GW is under construction and 288.2 GW has been announced wherein China is at the centre stage with a share of 94.7% and 88.17% respectively. To meet the targeted installed capacity of solar PV in 2030 (5345 GW), according to the NZS of BNEF, the production of cells must be increased annually with a growth rate of 40.0% in the coming years, wherein the present annual growth rate for the last 6 year 30.4%.

5.1.4. Solar Modules

A solar module consists of many solar cells interconnected in a circuit. To connect individual crystalline silicon solar cells in a module, the bus bars at the front side will be connected to the back contact of the neighbouring cell, the process is called contact tabbing. The more advanced way to place all the contacts at the back side of the solar cell is found in the interdigitated back contact (IBC) technology where both contacts are placed at the backside of the cells.

Module assembly entails electrically connecting cells into strings, arranging parallel cell strings into an array, electrically connecting the strings with metallic ribbons, and placing the array onto a layer of encapsulant on top of a sheet of glass or back sheet to develop the backside of the modules, and laminating another sheet of encapsulant and front glass onto the whole assembly to form the front side of the modules. The typical front and back encapsulants are thermoplastic material that melts when heated during the lamination process to encase the entire assembly between a sheet of glass on the front and a back sheet or another sheet of glass on the back. The ribbons are fed through a hole in the back glass or back sheet and interwoven on the back of the module within a junction box, which contains diodes to reduce cell mismatch and serves as the point of contact between modules in an installed system. Finally, an extruded aluminium frame is typically put around the perimeter of the module. Some firms have been developing glass-glass modules without an aluminium frame (including but not limited to options using bifacial cells) are also available.



As a result of the increase in wafer size and improvement in cell efficiency, the power output of individual modules has grown for the last few years. The standard module design of 60 and 72 cells is replaced by modules with half-cut cells like 120 or 144 half-cells. Subsequently, output from a single solar module in the market today offers even up to 700 W under standard test conditions (STC)[31].

Most of the components are relatively cheap to ship, including the aluminium frame and glass. Therefore, provided a manufacturing site has access to the PV supply chain, it can manufacture modules relatively inexpensively and without much capital expenditure or labour development.

Manufacturing Status and Key Suppliers

Global cumulative module manufacturing capacity, with an addition of 156.1 GW, stood at 656.7 GW in 2022. Due to the relatively simple processes involved in module manufacturing, especially when compared to the other stages of the supply chain, manufacturing capacity is more dispersed across countries. The module manufacturing capacity of the top six countries is plotted in Figure 91.

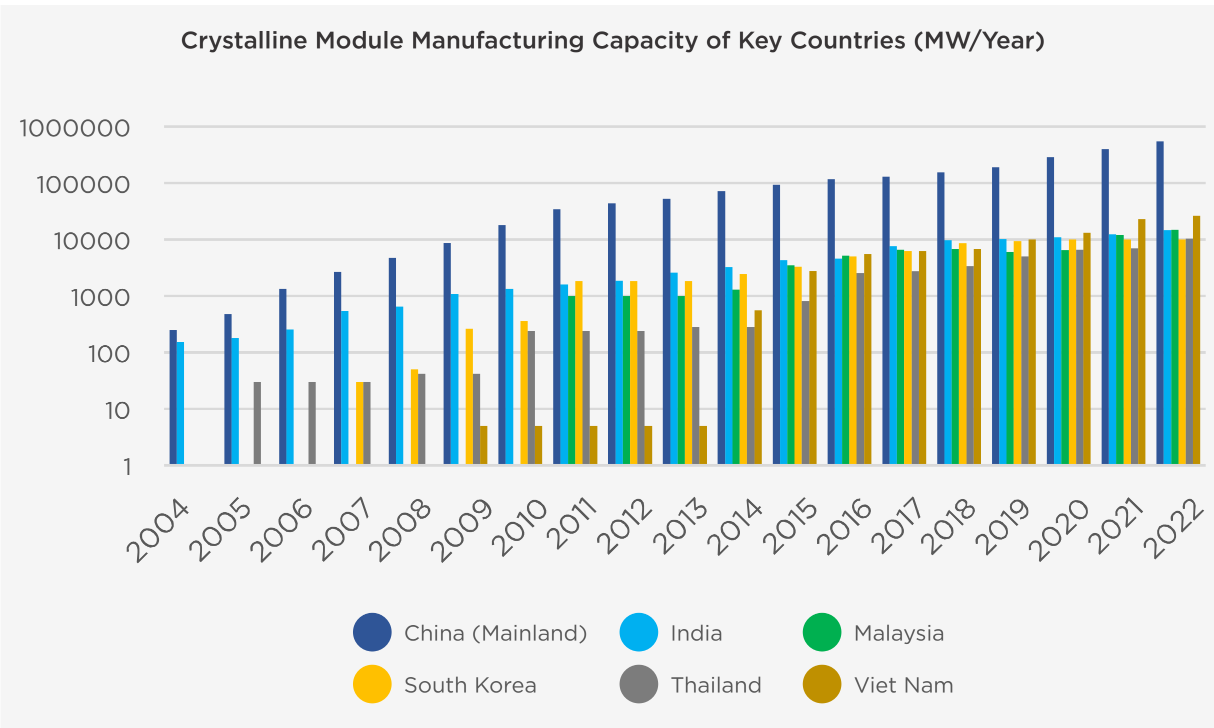


Figure 91: Crystalline Module Manufacturing Capacity of Key Countries (MW/Year)

Source: BNEF Database

[31] *IEA Special Report on Solar PV Global Supply Chain 2022.*

The top five countries in terms of module manufacturing capacity account for 92.7% of global capacity, implying significantly less geographical concentration than upstream manufacturing stages. Chinese module manufacturing capacity is far ahead of other countries, growing more than eleven times when compared to its capacity in 2012, and 35.7% in the last year alone. Though Vietnam stood in second place in production capacity, Thailand and Malaysia have seen rapid growth in the last year, with manufacturing capacity growing 50.6% and 24.2% respectively. The global solar module production capacity in 2022 is shown in Figure 92.

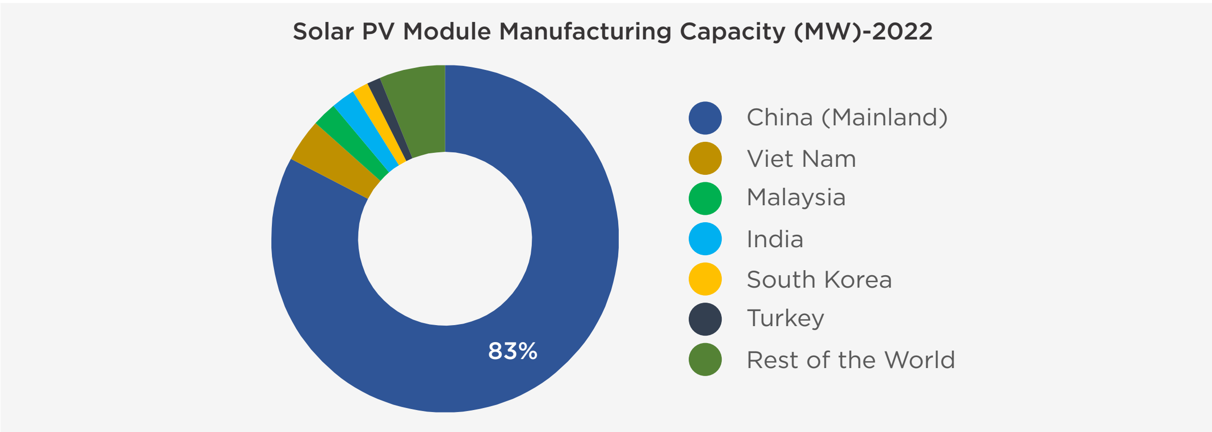


Figure 92: Solar PV Module Manufacturing Capacity (MW)-2022

Source: BNEF Database

Module production capacity is understandably dominated by Chinese companies, 83% of the global share, which are increasingly turning to larger-scale module production to maintain cost advantages in the increasingly competitive module market.

According to BNEF, total module production is estimated to be 368 GW (including thin film modules) in 2022 which is 58% higher than the previous year. However, merely 56.0% of the installed capacity has been utilized, considering the production in 2022. The production of modules in the last five years is shown in Figure 93.

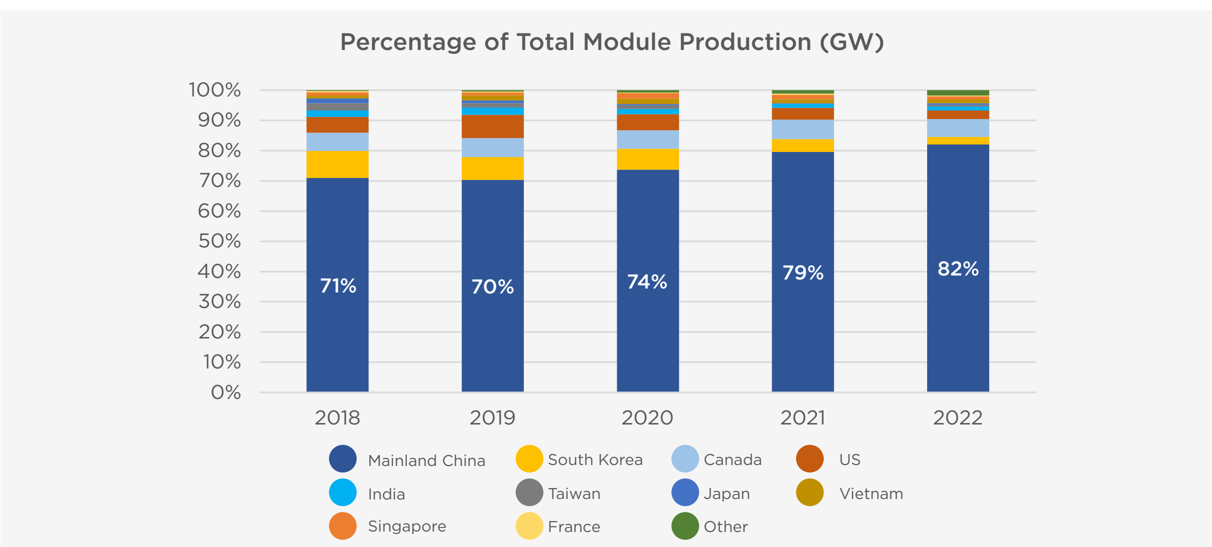


Figure 93: Percentage of Total Module Production (GW)

Source: BNEF -Solar PV Equipment Manufacturers 2022

China continued their dominance in module production for the last five years, from 71% in 2018 to 82% in 2022, followed by Canada and South Korea. All the top ten manufacturers of crystalline modules belong to China. The top ten module manufacturers based on their annual production are shown in Figure 94.

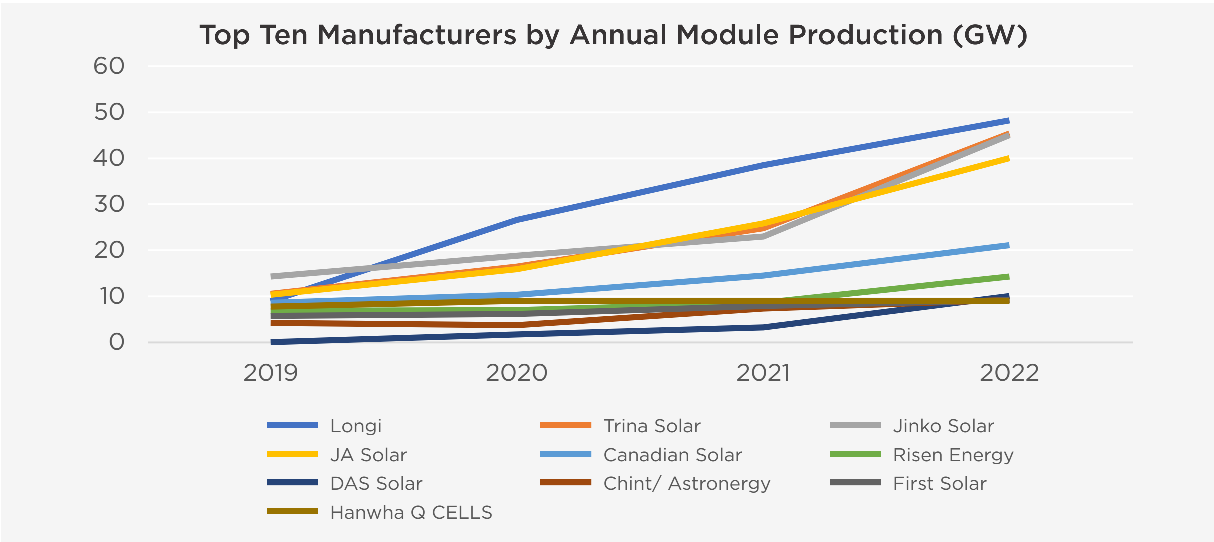


Figure 94: Top Ten Manufacturers by Annual Module Production (GW)
Source: BNEF - Solar PV Equipment Manufacturers 2022

All major manufacturing facilities of these companies are in China, though headquartered in other countries, covering 38.2% of the global module production in 2022. Longi maintained the top position in 2022 with a production of 48.2 GW. Manufacturers like Trina, Jinko and JA Solar were also expanding their production capacity with a year-on-year growth of nearly 50% and produced over 40 GW. First Solar, the only significant thin-film module manufacturer based out of the US, produced 9.1 GW modules in 2022[32].

Module manufacturing capacity under construction caters to 81.1 GW and the announced capacity is 243.3 GW. As in the case of other supply value chains, China upholds the top position in module manufacturing plants both under construction and announced. The NZS target of BNEF (5345 GW solar installation in 2030) demands an annual growth of 39.7% in module production in the next six years, while the annual growth of the previous six years is 36%.

It is easier for new competitors to enter the downstream supply chain stages such as cell and module manufacturing rather than polysilicon and ingot/wafer manufacturing. This is due to the significant capital expenditure requirements as well as the greater impact of economies of scale for the upstream stages. This leads to the entrenchment of existing manufacturers. The number of manufacturers across the various value chains, for the last three years, is illustrated in Figure 95.

[32] *BNEF- Solar Manufactures 2022 Production.*

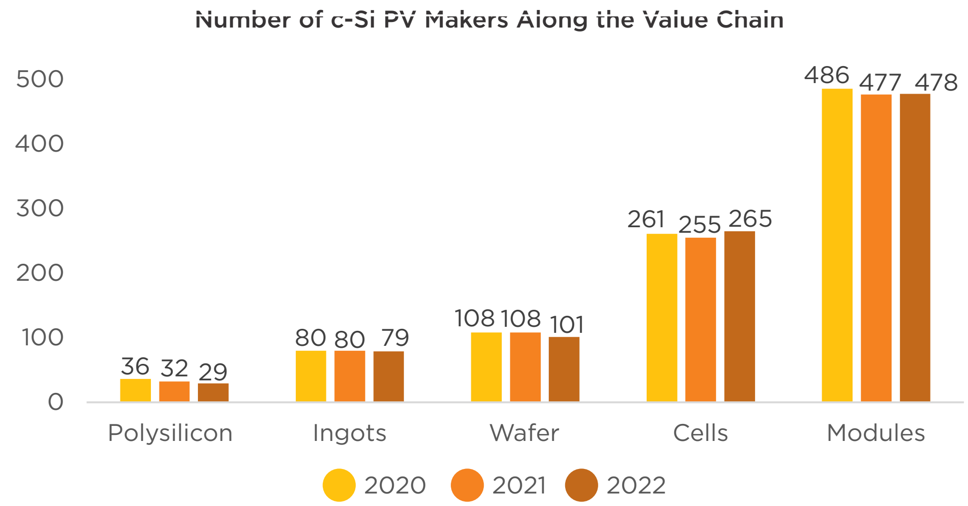


Figure 95: Number of c-Si PV Makers Along the Value Chain

Source: BNEF Database

Module manufacturing is by far the most accessible stage of the PV module supply chain for newer manufacturers, and this is reflected in the number of manufacturers for the stage is nearly double that of the preceding stage. It is also interesting to note the reduction or stagnation in overall number of manufacturers across the supply chain. This can be attributed to the oversupply situation that has been observed for solar PV. Additionally, acquisitions of struggling or smaller companies have led to further consolidation of manufacturing.

As expected, China is at the center of all shipments related to the PV manufacturing supply chain, both as a consumer (such as with polysilicon) and as a supplier. The global dependence of the solar market on Chinese manufacturing is significant and has led to energy security concerns and calls for increased domestic manufacturing by other countries.

5.2. Non-PV Specific Material

Although the crystalline silicon supply chain forms the heart of the silicon solar technologies manufacturing process, several other materials make up the overall module. Materials such as glass for front and back covers, polymers for encapsulant and back sheets, and metals such as aluminium for module frames are the major module bills of materials (BoM). These materials are used to manufacture the non-PV-specific components of a module.

5.2.1. Glass

Flat glass is typically used for PV module assembly. This glass generally has low iron content to ensure suitable transmissivity of sunlight. The glass is also tempered to improve resilience to the elements and given an anti-reflective coating to ensure that a maximum amount of incident sunlight can reach the PV cells within the module. The glass utilized for solar manufacturing typically uses silica sand as an input material. The glass used for crystalline silicon modules and thin film modules varies in terms of the manufacturing process which is mentioned below.

- The front glass typically used on crystalline silicon PV modules is typically rolled glass. This glass is slightly dimpled on the inner side to improve encapsulant adhesion.

- The front glass on thin-film PV modules is typically float glass produced on a float line. This is due to the need for a highly flat surface to act as a superstrate or substrate.

The rear glass component for thin film or bifacial crystalline silicon modules is typically soda lime glass. Soda-lime glass is the most common form of glass produced and does not have the specialized capabilities of the glass used for front glass components. However, this does not raise challenges for rear glass as high optical transmittance is not as important for the component, and the cheaper soda lime glass helps optimize module costs.

Float lines are primarily located in China, with other countries such as the USA, Taiwan, Japan, South Korea, Germany, and India having a small number of lines as well. Float glass lines may be able to be built in a relatively short time, allowing for a potential increase in float glass manufacturing capacities in other countries as required. The region-wise distribution of manufacturing float glasses is demonstrated in Figure 96.

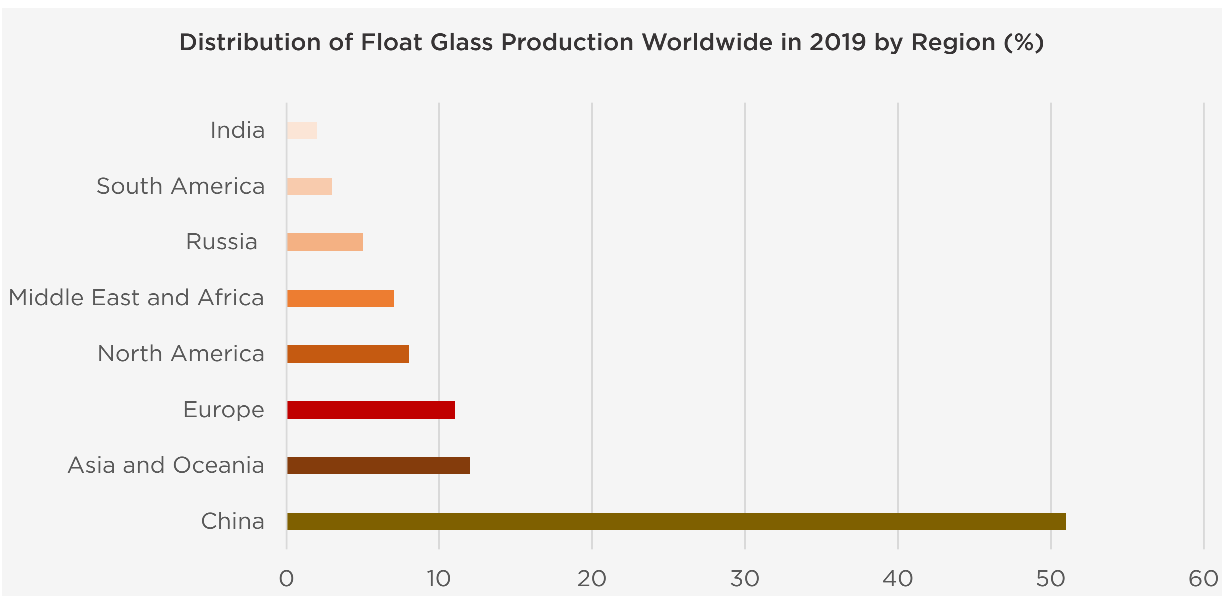


Figure 96: Distribution of Float Glass Production Worldwide in 2019 by Region (%)

Source: Statistica 2023

Few details are available regarding the distribution of rolled glass production. However, in general, most PV cover glass is produced in China. Since rolled glass has a higher proportion of labour costs as compared to float glass, it is much cheaper when produced in areas with low-wage labour, such as China.

Float glass is typically more expensive than rolled glass, and thus requires larger facilities to achieve the required economies of scale. A single float line is capable of producing approximately 2 GW of front glass per year and would require a capital investment of approximately $150 million. PV-specific float glass production brings challenges as well- to produce the low-iron pattern glass required for front glass for c-Si PV, float lines would have to be slowed down considerably, which would affect production capabilities and economic returns.

5.2.2. Encapsulant

Different polymers are involved in the manufacture of different components of a PV module. The major components where polymers serve as input materials include encapsulants and back sheets (which will be discussed in the next section).

Two main resin options are used to make encapsulants- ethylene vinyl acetate (EVA) (primarily used for monofacial PV modules), and polyolefin elastomers (POE), (primarily used for bifacial or thin-film modules). EVA is synthesized by polymerizing vinyl acetate monomers and ethylene[33]. Natural gas serves as the primary feedstock to produce both ethylene and POE. Solar manufacturers do not usually make the resins themselves. They are typically produced by a petrochemical company in resin form and sold to a film extruder which extrudes the resin into the film required for the module assembly process. These two steps are typically not vertically integrated, though some vertically integrated firms exist

Solar manufacturers do not usually make the resins themselves. They are typically produced by a petrochemical company in resin form and sold to a film extruder which extrudes the resin into the film required for the module assembly process. These two steps are typically not vertically integrated, though some vertically integrated firms exist[34].

[33 & 34] *Solar Photovoltaics Supply Chain Deep Dive Assessment*

5.2.3. Back Sheet

Back sheets served as the final back layer of crystalline silicon modules, but clear back sheets are now seeing use as the backing material for bifacial modules as well. Back sheets electrically insulate the module and protect it from environmental damage due to moisture and wind. Back sheet materials vary significantly across the market. Almost all back sheets use polyester (PET) but vary in terms of the material the PET is combined with. These other materials include polyvinyl fluoride (PVF), polyvinylidene fluoride (PVDF), polyethene, or less commonly polyolefin or polypropene.

Like the setup used for encapsulants, back sheet materials are typically first produced as resins and are then extruded into films. Back sheets are typically made of three films laminated together: the inner layer (touching the encapsulated cells), the core (middle) layer, and the outer layer which is exposed to air. The core layer is typically PET, while the outer layer is frequently PVF or PVDF. Firms typically carry out the lamination process independently, purchasing films and laminating the required films together into back sheets.

PVDF-based back sheets are reported to dominate the back sheet market; Fumotech, ZTT, and Arkema are major suppliers of PVDF resin. Some examples of vertical integration include ZTT in China, which produces PVDF resin and consumes about 50% of its resin to produce completed back sheets. Jinko and LONGi, two of the largest PV module producers, use PVF-based back sheets for most of their products.

There are a few major PET suppliers, mostly located in China, though the DuPont-Asia PET supplier is located in Japan. DTF is a major supplier of the PET core layer for back sheets. Most laminators are located in China, with some appearing in India more recently.

5.2.4. Aluminium Frame

The aluminium used in PV module frames or PV system racking can either be sourced through mining or recycling. Module frame production relies on extrusion and anodization or other coatings. The raw input aluminium must be suitably alloyed before use. Alloying occurs during the casting stage. The most popular extrusion alloy class, which is typically used in solar applications, is the 6000 series[35]. This alloy class is created by varying a combination of magnesium and silicon, depending on the strength required by the end use of the extruded aluminium profile. Once the desired alloy has been produced, it is extruded into the desired shape, then coated and cut (fabricated) as needed. The general structure of the aluminium extrusion industry encompasses the production of the desired alloy, extrusion into the desired shape, coating, or anodization, and finally fabricating or cutting as needed. Extrusion, coating/anodization, and fabrication processes are often co-located but may occur in separate facilities operated by different firms.

Some countries subsidize aluminium, which would result in PV frames and racking at a lower cost. Both extrusion and anodizing use large amounts of water, for cooling as well as cleaning and rinsing. Stricter regulations regarding water treatment will add to the cost of producing PV frames and racking. The United States has a significant capacity to produce aluminium for frames. China produces more than half the world's aluminium and steel[36].

[35 & 36] *Solar Photovoltaics Supply Chain Deep Dive Assessment*

5.3. Thin Film Technologies

Thin film solar cells are made from films that are much thinner than the wafers that form the base for PV cells, 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. Materials used in thin film technologies include silicon and other semiconductor materials to form thin film solar modules like amorphous silicon, cadmium telluride (CdTe), Copper Indium Gallium Selenide Sulfide (CIGS), Gallium Arsenide (GaAs) and Organic cells.

Rather than the crystalline silicon structure, thin film silicon has an amorphous structure. These amorphous silicon solar cells use many of the same materials as are used in crystalline silicon. Additionally, hydrogen is used for the passivation of the amorphous structure and zinc is used for the transparent conductive oxide (TCO) layer. Thin film silicon makes use of the same elements as crystalline silicon, with the addition of zinc, which is a major industrial metal, and hydrogen, the most abundant element in the universe. Thin film silicon, therefore, uses no rare or toxic elements. Manufacturing of thin-film silicon-based technologies such as amorphous silicon has remained stagnant and even reduced over the past 9 years.

Another class of thin-film solar cells are the chalcogenide solar cells. The term chalcogenides refers to all chemical compounds consisting of at least one chalcogen anion, from group VI, and at least one or more electropositive elements. First is CdTe, which currently is the thin-film technology with the lowest demonstrated cost per Watt-peak. The process for manufacturing the key thin film technology in the market- CdTe PV is fundamentally different than that followed for crystalline silicon modules. This class of chalcogenides uses materials like aluminium, zinc, and oxygen for the TCO layer. While the supporting materials like sulphur, aluminium and zinc are abundant, cadmium and telluride are not. Telluride is even among the rarest stable solid elements. Furthermore, cadmium is toxic, and it is very important to prevent cadmium from entering into the ecosystem.

The second group of chalcogenide solar cells are the chalcopyrite solar cells, which consists of elements from group one, three and six. Foremost among these are the CIGS. Copper and gallium are major industrial metals, but indium, selenide and cadmium are much less abundant. In addition, the current thin-film display industry depends on Indium as well. Because of the scarcity and toxicity of the required elements, the upscaling of the chalcogenide PV technologies might be limited.

III-V material thin film technology is mainly used in multijunction configurations, in which multiple III-V alloys are used. The III-V alloys are based on group III elements, like aluminium, gallium or indium, and group V elements, like phosphorus and arsenic. As some III-V concepts use a crystalline germanium wafer as substrate, it might not be considered a real thin-film PV technology. However, the III-V-based absorber layers can be considered as thin compared to the thickness of crystalline silicon wafers. Regarding the abundance of materials of III-V technologies, only aluminium and phosphor are abundant. Gallium, arsenic, and germanium are not rare or precious metals, but they are much less abundant than silicon. Indium, as we discussed earlier, is rare and in high demand. GaAs, therefore, is a very expensive material. Moreover, Arsenic is highly toxic, and it is strongly suggested that GaAs is carcinogenic for humans. Consequently, the expensive, III-V PV technology is mainly used in applications where the generated power density is the most important metric, such as for space applications and concentrator photovoltaics.

For organic PV, the used absorber materials are either conductive organic polymers or carbon-based organic molecules. A wide variety of materials are used for organic PV, from different groups. Even though organic solar cells themselves use cheap abundant materials like carbon, they require very expensive encapsulation materials and contacts to protect the organic materials from humidity, moisture, and air. Some of these materials, like platinum, ruthenium and Iodine are very rare. This constraint limits the industrial application of organic PV. Apart from dye-sensitized solar cells, Organic PV research has only been going on for the last decade and a half.

Perovskites are an organic-inorganic PV technology, that has received a lot of attention in the last decade, however, this is developed on a lab scale and become commercially available soon.

Malaysia has become the leading country for thin film module manufacturing capacity. The manufacturing capacity of thin film technology is given in Figure 97.

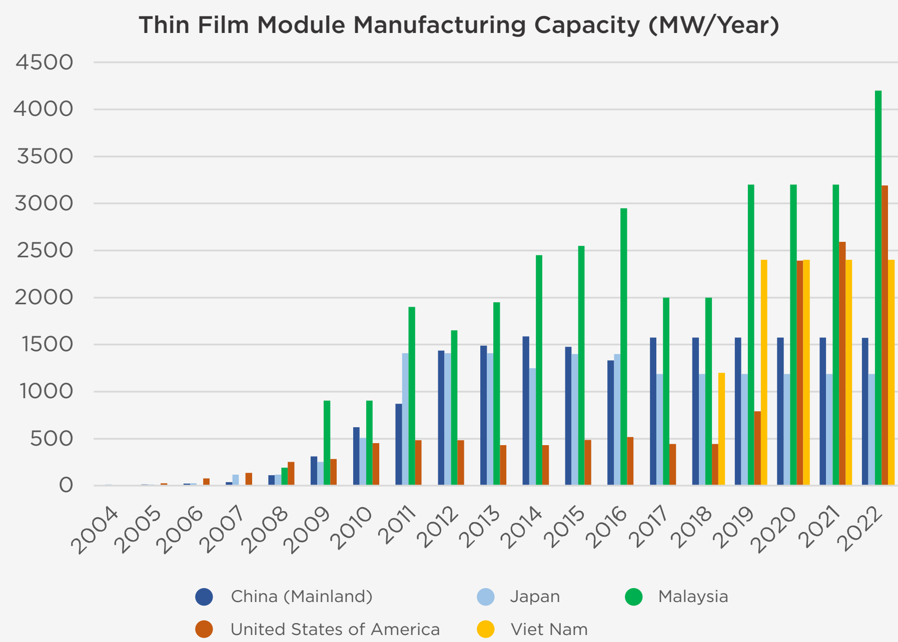


Figure 97: Thin Film Module Manufacturing Capacity (MW/Year)

Source: BNEF Database

The manufacturing capacity of United States is increasing recently and being an important market for CdTe modules. Vietnam has also seen a recent increase in thin film capacity. However, for other countries, manufacturing capacity is negligible and has remained mostly stagnant or slightly falling over the last 9 years

Non-silicon thin film modules may retain some of their appeal as CdTe modules do not rely heavily on Chinese suppliers, unlike the crystalline silicon module supply chain. Thus, countries with strained or unpredictable trade relations with China may be willing to explore a module manufacturing ecosystem based on thin film CdTe modules. Additionally, further work is being carried out for the development of suitable manufacturing capabilities for other thin-film technologies. For CIGS modules, GW-scale manufacturing facilities are in place, while pilot manufacturing lines for perovskite-silicon tandem solar cells are being set up. Additionally, further research is being conducted to develop organic PV manufacturing. Thus, the future may hold multiple options for the manufacturing of thin-film solar technologies.

5.4. Energy Consumption and Emissions in Solar PV Manufacturing

Manufacturing crystalline silicon solar PV panels is an energy-intensive process. The amount of energy consumed globally to produce polysilicon, ingots and wafers, and cells and modules reached 364 PJ (101.1 TWh) in 2021[37]. However, compared with the other large industries, the consumption in solar PV manufacturing is low, less than 0.2% of global industry energy use.

Production of polysilicon, being the stage with the highest electricity consumption in all supply chain segments, is accountable for 40% of all energy consumed to manufacture solar PV modules which is due to high temperatures of heat and the lengthy time essential to melt quartz, extract silicon and refine it to the level of purity required for solar cells. The Siemens process, employed for 90% of the manufacturing of solar-grade silicon, is the most mature as well as energy-intensive process that produces high-efficiency cells. The FBR process uses less energy compared with the Siemens process but also produces lower-purity silicon.

Ingot and wafer manufacturing stage found to be second largest energy consuming stage, after polysilicon production, due to the necessity of high temperature heat for long periods.

Finally, cells and modules account for less than one-third of total energy consumption for PV manufacturing because of requirement of less heat and lower temperatures for drying and cooling. In this stage, most of the electricity is used for automated mechanical work.

The increase in energy consumption of PV manufacturing industry for the last few years is shown in Figure 98.

[37] *IEA Special Report on Solar PV Global Supply Chain 2022.*

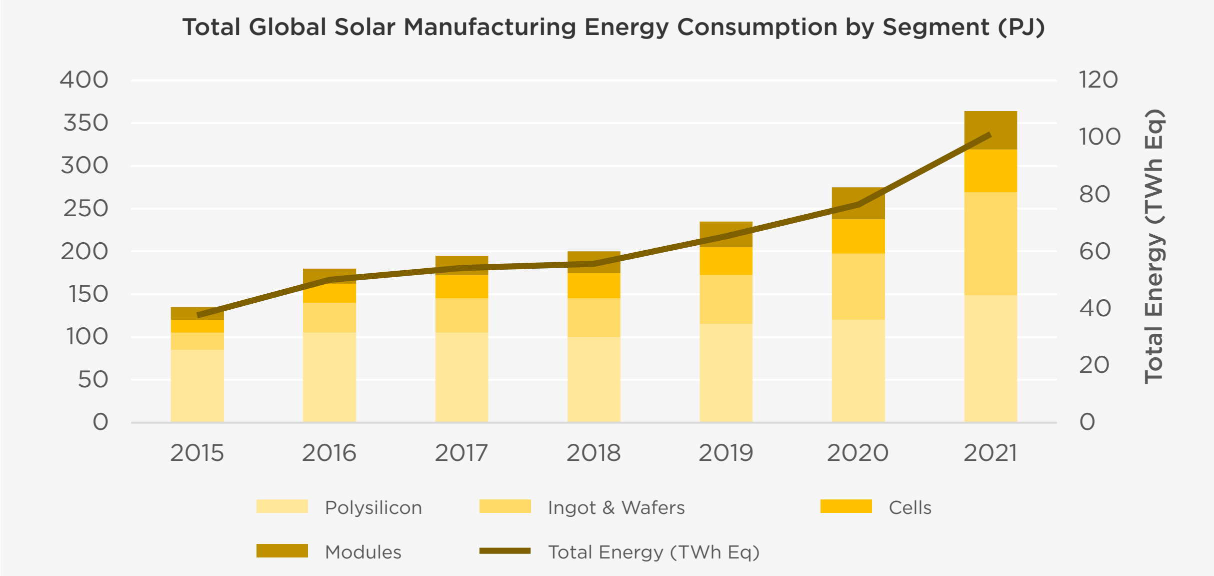


Figure 98: Total Global Solar Manufacturing Energy Consumption by Segment (PJ)

Source: IEA Special Report on Solar PV Global Supply Chains

Energy use for PV manufacturing has been growing since 2015 because of rising demand for solar PV. On analyzing the total production of solar PV module, according to BNEF, the energy consumption to produce one gigawatt module is reduced from 1.8 PJ in 2015 to 1.0 PJ in 2022.

Notably, electricity supplies 80% of the total energy required for module production. The electricity requirement in the production of 1 kW solar PV modules at different stages is illustrated in Figure 99.

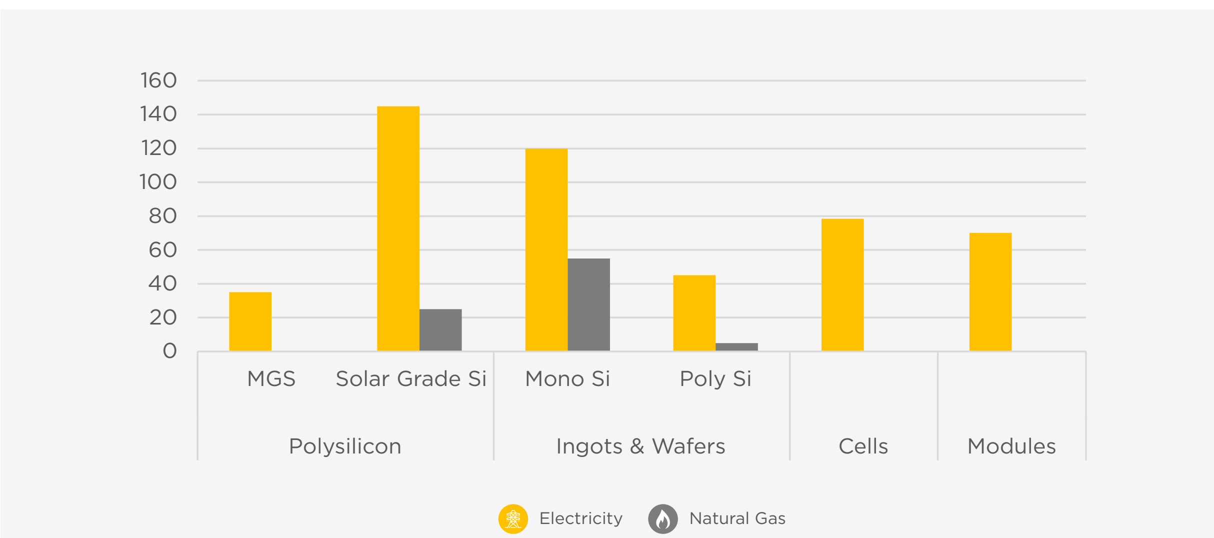


Figure 99: Solar Manufacturing Energy Consumption by Segment (kWh/kW)

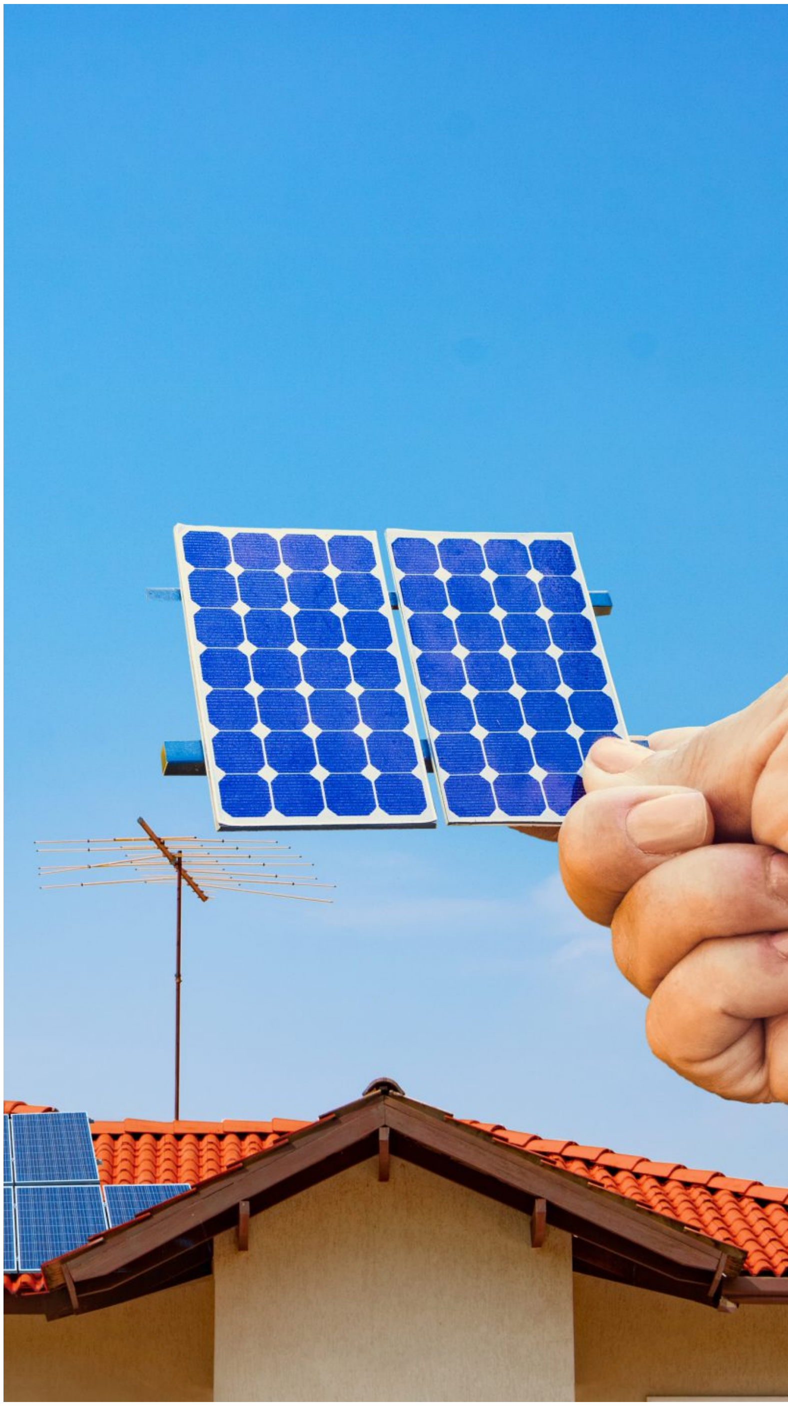
Source: IEA Special Report on Solar PV Global Supply Chains

Polysilicon and ingot production together make up to 72.8% of total electricity consumption due to their high heat requirements. Total equivalent electricity requirement to produce 1 kW solar PV module is 546 kWh. Considering a capacity utilization factor (CUF) of 17%, the energy required to produce a 1 kW solar module can be generated from the same in 134 days.

Global CO_2 emissions from solar PV manufacturing units increased from nearly 14000 kilotonnes of CO_2 (kt CO_2) in 2011 to more than 51900 kt CO_2 in 2021, accounting for almost 0.15% of total energy-related global emissions in 2021. Today, China is responsible for 87% of global emissions from solar PV manufacturing involving polysilicon, ingots, wafers, cells and modules, compared with only over 59% in 2011[38]. In the last decade, China's increase in production capacity surpassed global growth in all segments. As a result, the enlargement of its production and CO_2 emissions shares outpaced even global expansion. However, the CO_2 emitted during the production of 1 kW of solar module decreased from 500 kg CO_2 in 2011 to approximately 280 kg CO_2 in 2021. Considering an offset of 0.8 kg CO_2 from the generation of 1 kWh of electricity from solar, the CO_2 emitted during the process of production can be offset by 85.7 days. Furthermore, 1 GW of installed solar PV capacity could offset 1.5 million tons of carbon dioxide (Mt CO_2) annually from coal-fired generation.

5.5. Balance of System

Solar PV energy generation system comprised of inverters, solar mounting structures, AC and DC junction boxes, cables, protection and switching devices enabling the output from a solar PV module to be utilized by an external source. These components can be broadly termed as the balance of the system (BoS). Today, the manufacturing costs of BoS account for a significant chunk of the overall solar PV systems cost. It is difficult to quantify the production of BoS components (other than inverters) as they have fragmented production without significant centralized manufacturing and multiple players. The below section attempts to provide insight into the manufacturing of solar inverters.



[38] *IEA Special Report on Solar PV Global Supply Chain 2022.*

5.5.1. Solar Inverter

An inverter or a solar inverter forms a key component of a solar PV energy generation system. A solar module typically generates energy in the form of a direct current (DC) signal, whereas the supply of electricity to the grid, as well as the consumption of electricity by various electrical equipment, is in the form of an alternating current (AC) form. This conversion of electricity from a DC input to an AC output is done by an inverter. PV inverters have varying levels of capacity and functions, each with its own sets of advantages.

Solar inverter manufacturing is currently scattered in a manner that the power electronics and other components are manufactured in a standalone manner and later assembled into an inverter casing, except very few companies which have 100% vertical integration of the solar inverter value chain.

As per the BNEF 2022 data, the global solar inverter production has reached 381 GW (AC), dominated by Chinese companies. The annual inverter production for the last twelve years is given in Figure 100.

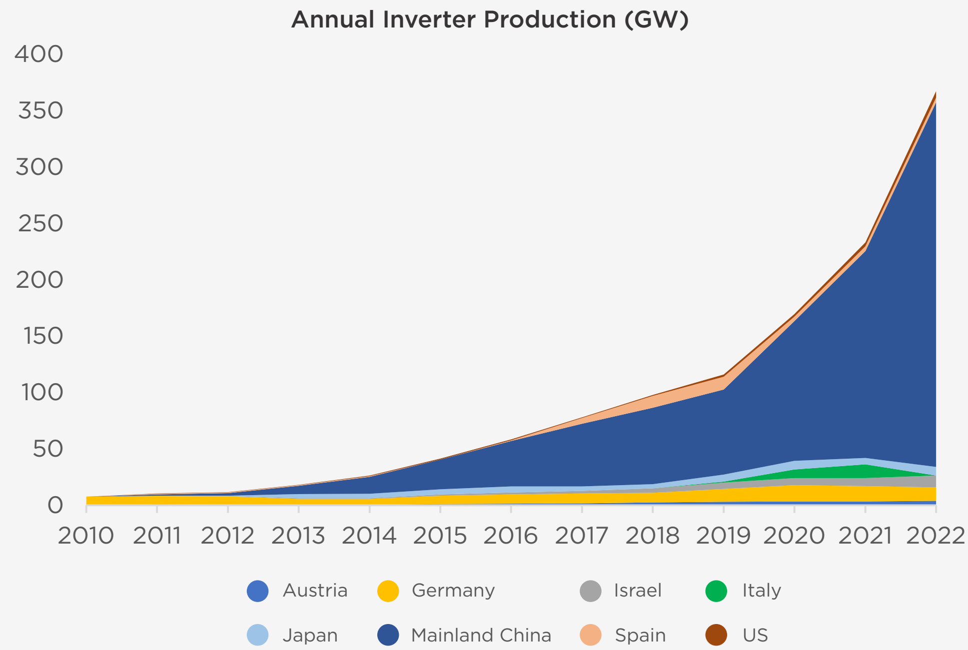


Figure 100: Annual Inverter Production (GW)

Source: BNEF -Solar PV Equipment Manufacturers 2022

The inverter production is increased from 11.8 GW in 2012 to 367.8 GW in 2022 in which China has been dominating rising the share from 19% in 2012 to 88% in 2022. Total inverter production has tripled from 2019 to 2022 as the solar installation continued to soar. Chinese inverter makers increased their production capacity by 146 GW in 2022[39]. Some of the key solar inverter manufacturers, globally, as per their production capacity, can be seen in Figure 101.

[39] *IEA Special Report on Solar PV Global Supply Chain 2022.*

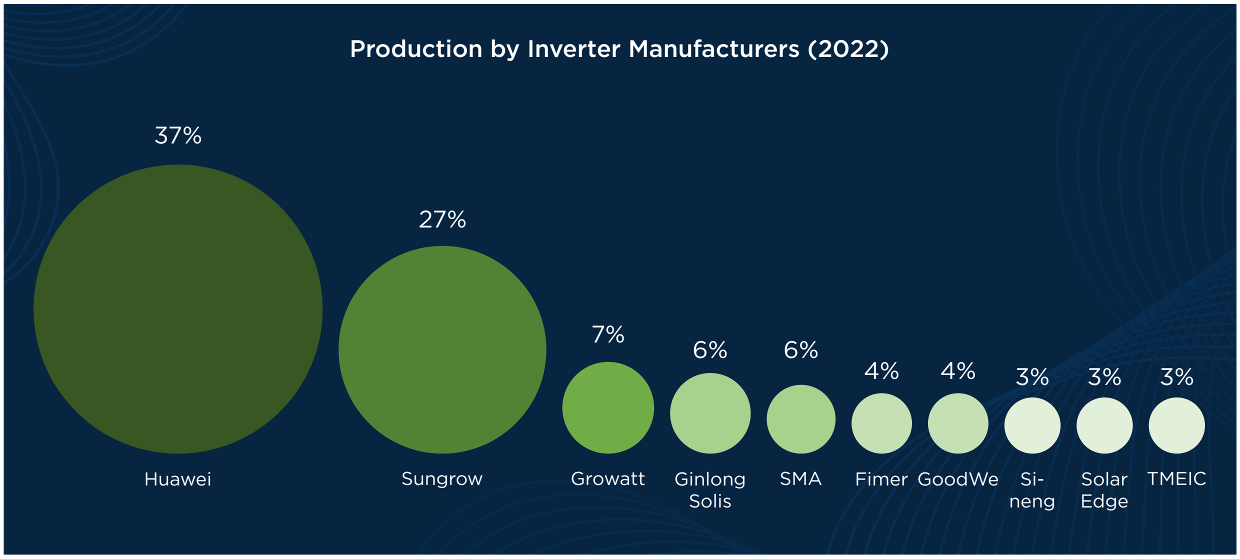


Figure 101: Production by Inverter Manufacturers (2022)

Source: BNEF - Solar PV Equipment Manufacturers 2022

According to BNEF, Huawei doubled their production as compared with preceding year and manufactured 112 GW inverters in 2022, a share of 37% among top ten inverter manufactures. Sungrow, followed Huawei in production with 82 GW of capacity, an increase of 26 GW compared to 2021. These two companies collectively met over half of the global inverter demand in 2022[40]. Micro inverters such as Solar Edge and Enphase have seen a strong demand in 2022, 10.5 GW (AC) and 5.7 GW (AC) respectively, 46% and 68% higher than in 2021.

Considering a DC-to-AC ratio of 1.25, meaning 381 GW inverter can be connected with 476.2 GW of solar modules, 4276 GW (AC) inverter capacity would be required to meet the NZS target of BNEF by 2030 (5345 GW of solar module installation by 2030). To achieve the same, inverter production must expand the production of inverter by an annual growth rate of 39.7% in the next six years, while the present annual growth rate previous six years is 35.9%.

5.6. Solar Waste

As the world is moving towards achieving Net-Zero emissions, rapid, terawatt-scale deployment of photovoltaic (PV) modules is expected in the coming years. However, this shall also lead to the challenge of large volumes of PV modules, approaching their end-of-life, to be disposed away. With a typical lifetime of 30 years, the solar PV waste generated by 2050, globally, is expected to be around 60 million tons (Mt)[41]. With the rapid developments in solar PV module technologies, and considering the efficiency drop of solar PV modules after the 25-year time, more and more solar PV plants shall be decommissioned and replaced with newer, advanced and much more efficient modules. This shall cause a rapid increase in solar waste, forming an "early loss scenario". In such a scenario, the Solar PV waste generated is estimated to be around 78 million tons (Mt) globally by 2050.

Policy action and technological solutions are required to address the challenges ahead, with

[40] *BNEF - Solar PV Equipment Manufacturers 2022*

[41] *IRENA: End of Life Management- Solar Photovoltaic Panels, 2016*

enabling frameworks being adapted to the needs and circumstances of each region or country. As can be seen in the above graph, China is forecasted to generate the maximum amount of Solar PV waste by the end of 2050. The waste generated shall also be directly proportional to the country wise ambitions for the solar PV installation targets. Despite the efficiency and manufacturing improvements, material demand will increase, eventually resulting in waste as deployed modules reach the end of life. Managing this solar PV waste is a major environmental challenge. Besides contradicting circularity principles, dumping of PV panels, consisting of hazardous materials such as lead shall subsequently lead to environmental pollution as well as health issues.

To avoid such a situation, and to minimize the use of virgin materials in the production line of new solar PV modules, solar PV recycling seems to be focused upon. Proper procurement guidelines and Circular choices for decommissioned modules could reduce waste and offset virgin materials. Furthermore, because such a step shall provide a domestic supply alternative, solar PV recycling can alleviate energy security concerns for countries which are heavily dependent on imports. It shall also lead to avoiding negative environmental, social and health impacts associated with raw-material mining, and eventually reduce the energy and environmental footprint of solar PV. An ideal solar recycling value chain is described in Figure 102.

Figure 102: Solar PV Recycling Value Chain

Assuming proper and systematic collection of end-of-life (EoL) solar PV modules, and an expected material recovery rate of 85%, cumulative secondary supplies from recycling all EoL solar PV modules could help meet 3-7% of the solar PV industry's material demands to produce new solar PV modules by 2031-2040[42].

This is with the assumption that with the emerging manufacturing technology, the material consumption for solar PV modules shall also decrease, as described in the previous sections. The material contributions of solar waste with recycling are shown in Figure 103.

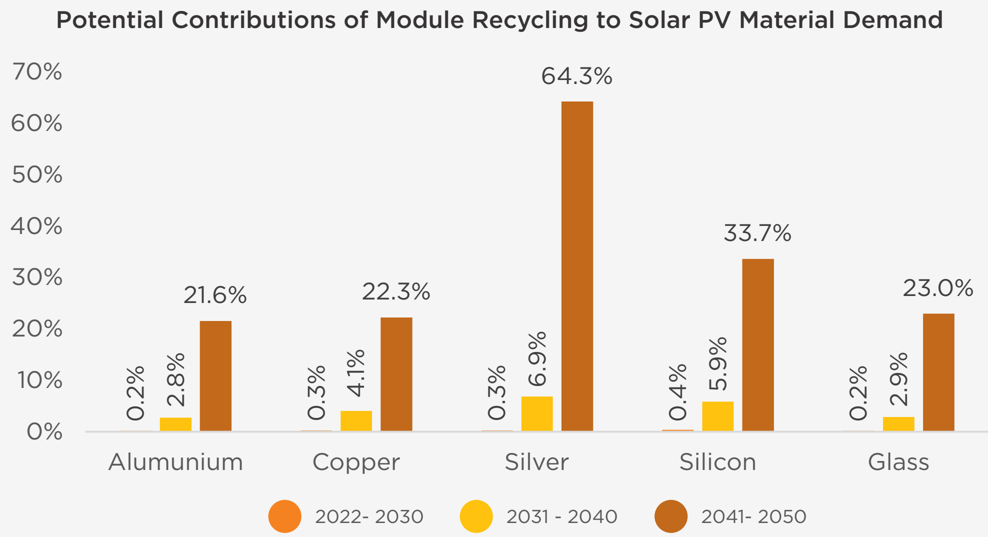


Figure 103: Potential Contributions of Module Recycling to Solar PV Material Demand

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

Being the major material in the production of solar module, 21.6% and 23% of glass and aluminium respectively in the demand in 2050 can be met by recycling the same from expected solar waste.

[42] *Special Report on Solar PV Global Supply Chain, IEA*

Fostering solar technology development: Addressing key gaps

6.1. Solar Value Chain

6.1.1. Manufacturing

Improving supply chain reliability is crucial in the manufacturing industry. Solar manufacturing, primarily for c-Si PV modules, is an increasingly important sector for countries that are planning large solar capacities to drive their clean energy transition ambitions.

Several aspects need to be considered to ensure that manufacturing remains steady:

Geographical concentration of the crystalline solar PV supply chain

The geographical concentration of the crystalline solar PV supply chain has evolved over the years, which is primarily concentrated in a few key regions. The solar supply chain is heavily dependent on China. The country has at least 77% of manufacturing capacity at each stage of the supply chain. Additionally, the key segments of ingot and wafer manufacturing are almost entirely located in China.

Relying on a single source of critical components or materials can be risky. Manufacturers should diversify their suppliers to reduce dependency on a single source. Thus, there is an urgent need for diversification and development of other manufacturing hubs. These new facilities will have to compete with large Chinese manufacturers who benefit from economies of scale, government support, and access to cutting-edge technologies.

Supportive policies and mandates, and financial aids, therefore, to promote local manufacturing will be required to kick-start the localized manufacturing initiatives. Technology transfer and capacity building will also be needed to develop the skilled workforce and technical expertise required for key stages of the manufacturing process.

Vertical integration of solar manufacturing value chain for energy security

As solar becomes the technology of choice for the energy transition, it becomes increasingly important for countries to secure their access to high-quality solar modules to help meet the demands of their projects and keep their clean energy commitments on track. Vertical integration in the solar manufacturing value chain can enhance energy as well as financial security which will enable the manufacturers to ensure supply chain control, quality assurance, cost efficiency, R&D etc. In China, a significant amount of vertical integration is seen between cell and module manufacturing, and this may often extend to ingot and wafer production as well. In China, a significant amount of vertical integration is seen between cell and module manufacturing, and this may often extend to ingot and wafer production as well. China has invested over $50 billion in new PV supply capacity – ten times more than Europe, since 2011[43].

Outside China, many countries have existing cell and module manufacturing facilities, as these downstream stages have shorter gestation periods, reduced capital requirements, and lower technological barriers than upstream segments (polysilicon and ingot/wafer). As discussed earlier, 97% of the ingot and wafer manufacturing units are situated in China. Other countries, therefore, are highly reliant on imports of polysilicon and wafers from China, leaving their supply chain vulnerable to external shocks. Consequently, vertical integration of manufacturing facilities will significantly benefit countries that are leading to the track of energy transition, which can address all stages of the crystalline silicon value chain.

Securing of non-silicon components for modules- glass, polymers (EVA), metals etc.

While silicon is understandably the key focus of manufacturing initiatives, it is important to note that, since silicon contributes a maximum share of 4% in the module manufacture, vertical integration must also consider the additional components that are required to prepare a solar module. Glass covers, back sheets, encapsulants, metallization pastes, and interconnection metals are all vital parts of module manufacturing. These components broaden the material requirement of modules to go beyond silicon, requiring high-quality glass, Polymers (such as EVA), metals (Copper, Silver, Aluminum, Zinc) and more. Thus, true vertical integration and supply chain de-risking will require securing access to these additional components as well. As seen with the shortage of solar PV glass in 2020, the disruption of these BoM components can cause disruptions to solar module manufacturing as well as an increase in costs.

[43] *IEA - Solar PV Global Supply Chains*

Overcapacity across the crystalline PV supply chain

The global solar PV supply chain is currently in an overcapacity situation, i.e., there is more capacity for manufacturing than there is demand for PV module components, as the total capacity addition of solar PV power plants in 2022 is estimated to be 189 GW as per the data of BNEF. The details of manufacturing capacity and production in 2022 are given in Figure 104.

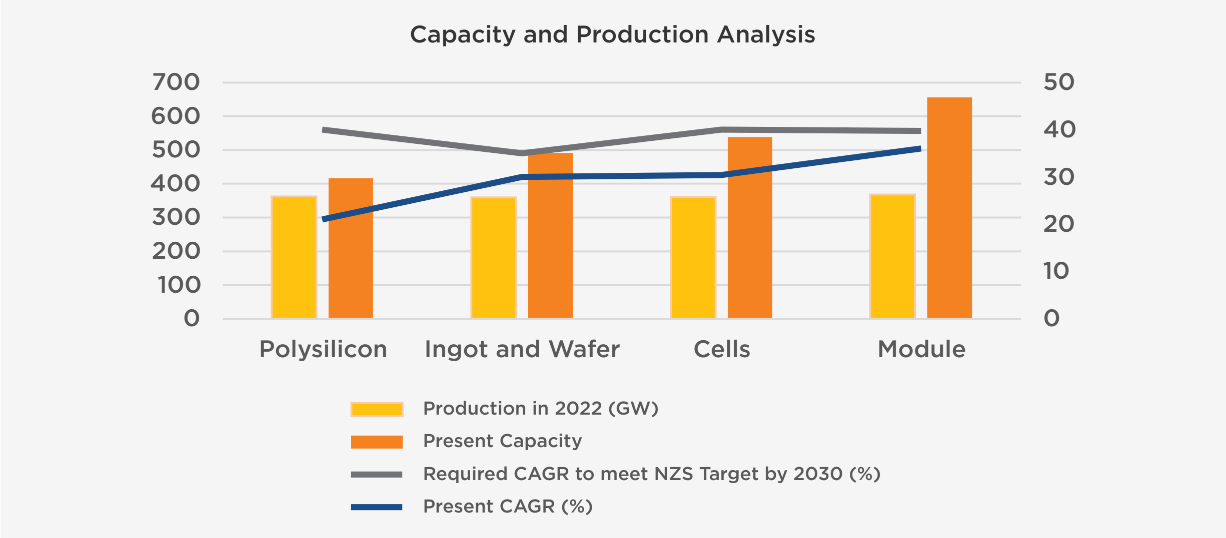


Figure 104: Capacity and Production Analysis

Source: BNEF and ISA Analysis

Polysilicon, which had seen severe capacity shortages post-2020, observed resilience in recent times, satisfactory with present demand. Additionally, the development of new polysilicon capacity, while underway, will require some time to ramp up production close to nameplate capacity. Meanwhile, wafer and cell manufacturing capacity are significantly higher than the global demand. The module manufacturing capacity is found to be nearly double as compared with the production in 2022.

Though there is overcapacity, there are cases of regional shortages as all regions apart from Asia must import huge quantities from China which has a monopolistic hold over capacity. In case of any disruption in China, the global solar industry will get a huge jolt as was seen during the COVID pandemic. The present overcapacity can be partially attributed to the presence of old and obsolete manufacturing lines. An estimated 30-40% of current manufacturing capacity was installed before 2018, and thus may require upgradation to become compatible with newer technology standards to reduce redundancy.

However, considering the NZS pathway, the CAGR must experience substantial growth in the next five years, to achieve the target in 2030. Polysilicon production should be increased with an annual growth rate of 40% in the next few years, while the present annual growth rate is 21%. Other supply chains also push their production in a way to achieve a 5-10% increase in annual growth rate.

Reduction of capital and operations expenditures

Capex requirements vary significantly across different geographies, depending on past installations in the region, the presence of cheap labour and machinery, the cost of construction etc. However, relative to the cost of plant operation, these capex requirements are relatively lower. Opex costs are primarily driven by labour and electricity costs, both of which vary across regions. For example, China benefits from subsidized electricity and cheap skilled labour, while an equivalent plant in Europe or the USA would be significantly more expensive to run due to the high costs of electricity and labour. As a result, manufacturers headquartered in other than China set up manufacturing units in China and benefited from the policy and financial support of China. It is imperative that countries looking to develop new solar manufacturing capacity provide subsidies/ financial support to allow manufacturers to mitigate the higher costs of operation.

Concentration of production among key manufacturers

Across the solar PV supply chain, production is dominated by the top ten or so companies, in some cases providing over 90% of manufacturing capacity. The share of the top ten companies is given in Figure 105.

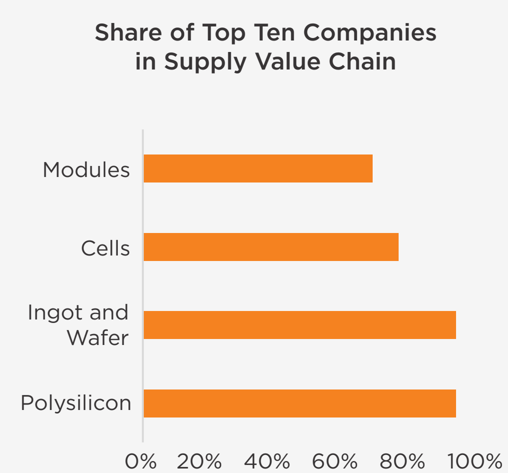


Figure 105: Share of Top Ten Companies in Supply Value Chain

Source: BNEF Solar Manufactures' Production and ISA Analysis

The share of the top ten companies in the production of polysilicon, ingot and wafers is 94%. While this also leaves consumers open to supply chain shocks. Accidents in manufacturing facilities, regulatory challenges, and other trade disputes can result in disrupted supply. Thus, resilience needs to be improved through diversification of the supply of materials.

6.1.2. Circularity: Soon to become a key concern

The priority of the solar manufacturing sector around the world so far has been the scaling up of the manufacturing of solar modules. However, as installed capacity increases and plants inch closer to the end of their lifetimes, it will become equally important to manage the waste generated due to solar modules. This can involve both recycling initiatives, as well as improved waste management and end-of-life planning.

Recycling solar waste

Recycling solar waste, which primarily consists of end-of-life solar panels for 30 years, is essential for the sustainability of the solar energy industry. Properly recycling solar waste helps reduce the environmental footprints of the solar industry, conserves valuable resources, and minimizes disposal of hazardous materials. It contributes to a more sustainable and eco-friendly approach to harnessing solar energy.

The recycling of solar waste is currently not considered a priority for various stakeholders due to the small amount of waste generated from PV modules. However, this will set to change as the global installation is expected to scale up rapidly. Assuming an expected material recovery rate of 85%, cumulative secondary supplies from recycling all EoL solar PV modules could help meet 3-7% of the solar PV industry's material demands to produce new solar PV modules by 2031-2040.

Solar waste disposal, where recycling is not possible

Although ideally solar waste should be recycled to extract as much useful material from the module as possible, this may not always be feasible. The lack of suitable processing equipment and expertise, as well as the lack of any mandate for recycling, may limit efforts. Additionally, the cost gap between recycling and simple disposal of modules is a key consideration that makes recycling challenging to promote over cheaper disposal methods. Some of the disposal methods of modules are manufacture take-back programs - solar panel manufacturers can have take-back programs in partnership with recycling facilities, reusing or repurposing solar modules.

Developing countries that are rapidly accelerating their solar capacity growth are particularly at risk for developing large installed capacities of solar power without the requisite end-of-life management capabilities that will be called into action in 20-25 years. Thus, it is crucial to introduce proper procedures and guidelines for disposing of solar modules and BoS where recycling is not feasible.

Policies required to push solar recycling

It is important to ensure the involvement of stakeholders in every step of the life of PV systems, solar waste management in particular, which demands the need for adequate policies and guidelines/regulations implemented with efficient processes for PV module end-of-life treatment. Development of life cycle management techniques and recycling technologies for material recovery shall be included in the regulatory frameworks. The prevalent regulations published by prominent regulatory bodies or countries are discussed below.

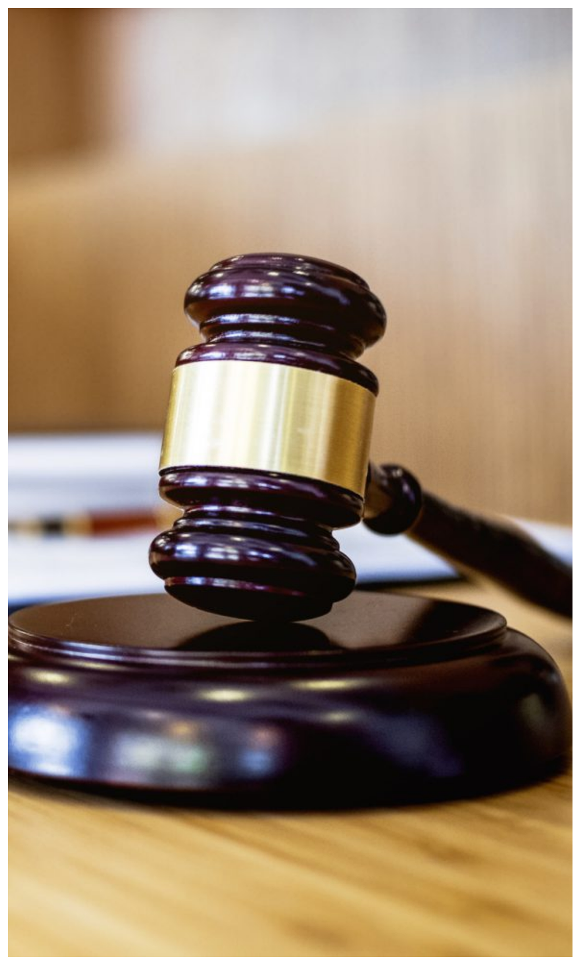
EU's Waste Electrical and Electronic Equipment Directive (WEEE Directive): The first WEEE directive, including end-of-life management of PV modules, with adequate provision to tackle the large-scale and diverse waste stream of PV module waste, came into force in August 2012. According to the directives, all 27 EU member states have framed programs to smoothen the collection of PV modules and handling and the state must fulfil a number of requirements as stated in the directives.

China's regulatory frameworks: The State Council of China disseminated the Waste Electrical and Electronic Product Recycling Management Regulation which came into force in 2011. However, at present, the recycling regulations keep silent on PV panel recycling. The National High-tech R&D Programme for PV Recycling and Safety Disposal Research formulated recommendations to develop policy guidelines to address PV waste challenges.

On the policy side, the recommendations include the need for special rules and regulations for end-of-life PV panel recycling, targets for recycling rates and the development of necessary financial frameworks. Whereas, technology and R&D side, recommendations focused on developing and demonstrating high-efficiency, low-cost and low-energy-consumption recycling technologies and processes for crystalline Si module and thin-film PV modules

Japan's regulatory framework: Japan Photovoltaic Energy Association (JPEA) published voluntary guidelines on how to appropriately dispose of end-of-life PV modules in 2017. As a huge number of modules disposal is expected in the coming years, the committee studied in advance the handling and disposal of PV modules where collection and handling of PV modules will be in accordance with the EU directives.

Many prominent countries like the USA, Korea and India have no specific regulations or guidelines for the proper handling of solar PV modules at the end of life. The lack of clear policy action on solar recycling is hampering the development of recycling facilities. Several countries have ambitious targets for solar installations and manufacturing development but do not have solar waste management policies or guidelines. These policy and regulatory gaps need to be plugged at the earliest as the recycling and waste management sectors will have to be readied to handle the waste generated as the world approaches TW-scale installations. Reliance on industry initiatives and state-specific policies will not be sufficient, and a cohesive national policy will be required.



Minimizing use of toxic materials that may hamper recycling and disposal initiatives

Solar modules, due to their complex composition, are already a challenging waste form to recycle or dispose of suitably (similar to e-waste). However, these challenges can be exacerbated by the use of certain materials that may hamper recycling abilities or increase the risk of impact on human health. For example, fluorine is used for the production of back sheets, lead soldering may be used in modules, and antimony may be used in the production of PV module glass. These materials raise health and safety concerns and may also increase the environmental impact of solar modules if improperly disposed of. More directly, thin film solar technologies based on Cadmium Telluride are also potential concerns. While this material is not harmful on its own, there are risks of potential leaching if improperly disposed of in a landfill setting. Thus, proper encapsulation and recycling methods are crucial to ensuring that no harm comes to animals, humans, or the environment. Efforts are already underway to identify alternative materials that do not require toxic components, as well as to develop end-of-life processes and suitable recycling methods to handle these materials.

6.2. Solar Project Development: Design can drive system improvements and reduce LCOE

6.2.1. Design optimization: striking the right balance between the cost and quality

Decision optimization in a solar power plant involves using various techniques and tools to make informed choices that maximize energy generation, efficiency, and profitability while minimizing LCOE and environmental impact. Decisions taken by the EPCs, and developers can play an important role in improving project LCOE, resource efficiency, and even the generation profile for the project.

System design considerations

Designing a solar system with a low LCOE requires careful consideration of various factors to maximize the energy output. EPCs can optimize plant LCOE by ensuring that the appropriate design methodology is used. This may vary based on the expected generation for the plant and load characteristics to be serviced. For example, certain locations may be willing to sacrifice the peak power obtained in a south-facing array for the flatter load curve of an east-west array. Similar innovations such as vertically mounted panels may also be explored. Thus, consideration of unconventional system designs including advanced technologies like robotics for cleaning can help improve the LCOE of a solar plant.

Training and skill development

It is important to keep in mind that providing quality EPC services requires a pool of skilled labour to meet project demands suitably. As the world rushes to install additional solar capacity, suitable training and skill development for various design and construction roles will be required. To date, the project developers have encountered a key challenge in developing a skilled, competent, and knowledgeable workforce essential to render operational renewable technology options available. The need for appropriately trained personnel is evident to cope with the increasing demand for the professionals in renewable energy segment, particularly for engineers and technicians who are specialists with advanced skills. Rapid implantation of solar energy systems created a skill shortage and deficiencies in solar installation and maintenance in many countries that are common in developed countries and would be experienced in developing countries also on their movement to NZS[44]. The consequences of a skilled labour shortage are already being felt in Europe. The current geopolitical situation and challenges around energy supply have resulted in a rush in demand for solar. However, Europe is unable to install panels fast enough as there is a lack of engineers to install the modules fast enough to keep up with orders. Installers are booked out for months in advance, and these labour shortages may well result in solar capacity in Europe not growing as fast as it could have had all demands been met[45].

Indeed, the market of green jobs in the renewable energy segment is promising, a growing market for specialist and lower-skilled personnel. Conversely, the pooling of advanced and lower-skilled professionals is necessary to keep pace with the rapidly growing solar demand.

Use of improved processes to reduce material consumption

Reducing material consumption not only conserves resources but also often leads to cost savings and improved competitiveness. Using improved processes to reduce material consumption is a sustainable practice that benefits both business and the environment. As highlighted earlier in the report, solar requires relatively lesser amounts of material usage as compared to other renewable energy sources such as wind power. This small material cost has been optimized over the years through improved land mapping, reduction in mounting and foundation preparation etc. Continuous improvement of these processes will allow for further reduction in material consumption.

6.3. Quality Standards: Crucial to ensure a sustainable ecosystem

Overall, adherence to quality standards is essential for the development, operation, and long-term sustainability of solar power plants. Quality standards pertaining to manufacturing, performance and integration play a vital role in the adoption of solar energy in a sustainable manner. Since various enabling applications are evolving, there is a need to extend standards specific to application usage design.

The International Electrotechnical Commission (IEC) is the leading global organization that develops and publishes consensus-based International Standards for electric and electronic products, systems and services, collectively known as electrotechnology. A subgroup of IEC, TC 82 "Solar photovoltaic energy systems" is responsible for writing all IEC standards in Photovoltaics. In addition, each country adopted IEC standards and formulated guidelines in accordance with their power scenario. Guidelines for using these standards are key, as they may be complex and difficult to understand for manufacturers.

[44] *UNESCO- Skills development for renewable energy and energy-efficient jobs*

[45] *BNEF - Solar Panels Piling Up in Warehouses in Energy-Starved Europe*

Significant disparities in quality across manufacturers

There may be significant quality variation between two modules, manufactured by two different units, with identical cell technologies and specifications. These quality variations lead to a lack of trust for certain manufacturing locations by developers, which in turn leads to capacity being underutilized. This in turn can lead to a concentration of demand for larger manufacturers, creating monopolies. Addressing these quality gaps will be crucial to developing a distributed manufacturing supply chain that is not overly reliant on a single region. These gaps may be addressed through the implementation of quality tests and increased technical due diligence. Additionally, specific procurement criteria from developers may help provide market signals that push manufacturers to improve product quality.

Quality standards are to be updated regularly to keep up with technology cycles

The solar technology cycle is rapid, with a roughly two-year cycle in place. Manufacturing facilities need to be upgraded with improved designs, processes, materials, and even brand-new technologies to replace older capacity. Similarly, R&D activities continue to drive learnings and improvements for the sector. In this fast-moving sector, it is thus important for quality standards to remain agile and updated regularly to ensure that the correct market requirements are reflected. This may also serve as a signal for phasing out certain technologies or processes, paving the way for more widespread industry adoption of modern technologies and methods.

Quality standards for local manufacturing

As highlighted in previous sections, the need for increased localization of manufacturing is apparent, and several countries have begun to promote their domestic ecosystem for solar manufacturing. However, in many cases, the development of a smaller, newer ecosystem for manufacturing may result in challenges with output quality. Therefore, normalized quality standards have to be in place to ensure the quality of the module manufactured as well as to increase the reliability of distributed manufacturing units.

Quality testing infrastructure

Establishing quality solar testing infrastructure is crucial to ensure the reliability, performance, and safety of solar panels and related components. In certain countries, the lack of sufficient testing facilities can lead to issues in introducing new modules to the market. Additionally, lower-quality testing infrastructure can result in modules that do not measure suitably to international standards. Thus, the development of quality testing infrastructure can help develop and maintain high-quality standards for solar modules which help diversification of manufacturing units.

Standardizing technical guidelines: A solar module for each use case

Solar has emerged as a key candidate to link with several other sectors to help drive decarbonization there as well. However, it is important to recognize the different requirements of each sector and there are a wide number of solar module types available for use, with varying characteristics. Thus, it is important to recognize the technical requirements for each application to guide module selection. Similarly, the BoS requirement for systems will also vary depending on application-specific requirements and constraints. For example, the requirements and characteristics of modules for residential applications are entirely different when compared with the characteristics of modules required for floating solar power plants.

6.4. Technology, R&D, and Innovation: Rapid innovation will drive rapid improvements

The exponential growth towards a multi-terawatt market for solar presents enormous opportunities as well as challenges for the industry. They affect all steps of the value chain, from product design to material procurement and recycling. With solar energy playing a significant role in the future global energy system, the challenges, and opportunities for complementary technologies, such as energy storage, grid integration, power to gas/liquids, and multiple-sector electrification, are also increasing. Research spanning materials science, module design, systems reliability, product integration, and manufacturing will be required to pave the way to multi-TW-scale PV deployment.

Promotion of process improvements for solar manufacturing

As described in the previous Section, the various stages of the solar module manufacturing value chain are highly energy-consuming. The increased production rate of solar modules also leads to high material consumption. Since solar manufacturing is ramping up, to achieve the goal of NZS, the reserve materials being used for production are still limited.

Over the last few years, a lot of research has been conducted for decreasing material usage and for the development of newer, novel designs. This research is not just limited to different types of solar cells made, but research also has been done in various other aspects, such as going from lead-containing soldering to lead-free soldering and Electric conductive adhesives. Research on areas such as reduced energy usage in manufacturing processes, as well as reduced material consumption needs to be promoted, leading to greener manufacturing and competency.

Promotion of R&D for newer technologies

Heightened focus on R&D for newer high-efficiency solar technologies such as TOPCon, HJ, IBC etc. will help drive down costs, improve efficiencies and stability, and thus speed up commercialization. Current R&D expenditure is driven by large solar manufacturers, and further government support may be provided for the development of these technologies. R&D need not be restricted to the c-Si PV value chain,thin film technologies have relevance in several niche applications and also provide an avenue for countries to pursue energy independence through delinking their solar supply from the silicon value chain.

Exploration/promotion of new avenues for sectoral linkages between solar and other technologies

There are various technologies for energy generation as well as energy storage that use solar energy as a primary energy source for round-the-clock power. Integrating solar panels in vehicles, building facades, or via agrovoltaics, enables proper utilization of the land space available. Energy storage technologies such as batteries, pumped hydro and green hydrogen promote the availability of solar energy for round-the-clock supply. Research in such fields is scaling up.

CSP also provides a new prospect for the utilization of solar energy because of its integration with existing coal plants. Moreover, coal plants can be repurposed with CSP with fewer architectural changes in the existing coal power plants.

The integration of CSP into coal-powered plants leads to the reduction of the pollutant effect and operational costs. CSP and coal power plants exhibit synergistic systems during their operation and can be considered as true hybrid power plants. During the daytime, solar energy is utilized to heat water, which can be converted to steam and fed into the turbine, reducing coal consumption and CO2 emission. During off-sunshine hours, coal supplies the energy to the system. The output from the CSP-coal hybrid system can be utilized to feed water preheating, air preheating, gasification and CO2 capture depending on the size and technology of CSP[45].

Developed countries like Australia, Canada, Germany, the United Kingdom, and the United States have significant coal capacities and are taking different initiatives to prevent and deviate away from coal, retirement/decommissioning, and repurposing. Repurposing coal power plant with CSP help overcome barriers to the retirement of coal power plants and represents a significant shift towards cleaner and sustainable energy generation.

[46] *Perspective on integration of concentrated solar power plants*

The importance of the technology adaptation includes that, the majority of the balance of plant (BoP) of a typical coal-fired power plant can be utilized while converting it to a CSP which leads to avoiding the decommissioning cost of the coal power plant as well as savings on the initial investment of a CSP. In a typical coal power plant, the saturated steam produced in the boiler will be superheated to about 540°C[47]. Therefore, in general, the water can be converted to heat and further heated up using a solar power tower/central receiver tower (which can achieve a temperature between 300 °C and 1000 °C), parabolic dishes (100 -700°C) which would be using coal to produce the steam. The produced steam from CSP can be directly fed into the turbine sidestepping the preheating, boiler and superheating systems, utilizing the succeeding part of the coal power plant. Some of the consideration for repurposing coal with CSP is given below.

Feasibility assessment:

Conduct a comprehensive feasibility study to evaluate the potential for CSP integration at the existing coal power plant site. This assessment should include factors like available land, solar resources grid connectivity and existing infrastructure.

Site selection:

Identify the best location within the coal plant site for CSP installation, ensuring that it maximizes the exposure to sunlight and allows for efficient CSP system placement.

CSP configuration:

Choose the CSP technology and configurations that best suit the site and energy needs. Options include a central receiver tower/solar power tower, parabolic dishes etc.

Thermal energy storage:

Consider the incorporation of thermal energy storage systems to store excess heat generated in the daytime which can be utilized for off-sunshine hours ensuring the round-the-clock electricity generation.

Integration with the existing electrical network:

The repurposing coal power plant can leverage the existing electrical network such as transmission lines, substations etc., helps reduce new infrastructure costs and facilitate grid connection.

Workforce transition:

Transition of the existing workforce of the coal power plant with proper training is possible to new roles associated with CSP operation, maintenance and construction.

Reduction in project timeline:

Due to the availability of infrastructure and resources at the site, the repurposing of the coal power plant and construction of CSP will require a comparatively shorter timeline than constructing the CSP plant afresh.

[47] *Basic Layout and Working of a Thermal Power Plant | electricaleasy.com*

Reduction in project timeline:

Due to the availability of infrastructure and resources at the site, the repurposing of the coal power plant and construction of CSP will require a comparatively shorter timeline than constructing the CSP plant afresh.

6.5. International Relationships and Trade Conflicts: De risking the supply chain is necessary for energy security

The development of the renewable energy industry is a priority in the economic policies in many countries since it is viewed as one of the key growth sectors in the economy, also playing an especially important role in mitigating climate change. At the international level, renewable energy is an issue of international cooperation but also an area of trade tensions between countries. While countries are actively working towards achieving energy security, many countries still lack a solid solar manufacturing value chain. While in some countries, there's surplus production of solar modules, there are some countries that totally rely on solar imports only, given the paucity of resources available

Enhance localized manufacturing and diversify international procurement

To hedge against the disruption of solar supply chains due to trade disputes and geopolitical disagreements, a twofold approach may be followed. Firstly, the development of localized manufacturing should be undertaken to the extent possible, as highlighted in the previous sections. Secondly, the manufacturing ecosystem should ensure that they are not overly reliant on a sole source or country for their supply chain needs that cannot be met by domestic manufacturing. International procurement should be done from two or more countries to ensure that all supply is not affected in the case of any disruption.

Though, currently, China plays an inevitable role in the import of wafers, cells, and modules for other countries, exempted for exempted North America which imports majority of modules from Asia-Pacific region[48].

Joint ventures or direct investments in resources

While trade/ business agreements may be utilised to ensure supply of vital components/raw materials, companies may go further to ensure that their supply chain is robust. Manufacturers may choose to enter Joint Ventures with key suppliers to ensure they have a stake in the production of their input material. Additionally, they may also choose to directly purchase stakes in natural resources such as mines, in order to maintain a steady supply of input materials in the long term.

6.6. Social and Environmental Aspects: Multifold benefits beyond clean energy

Solar has the potential to drive widespread impact in social, economic, and environmental spheres. Several direct and indirect benefits can accrue through the appropriate development of solar projects and manufacturing capacity.

6.6.1. Social

Skill development

The development of new solar manufacturing capacity, as well as solar installations, provides opportunities for job creation and skill development. A wide variety of roles are available across the value chain, ranging from unskilled labour to cutting-edge research and technology development. Thus, with the right training and capacity-building initiatives, solar power can provide several avenues for the development of a skilled workforce.

According to the IEA Special Report on Solar PV Global Supply Chains, the solar PV industry creates 1300 manufacturing jobs per GW production capacity. IEA estimate that job associated with manufacturing polysilicon, wafers/ingots, cells and modules globally, reached nearly 600000 in 2021 and are expected to reach 1 million by 2030.

China is the largest source of renewable energy jobs worldwide. The number of jobs in solar has grown over 3 times in the last 9 years, crossing over 4 million jobs in 2021. China has by far the most jobs in solar, thanks to its significant capacity installations as well as its dominance of the solar manufacturing supply chain. As a result, it has the greatest number of jobs per installed capacity, both cumulative and annual. IRENA and ILO estimates for the global solar sector show around 4.5 jobs per MW of installed solar capacity.

Benefits to remote communities

Solar manufacturing/project development can bring about benefits that can be extended to the local community. Large-scale solar project deployment and manufacturing capacity are often located in rural regions, away from major population centres. The development of these projects can result in an improvement in local infrastructure, opportunities for jobs in both construction and operations roles for the local populace, and potential benefits from company charitable initiatives in the region. Solar developers and manufacturers should be encouraged to support local communities and seek their buy-in during project development.

[48] *IEA Special Report on Solar PV Global Supply Chains*

Benefits to users in remote/impoverished regions

The impact of distributed solar power can be significant in remote or impoverished regions. Small-scale applications of solar such as cooking or lighting can open doors to significant improvement in quality of life, safety, and even education. Since 940 million or 13% of the world's population do not have access to electricity[49], many people depend on solar for their daily power supply. Some have to find alternatives for an affordable price with ideally little to no interruptions.

Additionally, solar power often replaces fossil fuel burning, which brings further health benefits. Furthermore, the development of microgrids can help bring power to remote and inaccessible locations where solar power plants are at center stage.

6.6.2. Economic

Reduction of import dependence on fossil fuels - subsequent benefits to foreign trade balance

The widespread deployment of solar power can help address the import dependence of non-fossil fuel-producing countries. For example, solar deployment to generate electricity can help reduce the need for coal, gas and oil imports where 57% of the electricity being generated from these three fossil fuels[50]. Additionally, the generation of green hydrogen through solar-powered electrolysis, or charging of EVs through solar, can further bring down the amount of fossil fuel that a country needs to bring in. Visibly, the generation of electricity from solar systems can significantly reduce the consumption of coal, oil and gas. This in turn can have significant benefits to foreign trade balance, especially in times of volatile fossil fuel prices due to geopolitical disturbances.

6.6.3. Environmental impact

Reduction of fossil fuel-based power for manufacturing

Current solar manufacturing capacity based in China relies heavily on cheap coal electricity to power its energy-intensive processes. IEA estimates, 62% of the electricity required for the solar module manufacturing supply chain is produced from coal which is higher than the share of coal in the global energy mix (36%)[51]. Reducing the indirect carbon emission of the solar manufacturing facility could thus be a prime opportunity for the PV industry to avoid the carbon footprint. This leads to an avoidable increase in the CO_2 emissions associated with solar power. Thus, it would be wise to use RE sources, including solar PV, to provide cheap, green power for new solar manufacturing capacity.

[49] *Access to Energy - Our World in Data*
[50] *BNEF database*
[51] *IEA- Special Report on Solar PV Global Supply Chains*

Benefits due to reduction of air pollution due to fossil fuel-based power plants

The power industry is responsible for 41% of the total CO_2 emissions[52]. Evidently, shifting to a solar power system helps abate CO_2 emissions. Annual direct CO_2 emissions avoided per 1 GW of installed capacity by solar PV by displacing coal is 1.4 million tones (Mt) of Co_2[53]. These emissions reductions not only help combat climate change, but also help mitigate health risks due to air pollution, and result in a direct impact on the quality of life of residents near fossil fuel power plants.

Benefits of combating climate change and associated impacts

As highlighted above and earlier in the report, solar power will play a key role in the fight against climate change. Not only is solar best placed to replace fossil fuel-based generation capacity, but the technology is also set to assist in the decarbonization of a number of linked sectors, including transport, buildings, agriculture, chemicals, and more. Solar systems are a vital tool in the fight against climate change. They provide a sustainable, low-carbon source of electricity, reduce greenhouse gas emissions, promote energy independence and contribute to the global transition toward a more sustainable and climate-resilient energy system.

[52] *BNEF database*

[53] *IEA database - Annual direct CO2 emissions avoided per 1 GW of installed capacity by technology and displaced fuel – Charts – Data & Statistics - IEA*

Conclusion

The threat of climate change has made the need to shift towards clean energy resources a pressing issue. Significant renewable energy capacities are being deployed to help minimize GHG emissions while meeting global energy demands, solar technologies being prominent among them. Solar energy plays a significant role in climate change mitigation due to its numerous environmental, economic, and social benefits.

The sector is seeing rapid technological innovation, a growing manufacturing supply chain, and a suite of technologies to ensure grid integration. Although solar is emerging as the preeminent renewable energy source worldwide, further work is required to help achieve terawatt scale installations.

1. While PERC remains the proverbial working horse of the global PV industry, in 2022 new cell and module production capacities were seen shifting from PERC to n-type based tunneling oxide passivated contacts (TOPCon) and silicon heterojunction (SHJ) technologies. Several promising solar next-generation technologies are currently under development or already approaching large scale commercial manufacturing. These technologies offer significant benefits and have the potential to drive future capacity installations. Further research and development activities are required to ensure that they achieve their potential.

2. Concentrated Solar Thermal (CST) technologies is expected to generate new opportunities especially in the repurposing of retired or to-be retired coal power plants, which will enable in smooth just transition.

3. Balance of System components such as inverters and trackers have a key role to play in bringing down solar costs and making the technology attractive for deployment. Additionally, energy storage is set to play a key role in integrating solar energy into the grid.

4. Plant design, Engineering Procurement and Construction, and Operation and Maintenance improvements are supporting in higher power generation and cost reduction throughout the lifetime of a solar plant. Developments of these activities will help ensure that solar plants are able to meet generation requirements in a cost effective manner.

5. Solar has significant potential for sector coupling, dovetailing with clean technologies across diverse sectors including transportation, agriculture, industries, buildings, and more. This potential for sector coupling is set to be a key driver for the growth of solar and allows the technology to become a key contributor to the broader energy transition.

6. Solar PV's demand for critical minerals will increase rapidly in a pathway to net zero emissions. The production of many key minerals used in PV is highly concentrated, with China playing a dominant role. Despite improvements in using materials more efficiently, the PV industry's demand for minerals is set to expand significantly. This rapid growth, combined with long lead times for mining projects, increases the risk of supply and demand mismatches, which can lead to cost increases and supply shortages. There is a urgent need to promote technology innovation in manufacturing processes that reduce material intensity, especially for critical minerals such as copper.

7. The solar manufacturing supply chain is geographically concentrated and vulnerable to supply chain shocks. Development of localized manufacturing with vertical integration is required to help de-risk the supply chain from geopolitical tensions and trade conflicts.

8. It is important that the non-silicon components of the supply chain are not overlooked when planning manufacturing capacity to cater to terawatt scale installations.

9. Recycling of solar PV panels offers environmental, social and economic benefits while enhancing security of supply in the long term. Solar waste disposal and recycling will soon play a key role in the overall lifecycle of solar modules. The development of cost-effective recycling technologies must begin before the need for recycling becomes overwhelming. There is need to support technology development efforts that improve solar PV panel design for recycling, reusability and greater durability.

10. Solar capacity deployment provides several socioeconomic and environmental benefits that must be recognized when planning the future energy mix.

Note

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