INTERNATIONAL SOLAR ALLIANCE

WORLD SOLAR TECHNOLOGY REPORT

Foreword

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The urgent need for a global energy transition has fostered significant developments in renewable energy. Within renewables, solar has emerged as the key technology over the last decade. Cumulative solar deployments approached the terawatt milestone in 2021, and are expected to nearly double by 2025, marking unprecedented growth. Solar's position as the lynchpin of the energy transition has been demonstrated by the market.

This growth in solar deployment is underpinned by the rapid development of solar technologies. Module efficiency, power output, and technology options have increased, while cost, material usage, and barriers to deployment have decreased. Technical and financial maturity, along with modularity and scalability, have made solar technologies viable for a wide range of consumers.

Developments in solar technologies extend beyond the solar module and encompass the wider ecosystem. Innovations in Balance of System components such as inverters and trackers, plant design and construction activities, and Operations and Maintenance have made solar deployment an attractive proposition. The solar manufacturing supply chain continues to see capacity growth as well as process improvements in material and energy efficiency. The challenge of grid integration, traditionally a barrier for intermittent sources such as solar, is being addressed with a suite of technical, infrastructure, and market based solutions.

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

Through this flagship annual World Solar Technology report, ISA aims to review the status of solar manufacturing around the world, track solar technology developments and sectoral data trends, highlight gaps to be addressed, and shine a spotlight on the multiple benefits that 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 2022 with the global solar community.

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Abbreviations

AC	Alternating Current
AEM	Anion Exchange Membrane
AFD	Agence Française de Développement
AfDB	African Development Bank
AI	Artificial Intelligence
AIM	American Innovation and Manufacturing
ALD	Atomic Layer Deposition
APAC	Asia Pacific
APV	Agri- PV
ASEAN	Association of Southeast Asian Nations
BCD	Basic Custom Duty
BESS	Battery Energy Storage System
BIPV	Building Integrated Photovoltaics
BMZ	Federal Ministry of Economic Cooperation and Development
BNEF	Bloomberg New Energy Finance
BoM	Bill of Materials
BoS	Balance of System
BSF	Back Surface Field
BTM	Behind the Meter
CAES	Compressed Air Energy Storage
CAISO	California Independent System Operator
CEEW	Centre for Energy, Environment, and Water
CIGS	Copper Indium Gallium Selenide
CIS	Copper Indium Selenide
CPSU	Central Public Sector Undertaking
CSP	Concentrated Solar Power
CTM	Cell to Module
CUF	Capacity Utilisation Factor
CVD	Chemical Vapor Deposition
CZ	Czochralski
DAT	Dual Axis Trackers
DC	Direct Current
DCR	Domestic Content Requirement
DS	Directional Solidification
DW	Diamond Wire
EIB	European Investment Bank
EIM	Energy Imbalance Market
EPC	Engineering, Procurement, and Construction
EPR	Extended Producer Responsibility
ESS	Energy Storage System
EV	Electric Vehicle
EVA	Ethyl Vinyl Acetate
EXIM	Export-Import Bank of the United States
FBR	Fluidized Bed Reactor
FPV	Floating Solar PV
FY	Financial Year
FZ	Float Zone
GDP	Gross Domestic Product
GH	Green Hydrogen
GHG	Greenhouse Gas
GTAM	Green Term Ahead Market
GW	Gigawatt
HDH	Humidification Dehumidification
HJT	Heterojunction
HSAT	Horizontal Single Axis Trackers
IBC	Interdigitated Back Contact
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ILO	International Labour Organisation
IP	Intellectual Property
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISA	International Solar Alliance
ITRPV	International Technology Roadmap for Photovoltaic

KIUC	Kaua'I Island Utility Cooperative
KSEB	Kerala State Electricity Board
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LID	Light Induced Degradation
MBB	Multi Busbar
MEB	Multiple Effect Boiling
MED	Multiple Effect Distillation
MEH	Multiple Effect Humidification
MGS	Metallurgical Grade Silicon
MSF	Multi Stage Flash Distillation
M-SIPS	Modified Special Incentive Package Scheme
MSP	Minimum Sustainable Price
MT	Metric Ton
MW	Megawatt
NDC	Nationally Determined Contributions
NGO	Non-Governmental Organisation
NREL	National Renewable Energy Laboratory
NTPC	National Thermal Power Corporation
PECVD	Plasma Enhanced Chemical Vapor Deposition
PEM	Polymer Electrolyte Membrane
PERC	Passivated Emitter and Rear Cell
PERL	Passivated Emitter with Rear Locally Diffused
PERT	Passivated Emitter, Rear Totally Diffused
PET	Polyester
PID	Potential Induced Degradation
PLI	Production Linked Incentive
PM-KUSUM	Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan
POE	Polyolefin Elastomers
PSG	Phosphosilicate Glass
PV	Photovoltaic

PVDF	Polyvinylidene Fluoride
PVF	Polyvinyl Fluoride
PVPS	Photovoltaic Power Systems Programme
RCRA	Resource Conservation and Recovery Act
RE	Renewable Energy
RO	Reverse Osmosis
RTC	Round The Clock
SCADA	Supervisory Control and Data Acquisition
SHJ	Silicon Heterojunction
SMES	Superconducting Magnetic Energy Storage
SOEC	Solid Oxide Electrolysers
SRV	Surface Recombinant Velocity
SSEF	Shakti Sustainable Energy Foundation
SWCT	Smart Wire Connection Technology
TCO	Transparent Conducting Oxides
TCS	Trichlorosilane
TOPCon	Tunnel Oxide Passivated Contact
TR	Tiling Ribbon
TW	Terawatt
UAE	United Arab Emirates
UHV	Ultra High Voltage
UK	United Kingdom
UMG	Upgraded Metallurgical Silicon
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
USA	United States of America
VIPV	Vehicle Integrated PV
VPP	Virtual Power Plants
VRE	Variable Renewable Energy
WB	World Bank
WEEE	Waste Electrical and Electronic Equipment

Executive Summary

The world has embarked on a significant transition by moving towards cleaner sources of energy. The 2021 Intergovernmental Panel on Climate Change (IPCC) Report found that average global temperature is expected to reach or exceed 1.5oC of warming over the next 20 years. The report has also attributed over 1oC 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.

Several sectors contribute to global greenhouse gas emissions, with the electricity and heat sectors being the biggest source, accounting for 31% of total annual emissions. Other key emitting sectors include manufacturing and construction, agriculture, industries, and buildings. These emissions are primarily driven by the usage of fossil fuels as a source for energy across sectors, and the need to replace these fuels is clear. There are a number of pathways to achieve the greenhouse gas abatements required to limit climate change, but all require the deployment of renewable energy sources. While multiple renewable energy technologies are available, the last decade has seen solar emerge as the leading RE technology, with cumulative installations growing over 20-fold in the last decade to reach 920 GW in 2021. This rapid growth is set to continue for years to come, fueled by technical and financial maturity and scalability. The future of solar also looks bright due its potential to enable or link with other technologies to abate sectors that pose complex decarbonisation challenges, such as transport, building, agriculture, manufacturing, among others. Solar is rapidly approaching terawatt scale global installations.

Solar technologies encompass a broad and ever-growing array of options, and are primarily divided into two major groups. Solar photovoltaic (PV) technologies which 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 remain 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 efficiencies increase from around 15% in 2010 to around 21% in 2021.

Additionally, average module power ratings have gone from just under 250 W in 2010 to just under 400 W by 2021, with 700 W commercial modules now available in the market.

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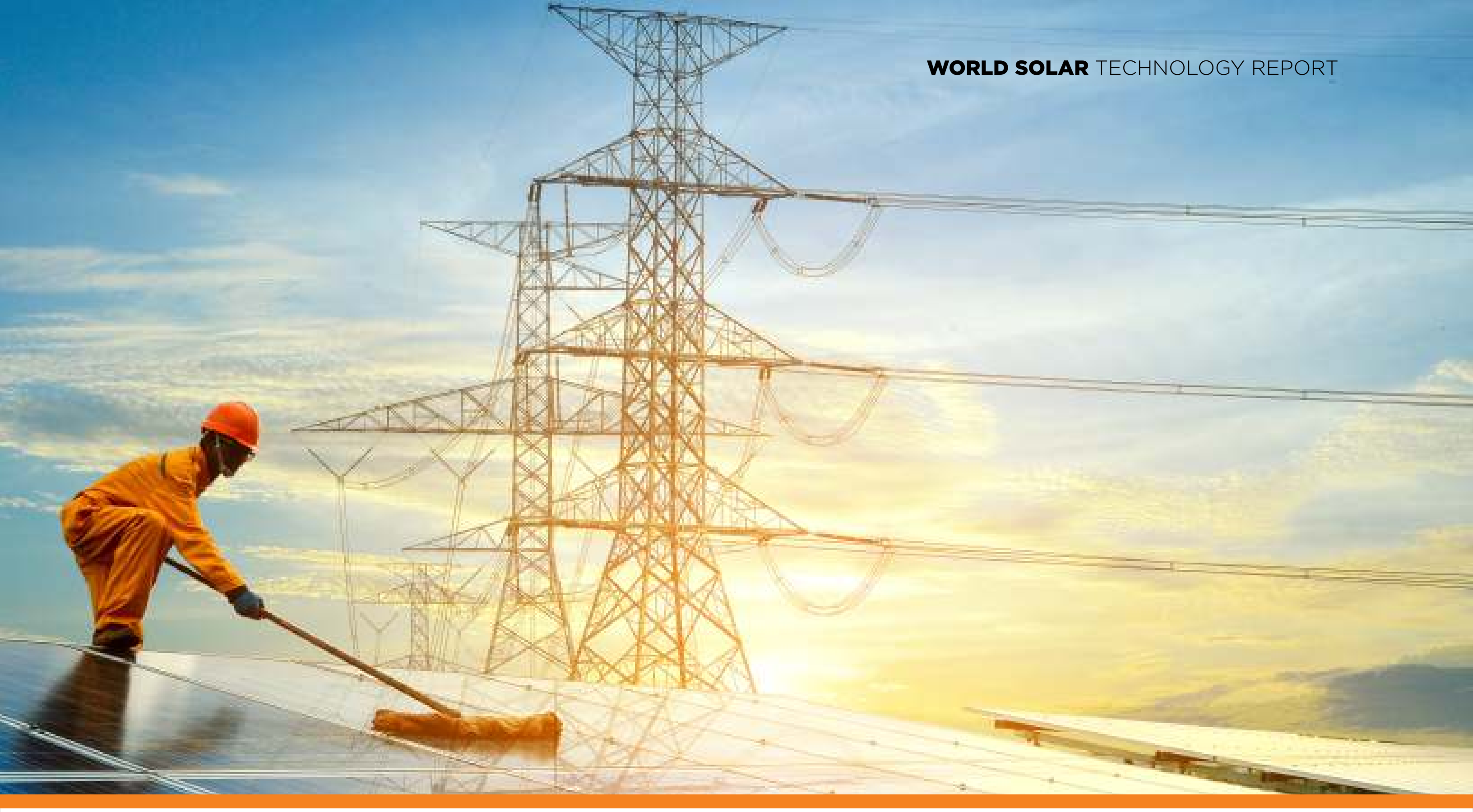
- deployed with energy storage to improve flexibility of generation
- used to charge electric vehicles to help decarbonise transportation
- used to generate green hydrogen for industrial decarbonisation
- integrated into buildings or vehicles for electricity generation
- deployed on agricultural land to improve land use efficiency
- deployed on water bodies to minimise land usage
- used to power heating and cooling at a variety of scales

These innovative applications and sectoral linkages are already seeing traction, and 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 2 terawatt by 2025, having just 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 direct components for manufacturing 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% 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 800,000 MT of manufacturing capacity worldwide. This undersupply situations has in turn seen prices increase multi-fold, affecting the supply chain as a whole. 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 diluted 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 420 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 500 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 minimise external dependencies while meeting solar demand.



The solar manufacturing supply chain must address a few key concerns in coming years. The geographic concentration of manufacturing capacity leaves the supply chain open to shocks. Additionally, current manufacturing capacity is oversized as 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 need to be addressed, with energy hungry processes being fuelled 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 such 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. In order to avoid this outcome, some grids have turned to curtailment, which is essentially wastage of potential generation, and an undesirable outcome.

In order 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 digitalisation activities. It is important to note that there is no 'one size fits all' solution- Instead, it is important to utilise 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 minimisation of toxic components and clear policy initiatives
- Improved project development through design optimisation, skill development, and market support for advanced technologies
- Standardisation of quality across manufacturing locations and companies, with frequent updating of benchmarks and improved testing infrastructure
- Optimisation of module bill of materials and greening of supply chains to minimise 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 NO_x, 80 MT of SO_x, 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 will be an annual publication that will aim 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.

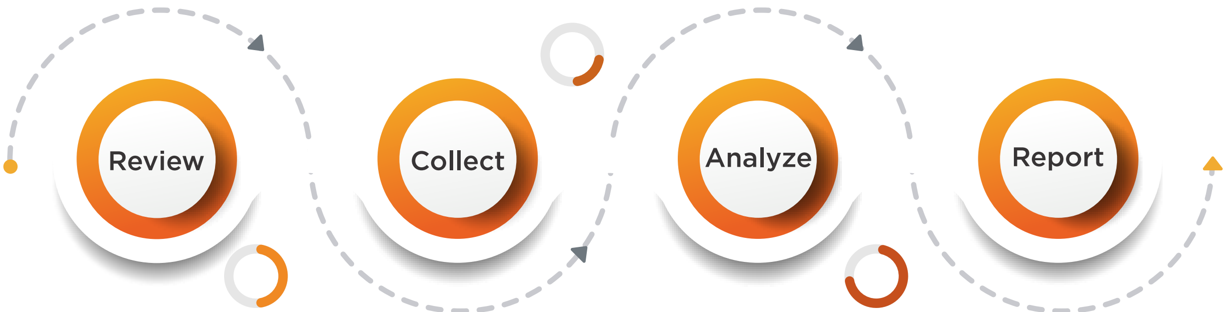
Approach & Methodology

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 the data and insights represented are accurate.

Approach

While the solar sector has seen significant growth over the past decade, there remain areas to be addressed in order 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.

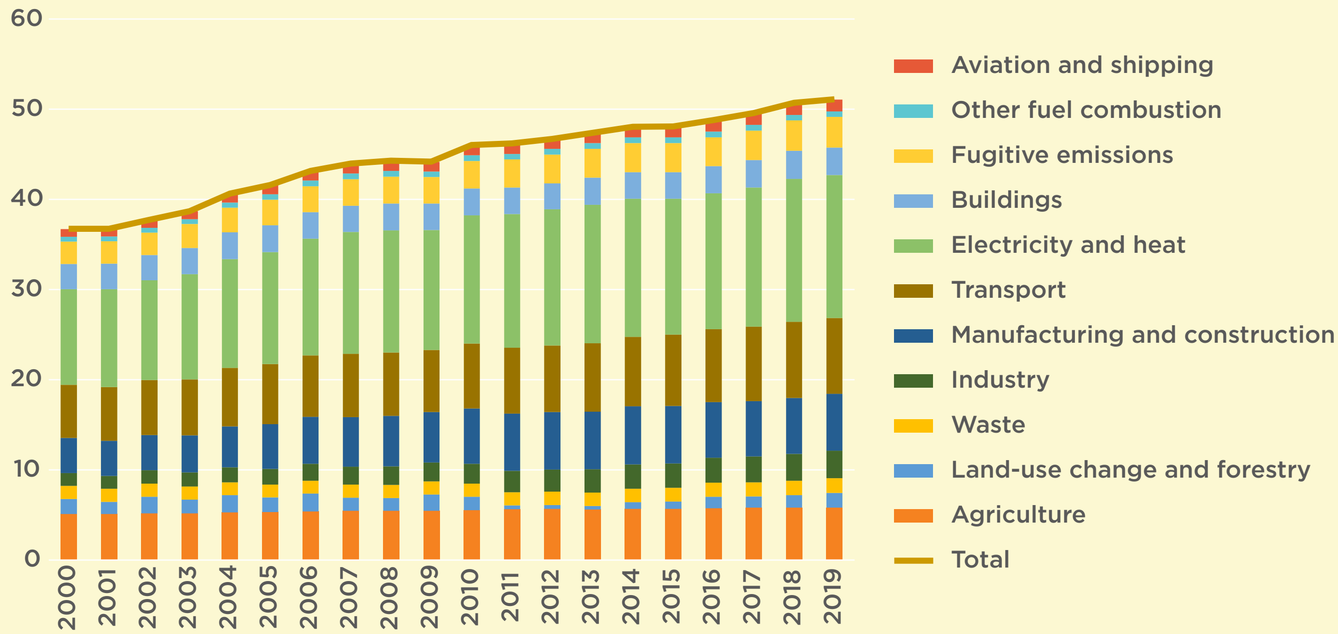
Energy Transition: Solar Technologies in the forefront

The Global energy transition and Decarbonization have taken centerstage with growing consensus on the deleterious impact of climate change. Increasingly abnormal weather patterns and higher probability of natural disasters such as wildfires, floods etc. have highlighted the threat of global greenhouse gas (GHG) emissions are not reduced.

GHG emissions have increased alarmingly over the past two decades, driven by the Electricity and Heat sector

GHG emissions have increased grown by almost 40% over the past two decades to cross 50 billion tons of CO_2 equivalent by 2019.

Worldwide Greenhouse Gas Emissions by Sector (Billion Tonnes CO_2 Equivalent)



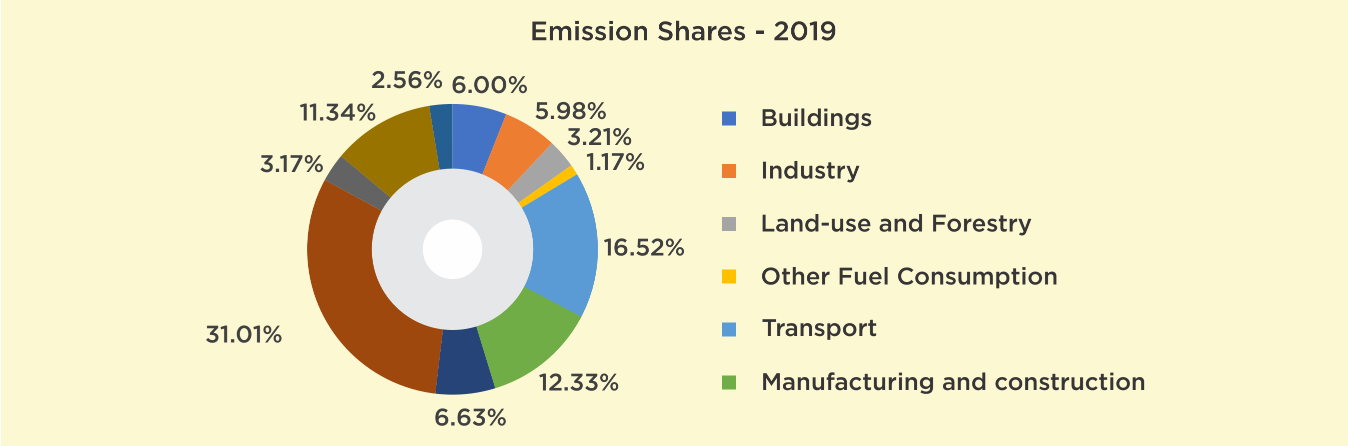
Source: Our World in Data and Climate Watch

	Over last decade (2009-2019)	Over last 4 years (2015-2019)	Over last year (2018-2019)
Total Emissions	15.7%	6.2%	0.74%
Electricity and Heat	18.9%	5.2%	-0.26%
Transport	22.3%	6.5%	0.2%

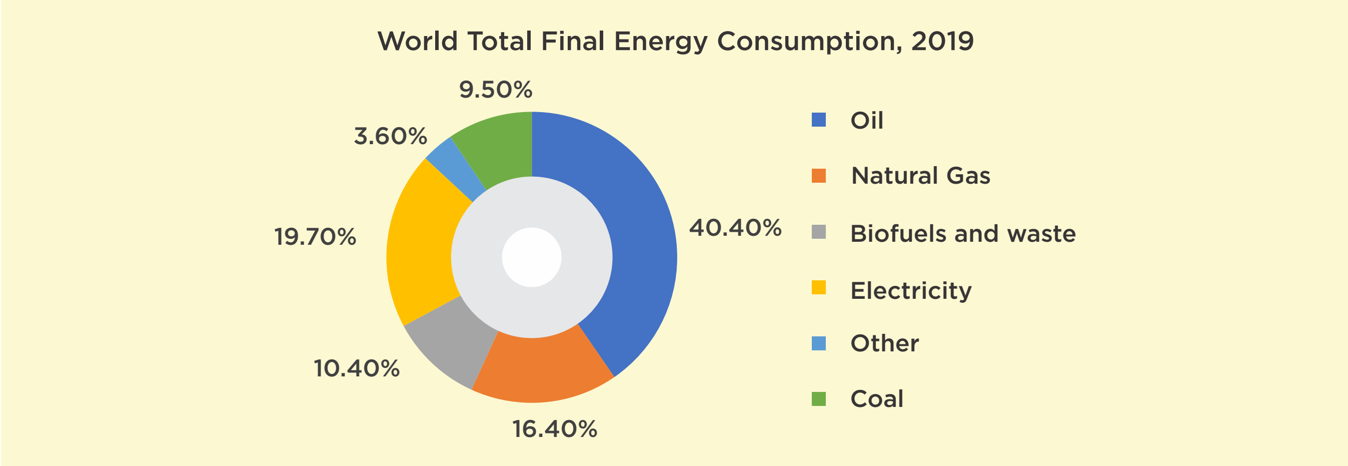
Source: Our World in Data and Climate Watch

GHG emissions, both direct and indirect, are produced across a number of key sectors. The major sectors accounting for these emissions are highlighted in the chart above. The electricity and heat is the biggest source of GHG emissions. In 2019, the sector accounted for nearly 31% of global GHG emissions, nearly double the next biggest emitting sector (Transport, at ~16%). Emissions from the sector have also grown ~50% over the past two decades and are unlikely to have peaked yet as demand continues to grow. Other key emitting sectors include manufacturing and construction, agriculture, industries, and buildings. Emissions are primarily driven by the usage of fossil fuels as a source for energy across sectors.

These emissions and their effects on the climate have been noted with significant concern. The 2021 Intergovernmental Panel on Climate Change (IPCC) Report found that averaged over the next 20 years, global temperature is expected to increase at least by 1.5 degrees Celsius of warming. Nations are recognizing that it is imperative to move away from fossil fuels such as coal, petroleum, and natural gas, and transition towards renewable energy sources.



As can be observed from the above figures, electricity which attributes to about 19.7% of the world total final energy consumption, accounts for a major chunk of GHG emissions, as per 2019. However, this share of 31% of emissions shall be reduced with the increasing capacities of renewable energy being installed. Solar Energy, owing to its modularity and affordability is one of the key drivers for this decarbonization.



Source: BNEF

Country specific ambitions for energy transition and relevant indicators

Net Zero Targets and NDC commitments for key countries/regions

India (Net Zero by 2070)

- 50 percent cumulative electric power installed capacity from non-fossil fuel based energy resources by 2030
- Reduce CO_2 emissions by 1 billion tons
- Reduce Emission Intensity of its GDP by 45%, from 2005 levels, by 2030.

China (Net Zero by 2060)

- Reduce Co_2 emissions per unit of GDP by over 65% from the 2005 levels.
- Increase the forest stock volume by 6 billion cubic meters from the 2005 levels.
- Achieve total installed capacity of wind and solar power of 1.2 billion kW by 2030.
- Establish a National Carbon Credit Trading Market
- Enact policies for minimum proportions of solar generation on roof areas in pilot cities

Japan (Net Zero by 2050)

- Reduce GHG emissions by 26% from 2013 levels by 2030.
- Promote green finance and support greater international co-operation for business led adoption of innovative technology to further reduce accumulated atmospheric Co_2 globally to “Beyond Zero”.

United Kingdom (Net Zero by 2050)

- End use of coal in UK energy system by 2025.
- Reduce economy wide GHG emissions by 68%, from 1990 levels, by 2030.
- Introduce Carbon Pricing, penalizing the emissions from burning fossil fuels.
- Introduce “Contracts for Difference” scheme to promote RE utilisation by large scale power generators.

United States of America (Net Zero by 2050)

- Reduce GHG emissions by 50%-52% from 2005 levels, by 2030.
- 100% carbon pollution free electricity by 2035.
- Policies and funds for R&D of low and zero-carbon industrial processes and products.
- Implementation of American Innovation and Manufacturing (AIM) Act to phase down the use of hydrofluorocarbons.
- Policies and funds to promote zero emissions in the transportation sector.

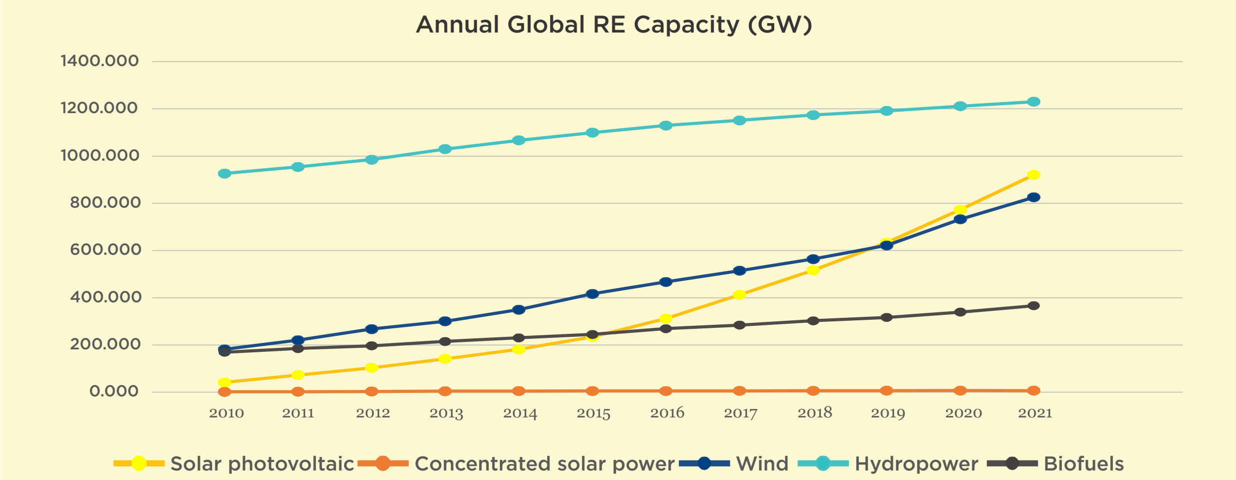
European Union (Net Zero by 2050)

- Reduce GHG emissions by at least 40% of 1990, by 2030.
- Achieve 32% of renewable energy in total Energy Mix by 2030.
- Aim to dedicate 30% of its overall budget for 2021-2027, to fund climate action plan.
- Aim to re-establish carbon sinks such as forests in a more sustainable manner.

Source: UNFCCC NDC Registry

Significant renewable energy capacity additions have been underscored by twenty-fold solar capacity growth over the last decade

A number of renewable energy sources have been deployed at scale, including hydropower, wind, solar, and biofuels. Hydropower has seen usage in large scale projects for several decades, while offshore and onshore wind power are important renewable sources as well. However, in recent decades, solar energy has seen significant growth in installations, leapfrogging wind and biofuel to become the renewable energy source of choice with the second largest installed capacity after Hydropower.



Source: IRENA- Renewable Capacity Statistics 2022 and Solar Power Europe

	Solar PV	Solar CSP	Wind	Hydro	Biofuels
Absolute growth over Last Decade	2144%	276%	275%	29%	98%
Absolute growth over last 2 years	45%	0%	33%	3%	16%
Growth over last year	19%	-2%	13%	2%	8%

Table: Installed capacity growth rates

Solar has grown over twenty-fold in the past decade to reach 920 GW of installed capacity, while wind power has grown by four-fold and hydropower has grown by just 30% in the same period. With this upward trajectory looking set to continue for years to come, it is not difficult to imagine that solar may become the largest renewable energy source in terms of installed capacity worldwide.

This rapid growth is testament to the development of solar as a mature technology. This maturity has been achieved in two main areas:

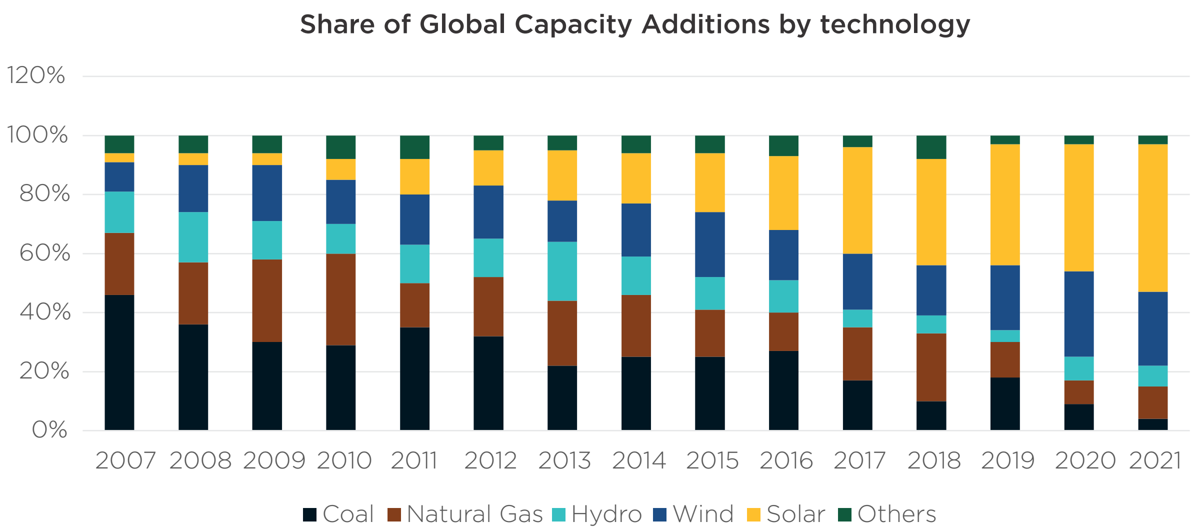
Solar PV has grown by 78% 3 years; highest than Wind (46%), Biofuels (21%), and Hydro (5%)

This rapid growth is testament to the development of solar as a mature technology. This maturity has been achieved in two main areas:

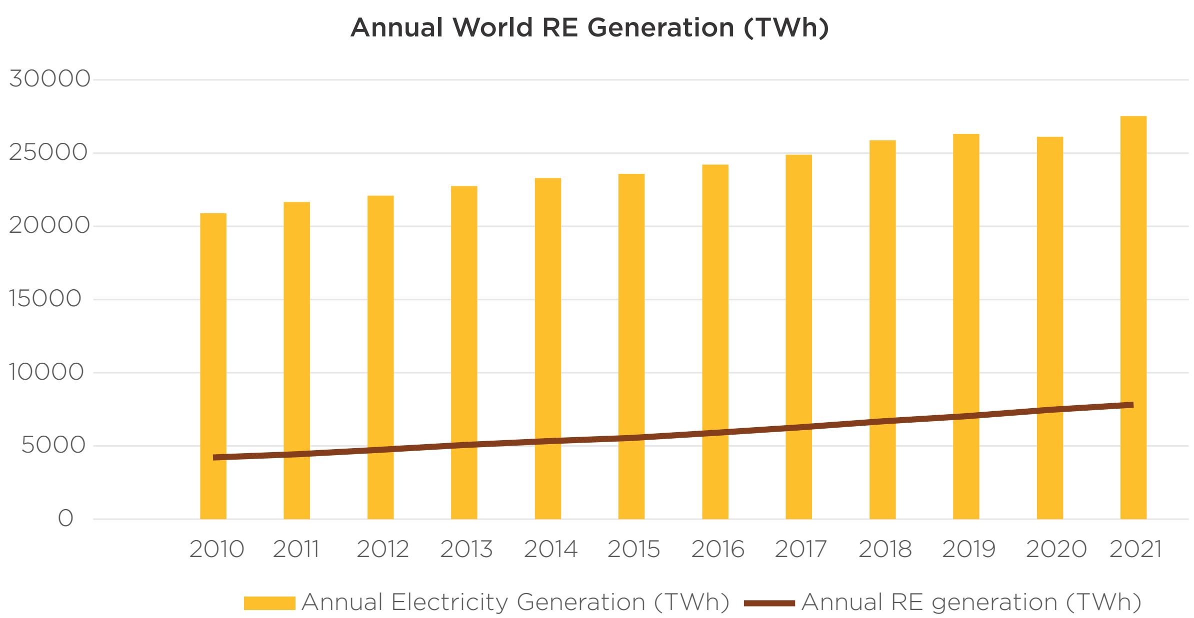
1. **Technical Maturity:** After years of research and development in the field, solar energy has a robust technological foundation as an energy generating technology. Both solar thermal and solar photovoltaic (PV) technologies have seen installations at scale. Solar PV in particular has seen the development of multiple technologies that have increased efficiency and power output from solar modules. Additionally, there have been significant improvements in system design, operations and maintenance activities, and individual balance of system components to help optimize generation.

2. **Financial Maturity:** Improvements in solar technologies have also translated to financial benefits to the sector as costs have fallen sharply. The LCOE for solar power plants has seen a steady decrease over the past decade. Additionally, the development of a strong supply chain for solar PV components has further helped drive down equipment costs while ensuring suitable quality and durability to increase solar plant operational lifespans.

3. The modularity and flexibility of solar lend itself to ease of deployment, which in turn has led to increased generation. The large portfolio of options, solutions, applications offered by solar allow it to address all sectors, with systems ranging from the kW size to the GW size.



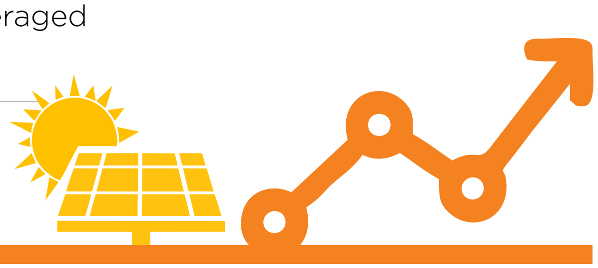
Source: BloombergNEF

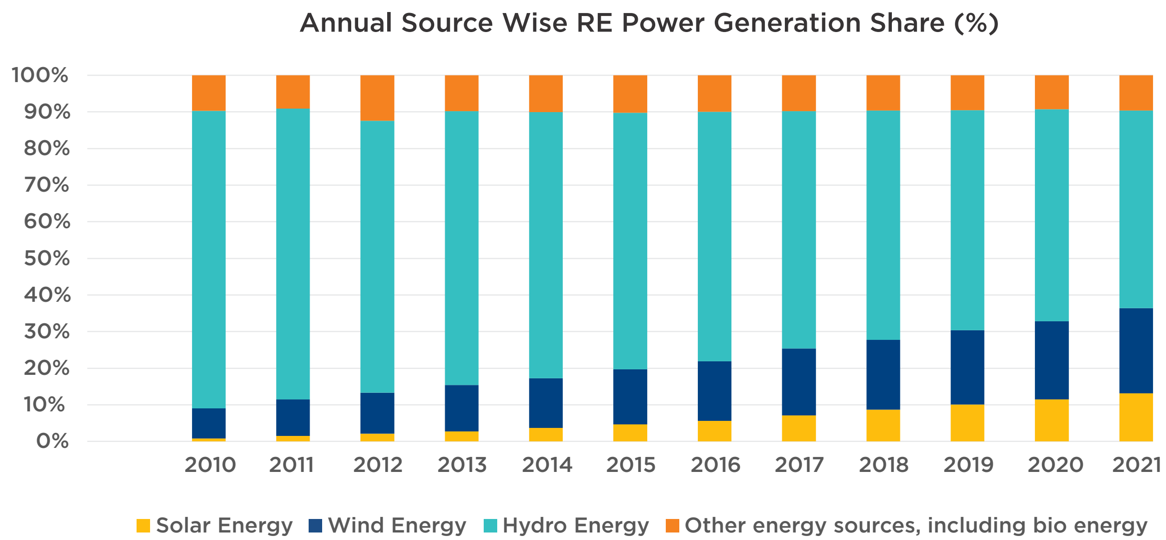


Source: BP Statistical Review of World Energy & Ember

2.3% per year: annual Electricity generation growth, averaged over the last two years

5.5% per year: annual RE generation growth, averaged over the last two years





Source: BP Statistical Review of World Energy & Ember

Annual renewable energy generation has increased by ~85% since 2010 as the importance of clean energy was recognized. During this time, solar generation has shown a steady growth trajectory, underlining its potential as the renewable energy technology of choice to power the energy transition.

Key Messages

GHG emissions have increased alarmingly over the past two decades, and the Electricity and Heat sector is the biggest source, accounting for 31% of GHG emissions.

To counteract the rise in GHG emissions, and to curb the global temperature increase to 1.5oC by 2100, countries have come out with targeted strategies to achieve Net-Zero GHG emissions. This helps drive the need to switch to low /zero carbon emission energy sources.

By the end of 2021, Solar had grown more than twenty-fold, from 72 GW in 2011 to 920 GW in 2021. At the same time, wind energy grew from 220 GW in 2011 to 824 GW in 2021, marking a roughly four-fold increase in installed capacity.

Rapid growth in the deployment of solar energy has been driven by high research spends that has been done to make solar energy technically as well as financially mature.

27.4%

Share of Installed Solar PV Capacity amongst all renewables in 2021.

19% per annum

the highest growth rate among renewables

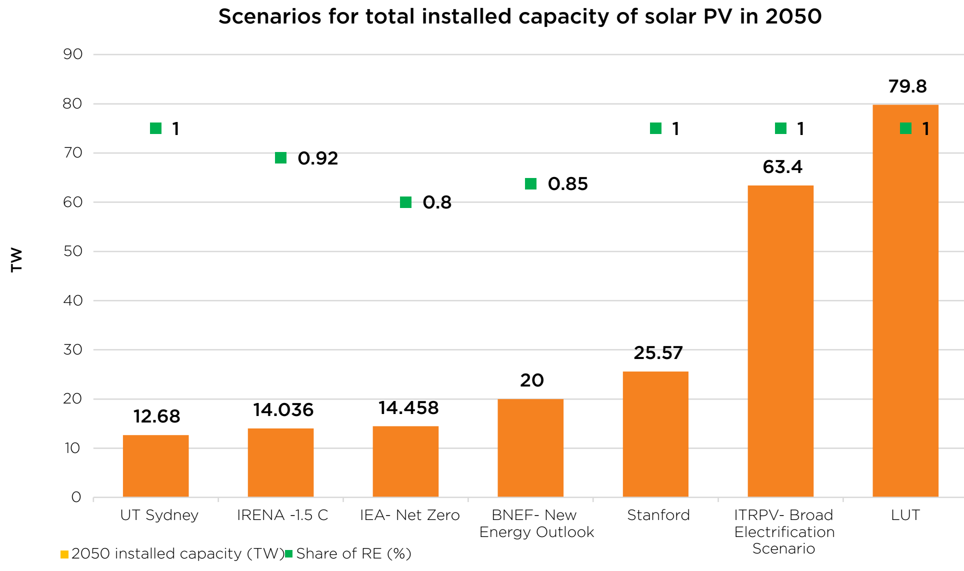
2.1 Renewable energy can play a prominent role across various energy transition pathways

Although it is apparent that the world is transitioning towards clean energy sources, there is no single approach or technology that can claim to cover all aspects required for a successful transition. A number of suitable pathways are available, each with their own set of enabling technologies. Key to this transition is the capability of a given pathway to reduce GHG emissions and limit the effects of climate change.

There are a number of viable methods to achieve the required emissions abatement,

There are a number of viable methods to achieve the required emissions abatement, each with its own set of benefits and

Energy Conservation and Efficiency	Renewable Energy
Direct Electrification of End Sectors	Hydrogen and its Derivatives
Carbon Capture and Storage/ Utilisation (CCUS)	Bioenergy/B iofuels



Source: Solar Power Europe Analysis , ITRPV (Scenario: Broad electrification: all sectors)

Key Messages

- Renewable energy, especially solar, is forecasted to be at the forefront of energy transition, to mitigate climate change and attain Net-Zero GHG emissions.
- Various institutions and organizations project at least 80% of renewable energy in the total global energy mix to meet the Net-Zero conditions by 2050.
- Solar to reach 50 to 60% of the whole energy mix according to some scenarios.

2.2 Solar energy, coupled with key enabling technologies, can drive the energy transition

While the solar energy's strong historical growth has been driven by the technological and financial considerations highlighted above, the future of the sector remains bright due to the technology's modularity and capability for usage in different applications.

Solar is uniquely placed due to its potential to directly generate clean energy as well as enable or link with other technologies to abate sectors that pose complex decarbonisation challenges. These linkages mean that solar energy has the potential to help decarbonize not just the energy and heat sector, but also tackle decarbonisation challenges in transportation, agriculture, manufacturing, and buildings, among other sectors. This usage of solar 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:

1. Solar energy can be used to power the production of Green Hydrogen, which in turn is set to be a key lever to help target hard to abate sectors and processes. Green Hydrogen and its derivatives may also serve as energy carriers or fuels for long distance transportation
2. Solar power has significant potential to provide electricity for Electric Vehicle charging, which is set to be vital for transport decarbonisation
3. Solar energy combined with Energy Storage can help provide round the clock renewable energy, allowing for clean energy usage even when the sun is not shining
4. The use of Agrivoltaics (Solar PV co-located with agricultural land) can help improve land use efficiency by using the same land area for energy generation and efficient farming
5. The use of building integrated PV to develop solar facades and other architectural solutions can help improve building energy efficiency while also generating clean energy for self-consumption

Solar PV can be deployed from the W or kW scale to the GW scale, and plant sizes can be varied depending on land availability, geographical conditions, electricity demand etc. Plants can be deployed on residential and commercial rooftops and can be utilised for distributed generation. Solar can also be deployed in remote regions with limited grid connectivity, providing clean energy in regions that would otherwise continue to rely on traditional non-renewable sources. The flexibility, mature ecosystem, and sector coupling opportunities associated with solar energy underline its credentials as the go-to technology for the energy transition.

In the upcoming chapters, the various details with respect to the evolution of solar energy technologies, manufacturing processes and utilization of solar energy for various purposes shall be discussed.

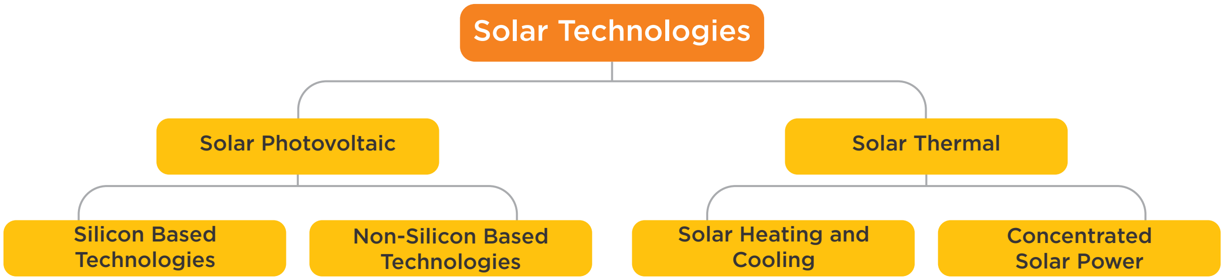
Key Messages

- **Solar energy has the potential to help decarbonize not just the energy and heat sector, but also tackle decarbonisation challenges in transportation, agriculture, manufacturing, and buildings, among other sectors.**
- **Being modular in nature, solar PV energy generation systems can be deployed, ranging from the W or kW scale to the GW scale , providing huge flexibility in terms of land availability, geographical conditions, electricity demand, financial availability etc.**
- **With the introduction of innovative methods and applications of solar energy generation such as Building Integrated PV, Agrivoltaics, Vehicle Integrated PV, solar CSP etc., solar energy provides a huge number of opportunities for the world to move towards cleaner energy solutions. Sectoral linkages, such as for the production of green hydrogen, will play a key role in driving solar growth.**

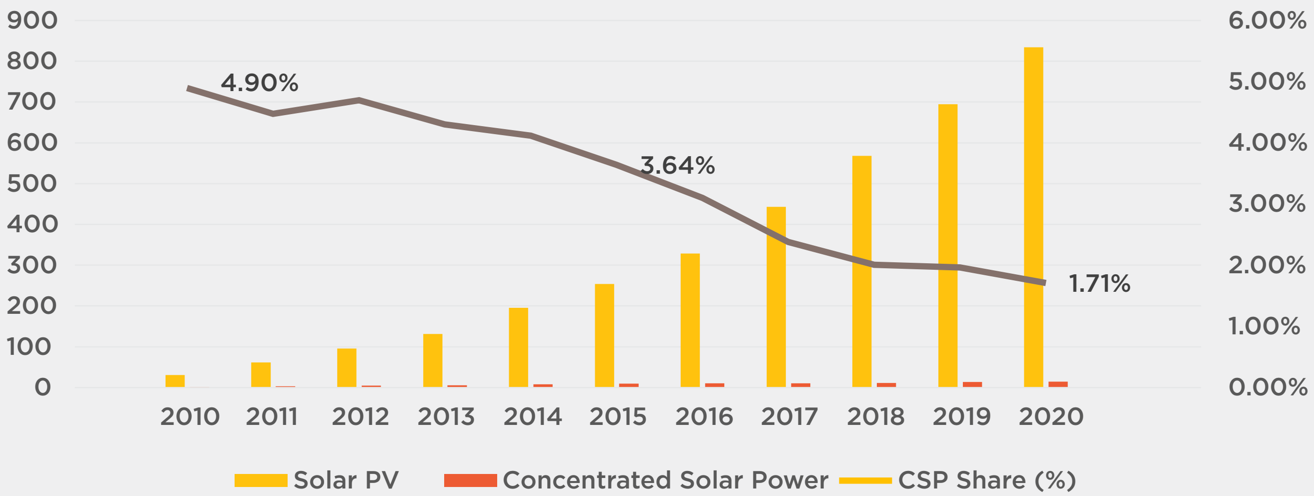
Solar Technologies: Cross-cutting applications across multiple sectors

At a fundamental level, solar technologies provide a pathway to convert light energy into a usable form of energy. The energy generated in this manner is most commonly used in the form of heat or electricity:

- **Solar Photovoltaic (PV)** technologies allow for the conversion of light into usable electricity. PV has become the key solar technology over the past two decades and has evolved into a mature technology seeing widespread global deployment. Silicon based PV technologies are the mainstay, although non-silicon technologies also do exist.
- **Solar thermal technologies** allow for the conversion of light into usable thermal energy. This may then be used for multiple applications in the Residential, Commercial and Industrial (C&I), and Utility sectors. Applications include heating, cooling, drying, cooking, and subsequent electricity generation. Solar thermal technologies have seen limited large-scale deployment but have many relevant use cases.



Annual World Solar Power Generation, Technology Wise (TWh)



Source: IEA(2021),Concentrated Solar Power (CSP), IEA, Paris and BP Statistical Review of World Energy & Ember

Comparing the two main solar power technologies available, Concentrated Solar Power (CSP) and Solar Photovoltaics (PV), it is apparent that Solar PV has been the dominant technology. In the last decade, with the rising deployment of Solar PV, it can be seen that the already small share of Solar CSP has shrunk further, while Solar PV has taken centre-stage. Concentrated Solar Power has seen limited deployment globally, and installations have primarily taken place in certain key markets. 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 Hybrid format alongside solar PV to provide round the clock power.

Key Messages

- Solar technologies provide a pathway to convert light into a usable form of energy. These pathways are of two broad types: Solar Photovoltaic to generate electricity, and Solar Thermal to generate heat.
- Both the technologies can be used for power generation, but solar PV has emerged as the dominant technology option

3.1 Solar Photovoltaics: Leading the way for Solar technologies

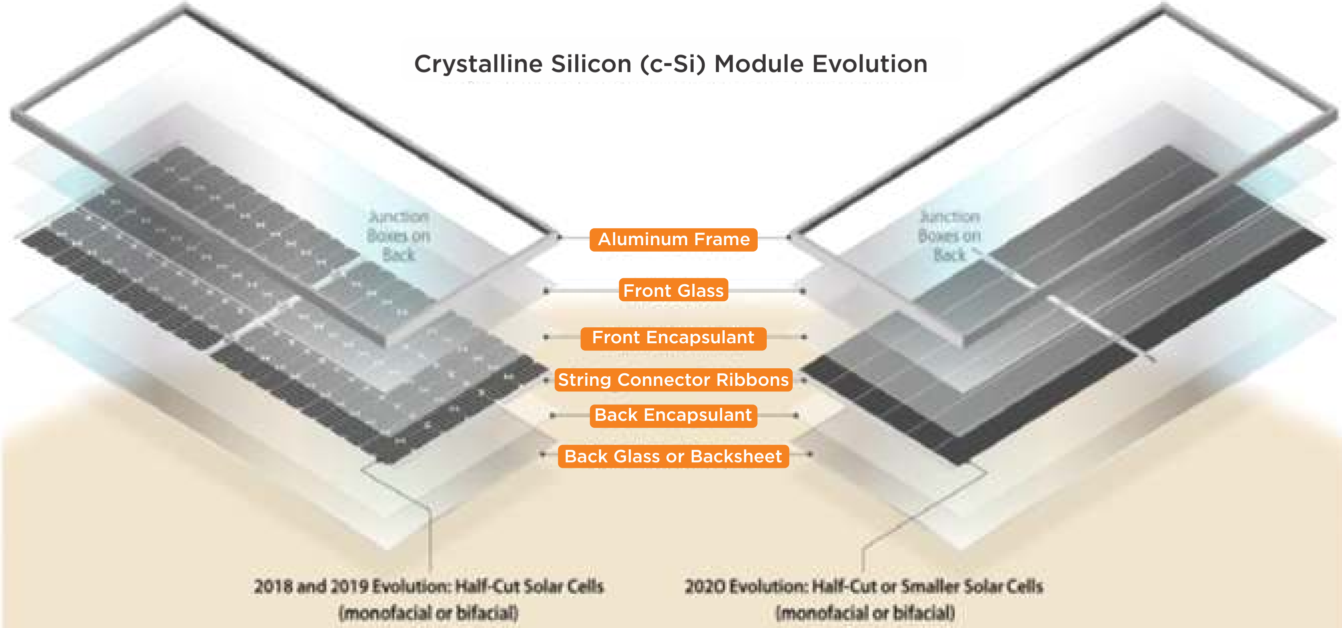
The heart of the solar module technology is the semiconductor PV cell. Although many different types of materials may be used to develop PV cells, Silicon is by far the most commonly used material type, accounting for ~95% of PV module production worldwide[1]. Silicon is non-toxic makes up 27.7% of earth crust and second most abundant element next to Oxygen. Crystalline silicon is the dominant form, although amorphous silicon solar cells are also produced. Non-Silicon based solar cells utilise a variety of other materials, with Cadmium-Telluride being the dominant technology in this category.

Albeit a solar module is the final product of the silicon PV, a solar cell is the basic unit of a fully functional PV system. Since the output power of one cell is low, several cells are interconnected electrically in series to form a matrix in order to reach a meaningful output power level. This interconnected matrix is encapsulated with several layers of polymers and glass to protect the electrical circuit from physical damage and weather. The laminate is usually framed and provided with a junction box to collect the power from the cell strings. it is important to consider the other materials that make up the majority of the Bill of Materials 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.

In addition to the solar modules, a number of additional components are required to complete the solar system. For solar PV systems, this includes a 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.

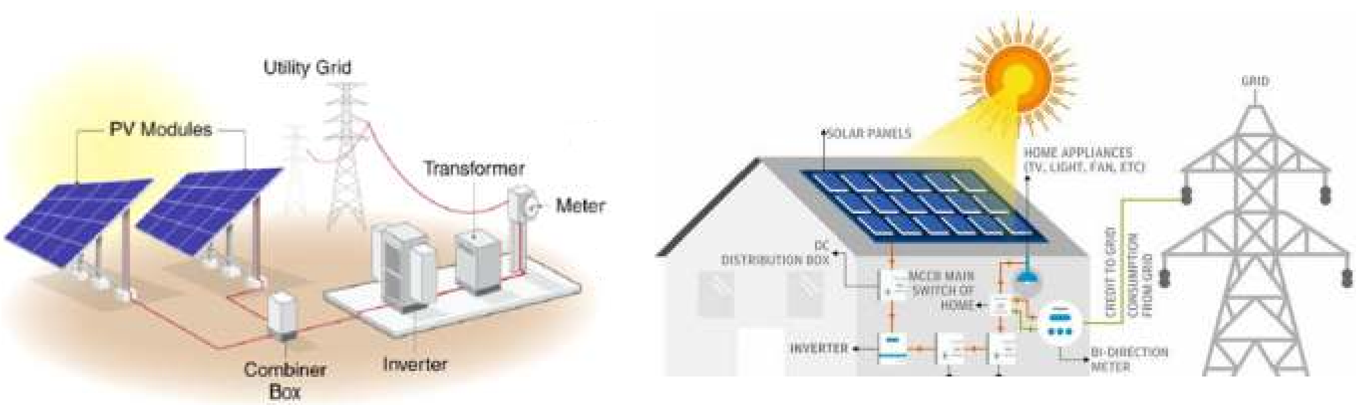
[1] *https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf*

Crystalline Silicon (c-Si) Module Evolution

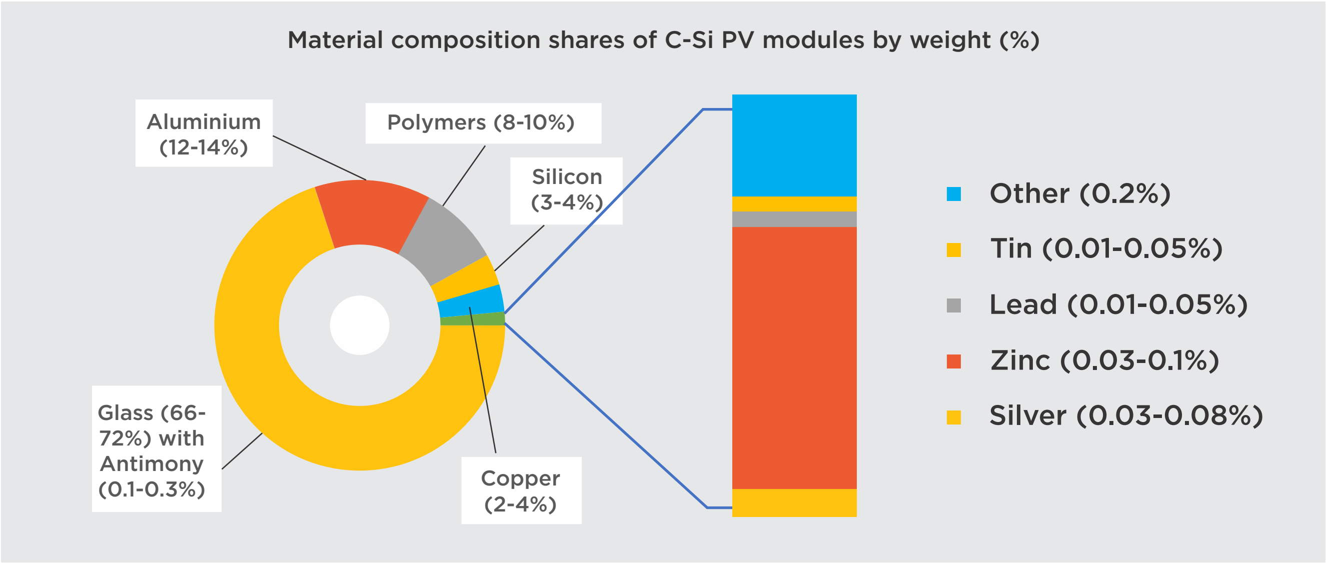


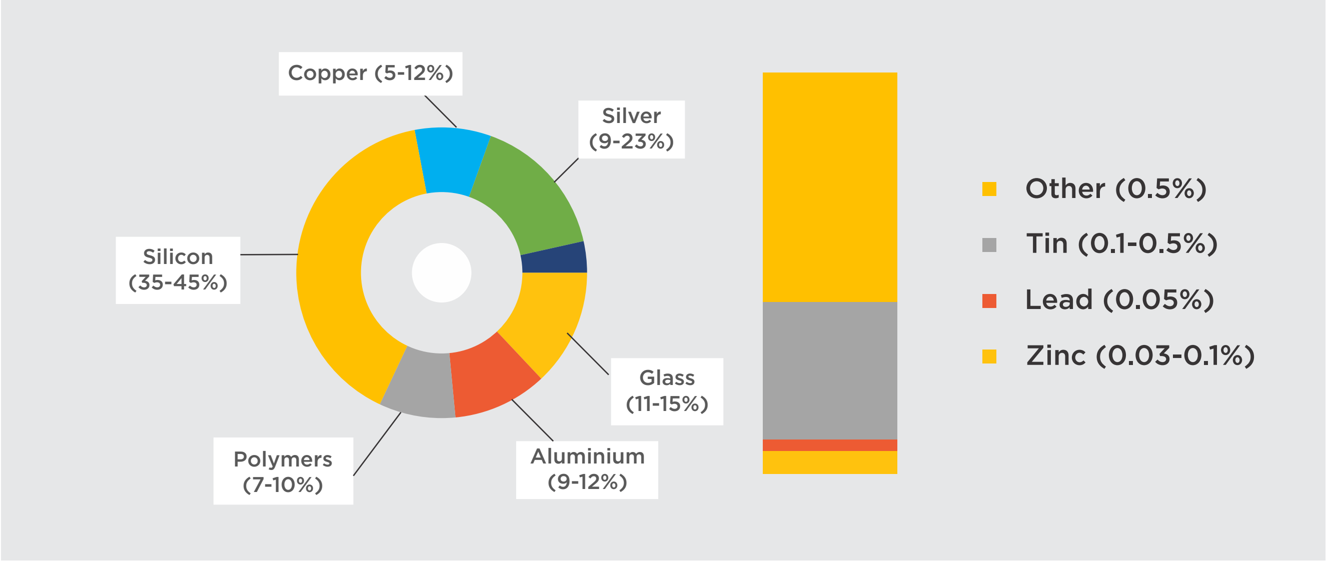
Source: NREL Solar Photovoltaics Supply Chain Deep Dive Assessment

Utility Scale Solar PV System (Left) and Solar Rooftop System (Right)



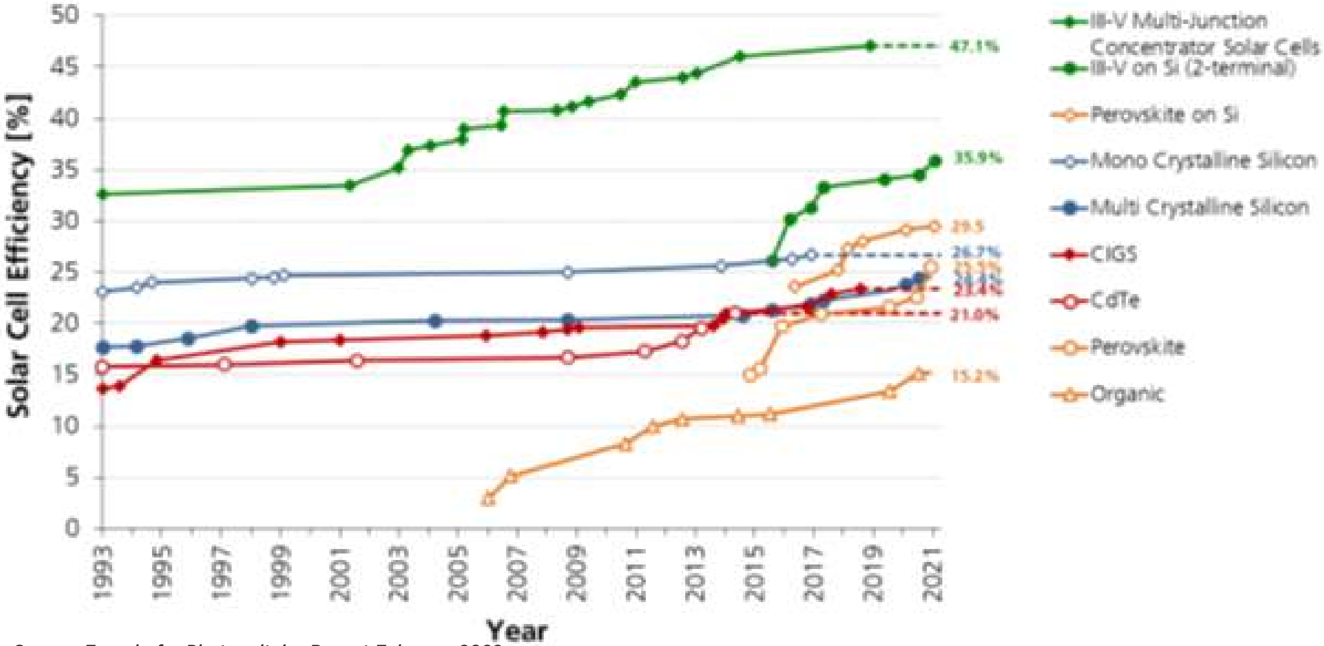
Source: NREL Solar Photovoltaics Supply Chain Deep Dive Assessment





Source: IEA Special Report on Global Solar PV Supply Chains

A wide variety of solar PV cell technologies have been tested and deployed commercially with constant research being conducted for enhanced efficiencies. Despite the emergence of exotic technologies such as III-V multi junction cells and organic cells, the dominant solar cell technologies still have been crystalline silicon based. Traditionally the crystalline PV technology has been bifurcated into Mono and Multi crystalline silicon, which have seen steady efficiency growth over the past decade (3.5%-4% for multicrystalline silicon and a little under 2% for monocrystalline). Newer technologies in earlier stages of development have seen significant efficiency gains, with organic PV gaining 7.5%, and Perovskite and III-V on Si gaining ~10%. 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. The below graph summarizes the efficiency progress of the different solar PV technologies at lab scale.



Source: Fraunhofer Photovoltaics Report February 2022

Figure: Evolution of different solar cell technologies

Key Messages

- Solar PV is the dominant solar technology available, and the semiconductor solar cell is the heart of the technology.
- A wide variety of PV technologies are available, with crystalline silicon being the dominant technology family
- In the last decade, mature technologies like Crystalline Silicon Modules have seen steady efficiency improvements of around 2-4%, while newer technologies have seen significant growth, with III-V junction cells, Perovskite, and Organic PV showing efficiency improvements of 7.5%-10%

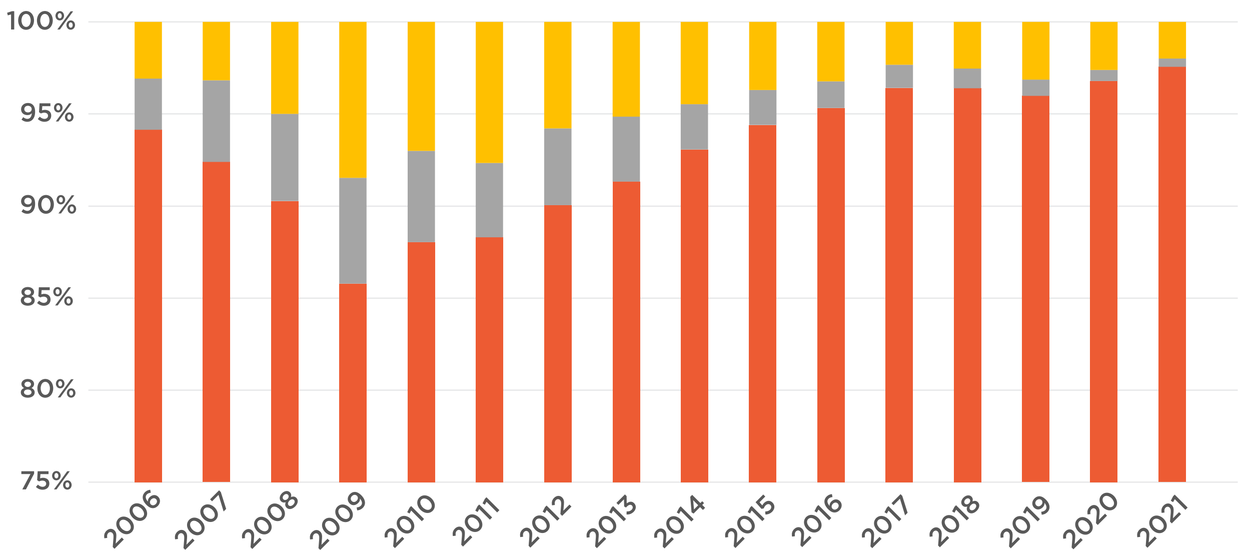
All solar technologies are improving in terms of efficiencies

The amount of materials, technologies and cell designs available are increasing

3.1.1 Solar PV technologies & learning curve

Although the basic photovoltaic effect had been demonstrated in the 19th century, it was not until the 1950s that the first practical silicon solar cell was developed at Bell Labs, USA[2]. Subsequently, following early government support in Germany and Japan in the 1980s and 1990s, silicon based solar cells have seen significant growth. This growth has been especially 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, in today's context, crystalline silicon PV evolved as synonymous to the silicon based PV.

Share of different Solar PV technologies (%)



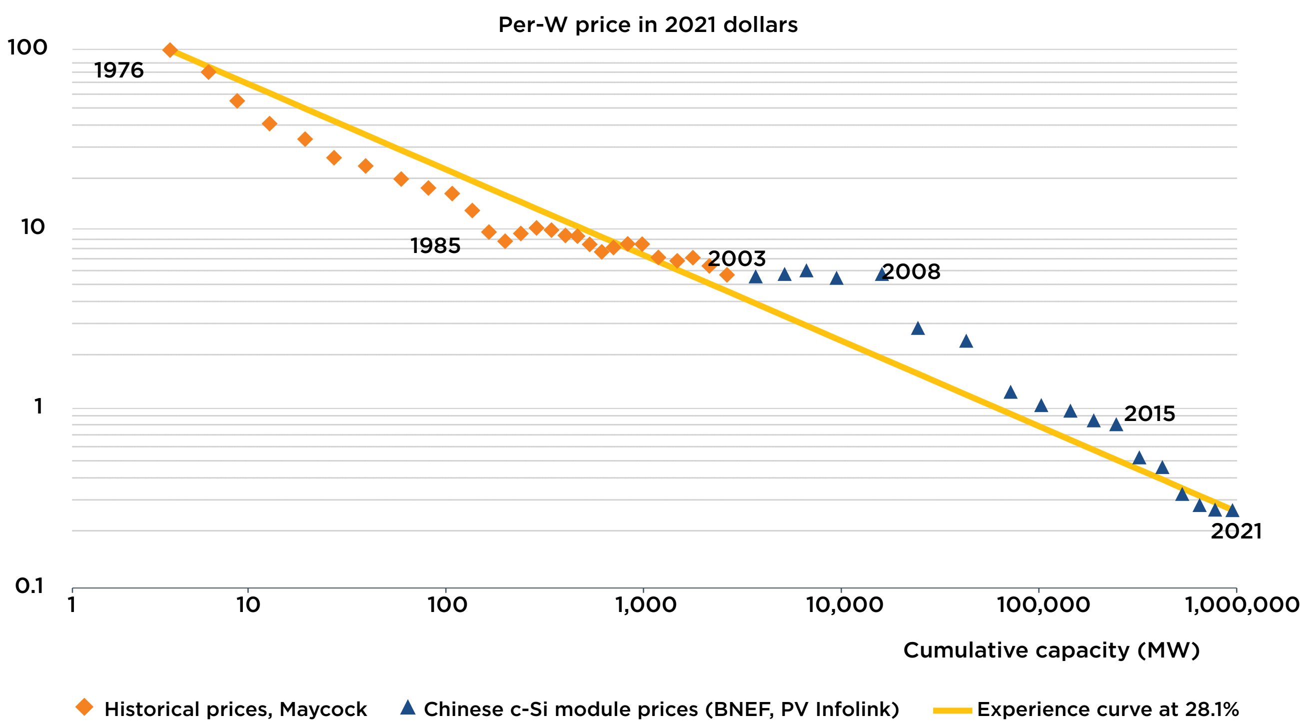
Source: BNEF Database

[2] *https://www.aps.org/publications/apsnews/200904/physicshistory.cfm*

As can be seen in the above graph, 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. While there are many reasons why crystalline silicon PV has developed as the key solar PV technology, innovations in technology have played a key role. There has been development of new cell and module types, increasing efficiency and power output. Crystalline silicon PV technologies have steadily grown in efficiency and are now the go-to technology for PV installations for a variety of applications. The optimization in manufacturing process, technological developments all along the supply and value chain and larger scale factories have enabled the PV technology to reduce the costs considerably that crystalline PV is now one of the cheapest energy sources of the world.

It is also evident from the below learning curve plotted with the average selling prices of the solar module as function of cumulative shipment of PV modules starting from 1976 till end 2021. The price of solar module price has been reduced significantly over the last 15 years; going from around 5 USD per Watt in 2008 to under 0.3 USD per Watt. The same period has seen cumulative capacity grow 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 28.1% from 1976 to 2021, 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.

Learning Curve for Crystalline Silicon Modules (Per-W price in 2021 dollars vs Cumulative Capacity (MW))



Source: BNEF (2Q 2022 Global PV Market Report), Maycock

This deep learning is achieved by two important parameters: improving the electrical characteristics of modules – power and efficiency – and reducing the costs of the PV device. Since crystalline silicon is a chain process, technological developments all along the value chain have contributed to both reducing the costs and improving the performance.

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 manufacturing section 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 silicon 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, which are the final product of the PV.

Key Messages

- **Crystalline Si based solar technologies have been the dominant technology for solar PV.**
- **The price of solar module price has been reduced significantly over the last 15 years; going from around 5 USD per Watt in 2008 to under 0.3 USD per Watt.**
- **The PV industry has registered a learning rate of 28.1% from 1976 till 2021**

3.1.2 Polysilicon: short supply & high price

Although polysilicon cannot be seen as the starting point of the value chain, since polysilicon production requires metallurgical silicon as raw material that is also used in other industries, polysilicon is still 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 polysilicon is typically supplied in two forms - chunks of silicon and granular -, the difference for which originates from the manufacturing process.

Most of the industry relies on the time-tested Siemens type Chemical Vapor Deposition (CVD) process using trichlorosilane (TCS) as feedstock. Siemens CVD remains the workhorse of the solar industry and enjoys a near monopoly for producing solar silicon. According to the latest ITRPV report, while Siemen's type CVD reactors technology will be the mainstream technology in the future as well, FBR is expected to grow to about 20% in next 10 years from its current market share of 5% in 2021. While no progress is expected in case of UMG-Si, the material is expected to stay available in the market. Using monosilane instead of TCS is a slight variation to the mainstream approach and is offered by a single company. However, this technology not very popular in solar related applications.

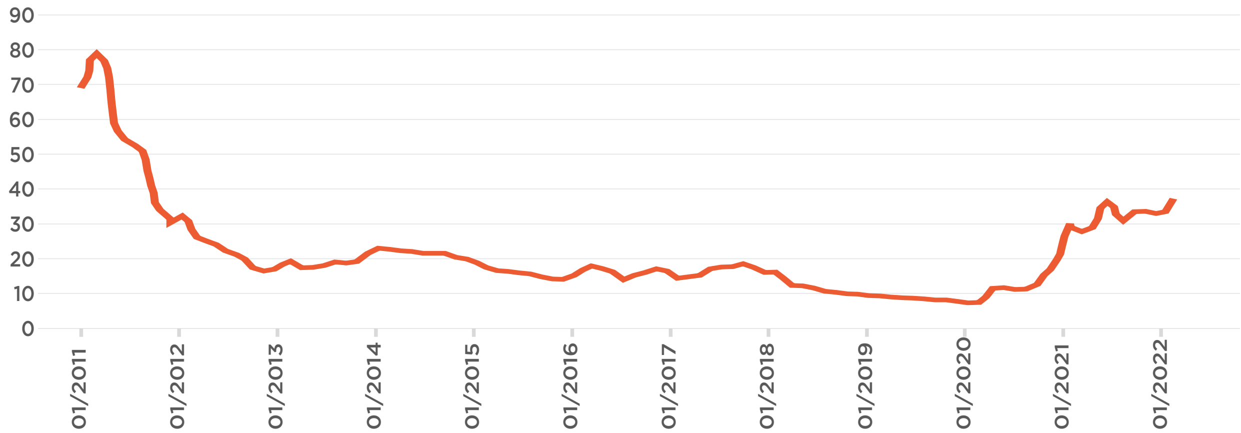
While the silicon produced from the CVD process is supplied as chunks, Fluidized Bed Reactor (FBR) technology produces granular polysilicon. FBR technology is owned by few polysilicon makers, and occupies a minor market share relative to the Siemens CVD process. Upgraded metallurgical silicon (UMG) was also a low cost and low-quality alternate to traditional silicon, but the technology was not very successful.

Insights and Trends

The key development related to polysilicon that is not only affecting the segment, but the PV industry at large, is the short supply of polysilicon and subsequent price hike in recent times. 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(e.g. 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. As per Bloomberg, 500 GW of polysilicon production capacity shall come online by the end of 2023[3]. Although nominally there is enough silicon capacities, 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 85 CNY ($9.5) /kg at the beginning of 2021 to more than four times that level, reaching 303 CNY ($48) /kg recently.

However, key industry players are expecting that with additional capacity coming online by end of this year, the prices would come down from the from 2023 onwards. By the end of 2022, more than 285 GW of available polysilicon capacity is expected to be online and will suffice to service global installations of around 244 GW.



Source: BNEF

Key Messages

- **The Siemens CVD process for polysilicon production is set to remain as the dominant technology in coming years**
- **Polysilicon prices have recently increased significantly after several years of oversupply.**

[2] https://www.aps.org/publications/apsnews/200904/physicshistory.cfm

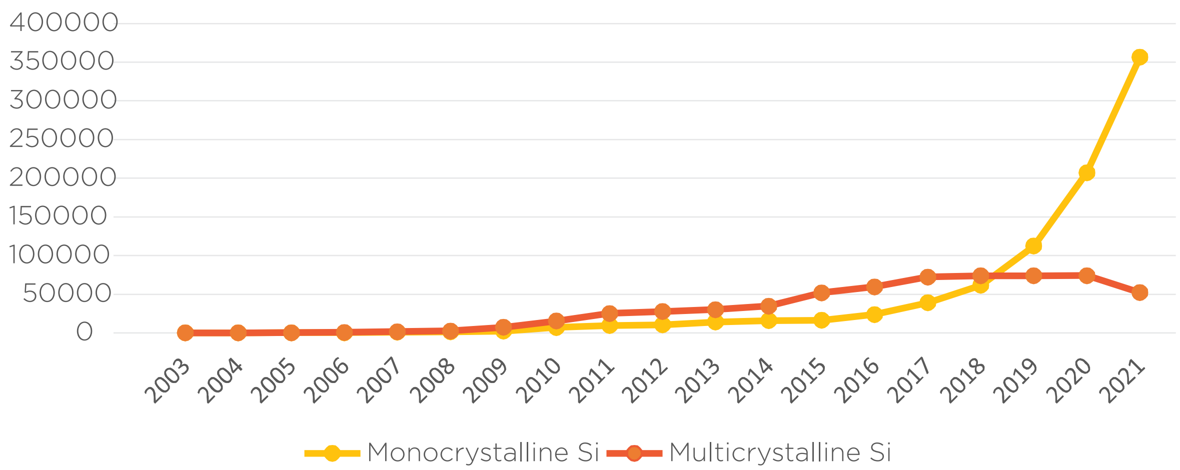
3.1.3 Ingot and wafering

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

Ingot

It is ingot making section that determines whether the produced silicon materiel is monocrystalline or multicrystalline depending on the method employed to produce the ingot. Using a czochralski method, monocrystalline ingots are carefully pulled from the molten silicon in a quartz curricle. The same process is also used in semiconductor manufacturing. However, in a PV specific process, the silicon is directionally solidified in the same crucible from bottom to top. The difference is, the latter results in multicrystalline, characterized with presence of gain boundaries misses the periodical arrangement of the silicon atoms in the crystal lattice are missing. While multicrystalline is low cost, the monocrystalline with proper arrangement of atoms in crystal lattice supports higher efficiency potential. In fact, multicrystalline 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. As shown in the below graph Monocrystalline Si is now by far the dominant technology being utilized for solar cell production, while multicrystalline Si manufacturing capacity has stagnated and started to fall as the technology is no longer the preferred material for C-Si cells.

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



Source: BNEF Database

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. 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. T. Within just 2 years, the approach became the state of the art; ITRPV estimates that more than 95% p-type wafers were produced using gallium as dopant and by 2024 the entire production of p-type wafers to be based on gallium doping.

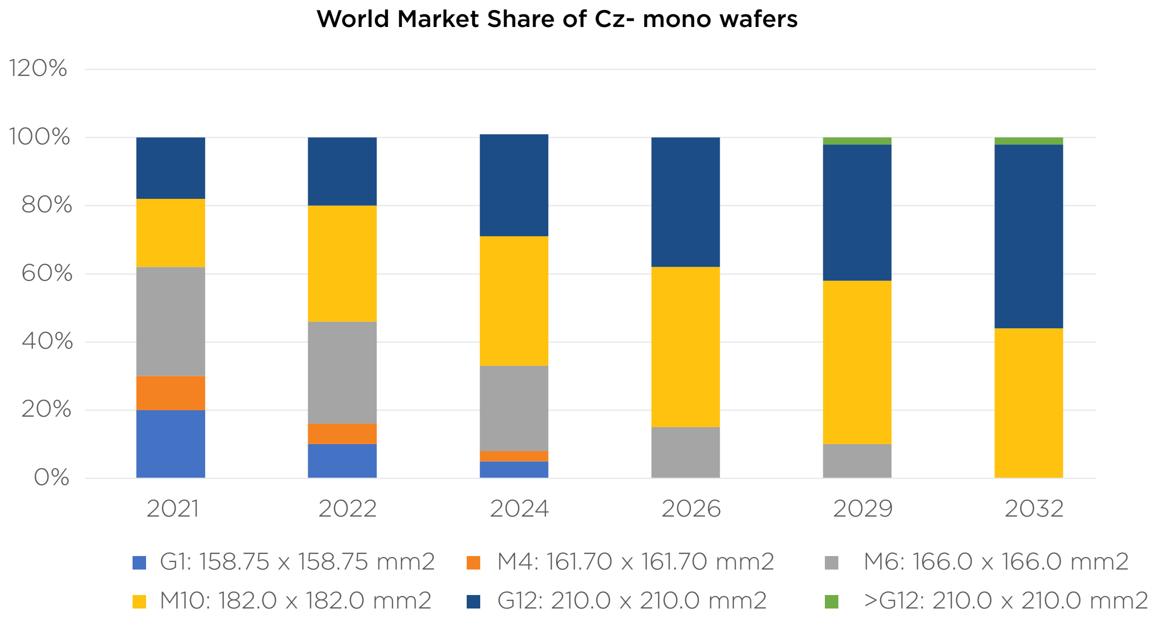
Another important development with the doping all advanced cell architectures beyond PERC are typically employed on n-type base wafer. The phosphorus doped silicon substrates have longer lifetimes, as the holes of n-type material are less sensitive to many common metallic impurities in silicon, such 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 that is incurred when a p-type silicon solar cell is first exposed to the light is now avoided with cell structures based on n-type wafers. However, the subject lost its prominence as the industry has move to gallium doping which facilitates p-type to be LID-free. All the advanced cell architectures based on n-type wafers typically exhibit lower temperature coefficient, which means that lower efficiency reduction is incurred as ambient temperature increases. For these advantages majority of the advanced cell architectures are based on n-type base wafers.

Wafering trends

When it comes to wafering, the most important development in the process has been the shift to Diamond Wire (DW) based sawing from the slurry technology. DW based sawing is now considered 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.

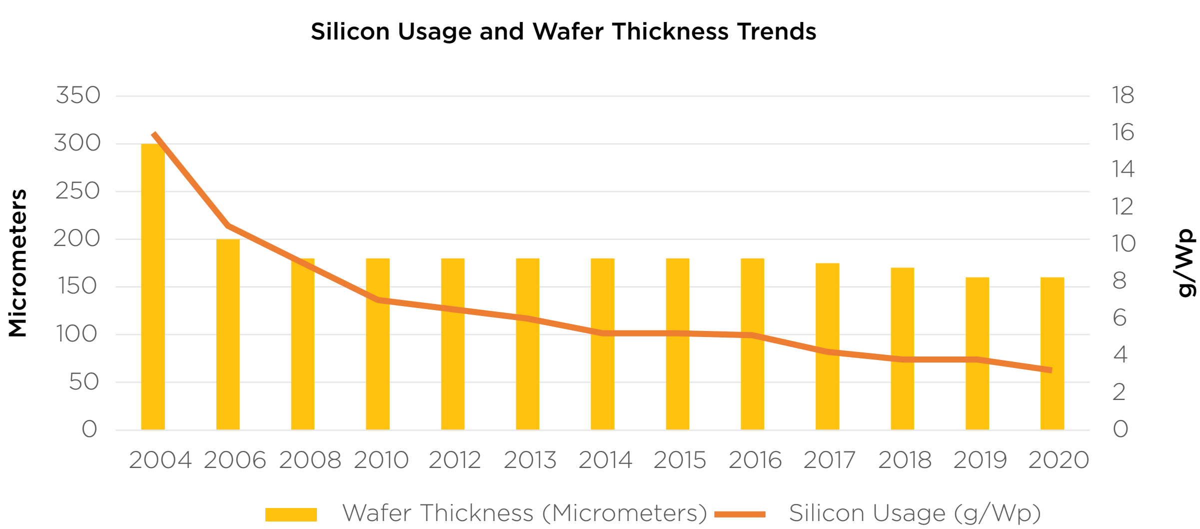
The key performance indicators of the wafers are wafer size and thickness. One of the most important developments related to wafering that has influenced the downstream value chain components has been larger wafer formats. The rationale behind the approach is that the output power of a PV device is a 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 recently 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 156.75 mm 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 full square called G1 and 161.75 denoted as M4. In 2018, M6 was first introduced on multicrystalline followed by monocrystalline during 2019. M6 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 was introduced. In response to this move, vertically integrated companies came out with 182 mm wafers in 2020. in today's market M6, M10 and G12 are the mainstream wafer sizes, and the larger formats are expected to take over the market as shown in the below graph.



Source: ITRPV 2022

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 reduced either by reducing the kerf or thickness of the wafer. Thus, reducing the silicon consumption per watt has always been a subject of the optimization and it became even more important with the polysilicon shortage. The rationale is simple: thinner wafers reduce silicon consumption. In the past, at least until 2020, the rule of thumb was that a reduction of 10 µm in wafer thickness reduced wafer costs by $0.01. A recent wafer price list from leading supplier indicated that a 20 µm reduction in wafer thickness results in savings of 4.5% on wafer price. As to the gap between p-type and n-type wafers – a very important aspect of benchmarking advanced cell technologies to PERC – are about 6% more expensive than p-type wafers of the same thickness. The below graph summarizes the trend of silicon consumption per watt.



Source: Fraunhofer PV Report 2022

The silicon usage per Wp has fallen significantly to about ¼ from 2004 to 2020. This outsized drop in silicon usage has been achieved in three ways – reducing the wafer thickness, reducing the kerf and improving the cell efficiency- and the industry has progressed in each of these aspects. For wafer thickness, 180 µm remained the mainstream for quite a long time from 2004 to very till 2016. Since the silicon shortage hit the industry, the industry is gradually thinning down the wafers. While the typical wafer thickness with PERC is about 160 µm, the first 150 µm cells have hit the marketplace. It is also important to note that the wafer thickness also depends on the cell technologies. For example, cell technologies such as HJT support wafer thicknesses of up to 10 to 15 µm lower than those used for PERC architecture.

Reducing the kerf loss, which is the silicon lost during the slicing process for wafering, is also an effective way of reducing 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 60 µm, which is expected to go below 50 µm in next 10 years, according to ITRPV.

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, kerfless wafering technologies are not a significant focus area. A single company in Europe, NexWafe, is pursuing the technology. Nexwafe recently saw an investment of nearly USD 30 million by Indian company Reliance Industries Limited, which is looking to enter the solar manufacturing sector in India.

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 increases vary across categories but range from 60-90% from 2020 to August 2022. 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.

Source: ISA Analysis

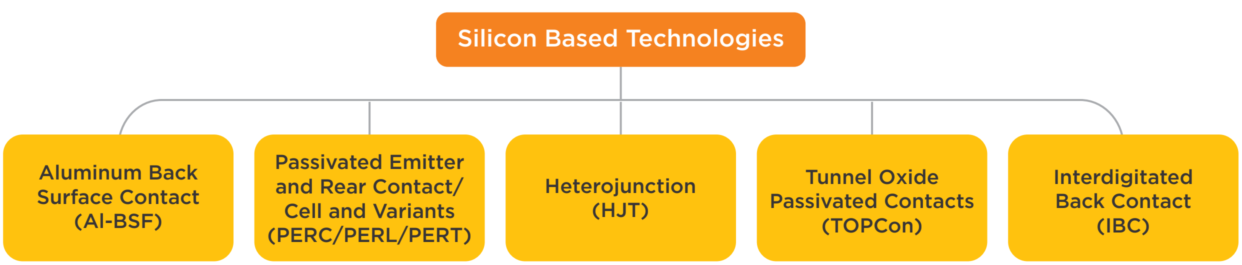
Key Messages

- **Ingot processing is dominated by the Czochralski process, whereas Wafering primarily uses diamond wire cutting to efficiently slice the ingots**
- **Monocrystalline, Polycrystalline, and Thin film technologies had a roughly equal market share in the early 2000's. Polycrystalline then dominated market share until the rise of PERC since 2015.**
- **Manufacturing is highly concentrated at a country and company level. It is located almost exclusively (98%) in China, and the top 10 manufacturers account for around 90% of global production**
- **Reduction of wafer thickness and minimizing of kerf loss during the wafering process are the key trends reducing material consumption, and subsequently improving process efficiency and cost effectiveness**

3.1.4 Solar cells

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 several wet-chemical, thermal and deposition processes. Cell manufacturing is the most sophisticated stage across the crystalline PV value chain. There are also several options to choose from a variety of available cell architectures such as PERC, TOPCon, HJT and IBC. Every cell architecture has a different structure and a different manufacturing flow. However, from a broader perspective, the passivation scheme and corresponding metallization are the key differentiating elements for all these high-efficiency cell technologies. The selected cell architecture also determines the key performance indicator of the cell, the efficiency.

The key silicon solar cell technologies are highlighted below:



- **Aluminum- Back Surface Field (Al- BSF):** Al-BSF technology was once the dominant silicon-based cell technology for many decades till 2014/2015. The main characteristics of the most advanced mainstream BSF structure was that it is passivated with silicon nitride on front side and printing of a full aluminum layer on the back of the cell that alloys with silicon during a firing step to form a p+ region acting as BSF on the rear side. This BSF provides field effect passivation that improves cell performance by reducing Surface Recombinant Velocity (SRV), a parameter that is a key impediment to increasing a solar cells efficiency.
- **Passivated Emitter and Rear Contact/Cell (PERC):** For PERC cell architecture, its most prominent upgrade as compared to BSF is its replacement of the Aluminum BSF with a full-scale passivation on the rear of the standard cell, similar to the layer that is usually deposited on the front side. This passivation, covering both chemical and field

effect, further reduces Surface Recombination, leading to a more efficient solar cell. PERC is currently the state-of-the-art cell architecture in the mainstream and still provides the best cost performance ratio.

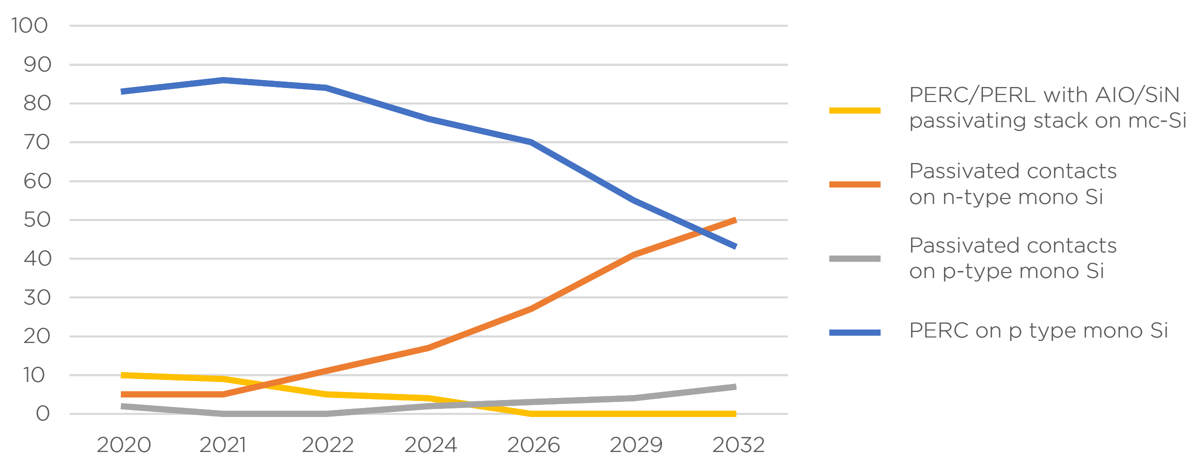
Both BSF and PERC are based on p-type semiconductor wafers, which have been the industry standard for solar cells. However, there has been significant growing interest on n-type wafers of late. As discussed in the wafering section, the n-type wafers have several advantages including high potential to support higher efficiency. Thus, many of the advanced cell architectures are based on n-type wafers.

- **Passivated Emitter, Rear Totally Diffused (PERT):** PERT is the entry level cell architecture for n-type wafers. Differing from the PERC process, PERT involves a second step to form a Phosphorous BSF, which leads to enhanced passivation. Several variants of the technology are available depending on the material and method of passivation.

- **Passivated Emitter, Rear Locally Diffused (PERL):** PERL aims to combine the advantages of PERC and PERT as the front and rear surfaces of the cell are passivated but the rear is locally diffused only at the metal contacts.

While a few companies commercialized PERT and PERL technologies, but the unprecedented progress of the PERC in inters of both lowering costs as well as improving efficiency has made these two early n-type technologies less attractive. And PERC continued to make further progress. However, 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.

World Market Share of PERC/PERL/TopCON technology (%)



Source: ITRPV 2022, ITRPV 2021

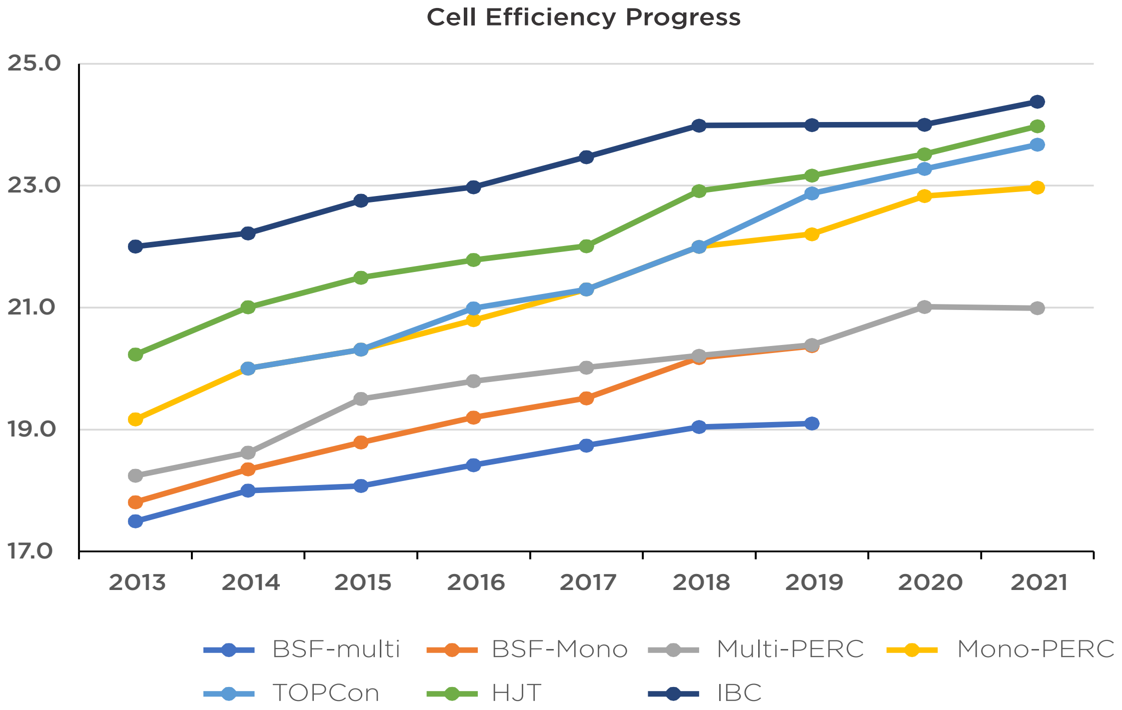
- **Tunnel Oxide Passivated Contact (TOPCon):** TOPCon, in this context, is considered a natural successor of the PERC cell structure and involves a few additional process steps over standard PERC. The key feature of the technology, passivated contacts, serve to address a major shortcoming of previous passivated cell structures, i.e. losses at the points of metal contacts of the cell. The crux of the process lies in applying very thin nanometer-scale tunneling oxide topped with doped polycrystalline silicon layer. And in today's context the TOPCon is generally referred to applying passivated contacts structure on to the rear side of n-type wafers.

- **Heterojunction (HJT):** HJT is another variant of the passivated contacts approach and aims to take combine the positive attributes of wafer based solar technology as well as thin film solar technology. HJT cells are made by fusing two different materials (Silicon HJT involves forming a junction of crystalline and amorphous silicon materials). In HJT, a n-type wafer is sandwiched between the intrinsic and oppositely doped amorphous silicon layers.
- **Interdigitated Back Contact (IBC):** Back Contact cells aim to shift all electrical connections to the rear side of the cell. Multiple technology variants for Back Contact cells exist, although commercialization has remained a challenge. IBC cells have been a contender to hold record cell efficiencies, and several research bodies and companies are working to simplify production processes and bring down costs.

TOPCon, HJT 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 also to bring down manufacturing costs to competitive levels with respect to the current dominant cell technology, PERC.

All the above mentioned technologies are limited by physical constraints in terms of the efficiencies they can achieve. These constraints can be overcome through the use of 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.

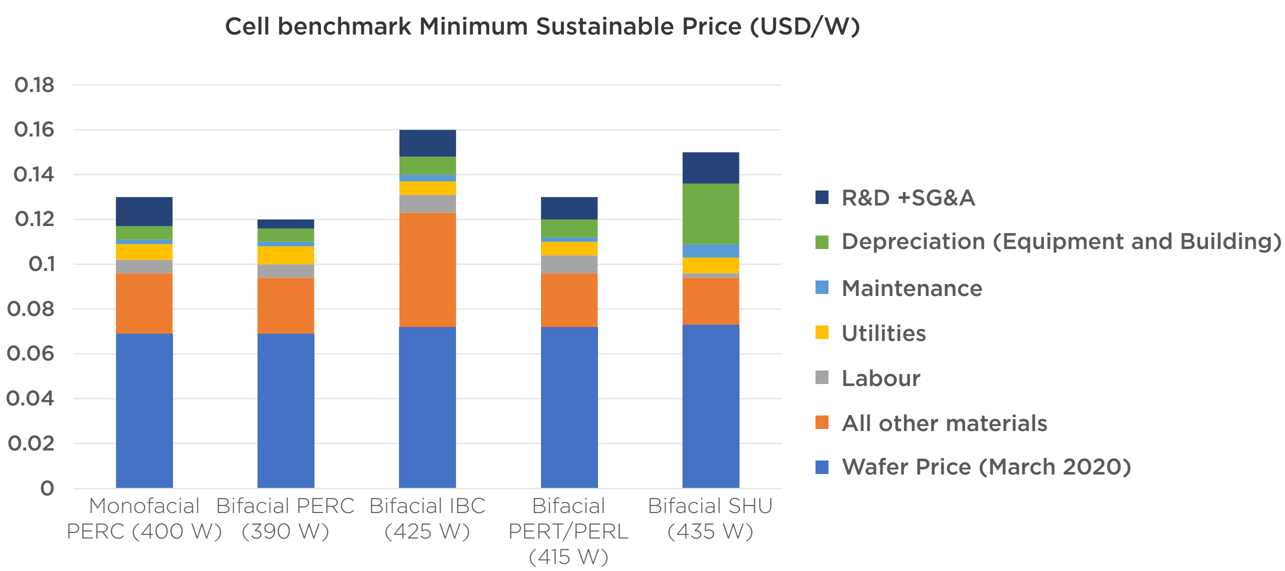
All these advanced cell technologies are at different levels of efficiency and are progressing at a different pace. IBC so far remined most effacement technology in the commercial space with an average cell efficiency of 24.4%, which has consistently increased from an already high base of 22% in the last 10 years. HJT and TOPCon are the next with about 24% average cell efficiency, but the increase is significant at about 4% absolute over the base of 20%. Mono PERC is the market leader and has seen the highest increase in efficiency, likely due to it being the in focus technology of the last decade. On average, the key cell technologies showcased have seen efficiency increases of ~3% since 2013. 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.



Source: Taiyang News and SolarPower Europe Analysis

Insights and Trends

The use of different cell architectures leads to variations in cost. However, these cost variations are not necessarily driven by the same component or aspect of module production.



Source: NREL This analysis assumes 2-GW facilities in urban China, not including tariffs. A 10% price premium is applied for n-type wafers.

As per NREL Benchmarking activities, IBC and SHJ technologies can cost 15% - 33% more than the market dominant PERC architecture. For IBC, this cost increase is driven using additional materials used for the cell architecture and also the process complexity. When it comes to HJT and TOPCon, the higher costs are mainly driven by the materials costs and production equipment CapEx. Both the technologies use n-type wafers, which are typically about 5% expensive than the mainstream p-type. Then both TOPCon and HJT uses silver pastes on both sides, that nearly doubles the consumption of the silver compared the PERC that employs silver only on front side, while low-cost aluminum is used on the rear side. The silver consumption is particular more in case of HJT as it employs low temperature cured pastes that requires high amounts of silver to make up for the conductivity. The optimization of pates composition, improving the metallization layout and screens are expected to drive the down the paste laydown in future. ITRPV for example expect that silver consumption for PERC cells from 12 mg/W will be reduced to 7.5 mg/W in next years. This is especially important as Topcon and HJT cell architectures are estimated to consume upto 140% of the silver consumed by PERC architectures. Considering the expectations of these two technologies to overtake PERC in coming years, the reduction of silver usage for cells will help ensure cost reductions can continue. Copper has been considered as an alternative material for metallization, but silver is expected to dominate the market in the coming years.

The HJT further employs indium targets for TCO deposition, yet another expensive materiel that drives the costs higher. However, stacking with other layers of TCO is under evaluation. Equipment CapEx is also a major cost contributor for these new technologies. In case of HJT, production equipment are about 3 times expensive than that tools used for PERC and for TOPCon it is about 1.3 times. PERC remains the dominant technology but is being challenged by new technologies such as TOPCon, HJT, and IBC. However, these technologies require further R&D to obtain full efficiency gains and also to bring down manufacturing costs.

Key Messages

- Cell manufacturing stages vary significantly based on the specific cell architecture
- Minimization of metallization pastes containing silver and aluminum will be key in keeping cell costs low in the near future.
- Cell manufacturing is primarily located in China, and a steady increase in plant sizes have been observed as manufacturers seek to meet growing demand and take advantage of economies of scale.

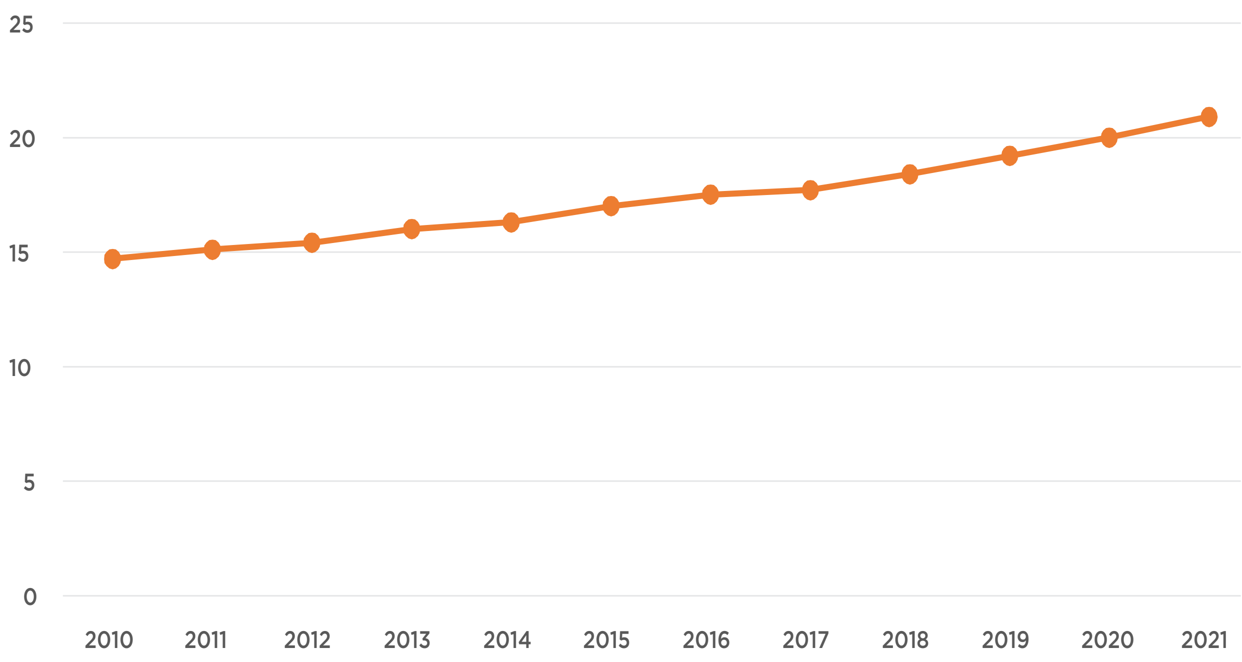
3.1.5 Modules

Module assembly is the final stage of the solar PV manufacturing process. Unlike other parts of the c-Si value chain, this step is more assembly 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.

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.

The average efficiency of a solar panel has been ever increasing with many advancements taking place at both the cell and module levels. According to ITRPV, the average module efficiency in 2020 was 20%, a leap of 0.8% absolute over 2019's level of 19.2 — same as the level of improvement observed between 2018 and 2019.

Module average efficiency progress (%)



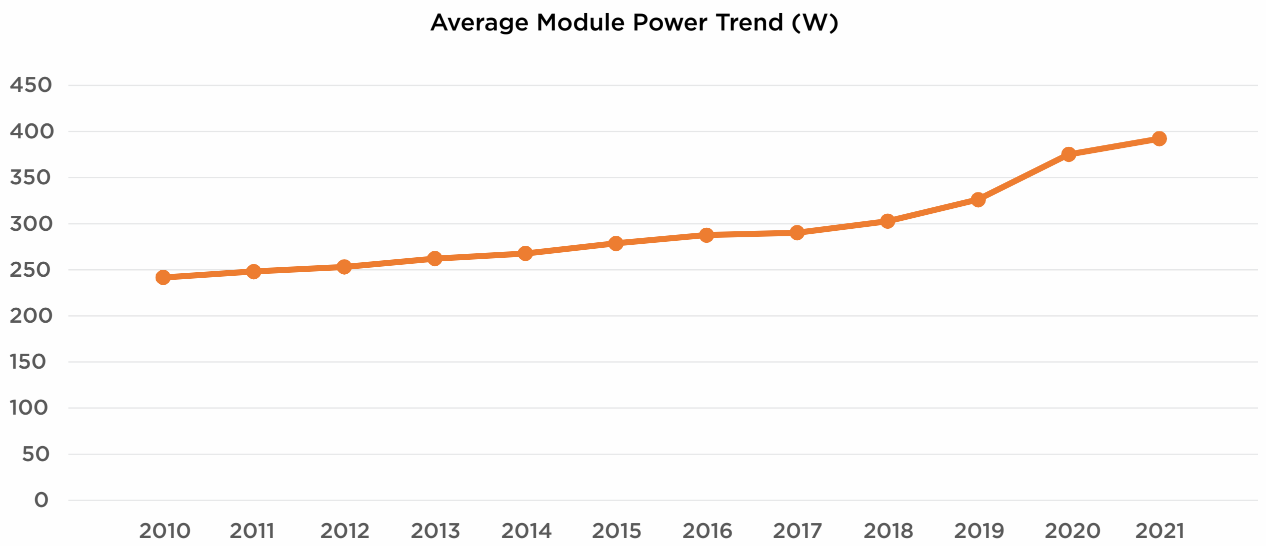
Source: ITRPV 2022

The above chart provides average efficiency progress for set module parameters (60 Cell modules with average area of 1.64 m2 (1.7 m2 for 2019). Average efficiency ranged around 9% in 1980. In the past decade, average efficiencies have crossed 20% for the first time. The current increase in module efficiency can be attributed to improvements in PERC/PERT/PERL type cells and the emergence of newer technologies such as TOPCon and Heterojunction Cells. ITRPV expects this increase in module efficiency to continue for the coming decade with improvements in the efficiencies of existing cells and emergence of technologies such as Si based Tandem Cells, that may achieve ~28% efficiency by 2032.

Increase in PV module power ratings

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. Average module power has increased from 250 W in 2011 to 400 W in 2021.

This trend in power increase has accelerated rapidly in recent years. 2011-2018 saw an increase of ~50 W while 2018-2021 has seen an increase of ~100 W. This increase in average module power can be attributed to increase in wafer and module size.

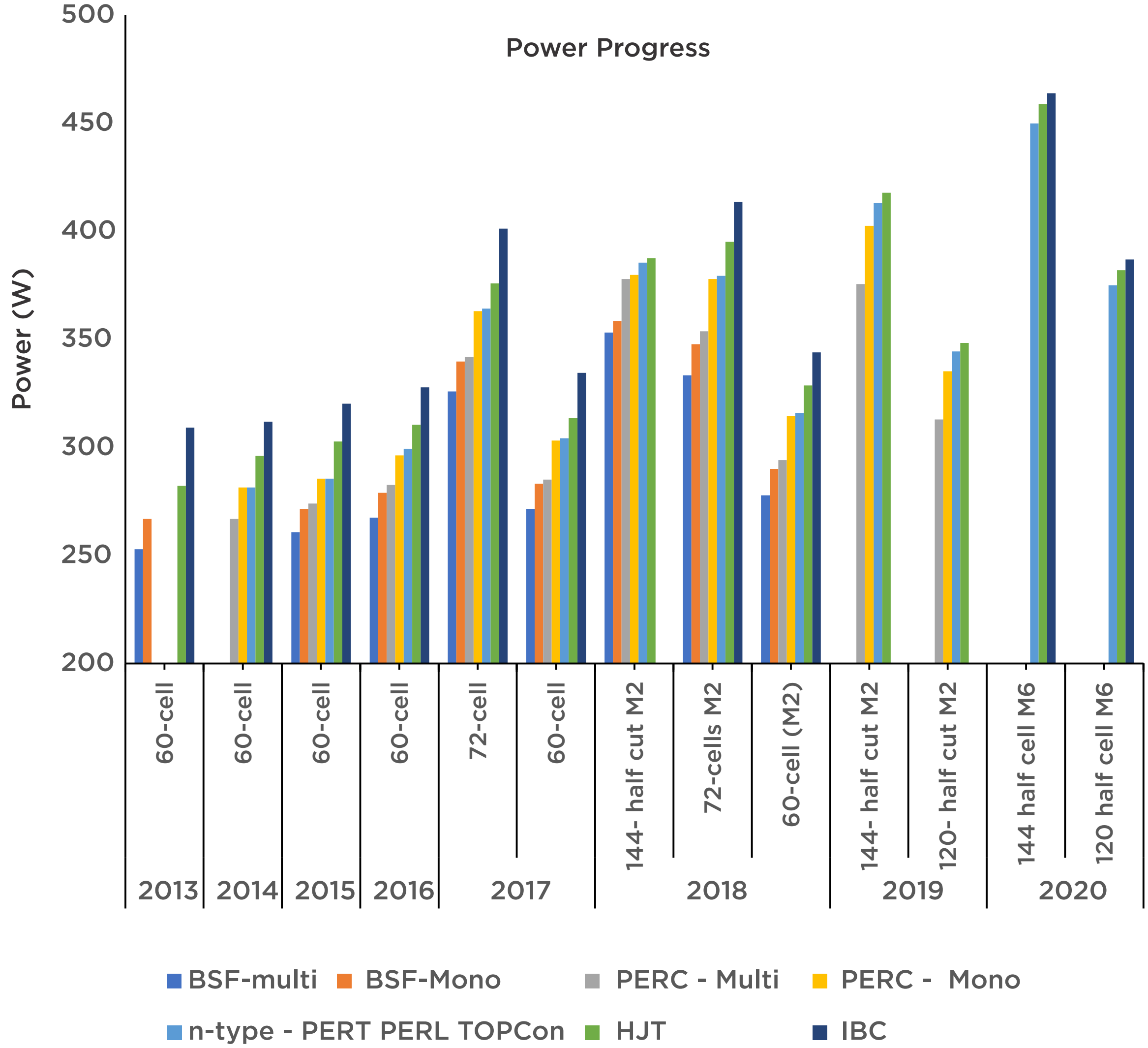


Source: ITRPV 2022

Increasing Wafer Size driving higher power output

Solar modules made of larger wafers are becoming the new mainstream product, driving increase in power output per module by about 100 watts, with approximately the same or a smaller number of cells assembled. Large manufacturers have accelerated the transition in the past two years. The newer, larger wafers have a side length of 210mm or 182mm compared to previous wafers of 166mm. By 4Q 2021, more than half of established cell and module production capability was able to process wafers sized 182mm and above.

Vertically integrated module manufacturers, especially large Chinese manufacturers, have led the transition towards 182 mm wafer size products. Capacity for 210mm products has also been rising, primarily due to support from vertically integrated manufacturers as well as cell manufacturers. The two sizes are likely to co-exist in near term, although solar makers will likely stay flexible to upgrade production to process larger sizes as the market evolves.



Source: SolarPower Europe Analysis

It is also evident from the above graph the that increasing number of cells and moving to larger wafer formats has mainly boosted the power of the solar modules. Today there are modules with power rating of 700 W using advanced cell architectures and larger G12 wafer formats. The key driver for higher increasing module power is to reduce the BOS costs, there by LCOE of the PV power. On other hand, there are also a few developments at modules level that have enabled to improve the module power independent to cell level.

Rise in Cell to Module (CTM) 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 each of the cells embedded in the module, is a good metric to assess developments and the stability of the entire module production process.

Several module processing steps, such as interconnection, stringing and lamination, lead to optical gains. 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. In parallel, advanced interconnection helps in reducing the resistance losses, pushing CTM power ratios further up. The half-cell approach is one good example here.

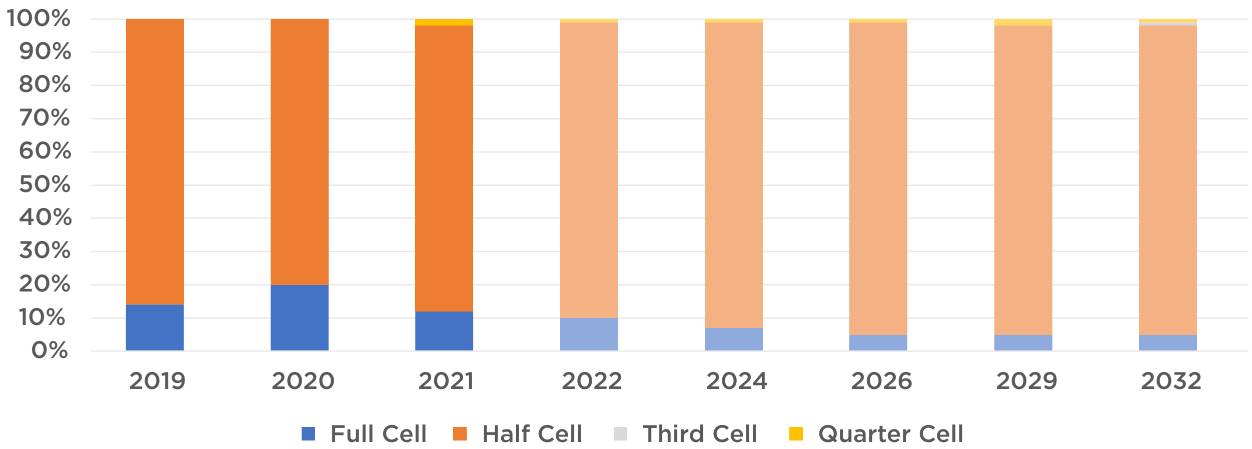
Improving light management primarily involves changing the BOM. Antireflection coated glass is already a standard. The increasing interest in white EVA is a clear sign of efforts in this direction. White EVA is used as the bottom encapsulation layer, which in a finished module increases the light reflection 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.

The effort to reduce resistance losses requires considerable optimization/change in module making, and these approaches have evolved as advanced module technologies half-cell, MBB and shingled. Interconnection technologies supporting reduced may not directly contribute to the CTM increase, but improves module efficiency due to better surface area utilization. Bifacial is altogether a next level technology; while there is no performance gain at module, the technology improves the energy yield at system level. Below is a brief summary of these advanced module technology.

Multi Busbar (MBB): Reducing electrical losses 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 HJT makers have already commercialized products with 15-busbars and are evaluating the options to increase further up to 24.

Slicing cell: While it sounds counterintuitive, carefully slicing processed cells 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 1/3 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 also needs a laser tool to slice the cell. With increasing wafer sizes, which correspondingly increases cell currents, the half-cell is more or less becoming inevitable. There is an industry-wide belief that the full-cell configuration does not make much sense starting from the M6 wafer format. On the flip side, the half-cell configuration causes edge losses, which are more evident with high efficiency cell architectures such as HJT. However, the industry along with larger wafers has been predominantly adopting non-destructive laser cutting. Some companies are also making half wafers, meaning the slicing of silicon substrate is done in wafer fabs, especially with G12 formats used for HJT.

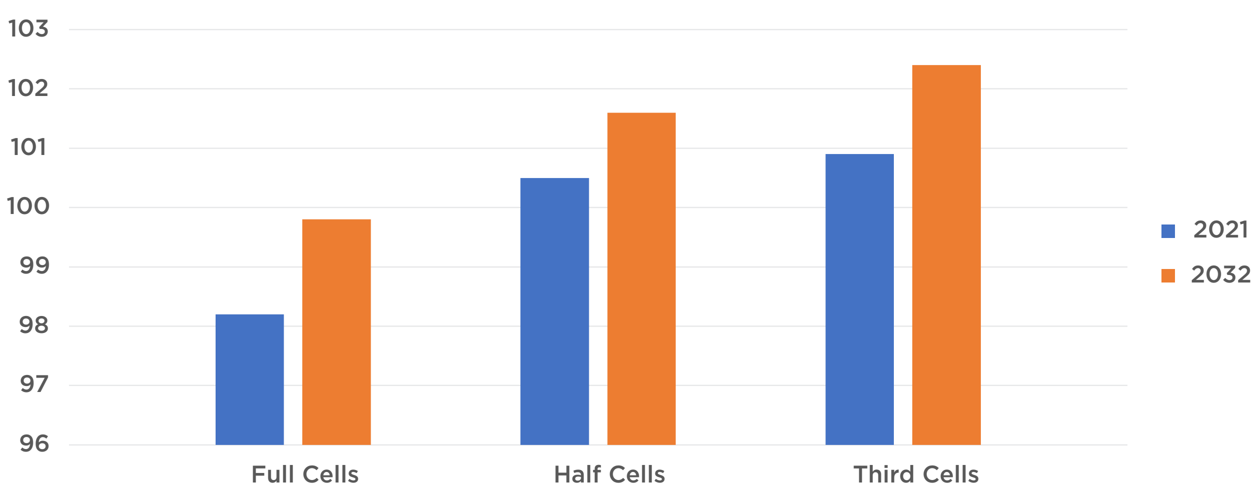
World market share of different cell aspect ratios (%)



Source: ITRPV 2022, ITRPV 2021, ITRPV 2020

The below projection of CTM for full cell, half cell and third cell is just an indicative as full cells are not used for cell sizes above M6, while third cells do have a presence, but are very niche as of now. Half cell being the mainstream has already enabled to improve the CTM to beyond the 100% bench mark. But slicing cell into two pieces alone will not enable reaching high CTM.

CTM Power Ratio: Current and Projected (%)



Source: ITRPV 2022

CTM ratio has been positively affected by the introduction of half cut cells. Third and quarter cut cells are also available but are still niche. Full cells are no longer used for large wafers. The CTM ratio increases as the solar cell is cut into smaller sizes. 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: Ideally, the solar cells in a PV module must be packed as densely as possible to save on the materials. 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. However, the technology is strongly protected with patents with Maxeon and Solaria claiming ownership of the IP.

JinkoSolar 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. In order 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.

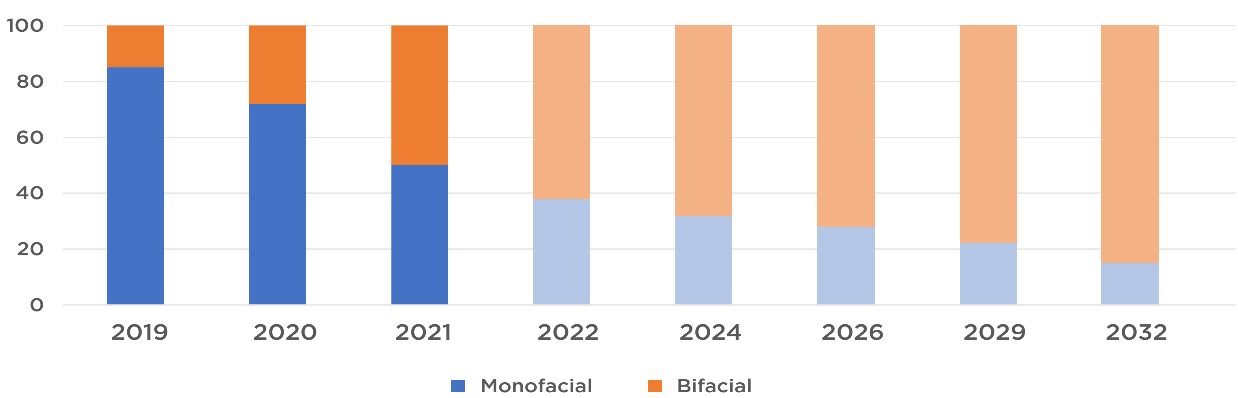
Bifacial Modules: Technically speaking, making a PV device light sensitive on both sides is more of an effort at the cell level than at the module level. However, every advanced cell technology is naturally bifacial, and tweaking PERC into bifacial is easy. It does, however, require a considerable change in BOM. The first one is to make rear cover transparent, and glass has naturally been the choice to replace the opaque backsheet. The glass-glass configuration is the key enabler of bifacial technology. There is an industry-wide belief that double-glass modules can last longer, so much so that module makers are confident enough to extend the power warranty to 30 years from 25 years. While 3.2 mm glass is used for the front cover in monofacial modules, using two sheets of glass with 2 mm thickness is the mainstream practice, 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 POE on the rear to provide extra protection from Potential Induced Degradation (PID).

A transparent backsheet as the rear cover of a bifacial module is an alternative to glass and has its own set of advantages. Modules with transparent polymer rear covers naturally weigh the same as standard modules with opaque backsheet, and do not require any extra care in handling while the manufacturing process remains the same. A few module makers are also offering a 30-year warranty with their bifacial modules with transparent rear cover.

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 backsheet 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 backsheet in a standard module, giving the bifacial solar panel the appearance of a monofacial module from both sides. Bifacial technology is a vast subject on its own with developments across the supply and value chain.

Bifacial PV modules are light sensitive on both sides and are thus able to generate electricity from incident light on both the front and back surface. Thus bifacial modules are able to increase power generation 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%. The successful implementation of bifacial technology can help a PV installation maximize its system performance and minimize LCoE.

Monofacial and Bifacial Cells Market Share



Source: ITRPV 2022, ITRPV 2021, ITRPV 2020

Bifacial cells already accounted for half the market in 2021, and this share is only expected to grow, reaching a market dominant 85% by 2032. This increase in market share is expected due to the benefits to generation achieved through the use of bifacial generation as project developers strive to drive down Solar LCOEs and maximize generation.

Key Messages

- Wafer sizes have been increasing with a focus on 182mm and larger. This in turn has resulted in increasing module power, with average power reaching around 400 W, and certain modules reaching 700 W power
- N type wafers is expected to be the future material for crystalline silicon PV, with the top modules in the market are already utilising n type polysilicon
- TOPCon, HJT, and IBC have overtaken the efficiencies of market dominant PERC and are set to be key future technology types in usage
- Bifacial PV modules are seeing increasing usage with a market share of 50% in 2021 that is projected to reach ~85% by 2032

Time from lab to fab is around 10 years

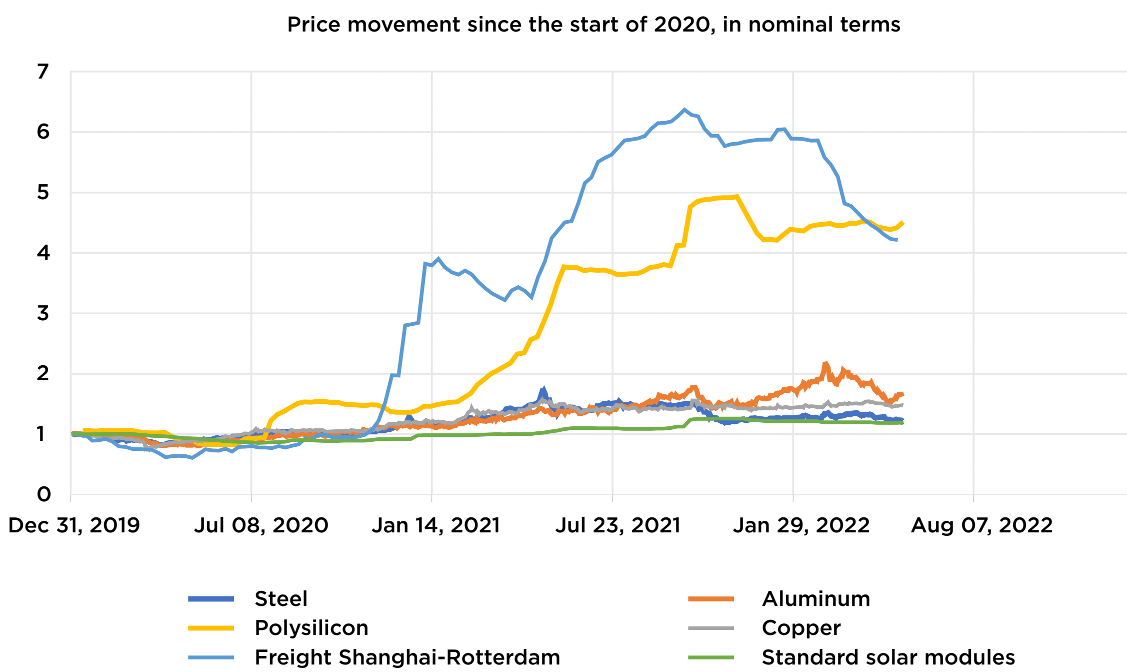
Trends and Progress: Bigger is Better, with increasing efficiency, power, and wafer sizes

The efficiency of global PV technology has benefited from some major shifts in the past decade. Moving from polycrystalline to monocrystalline silicon has improved efficiencies, and so has the shift from BSF to PERC cell technology. A number of key trends are being observed that will drive future progress for PV:

Insights and Trends:

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.

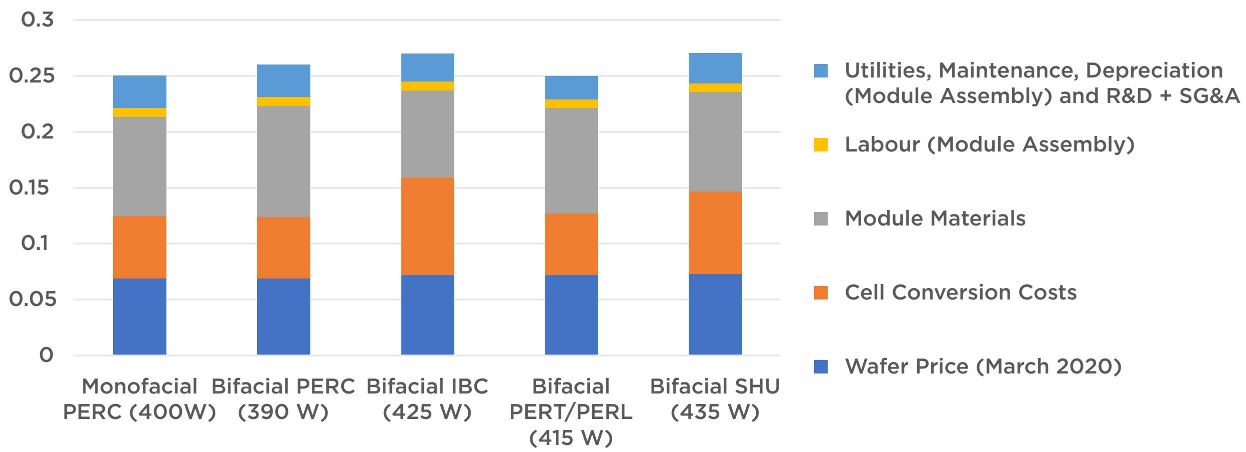


Source: BNEF 2Q 2022 Global PV Market Outlook

When it comes to module level costs, The cost differential between modules of different types do not differ significantly, with only a ~10% differential between the most expensive and least expensive MSP calculated by NREL.

Variations in cell conversion costs (covered in the above subsection) and the module materials utilized were the main drivers for cost differences.

c-Si PV module Minimum Sustainable Price benchmarks by cell technology, 2020



Source: NREL Photovoltaic (PV) Module Technologies: 2020 Benchmark Costs and Technology Evolution Framework Results

Module Bill of Materials:

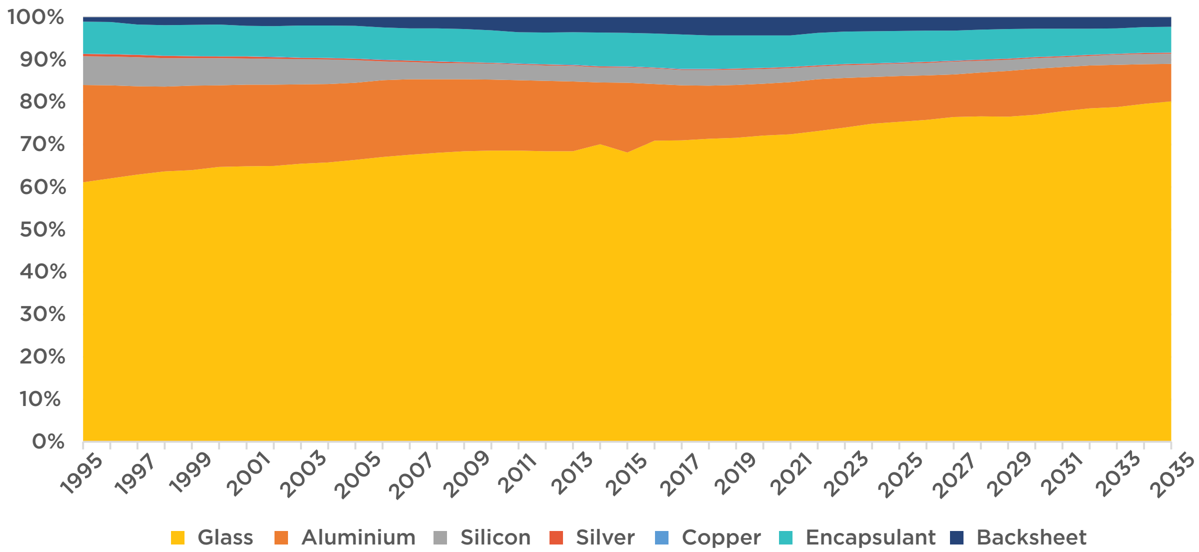
Although the primary function of the solar module has not changed, its Bill of Materials has been altered to generate electricity more efficiently and drive down costs. The share of glass utilized has increased, more so in recent years with the rise of bifacial solar cells. Increased efficiency in material usage has led to the reduction in the share of silver and polysilicon utilized per module.

A solar module comprises of various components such as:

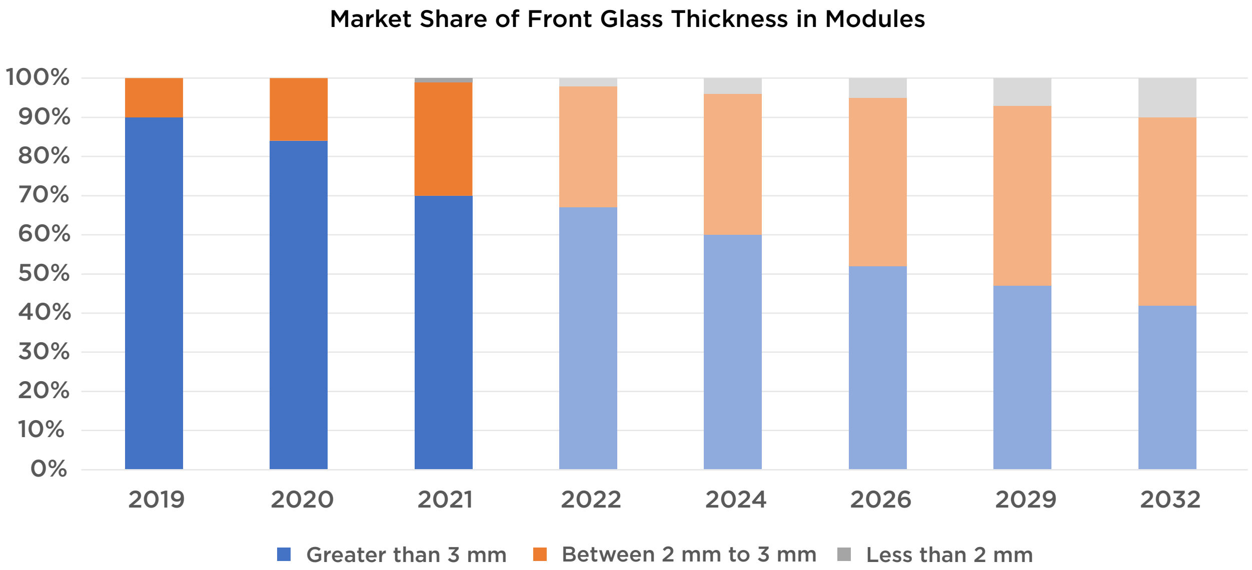
- Solar Cells
- Cell interconnectors
- EVA backsheet
- Front Glass
- Encapsulant

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.

Average Module Composition by Mass over Time (%)



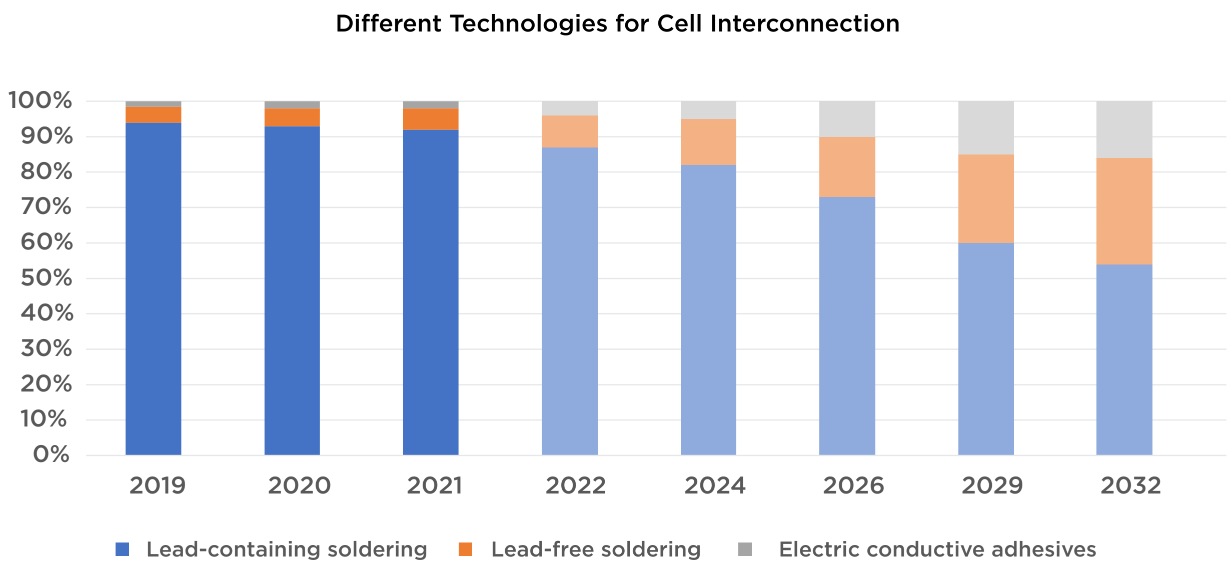
As can be observed in the above figure, there has been a considerable amount of shift in the percentage of each material used to produce a solar module. Glass, which used to be around 63% of the composition of a solar module in 1995 has risen to about 75% of the average module composition by 2021, and is expected to compose 80% of a solar module by the year 2031. 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. Constant research and development have resulted in various technologies emerging and competing in the market. Each offers its own set of benefits such as lower cost, ease of production, longer lifespan, increased efficiency and so on.



Source: ITRPV 2022, ITRPV 2021, ITRPV 2020

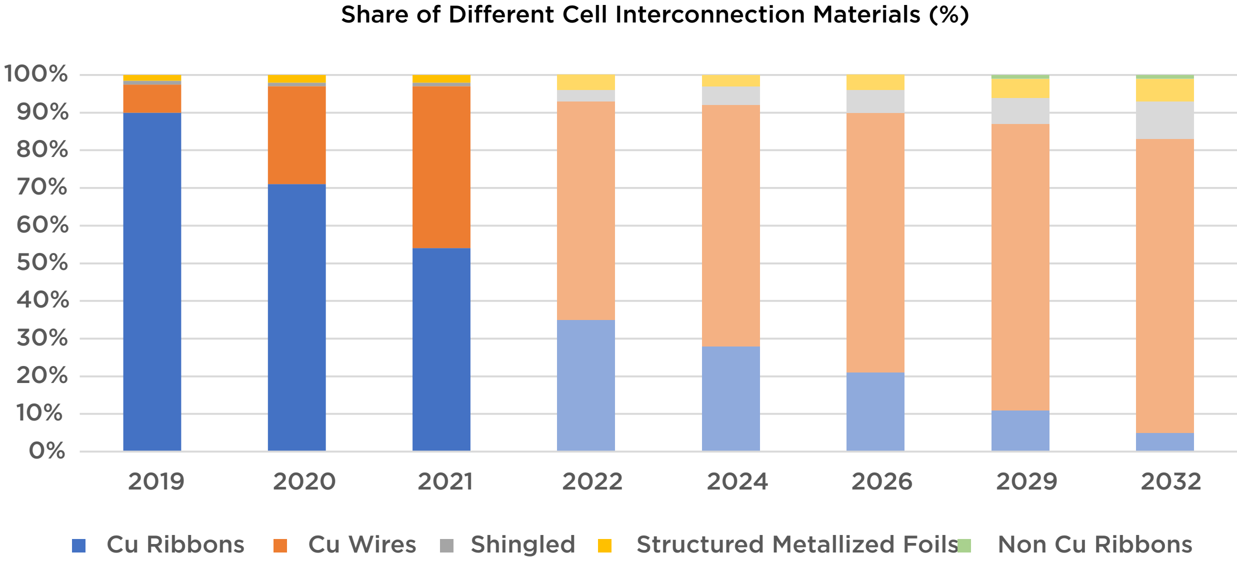
Glass thickness is relevant as it is the most significant material by weight in a PV module. Glass thickness is also relevant for the mechanical stability of the overall module.

Thickness above 3 mm is mainstream, and the industry is now tending towards thinner glass between 2 and 3 mm.



Source: ITRPV 2022, ITRPV 2021, ITRPV 2020

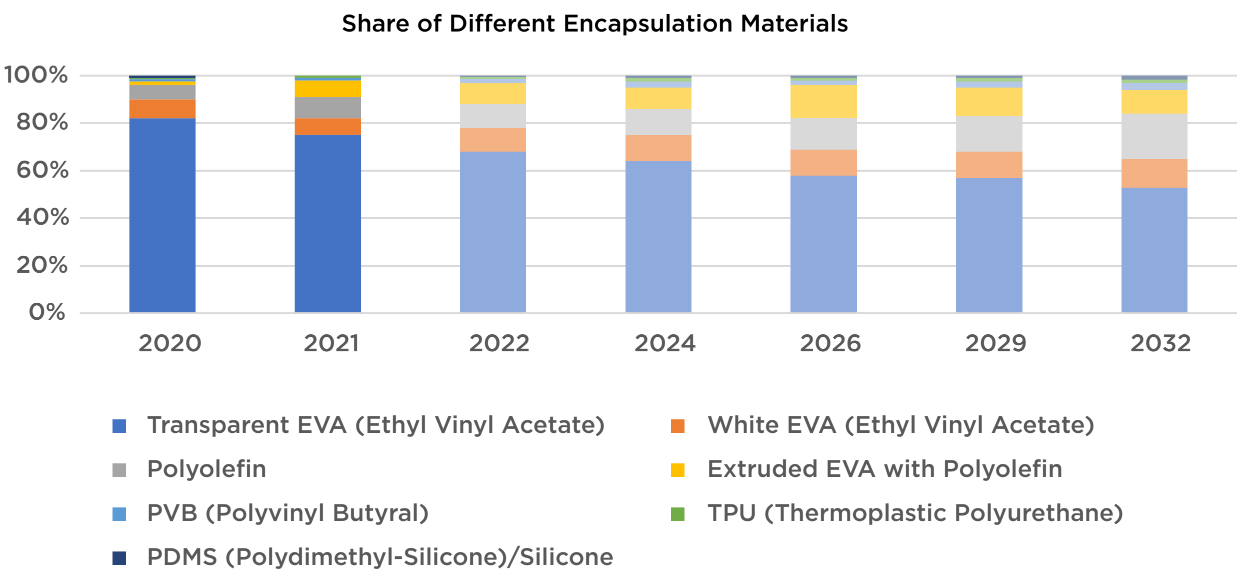
Lead soldering for cell interconnections is the industry standard but lead free alternatives and electric conductive adhesives are also entering the market as alternatives for SHJ and IBC cells. However, it is lead soldering will remain the market dominant option in the coming years.



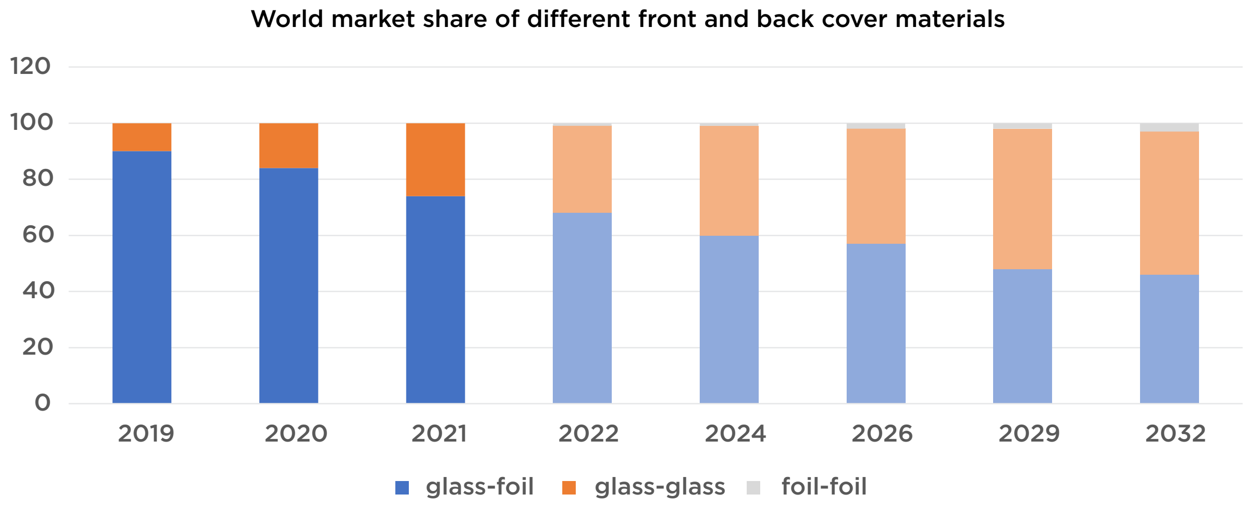
Source: ITRPV 2022, ITRPV 2021, ITRPV 2020

Copper ribbons have lost their dominant position as the primary method used for cell interconnection. In its place, copper wires have been gaining in market share and are expected to become the dominant technology over the next ten years, driven by the increasing usage of half cells in modules. Overlapping interconnection technologies such as shingles and other methods such as structured foils are also expected to see increasing usage in coming years.

Encapsulation materials and back sheet/back cover materials are key module components that contribute to module stability. They are also major cost contributors in manufacturing. Thus, performance and cost improvements in this area will help ensure module service lifetime expectations are met. A wide variety of material options exist, including opaque or transparent encapsulants. Encapsulants may also vary based on whether they use certain materials such as fluorine or antimony, which may impact end of life procedures. EVA is expected to stay as the dominant encapsulant material in coming years.

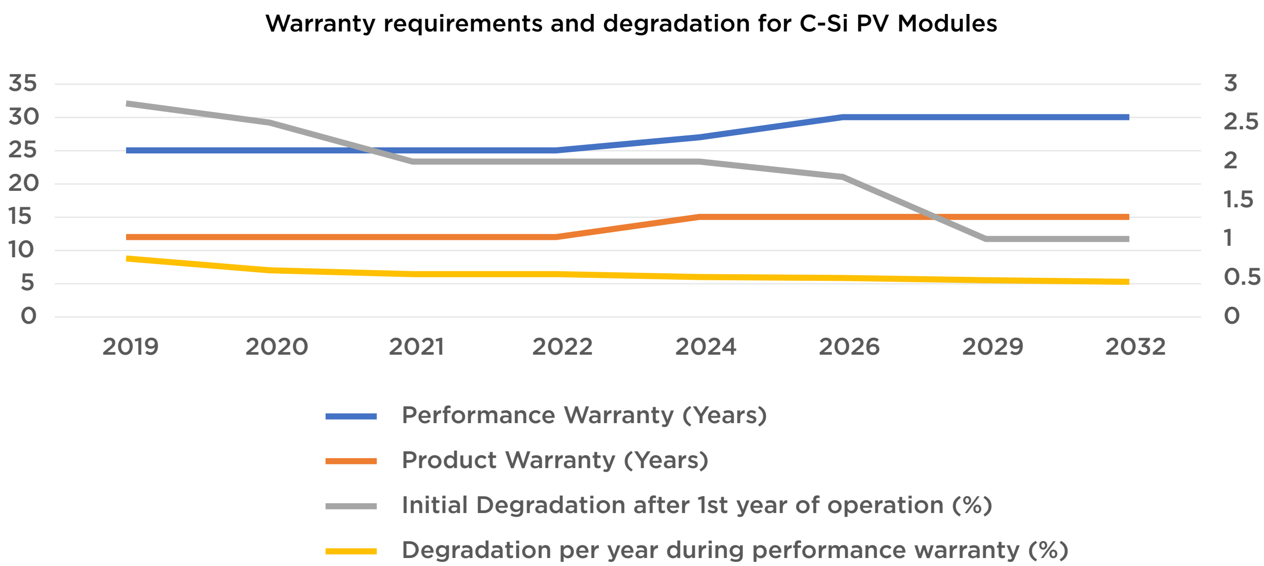


Source: ITRPV 2022, ITRPV 2021



Source: ITRPV 2022, ITRPV 2021, ITRPV 2020

Glass thickness is relevant as it is the most significant material by weight inaThe rise of Bifacial modules has brought a change in the traditional backsheets materials used in modules. The traditional glass-foil combination is expected to stay mainstream in the coming years but will see its market share reduced due to the increasing share of bifacial modules driving a shift towards glass-glass modules. a PV module. Glass thickness is also relevant for the mechanical stability of the overall module. Thickness above 3 mm is mainstream, and the industry is now tending towards thinner glass between 2 and 3 mm.



Source: ITRPV 2022

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 in the near future. This performance warranty is accompanied with the expected reduction of initial module degradation as manufacturing processes.

Key Messages

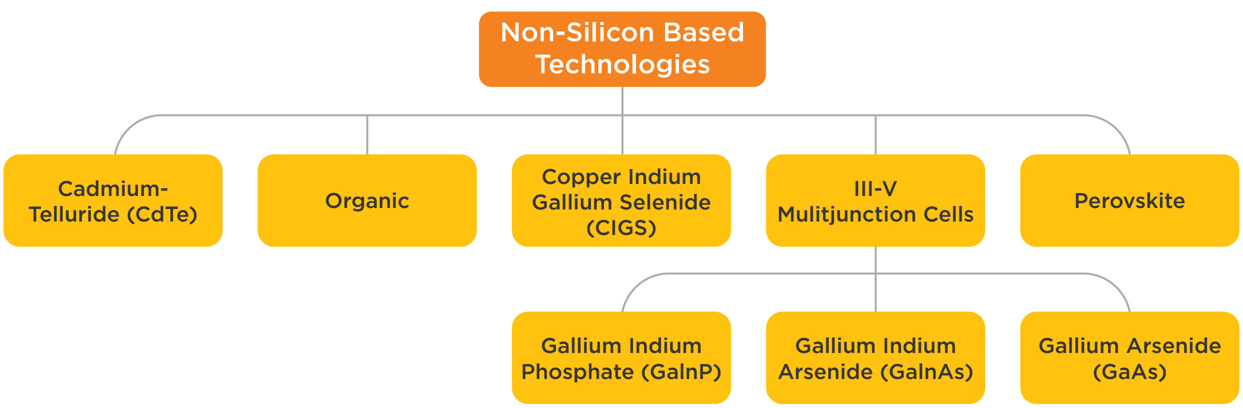
- Module manufacturing is the least concentrated stage of solar manufacturing, with a large number of active manufacturers and locations. However, Chinese manufacturers and installations still dominate the market
- Several improvements in module manufacturing have been observed in recent years, including the usage of half cut cells, multi busbars, bifacial module development, and more. A wide variety of module options exist for the end consumer.
- Module prices do not differ significantly across technologies, and the final module price has remained relatively stable despite sharp increases in input material and shipping costs over the last two years

3.1.6 Non-Silicon Based Technologies: Niche technologies that warrant further development

Although crystalline silicon based PV has become the dominant technology worldwide, PV cells based on non-silicon materials are also available. Thin film solar cells consist of micron-thick photon-absorbing material layers deposited over a flexible substrate. As a result, thin film PV cells are significantly thinner, lighter, and more flexible than the rigid 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 up avenues for its deployment in other applications such as Building Integrated Photovoltaics (BIPV) as they can be installed on curved surfaces.

Technology overview



CdTe is the dominant thin film technology, accounting for most of non-Si production globally. Other non-Si technologies include CIGS, GaAs. However, these do not account for a significant or growing share of the market and are often relevant only for niche applications such as use in triple junction cells, or for power applications in space.

Cadmium-Telluride (CdTe): CdTe solar cells are the second most common photovoltaic (PV) technology in the world marketplace after crystalline silicon. CdTe thin film technology is more efficient than its thin film technological predecessor, amorphous silicon, as its band gap (the energy needed to excite an electron from its atom into a state where the electron can move freely) matches the solar spectrum very well. CdTe also takes advantage of high throughput manufacturing methods to produce modules from input materials rapidly, allowing for quick and relatively inexpensive manufacturing. The most common CdTe solar cells consist of a p-n heterojunction structure and are completed using a back electrical contact. The highest efficiency recorded for CdTe was from First Solar's technology, providing a cell efficiency of 22.1%.[4]

Copper Indium Gallium Selenide (CIGS): CIGS solar cells feature a thin film of copper indium selenide and copper gallium selenide and a trace amount of sodium, which is then deposited onto a substrate. CIGS cells originate from the exploration of Copper Indium Diselenide as a solar PV technology. This initial technology was improved upon through the partial subsitution of Gallium for Indium, resulting in an improvement in overall efficiency. Due to the difference in materials utilised, CIGS solar cells benefit from fewer environmental and health concerns that CdTe cells. However. CIGS solar cells are considered to be in the early stages of large-scale commercialization, and more effort is required improve the performance and reliability of the technology, and to bridge the gap between obeserved lab efficiencies and commercially available modules.

III-V Multijunction Cells: III-V Multijunction solar cells are a class of cells that encompass a number of cell technologies utilising non silicon materials. As the name implies, multijunction solar cells use multiple p-n junctions that are tuned to absorb a wider range of solar spectrums in order to create cells with record efficiencies. The theoretical efficiency of a cell with a single junction is around 33.5%, whereas multijunction devices have been able to achieve efficiencies of over 45%, especially when using concentrators to intensify sunlight to the cell.

Early research into multijunction devices utilised the semiconductor properties from elements in the III and V columns of the Periodic table, such as gallium indium phosphate (GaInP), gallium indium arsenide (GaInAs), and gallium arsenide (GaAs). This architecture also has the potential to be utilised with other existing solar technologies.

Multijunction cells have typically been utilised in space applications due to their high efficiencies. However, multijunction cells are more expensive than other solar technologies, and have thus seen limited utilisation in more generic applications. This high cost has the potential to be offset through concentrating devices such as fresnel lenses, although adding such elements also contributes to the overall cost of the system.

[4] https://www.energy.gov/eere/solar/cadmium-telluride

Perovskite: Perovskite solar cells are an emerging area of research for non silicon based technologies. The technology gets its name as the materials utilised to manufacture them have the same crystal structure as the first mineral having a perovskite structure, calcium titanium oxide. Perovskite materials can be designed in order to have a wide variety of optical, physical, and electrical properties, including those relevant to solar PV. Perovskite solar cells can be manufactured using additive deposition techniques like printing in order to produce cost and energy effective solar PV cells. The compositional flexibility of perovskites also allows them to be modified to ideally match the sun's spectrum.

Perovskite cells have been able to achieve significant laboratory efficiencies of around 25%. However, significant further research is required in order to improve the stability of perovskite PV cells in order to achieve commercial deployment as they currently have limited operational lifespans. Additionally, modern perovskites contain a small amount of lead, which has led to concerns regarding potential toxicity that need to be addressed prior to widespread deployment.

Organic: Organic solar cells utilise molecular or polymeric materials as the light absorbing layer for the solar cell. This allows for the replacement of the relatively expensive polysilicon utilised in crystalline silicon PV cells with organic dyes, and allow for the usage of simpler manufacturing techniques. Since there is flexibility with regards to which absorber is utilised for the cell, coloured or transparent organic PV cells can be fabricated. This allows for potential usage in certain markets where PV cell aesthetics are a key factor, such as BIPV.

Material property constraints force Organic PV cells to use thin active layers, which affect cell performance. Thus, at present, organic PV is significantly less efficient than inorganic solar PV cells. Additionally, organic PV cells have significantly shorter operational lifetimes than inorganic PV cells. Thus, Current research focuses on increasing device efficiency and lifetime.

Thin film remains confined to a niche in the face of Silicon based dominance

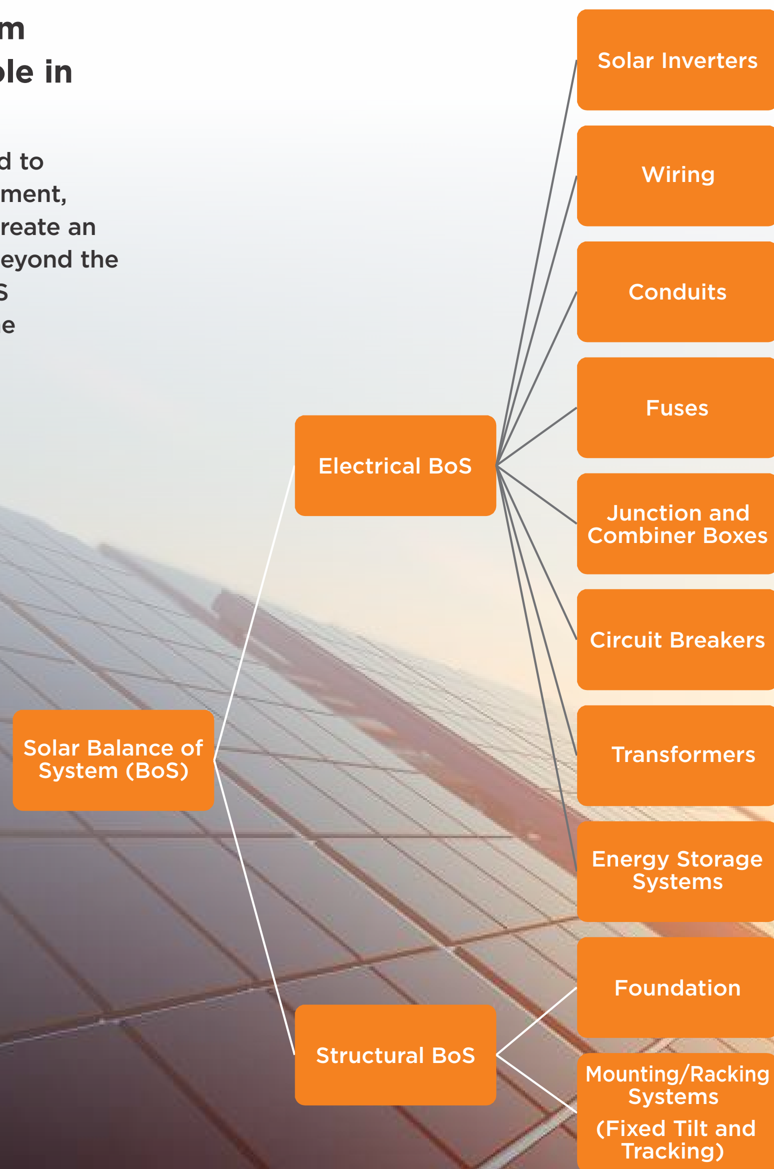
Certain thin film solar cell technologies have achieved significant efficiencies in laboratory settings, exceeding even crystalline silicon cells. CdTe and CIGS cells have showcased lab efficiencies exceeding 21%, while three-junction devices using III-V semiconductors have reached efficiencies of greater than 45% using concentrated sunlight. There have been innovative applications of thin film solar cells, such as solar cloth, an ultra-lightweighted solar polymer textile based on transparent electronic fabrics which can be stitched together to clothes, car covers, armors etc. However, thin film technologies have failed to capture any significant market share in the PV sector due to the difficulty of achieving economically viability in comparision to silicon PV technology. Few companies have achieved cost effective commercial operations at a time when the cost of polysilicon for crystalline silicon solar has come down significantly. Additionally, thin film solar technologies have also struggled to achieve module efficiences of their crystalline counterparts in real life settings, leading to higher LCOEs and thus reduced popularity in the market. Research has also focused on improving cell stability as certain promising technologies, such as Perovskites, are prone to rapid degradation.

Key Messages

- Thin film technologies are promising in terms of their cost effectiveness and cell efficiency, but struggle with module level efficiency, stability, and commercial scale production
- There is keen interest around the development of high efficiency potential materials such as Perovskite, Organic PV and III-V junction cells, but significant research barriers need to be overcome for widespread usage.
- Thin film technology also has some innovative applications such as solar fabric etc.
- Thin film is unlikely to replace crystalline silicon technologies and will likely remain more relevant for niche applications such as space based deployment and BIPV.

3.1.7 Solar Balance of System (BoS): Playing a key role in LCOE optimisation

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:



Insights and Trends

Initial Improvements in Solar PV systems were focused on the solar cell and module technologies. However, BoS components also need to be optimized in order to have a competitive LCOE for a system. Solar PV BoS improvements have typically been focused on the structural BoS, with the development of improved racking systems and mounting systems. The primary improvement for these systems have been the development of trackers, which are covered in greater detail in section 3.1.7.3 of this report. Additionally, the usage of materials such as concrete for project foundations or ballasting has been optimized to ensure a suitable structural weight is achieved within reasonable cost.

Electrical BoS improvements have also been seen. The usage of modules with higher power ratings has led to higher DC voltages in the solar system. This in turn has prompted the use of thicker wires, which can reduce energy losses due to heating and resistance.

3.1.7.1 Solar Inverters: Higher efficiencies leading to lower costs

The energy generated by a solar PV module is in the form of Direct Current (DC), whereas to be supplied to the electricity grid, it needs to be converted into an Alternating Current (AC) signal. This conversion is done by a solar inverter. PV inverters have varying levels of capacity and functions and can be broadly divided into the following categories:

- **Central Inverters:** Typically used in utility scale projects, their size varies from 1 MW_{ac} to 5 MW_{ac}. They are ground/ floor mounted inverters, converting DC energy from multiple PV strings, into AC energy.
- **String Inverters:** String inverters are typically found in homes or small scale solar PV plants such as rooftop solar installations. This class of inverters are connected to a single string of PV arrays only. String inverters are available in three phase and single phase variants
- **Module Level Power Electronics:** includes both microinverters, which convert the energy from a single module and dc-dc optimizers which optimize the power supply for each individual module but work with three-phase or single-phase string inverters.

Key characteristics for the above inverter categories are highlighted below:

Key characteristics for the above inverter categories are highlighted below:

Inverter/ Converter Type	Power	Efficiency	Estimated Market Share	Remarks
String Inverters	up to 150 kWp	up to 98% (DC/AC)	64.4%	• 3 – 17 €-cents /Wp • Easy to replace
Central Inverters	More than 80 kWp	up to 98.5% (DC/AC)	33.7%	• 3 – 5 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-97% (DC/AC)	1.4%	• ~25 €-cents /Wp • Ease-of-replacement concerns
Power Optimizer	Module Power Range	up to 99.5% (DC/DC)	5.1%	• ~8 €-cents /Wp • Ease-of-replacement concerns • Output is DC with optimized current • A DC/AC inverter is still needed

Note: Total Market Share related to shipment in Mwac is greater than 100% because DC/DC converters are required to be paired with string
Source: Fraunhofer Photovoltaics Report February 2022

Component Breakdown

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 block (or power module) and passive components such as capacitors and inductors. They also consist of various circuit breakers and fuses for equipment protection. A typical breakup of a Silicon Carbide Inverter material costs is given below.

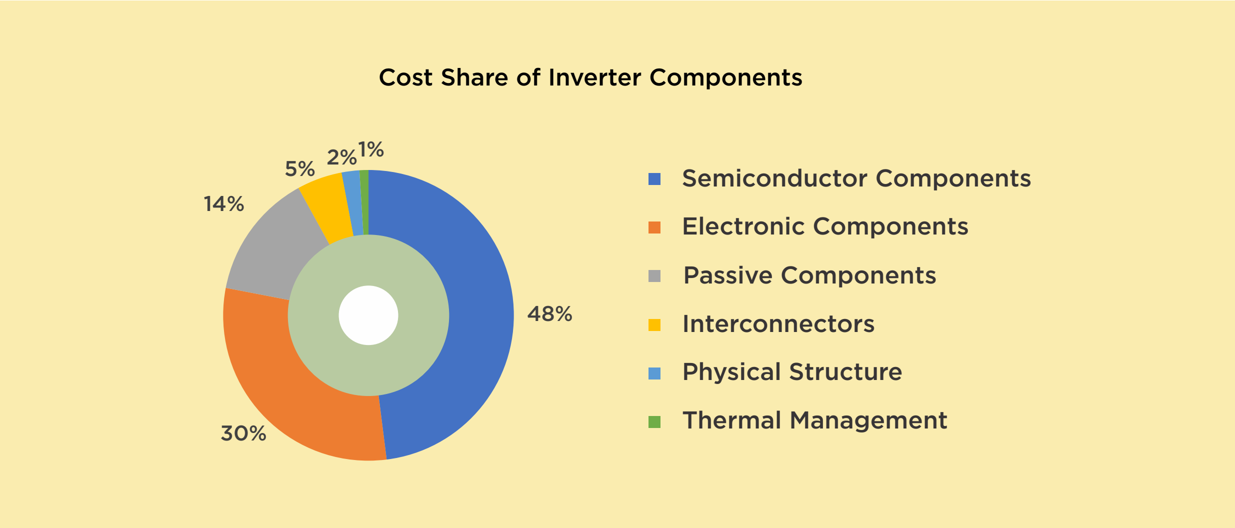


Figure: Breakdown of Silicon Carbide Cost (Source: Solar Photovoltaics: Supply Chain Deep Dive Assessment, NREL)

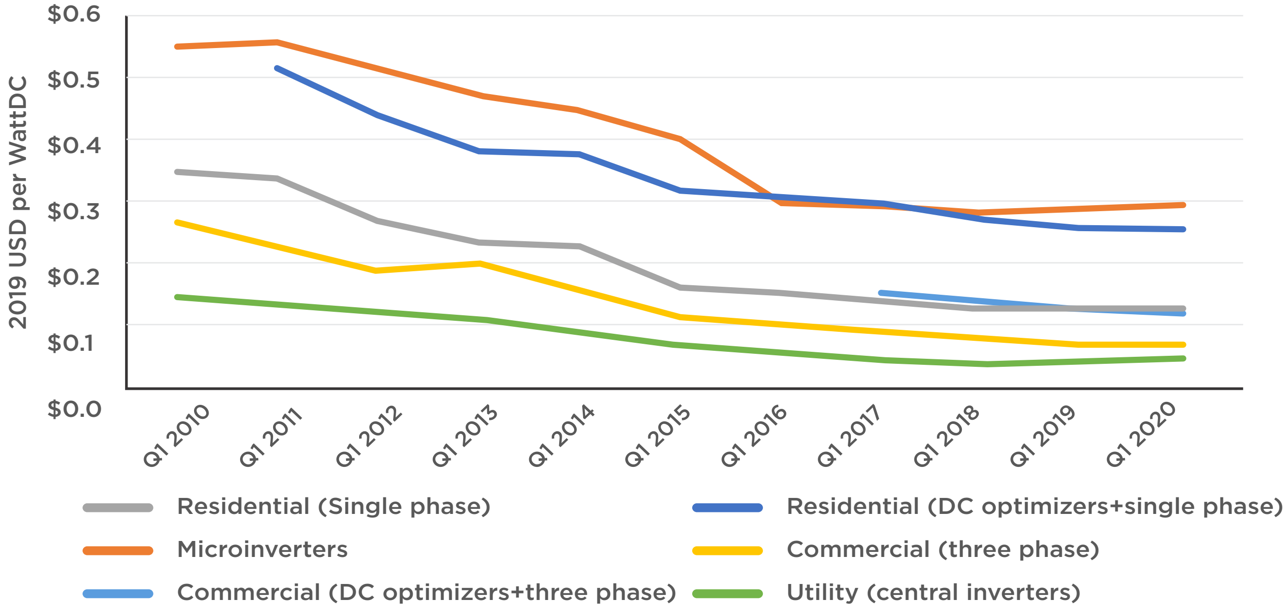
Insights and Trends

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 in order 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 AC 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 upto 1.35- 1.40, 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 (Si), Silicon Carbide(SiC) and Gallium Nitride (GaN) based power devices. GaN has superior electron mobility and bandgap than the SiC and Si, and has other advantages than the 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, 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.



Source: U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020, NREL

As can be seen in the above figure, there has been a steady reduction in inverter costs across all types (Micro, String, 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 a MW scale for solar utility plants have the cheapest per watt production rate, when compared to microinverters.

Key Messages

- String inverters (64.4%) and Central Inverters (33.7%) dominate the market
- Solar inverters have reached significant efficiencies of around 98% from 94%-95% in 2010
- Inverters are increasingly being digitalized and are seeing optimized usage through the adoption of high inverter loading ratios of upto 1.35-1.40
- GaN based Solar Inverters can lead to size and weight improvements, leading to a cheaper product

3.1.7.2 Solar PV Mounting/Racking: Declining costs across all segments

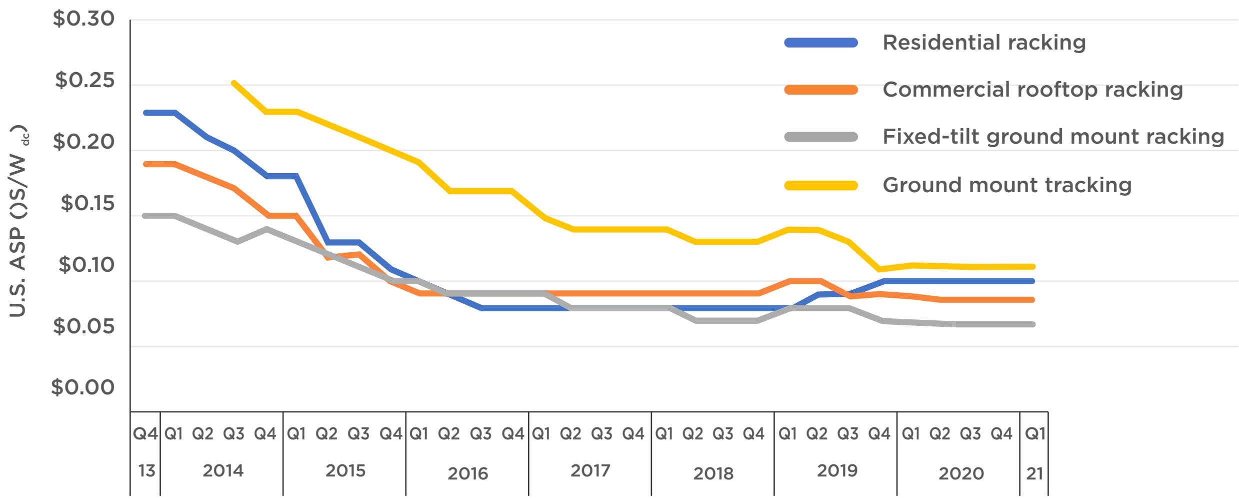
A solar PV mounting or racking system helps safely affix PV panels to the surface on which they are to be installed. Racking systems thus vary based on where the plant has to be deployed (usually on rooftops or on the ground). Racking systems should also ideally provide room for air circulation underneath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

Insights and Trends

Racking systems must take into account 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. The racking system must also be weather resistant, which translates to having sufficient galvanization depth to withstand rain and other elements.

Building Integrated Photovoltaics (BIPV) and vertical solar installations on the sides of buildings are innovative forms of mounting solar PV in urban locations. Suitable mounting structures can also help shade particular areas of a residential space (for e.g. by serving as a patio cover)

Solar Racking costs have reduced significantly since 2013



Source: NREL Solar Photovoltaic Supply Chain Deep Dive Assessment

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, showcasing how BoS improvements can impact project LCOE.

Key Messages

- **Optimisation of BoS components, especially structural BoS, is crucial for LCOE reduction as solar costs fall and technological maturity is achieved**
- **Increasing module power trends have seen the usage of higher DC voltages in solar systems, thus prompting the use of thicker electrical wires that minimize energy losses**
- **Cost reductions of 50-60% have been seen for all racking types, showcasing how BoS improvements can impact project LCOE**

3.1.7.3 Solar Trackers: Increasingly cost effective for a variety of PV installations

Solar PV trackers are used to follow the Sun's path and orient modules towards the sunlight in order to maximize energy production per module. They serve as a tool to enable cost reduction for utility-scale solar power generation in many locations. Such systems can be designed in two different main configurations based on the tracker's degrees of freedom, one-axis and two-axis systems.

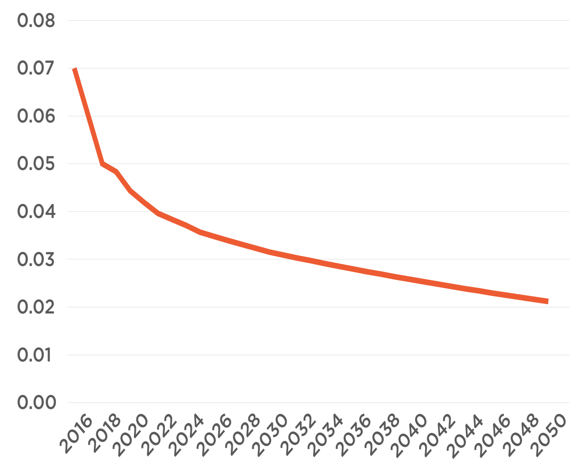
Single-axis trackers have one degree of freedom, while dual-axis trackers (DAT) have two degrees of freedom. Today's utility-scale PV plants almost exclusively use singe-axis devices. Although there are different types of tracking systems, horizontal-single axis-trackers (HSAT) are opted for by most power plants implementing trackers.

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. 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.

Insights and Trends

As solar PV costs continue to get optimized, a number of trends have emerged in the tracker industry to help improve their product offerings. Software components such as tracking algorithms are utilised to help optimize generation. This tracking software are 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 take into account inverter loading ratios and the use of bifacial modules to help maximize generation. As per BloombergNEF, with the improvement in technology, as well as the growing demand, it is important to note that the cost of single axis tracking systems have shown a 42.86% decrease in costs, from 2016 to 2022.

Cost of Single Axis Tracking System per kW



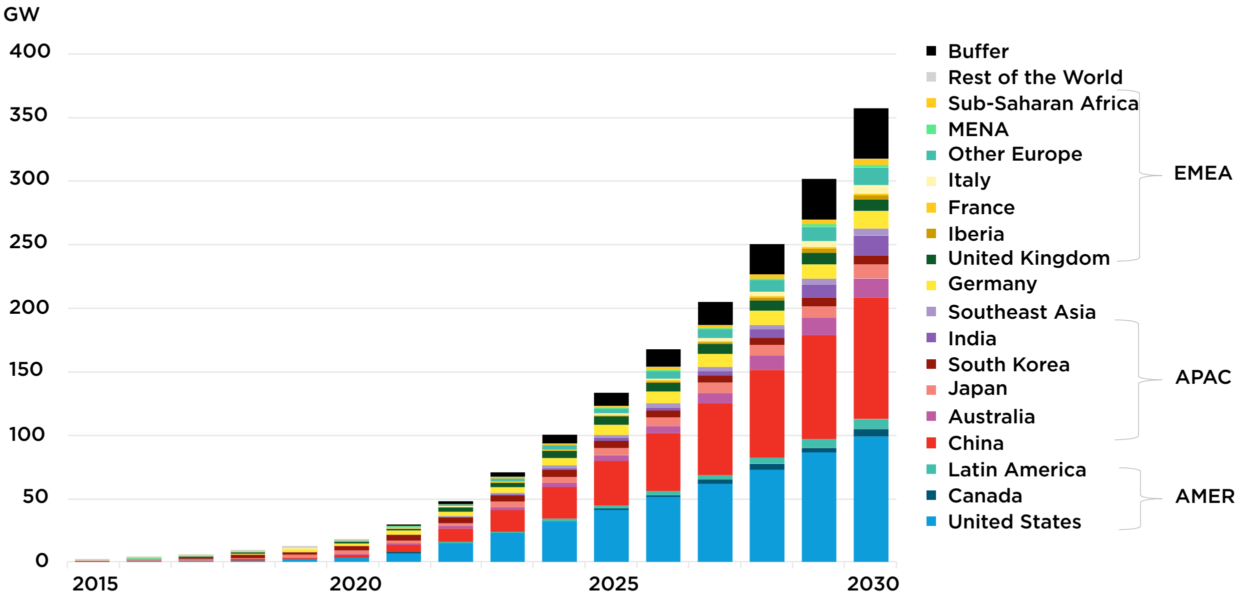
Another key trend for trackers has been the need to ensure tracker endurance and survivability in harsh conditions considering the number of moving elements involved when compared to rigid racking systems. Tracker material is designed to be resistant to harsh weather conditions, including protection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

Key Messages

- **The premium for solar trackers over fixed mounting systems is being increasingly justified through efficiency gains**
- **Trackers are becoming more and testing ensures robust to withstand challenging weather conditions over longer duration**
- **Trackers have begun to utilise smart algorithms and AI optimized tracker control to help maximize generation**

3.1.7.4 Energy Storage

As showcased in the above chapters, renewable energy installations have been growing year on year since 2001, reaching a cumulative installed capacity of 3,068.3 GW in 2021. Solar itself has shown a growth of more than twenty-fold, in the last decade, reaching an installed capacity of 920 GW, in 2021. While renewable energy is taking a shift from secondary source of energy to slowly aiming to become a primary source of energy, the role of energy storage is also taking a centerstage.



Source: BloombergNEF

Energy storage systems provide a wide array of technological approaches to managing our power supply in order to create a more resilient energy infrastructure and bring cost savings to utilities and consumers. ESS is one of the key solutions for issues related to grid integration of Variable Renewable Energy (VRE), as well as promote self-generation and self-consumption of VRE by individuals.[5]

[5] IRENA, 2015; IRENA 2016b, IRENA, 2017a)

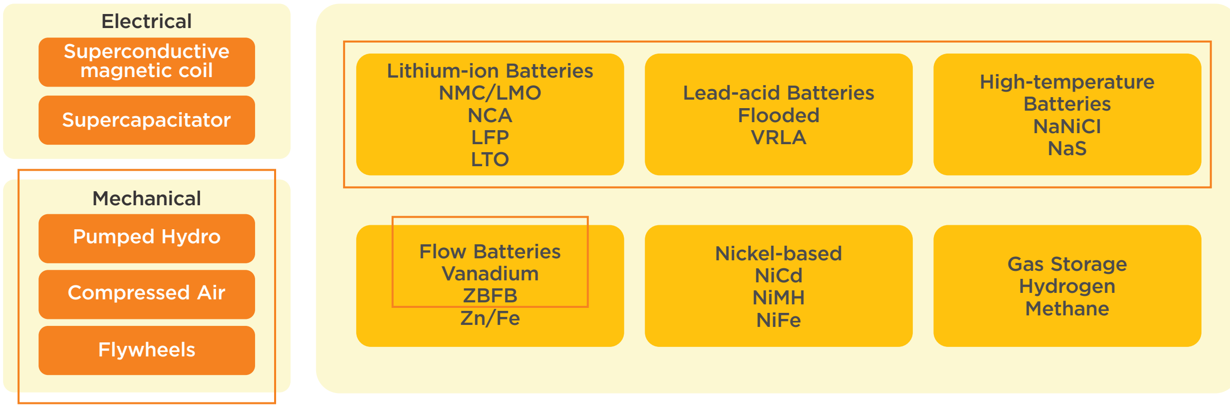
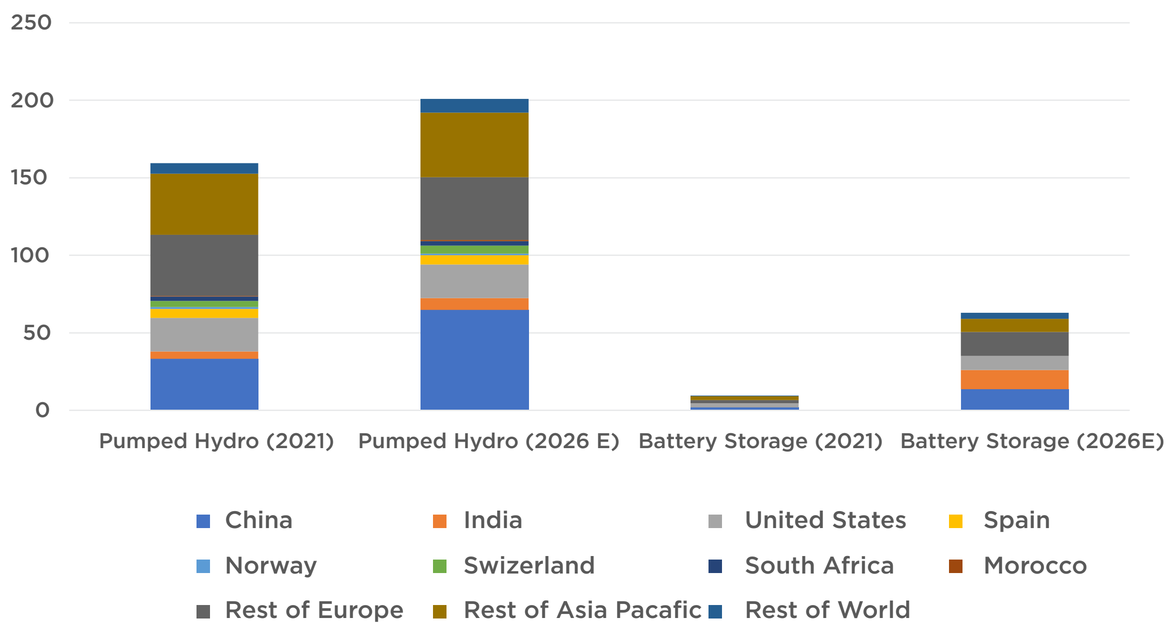


Figure: Electricity Storage Technologies

There are various factors that determine the applicability of an Energy Storage Technology. Intrinsic properties such as discharge times, rated power and system power ratings, energy and power density of the technology, duration ranges of the continuous charging and discharging time period and cost influence the suitability of ESS for different applications.

Technologies such as a mechanical flywheel, supercapacitors and batteries are often used in areas which require faster backups, such as for Uninterrupted Power Supply Units, whereas batteries, compressed air, CAES, pumped hydro, Green Hydrogen etc., may be used for higher capacity energy storage for longer durations. Pumped Hydro systems 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 storage of energy, Pumped Hydro systems 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 into.

Installed Capacities- Energy Storage Systems

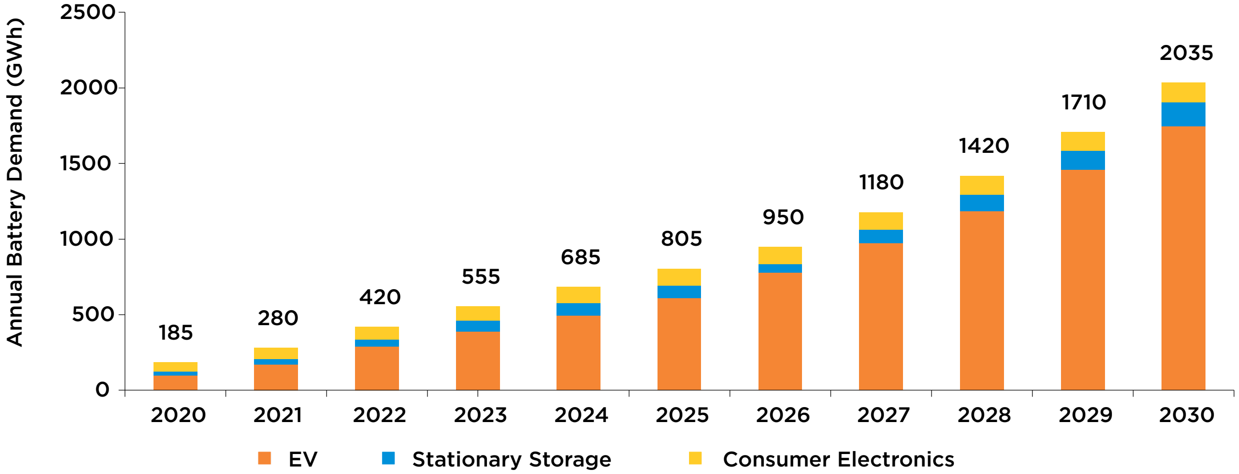


Source: IEA[6]

[6] IEA, Concentrated solar power, pumped hydro and batteries, installed storage capacity in 2020 and 2026, IEA, Paris https://www.iea.org/data-and-statistics/charts/concentrated-solar-power-pumped-hydro-and-batteries-installed-storage-capacity-in-2020 and-2026

With a total installed capacity of 160 GW in 2021, pumped-storage hydropower is still the most widely deployed grid-scale storage technology today. In 2020, pumped hydro storage accounted for over 90% of total global electricity storage, with a total capability of around 8,500 GWh[7] . The majority of these plants are used to provide daily balancing.

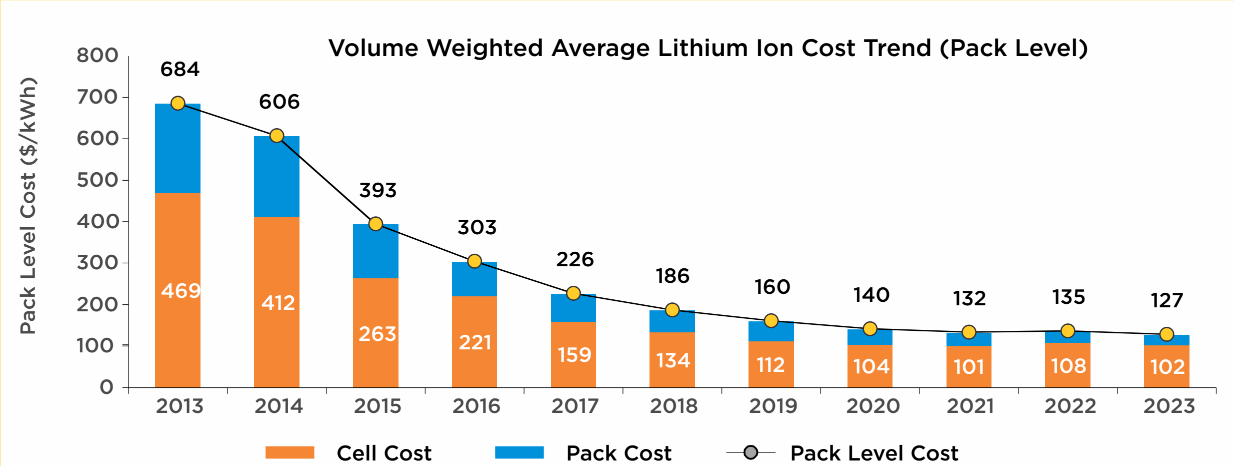
Although the installed capacity of grid-scale battery energy storage systems is far smaller than pumped hydro energy storage, grid batteries are projected to account for the majority of storage growth worldwide. BESS is typically employed for sub-hourly, hourly and daily balancing. Currently, the total BESS installed capacity was close to 16 GW at the end of 2021, rising by 60% when compared with 2020. The United States, China and Europe led the market, each registering gigawatt-scale addition.



Source: Statista, 2021

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 up 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. As can be seen in the above figure, global battery demand is expected to grow 11x by 2030, from 185 GWh in 2020, driven significantly by EV demand. Aiding to this development is the fact that Li_Ion pack level costs have seen a 90% decline in cost over the last decade, as can be seen in the above figure.

[7] IEA (2022), Grid-Scale Storage, IEA, Paris https://www.iea.org/reports/grid-scale-storage



Source: BloombergNEF

Key Messages

- **ESS is one of the key solutions for issues related to grid integration of Variable Renewable Energy (VRE).**
- **At the end of 2021, PHS had an installed capacity of 160 GW, whereas battery energy systems accounted for 16 GW of installed capacity, globally.**
- **Global battery demand is expected to grow 11x by 2030, from 185 GWh in 2020, driven significantly by EV demand.**

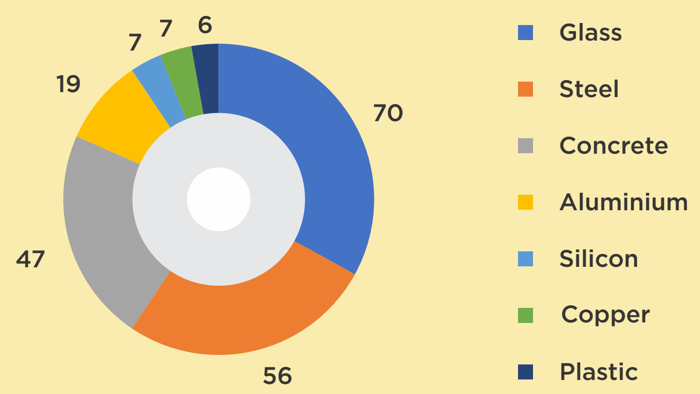
3.2 Solar PV Systems: High efficiency, low emissions

The various solar equipment highlighted in previous sections come together to form a complete solar PV system. Although component level improvements drive increases in generation and efficiency, system level decisions also play a role in optimizing output. System considerations also tend to impact human populations more directly, as solar PV systems are deployed in residential and commercial and industrial (C&I) sites. Additionally, land requirements for large utility scale projects may also raise concerns with other land intensive applications such as agriculture.

System Type	Land Use Categorization	Current applications	New dedicated applications
System Type	Land use	Ground-mounted	Round the Clock (RTC) Power
	No Land use	Floating solar	PV + Hydro
Small-scale solar	No land use	Commercial and Industrial rooftops	PV + Electric Vehicle charging stations
		Floating solar	PV + Behind The Meter Storage
	No land use	Off-grid-solar: lanterns, solar home systems	
	Very marginal land use	Off-grid solar: minigrids, pumping stations	Agri PV Desalination systems

Material Consumption is more efficient as compared to some other renewable energy sources

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 is the primary material by weight used in a solar plant. Glass is closely followed by steel usage for various BoS structures and concrete for foundational structures.



Source: IRENA, Measuring The Socio-Economic Footprint Of The Energy Transition: The Role of Supply Chains

Material consumption for solar installations is expected to decline as solar plant designs and processes continue to improve.

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, taking into account 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 technologies.

For direct-area requirements the generation-weighted average is 1.17 hectares/GWh/yr., with 49% of power plants within 1 and 1.41 hectares/GWh/yr. On a capacity basis, the total-area capacity-weighted average is 3.6 hectares/MWac, with 22% of power plants within 3.2 and 4 hectares/MWac. For direct land-use requirements, the capacity-weighted average is 2.95 acre/MWac, with 40% of power plants within 2.4 and 3.23 hectares/MWac. Other published estimates of solar direct land use generally fall within these ranges[8].

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. In order 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

[8] NREL Land use requirements for solar power plants in the United States

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 actually hold benefits that allow them to coexist with agriculture. Solar can be utilised 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 agrivoltaics as a solar application has further opened the possibilities of integration between solar and agriculture for mutual benefit.

Solar Energy leads other renewable energy sources in lifecycle carbon emissions, and has a low energy payback time

The US Department of Energy estimates Lifecycle greenhouse gas emissions for solar power (gCO2e/kWh) to range between 20 gCO2e/kWh –100 gCO2e/kWh (25th Percentile – 75th Percentile). Their analysis also found the maximum value to be around 250 gCO2e/kWh, although this is a clear outlier figure. The wide range of figures can be attributed to variance due to 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 median lifecycle GHG emissions of under 30 gCO2e/kWh[10].

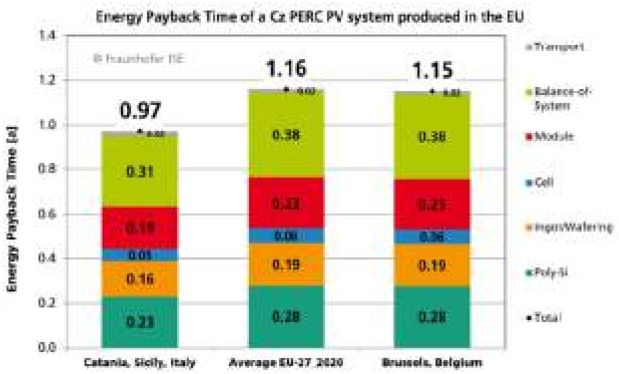
Emissions for 1 KWh electricity from 3 kWp residential system in Europe have been modelled for 4 cell types[11] and found to be clearly under 50 gCO2 eq.

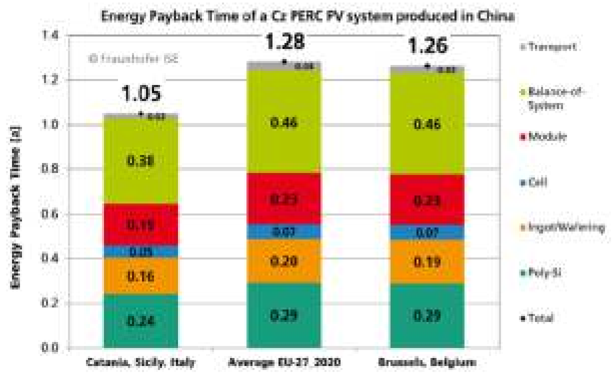
	Unit	Mono-Si (19.5% efficiency)	Multi-Si (18% efficiency)	CIS/CIGS (16% efficiency)	CdTe (18% efficiency)
Greenhouse Gas Emissions	gCO2 eq	42.5	42.3	36.3	26.5

Source: IEA PVPS Environmental life cycle assessment of electricity from PV systems

[9] https://www.energy.gov/eere/wind/articles/how-wind-energy-can-help-us-breathe-easier
[10] https://www.nrel.gov/docs/fy21osti/80580.pdf
[11] https://iea-pvps.org/wp-content/uploads/2021/11/IEA-PVPS-Task12-LCA-PV-electricity-_-Fact-Sheet.pdf

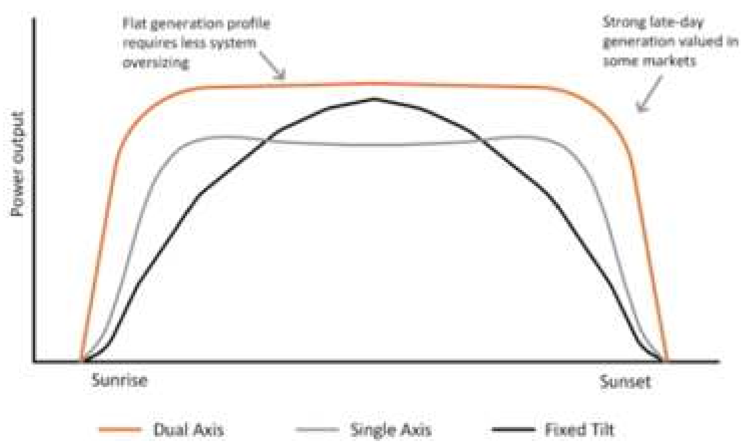
The energy payback time for solar PV systems in Europe range from just under 1 year to ~1.3 years.

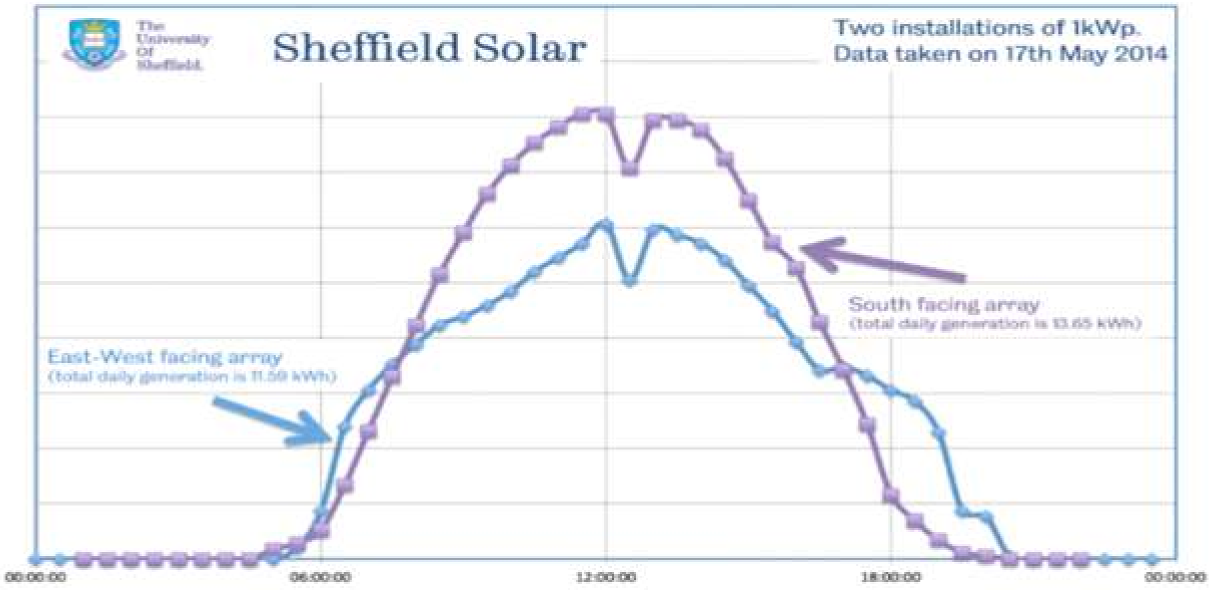




Source: Fraunhofer 2021

Tracker usage and plant design can be optimized to achieve the desired generation curve





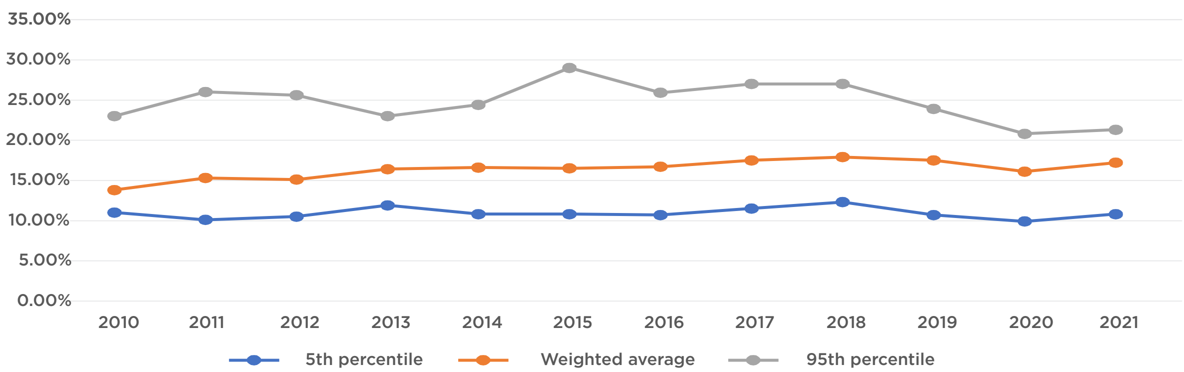
Design	Typical daily profile	Main Features	Cost
Conventional set-up: Fixed tilt, equator-facing	• Low generation in morning and evenings, significant peak at midday	• Standard design for PV plants	• Lowest cost
1-axis tracker	• Smoothed generation peak compared to conventional setup • stronger early and late day generation	• Horizontal and vertical one axis trackers available	• Increased cost over fixed tilt systems due to tracker installation
2-axis tracker	• Similar flatter profile with early and late day generation like the one axis tracker, but with increased overall output	• Offer highest yields due to capability to follow both Sun's elevation and azimuth	• More expensive tracker option than 1 axis trackers
East-West facing	• Slightly reduced overall output compared to conventional setup (~15%) • Flatter generation curve due to greater morning and evening generation	• Increased project generation capacity due to being able to increase number of rows and panels for the plant.	• Increased cost due to greater number of rows
Vertically mounted, for linear applications	• Improved generation when further from the equator due to low angle of Sun	• Potential for vertical panels on sides of buildings to generate electricity and reduce building heat due to direct sunlight	• Increased cost of installation and maintenance

It is important to recognize that the suitability of tracker systems and alternative panel orientations in achieving cost optimisation is dependent on a number of 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 are able to maximize additional PV yield in locations with cheap land and high irradiance. East-West facing systems are land use efficient, and this are 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.

Capacity Utilisation Factor (CUF)

Capacity Utilisation Factor is a parameter to judge the performance of a solar PV plant. It is the ratio of actual energy generated by the project over the year to the equivalent energy output at its rated capacity over the yearly period. Global weighted average CUFs for utility scale PV has increased by approximately 25%, from 13.8% in 2010 to 17.2% in 2021. The 95th percentile CUF in 2021 was 21.3%, while the 5th percentile CUF stood at 10.8%.

Global Weighted Average CUFs for Utility Scale PV (%)

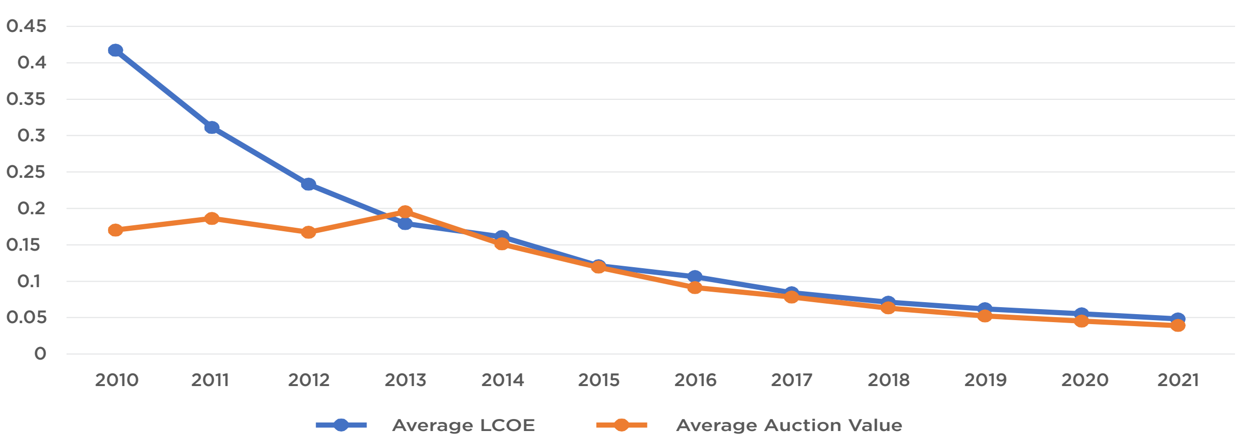


Source: IRENA Renewable Power Generation Costs in 2021

LCOE and Auction Value Trends

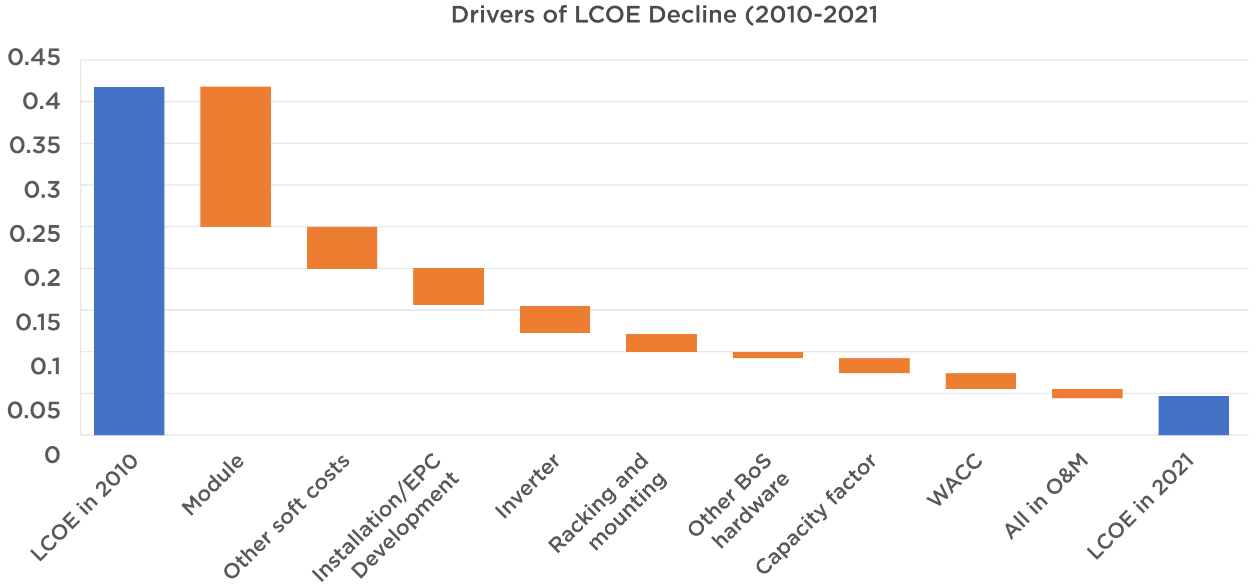
Average solar PV LCOE has declined 88% since 2010, falling from 0.417 USD/KWh in 2010 to 0.048 USD/KWh in 2021. In 2021, the year on year reduction was 13%. At an individual country level, the weighted average LCOE of utility-scale solar PV declined by between 75% and 90% between 2010 and 2021. Alongside LCOE reductions, auction values have fallen as well, coming down to 0.039 USD/KWh in 2021 from 0.17 USD/KWh in 2010. These reductions underline solar PVs status as an affordable renewable energy technology.

Average PV LCOE and Auction Value Trend



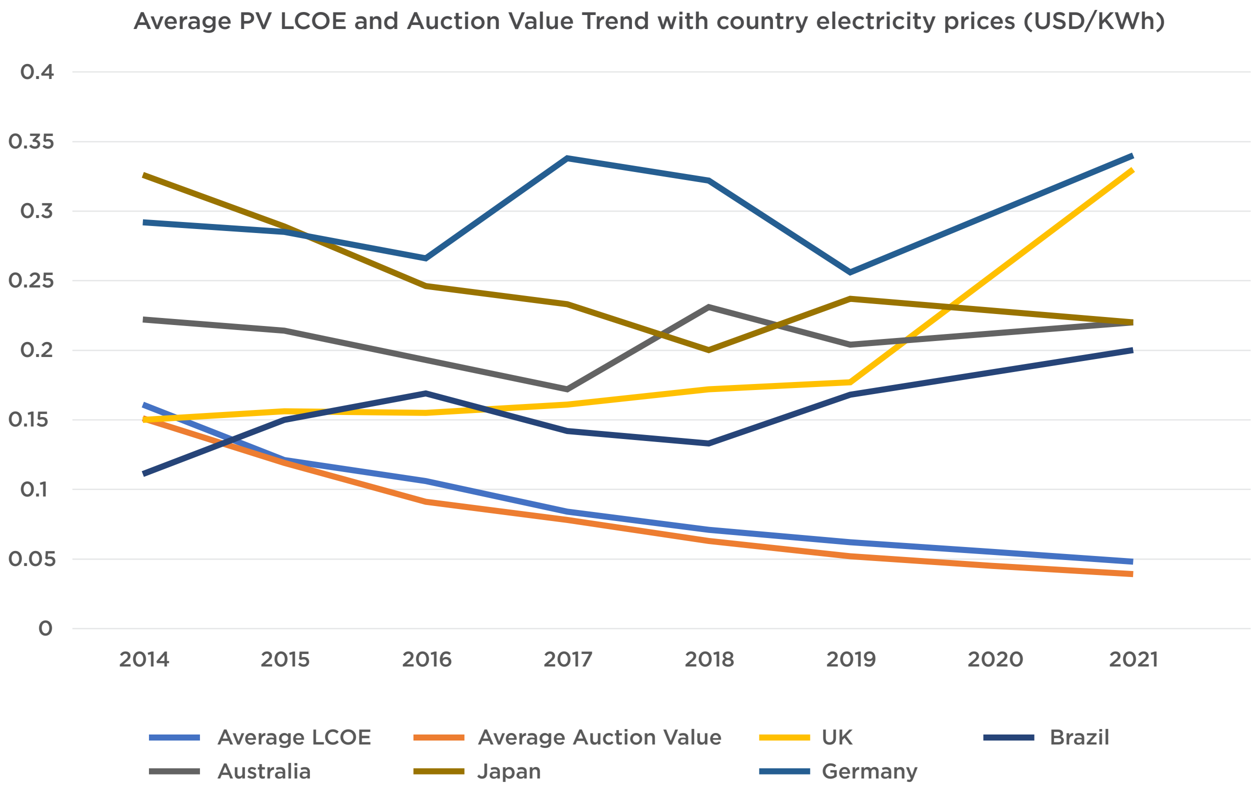
Source: IRENA Renewable Power Generation Costs in 2021

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%).



Source: IRENA Renewable Power Generation Costs in 2021

The fall in LCOE and auction values of solar PV has left them well below electricity prices in major countries, further emphasizing the affordability of solar power.



Source: IRENA, World Bank, Statista

Key Messages

- Solar is unique in the fact that glass is the primary material by weight used in a solar plant. Glass is closely followed by steel usage for various BoS structures and concrete for foundational structures.
- Solar plants utilise far less materials than equivalent capacities of wind power
- Solar land usage varies significantly depending on plant size and technology type, including use of trackers etc. Land usage ranges from 1.2 - 4.1 hectares per MW
- Electricity from solar has low median lifestyle GHG emissions of under 50-60 gCO2e/kWh

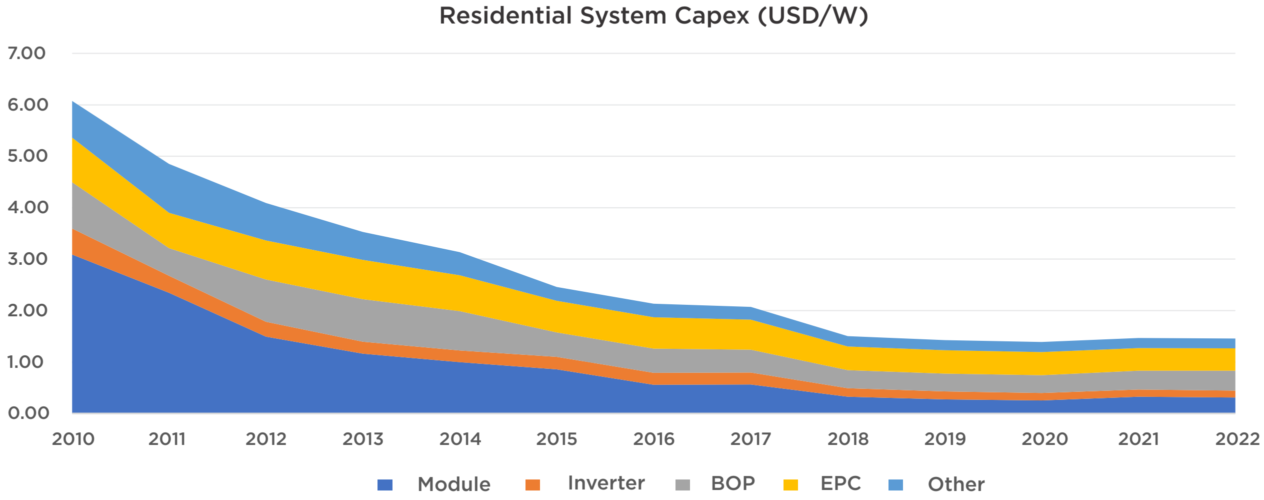
3.2.1 Solar PV Plant Design: Three key segments with differing needs

In order to discuss solar PV plant design, it is meaningful to divide PV systems into the three key segments in which they are deployed, namely, residential systems, systems installed by businesses or industry members (Commercial and Industrial (C&I)), 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 trend for each segment should be considered individually.

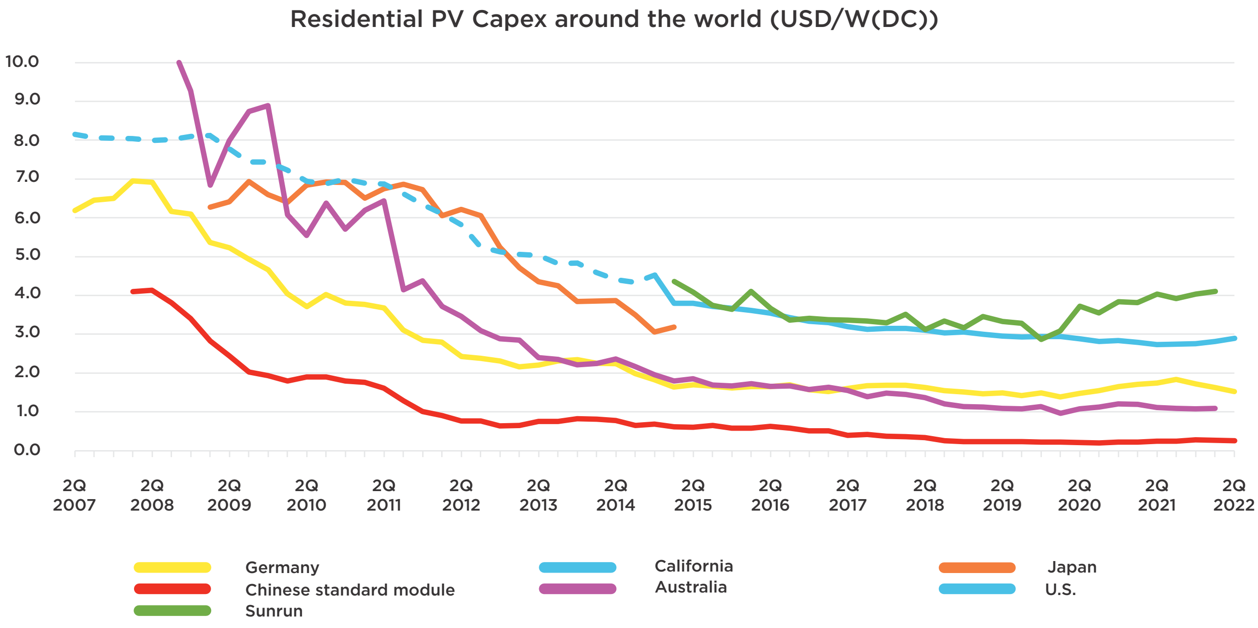
3.2.1.1 Residential

As showcased in the above chapters, renewable energy installations have been growing year on year since 2001, reaching a cumulative installed capacity of 3,068.3 GW in 2021. Solar itself has shown a growth of more than twenty-fold, in the last decade, reaching an installed capacity of 920 GW, in 2021. While renewable energy is taking a shift from secondary source of energy to slowly aiming to become a primary source of energy, the role of energy storage is also taking a centerstage.



Source: BNEF 2Q 2022 Global PV Market Outlook

Residential capex has dropped sharply over the past 12 years, from 6.07 USD/W in 2010 to 1.46 USD/W, a roughly 75% decrease. This reduction has primarily been driven by falling module costs, although more modest reductions have also been seen 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.



Source: BNEF 2Q 2022 Global PV Market Outlook

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.

Trends in Residential Solar PV systems

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 parameter for the modules utilised is primarily high power per unit area in order to maximize generation in the space available. However, modules used for rooftop solar plants cannot be as large as utility scale modules due to potential for partial shading and limited space for installation. 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, 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 specialised 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, trade on the same markets as utility scale power plants and industrial consumers.

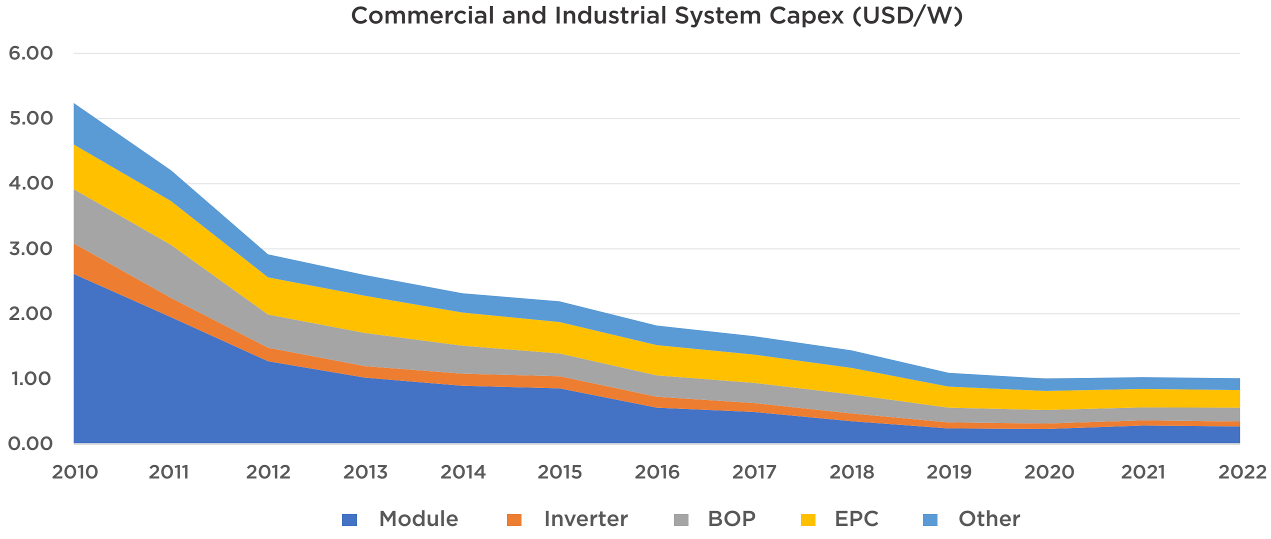
Residential systems bring the additional consideration of aesthetics since plants may be located on slanting roofs and thus be visible to the general public. As a result, single color modules such as black modules with black backsheet and frames have proven popular for residential applications.

Key Messages

- **Residential capex has dropped sharply over the past 12 years, from 6.07 USD/W in 2010 to 1.46 USD/W , a roughly 75% decrease. This reduction has primarily been driven by falling module 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.**
- **Residential solar prioritizes module power per unit area due to space constraints, and newer trends include the use of virtual power plants and behind the meter storage to unlock new applications and benefits.**

3.2.1.2 Commercial and Industrial (C&I)

As showcased in the above chapters, renewable energy installations have been growing year on year since 2001, reaching a cumulative installed capacity of 3,068.3 GW in 2021. Solar itself has shown a growth of more than twenty-fold, in the last decade, reaching an installed capacity of 920 GW, in 2021. While renewable energy is taking a shift from secondary source of energy to slowly aiming to become a primary source of energy, the role of energy storage is also taking a centerstage.



Source: BNEF 2Q 2022 Global PV Market Outlook

The fall in Commercial system capex from 5.24 USD/W in 2010 to 1.01 USD/W in 2022, a roughly 80% decrease, has been driven primarily by module costs declining from 2.61 USD/W in 2010 to 0.27 USD/W in 2022. This is similar to the residential sector Capex. However, unlike the residential sector, Module and EPC costs are tied for the highest capex share for the sector.

Trends in Commercial and Industrial Solar PV systems

The Commercial and Industrial segment falls between residential and utility scale systems when it comes to size. 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 availability of flat reflective roofs of significant size or open land may open the door for bifacial modules to be deployed.

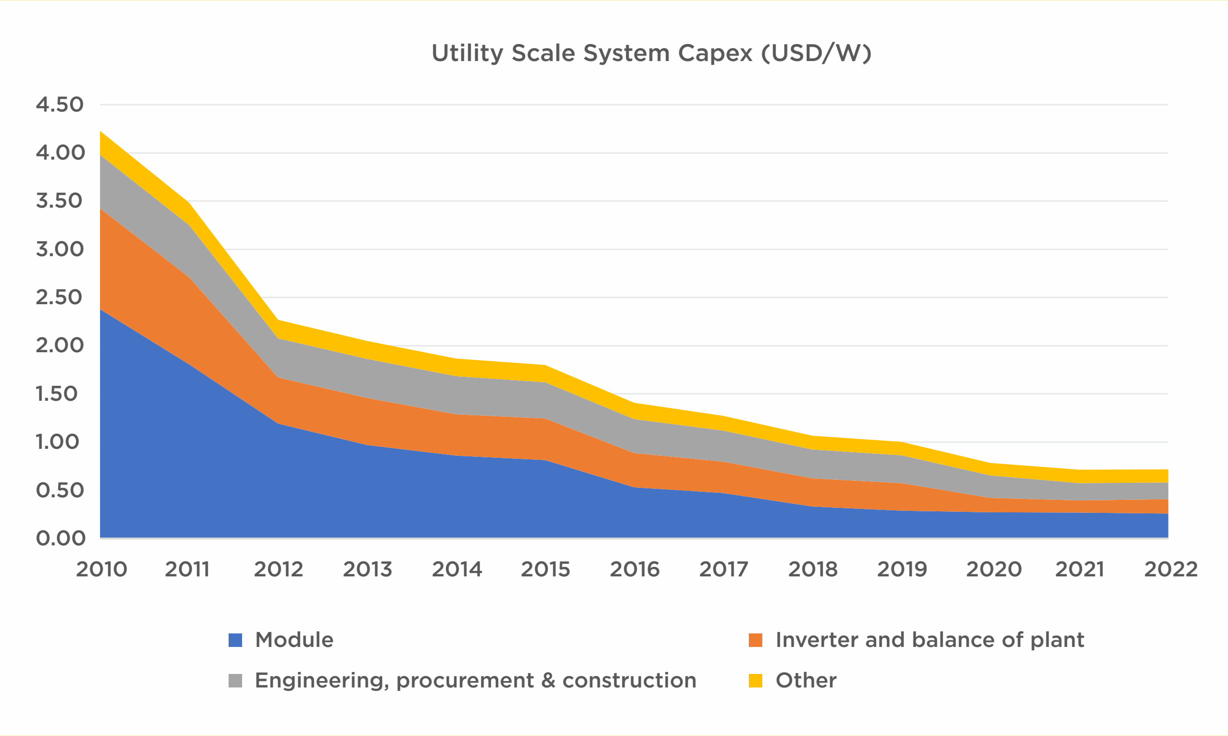
Commercial and Industrial locations may often have significant energy requirements and the energy produced by the PV system may be primarily used for self-consumption. Through the deployment of Behind the Meter (BTM) Battery Energy Storage Systems (BESS), there is also significant potential for demand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

Key Messages

- The fall in Commercial system capex of around 80% to 1.01 USD/W between 2010- 2022 has been driven primarily by module costs declining from 2.61 USD/W in 2010 to 0.27 USD/W in 2022
- Commercial and Industrial segment falls between residential and utility scale systems when it comes to size. Systems may be ground mounted or rooftop based, and plant capacities may range from low kW scale to 2 digit MW scale
- Commercial and Industrial locations may often have significant energy requirements and the energy produced by the PV system may be primarily used for self-consumption

3.2.1.3 Utility

As showcased in the above chapters, renewable energy installations have been growing year on year since 2001, reaching a cumulative installed capacity of 3,068.3 GW in 2021. Solar itself has shown a growth of more than twenty-fold, in the last decade, reaching an installed capacity of 920 GW, in 2021. While renewable energy is taking a shift from secondary source of energy to slowly aiming to become a primary source of energy, the role of energy storage is also taking a centerstage.



Source: BNEF 2Q 2022 Global PV Market Outlook

The fall in Utility system capex from 4.23 USD/W in 2010 to 0.72 USD/W in 2022, an 82% decrease, has also been driven primarily by module costs declining from 2.38 USD/W in 2010 to 0.26 USD/W in 2022. Modules are the highest cost component in the capex, with EPC costs in the second place.

Trends in Utility Scale Solar PV systems

For large 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 Levelised Cost of Energy (LCOE, USD per kWh) as the more relevant metric to evaluate a solar plant.

High power modules can bring down project LCOE as they can optimize EPC and Balance of System costs. However, high power modules can only bring down BoS costs if the module voltage can be held constant and current can be increased, thus ensuring string length does not increase excessively and electrical BoS costs are controlled. The usage of bifacial technology is also helping optimize generation in locations with reflective ground surfaces (high Albedo factor).

As highlighted above, the optimisation of Balance of System components has become an important method to minimize LCOE for large solar power plants. Solar inverters are a key BoS component that directly affects plant output. Thus, the use of high efficiency central inverters can help optimize generation. Additionally, as covered in section 3.1.3, high inverter loading ratios are utilised to optimize revenue and boost capacity factors.

The focus for installations have shifted to the use of monocrystalline silicon technologies due to their superior efficiencies over polycrystalline technologies. Additionally, the usage of advanced cell technologies such as TOPCon for utility scale projects is also seeing traction.

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 needs greater spacing to avoid shadowing of panels. Appropriate spacing is also relevant considering the large size of modern modules.

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Key Messages

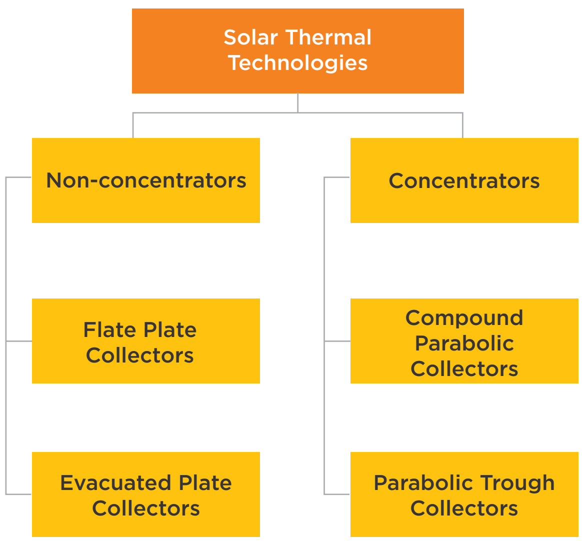
- **The 82% fall in Utility system capex from to 0.72 USD/W between 2010 and 2022 has been driven primarily by module costs declining from 2.38 USD/W in 2010 to 0.26 USD/W in 2022**
- **For large utility scale projects that can reach the hundreds of MW or even GW scale, ensuring that module costs are kept low. However, recent focus has shifted to the Levelised Cost of Energy (LCOE, USD per kWh) as the most relevant metric to evaluate a solar plant.**
- **The use of bifacial modules, solar trackers, high inverter loading ratios, and superior module technologies all help optimize utility scale generation.**

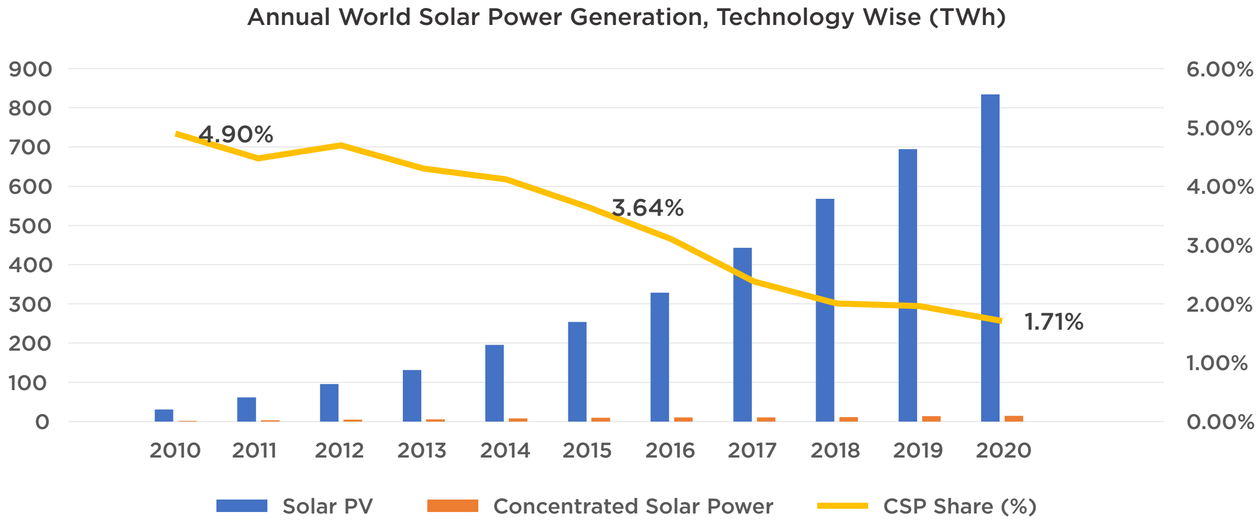
3.3 Solar Thermal: Potential to play a greater role in the energy transition

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 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.

A solar thermal system mainly consists of a solar collector, heat exchanger, working fluid or the heat transfer fluid and a thermal storage technology. In the recent times, a lot of research has been done regarding the Heat Transfer Fluid to be used for various solar thermal technologies and the thermal storage technology to be used. These two components are important as they enable Solar Thermal technology to provide energy, not only during the solar hours, but also during the non-solar hours.

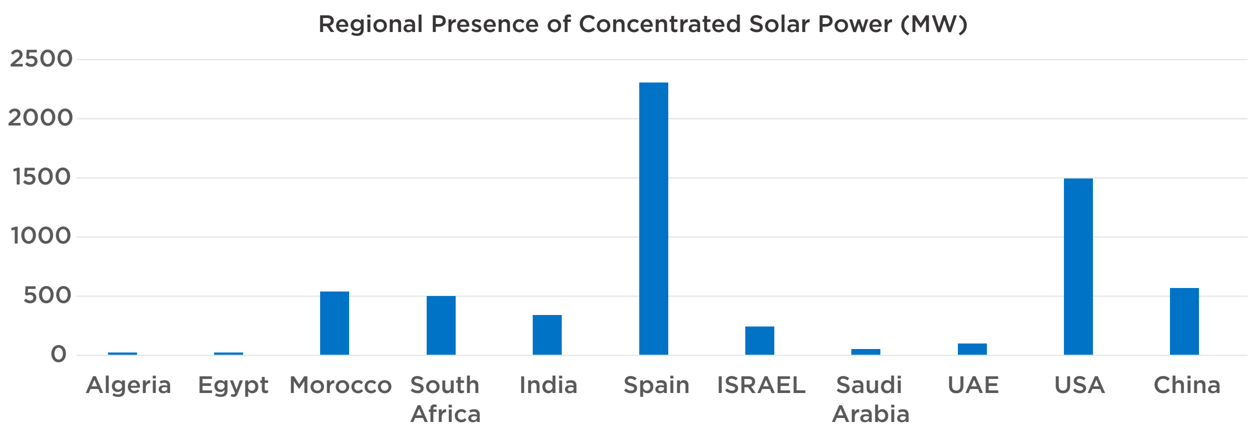
While there are various forms in which solar thermal technologies can be harnessed, Solar Concentrators is the most widespread in use. Flat plate collectors and evacuated plate collectors are technologies deployed for domestic heating and cooling purposes. Flat plate collectors are often used for domestic 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 the 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 Concentrated Solar Power is slowly rising again. 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.





Source: IEA(2021), Concentrated Solar Power (CSP), IEA, Paris and BP Statistical Review of World Energy & Ember

Comparing the two main solar power technologies available (Concentrated Solar Power (CSP) and Solar Photovoltaics (PV)) it is apparent that Solar PV has been the dominant technology. In the last decade, with the rising deployment of Solar PV, it can be seen that the already small share of Solar CSP has shrunk further, while Solar PV has taken centre-stage. Concentrated Solar Power has seen limited deployment globally, and installations have primarily taken place in certain key markets. 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 Hybrid format alongside solar PV to provide round the clock power.



Source: IRENA (2022), Renewable capacity statistics 2022, International Renewable Energy Agency (IRENA), Abu Dhabi

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, owing to the fact that 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.

Key Messages

- Solar Concentrators are often deployed for heat requirements in industries, where process heat of less than 250° C is required.
- Spain leads in the solar thermal energy space, with an installed capacity of 2304 MW.

3.4 Enhancing Flexibility of Solar: Diverse applications across sectors will drive future growth

Solar is now a well-established technology worldwide. Large utility scale solar projects have been developed across the globe, and a number of mature residential and C&I markets for solar have been established in recent years. These three sectors are expected to continue to grow in coming years thanks to increased access to finance, awareness creation, technology improvements, and cost reduction. Additionally, the presence of several underserved markets with potential provides significant scope for growth. For example, Africa is largely an untapped market for solar energy deployment.

However, Solar has significant potential beyond its current usage. Sector coupling is expected, as solar energy is deployed to meet various sector specific needs. This coupling is expected to go beyond procurement of solar power from the grid and may include deployment of solar capacity to meet sector specific energy requirements. For example, solar may be used to meet the significant electricity demands expected to arise from green hydrogen production. Additionally, solar deployment in the agricultural sector can help meet multiple objectives including improved land use efficiency, decarbonisation of agricultural applications, and improved energy access in remote areas.

In order to highlight some of the key applications for solar, a number of case studies have been presented below:

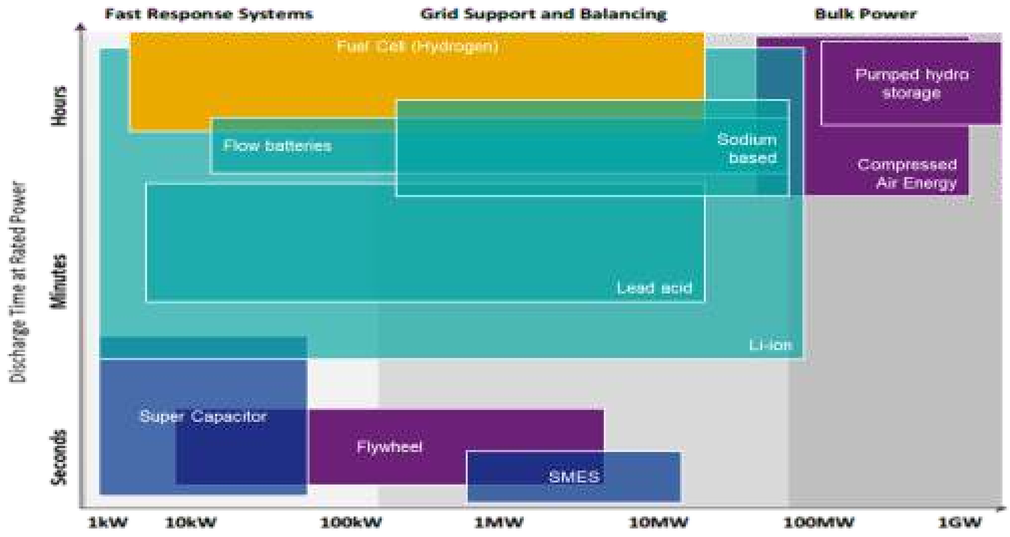
3.4.1 Electricity as an end use

3.4.1.1 Solar Integrated with BESS

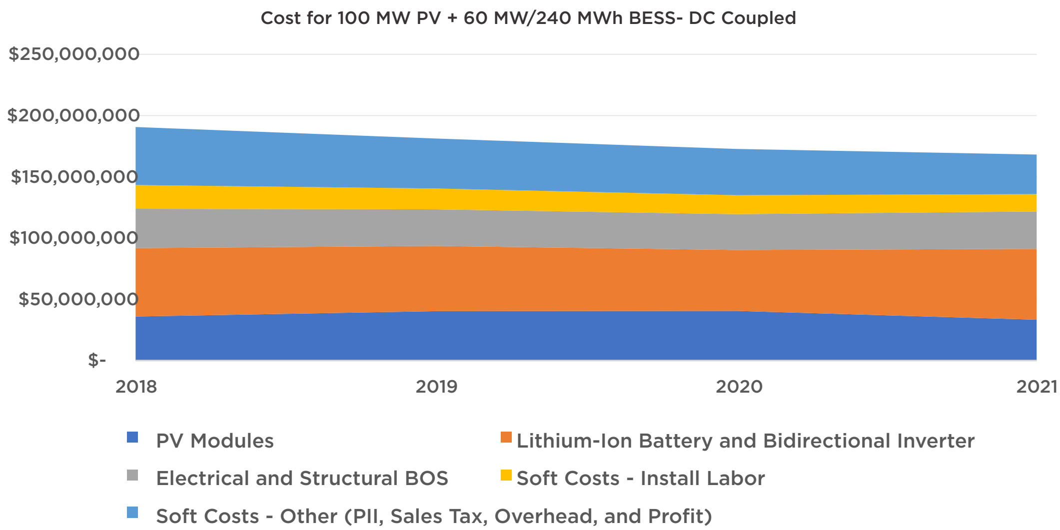
In the journey of shifting towards cleaner sources of energy, the one aspect where Solar Energy is found lacking with respect to other sources of energy is "Round The Clock" power availability. Since solar energy can be generated only for a limited number of hours, while the sun shines bright, power availability during the non-solar hours raises a huge concern. This issue can be mitigated through energy storage in batteries, to be utilized in the non-solar hours. Battery Energy Storage Systems (BESS) further provide the opportunity for storage of excess energy during peak hours, and supply energy when the generation output is low. This in turn shall also lead to grid stabilization of power grid.

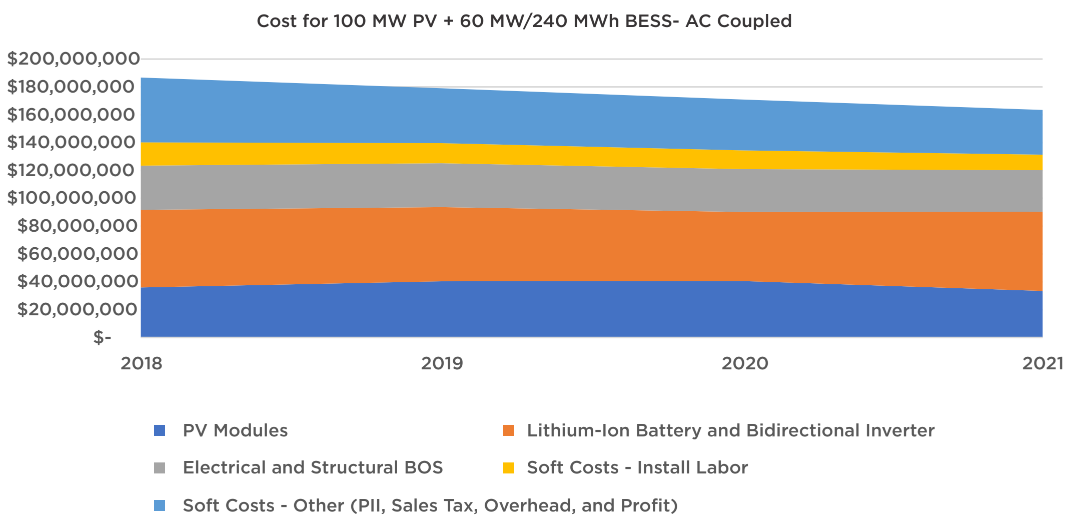
A wide variety of energy storage technologies are available, utilising different mechanisms. Categories for energy storage include electrochemical solutions (Battery storage technologies including Li Ion, Flow Battery, Lead-Acid, Sodium based etc.), Mechanical Energy Storage solutions (Flywheels, Pumped Hydro, Compressed Air), and other storage sources such as Supercapacitors and Superconducting Magnetic Energy Storage (SMES)

Battery Energy Storage Systems have emerged as a key technology for energy storage. Batteries are capable of providing short-to-medium term storage over a wide range of output capacity. Being modular and scalable, batteries can provide any scale of power capacity and improving technologies (e.g. Li-ion) are capable of for both fast and slow discharge rates.



Costs for BESS combined with solar have been on a steady decline in recent years, falling by about 13% since 2018. The increased affordability of these systems will drive further deployment and unlock more use cases for the technology.





Source: NREL

Case Study: Replacement of old peaking Diesel Generators with Solar + Storage in Hawaii

Background

Kaua'I Island Utility Cooperative, Kauai Island, Hawaii has a service area that is abundant in solar energy. Taking full advantage of this resource, solar energy was the primary energy source for day-time electricity. Distributed and utility-scale solar resources supplied upto 80 percent of the KIUC system load during the day, with other renewable resources (hydro and biomass) enabling close to 100 percent. With such a high percentage of renewable energy resources in the energy mix, the stability of the grid was a major concern during the day. Also, to cater to the electricity loads during the non-solar hours, diesel generators were being run.

Project

In order to tackle the issue of instability in the grid caused due to intermittency of solar energy during the day, KIUC, along with Solar City (now Tesla) pioneered the nation's first utility scale solar and battery storage system. The project included a 13 MW solar array with a 52 MWh Battery Energy Storage System and achieved commercial operation in May 2017. Furthermore, to avoid the usage of diesel generators for electricity generation during the non-solar hours, KIUC, in partnership with AES set up two more solar PV with Battery Energy Storage Systems.

Project 2: 20 MW solar array with 100 MWh Storage

Kaua'i Island Utility Cooperative

Your Touchstone Energy® Cooperative

Battery Technical Specifications:

Project 1

Power:	13 MWac + 13 MWac solar
Capacity:	52 MWh
Duration:	4 hours
Technology:	Li-ion
Supplier:	Solar City (Tesla)
Date Installed:	May 2017

Lawa'i Solar & Energy Storage Project

Power:	20 MWac + 20 MWac solar
Capacity:	100 MWh
Duration:	5 hours
Technology:	Li-ion
Supplier:	Samsung SDI
Developer:	AES
Date Installed:	December 2018

Kekaha Solar & Energy Storage Project

Power:	14 MWac + 14 MWdc solar
Capacity:	70 MWh
Duration:	5 hours
Technology:	Li-ion
Supplier:	Samsung SDI
Developer:	AES
Expected COD:	Q1 2020

Takeaway

With the help of the above-mentioned Solar + Battery Energy Storage Systems, KIUC was able to supply roughly 65 percent of night-time peak load by renewable energy. This enabled KIUC in reducing their reliance on fossil fuel run generators. This further helped in mitigating the issue of grid instability caused due to the high amount of variable renewable energy in the grid during the day-time.

3.4.2 Heating/cooling as an end use

Context: Applications and cost trends and comparison of different enabling technologies – in terms of tariff, auction results, LCOE etc. Region specific overview and insights

3.4.2.1 Water Desalination

Availability of drinking water is a huge concern in today's time. Solar Energy provides an interesting solution for the same, wherein the sun's energy is utilized to mimic Earth's natural water cycle, i.e., the process of generating rainfall. At the rudimentary level, water desalination via solar energy is using the heat from solar energy to evaporate water that's stored in stills. This water once evaporated leaves behind salts in the still, while the water vapor is then condensed in a collection chamber. The condensed water is devoid of the salts and other impurities, and hence can be used as drinking water. This method is known as **"Direct Solar Desalination".**

Direct solar desalination works well for purification but, because of the low operating temperature of the unit, does not produce a lot of water per day. The amount of drinking water produced in a direct desalination unit is proportional to the surface area of the device. The typically easy-to-operate design, however, makes it ideal for small-scale needs of families in remote areas, since the average person needs about two liters of water per day to survive. The process is driven solely by solar energy, so weather conditions and variable solar intensity (due to the shifting position of the Sun throughout the day) can negatively impact efficiency.

Since the output from a direct solar desalination unit is too low, we can also use solar energy, in an indirect form for water desalination. **Indirect solar desalination** is an arrangement of two different systems- a solar collection array, consisting of solar PV and/or fluid based thermal collectors and a conventional desalination unit. Production by indirect method is dependent on the efficiency of the plant and the cost per unit produced is generally reduced by an increase in scale. Many different plant arrangements have been theoretically analyzed, experimentally tested and in some cases installed. They include but are not limited to multiple-effect humidification (MEH), multi-stage flash distillation (MSF), multiple-effect distillation (MED), multiple-effect boiling (MEB), humidification–dehumidification (HDH), reverse osmosis (RO), and freeze-effect distillation.

Al Khafji Solar Water Desalination Plant

Background:

As a desert country with no permanent rivers or lakes, and limited rainfall, Saudi Arabia must ensure that it is capable of providing adequate water for its 35 million plus residents. This need for water sustainability and a secure water supply is especially underlined by climate change and the increasing global scarcity for water due to shifting weather patterns and declining groundwater reserves. In this context, the country has turned to desalination in order to meet its drinking water needs. Large scale desalinations energy demand, combined with the country's significant solar resources, made coupling with solar power an attractive option to consider.

Project:

The Al Khafji Solar Water Desalination Plant is the largest solar powered water desalination plant in the world. The plant is estimated to cost around USD 130 million and has the capacity to supply over 60,000 m^3 of water, with a peak production capacity of 90,000 m^3. The solar power plant associated with the water plant provides 10 MW of electricity daily to operate the desalination plant. The plant utilizes Reverse Osmosis (RO) in order to carry out water desalination. There are two main processes available for water desalination, distillation and RO. Distillation consumes upto 25 kWh per cubic meter of water produced, whereas RO processes consume less than 4 kWh for the same amount of water produced. Thus, through the selection of energy efficient technologies, as well as the use of solar electricity, the emissions associated with the plant can be minimized.

Takeaway:

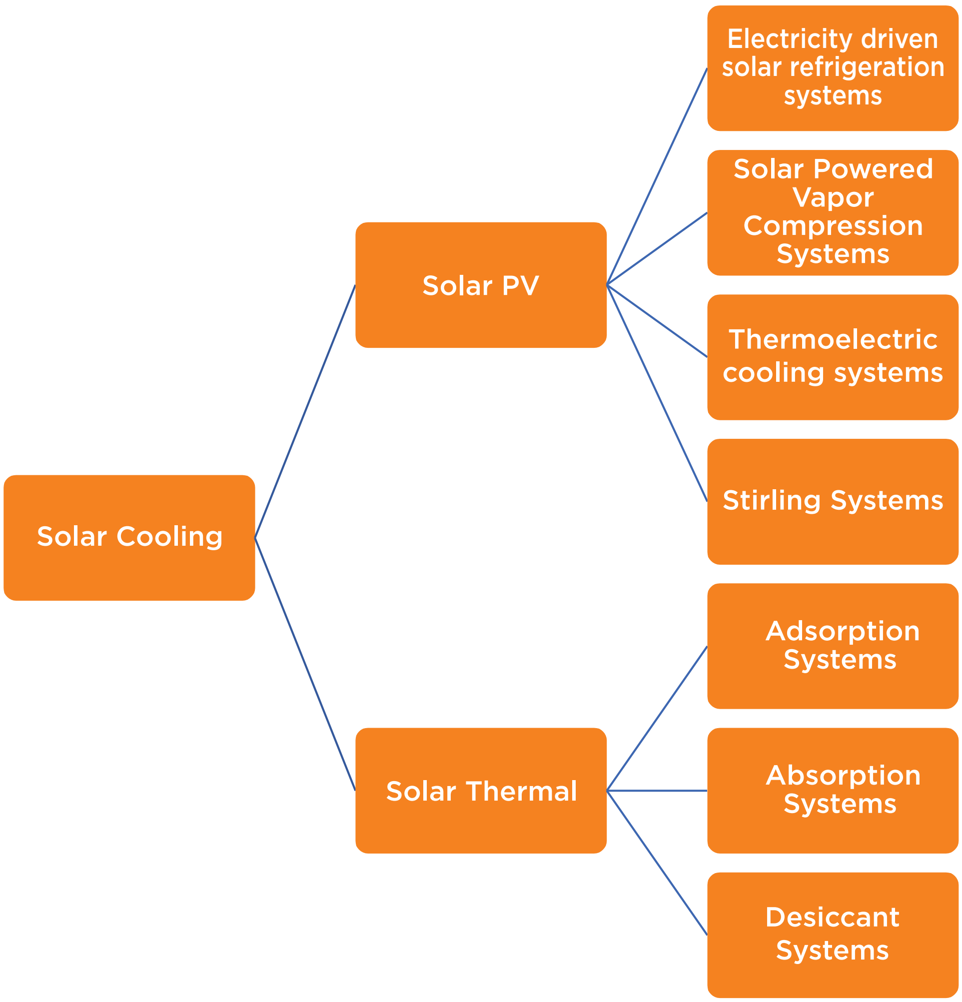
The Al Khafji Solar Water Desalination Plant has desalinated 7 Million m^3 since its inception. The plant also aimed to reduce the m^3 per day cost of water desalination, and the project has brought about a 40% reduction in the cost of water desalination per m3. Using solar power instead of fossil fuels has brought about significant benefits to the environment as well. The plant has reduced 14,000 tons of CO_2 emissions and has avoided the consumption of 1.1 Million barrels of crude oil. An additional side benefit for the plant has been the increase in habitability for the region. Since the project inception in November 2018, there has been a 2.2% increase in the rate of population growth and reverse migration. Overall, the Al Khalfji desalination plant serves to demonstrate the wide ranging impact of solar when combined with other sustainability related sectors.

In order to minimize the impact of the variable nature of renewable energy, the desalination process has been divided into 6 lines/trains that are designed to stop and restart frequently, to allow the best use of the variable solar power.

3.4.2.2 Cooling

In today's era, the demand of cooling systems and refrigeration is on the rise and constitutes the major chunk of electricity load of a building. Use of solar energy to cater to the same shall result in lowering the CO2 emissions in the building sector due to the use of air conditioning system, and also in reducing the peak energy consumption of air conditioners using vapor compression systems.

Solar energy can be innovatively and efficiently used in a cooling system, by using either Solar PV technologies or Solar Thermal technologies. In solar thermal cooling technologies, the cooling process is driven by solar collectors collecting solar energy and using this energy to drive thermal cooling systems such as absorption, adsorption and desiccant cycles, to name a few. Solar PV cooling systems is a method of direct electrification of cooling systems in a building, with the solar PV energy generation unit. Both types of solar cooling can be used in industrial and domestic refrigeration and air-conditioning processes, with up to 95% savings in electricity.



Solar powered cold storage to store and ripen bananas in rural Uttar Pradesh

Background

India is the largest producer of Bananas in the world, with a production of nearly 30 million MT a year. However, upwards of 15% of these production is lost to wastage. Banana's are artificially ripened in cold storages, which are often run on diesel generators which are expensive to operate and contribute to pollution. Additionally, unreliable power supply and lack of cold storage facilities leads to farmers selling unripened bananas on the market, resulting in a missed opportunity for value addition. In this context, solar powered cold storage systems can provide multiple benefits, including reduced reliability on grid connections, improved local value addition and income, reduced wastage of fruits, and mitigation of emissions from potential fossil fuel use.

Project

A 5 MT solar powered cold storage system was installed at a total cost of ~USD 20,000 in a village in Balrampur District in the northern Indian state of Uttar Pradesh. The area has around 18,000 MT of annual banana production but faces frequent and long lasting power outages on a scale from hours to days. The nearest cold storage facilities are 100-150 km away. An NGO rents the installed cold storage to farmers for a small fee (INR 0.25/kg/day) and provides training and material for ethylene based ripening techniques. The cold storage has been running since July 2021 in fully off-grid mode. The 5 MT capacity system is powered through 7 kWp solar PV panels, which has enough cooling capacity to ripen 100-200 MT bananas per annum when installed in completely off-grid locations. Additionally, the system is modular and can be expanded to upto 100 MT. The installed cold storage system was utilised by 10 farmer families and ripened 25,000 kg of bananas within 4 months of beginning operations.

Takeaway

Solar powered cold storage makes banana ripening viable at village level, which helps to reduce food wastage and provides economic opportunities to the farmers by enabling them to sell ripened bananas in place of green ones which adds value to their produce. A farmer can make INR 9-14 more per kg if he sells ripened bananas instead of green bananas, accounting for the cost of renting cold storage space. As a result, the installation of the solar cold storage has improved the livelihoods of at least 10 farmer families, who have doubled their income to INR 7,00,000 (~US$9,333) per annum, reduced their carbon footprint by 27 MT per annum and avoided food wastage of around 5 MT per annum. The system also has reasonable payback periods, with the study period showing that if utilisation is maintained, the cost of purchasing and installing the system can be paid off in under 2 years. Additional benefits of having the solar powered cold storage solution include affordable and higher quality bananas for the local consumers. Thus, it is apparent that the deployment of solar solutions in rural locations can provide benefits in areas beyond energy, including finances, health, environment, infrastructure etc. However, the high up front capital expenditure, lack of access to financing, skill development requirements, and large storage capacities required mean that deployments at scale need to overcome several barriers to allow benefits to extend to a larger section of the community.

3.4.2.3 Clean cooking

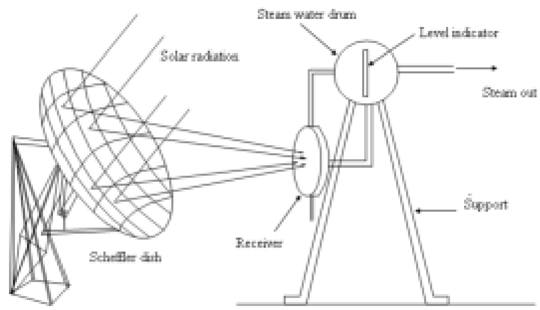
Case Study: Solar for large scale clean cooking in India

Background

Energy requirements for cooking around the world are primarily met through fossil fuels. Although electric induction plates exist, cooking is usually done through burning gas, wood, or other biomass materials. The use of such fuels leads to air pollution, potentially adverse impact on health, and a recurring expenditure on consumption of fuel. The utilization of solar energy for cooking can help address these constraints. Steam cooking has been found to be a clean, efficient and hygienic way of cooking, especially when cooking for large numbers of people. In India, a number of places of worship provide free or nominally priced meals to devotees and the needy. This open kitchen system results in the need to cook large quantities of food, which usually entails consumption of significant amounts of gas or wood. Solar cooking may be able to provide a solution to help eliminate this fuel consumption, making large scale cooking more cost effective, and reduce energy consumption.

Project

The town of Shirdi in the state of Maharashtra, India is a major destination for pilgrims. The local temple operates a large kitchen to provide meals to devotees at nominal costs. This results in the preparation of thousands of meals per day. In order to reduce their overhead costs, the kitchen decided to replace the existing cooking system with a Scheffler type concentrating solar steam cooking system. The system was commissioned in July 2009. The use of Scheffler reflectors can result in effective water heating by using the non-uniform distribution of solar radiation on the cylindrical absorber surface. In most of this system the part of the cylindrical absorber is thermally insulated in order to reduce storage tank thermal losses A total of 73 Scheffler concentrators raise the water temperature to 550°C to 650°C and convert it into steam for cooking purposes. This system is integrated with the existing boiler to ensure continued cooking at night and during rainy or cloudy weather. The solar cooking system installed at Shirdi follows the thermosyphon principle and so does not require electrical power or a pump.



Takeaway

The current system was installed with a total cost of INR 1.33 Crores, out of which INR 58.40 Lakh subsidy was provided by the Government of India[12]. The project has a steam generation capacity of 3500 kg/day[13] to be used for cooking. The system saved over 250 Kg of cooking fuel per day, resulting in daily savings of around INR 11,000 that would have been spent on cooking fuel[14]. Additionally, the project helped develop nearly INR 3,00,000 worth of carbon credit savings. Overall, along with the government subsidy, the project paid itself off in 2 years and avoided nearly 2000 MT of CO_2 Thus, the use of solar cooking systems can result in significant commercial and environmental benefits, especially when used for large scale requirements.

[12] https://pib.gov.in/newsite/erelcontent.aspx?relid=51224

[13] Dawange Sahebrao S. Renewable Energy Technology: A Case Study of Solar Steam Cooking System at Shri Saibaba Sansthan Trust, Shirdi, MS, India, Int. Res. Journal of Science & Engineering, January 2018, Special Issue A4 : 1-6.

[14] Commercial gas rate of INR 40.27/kg considered.

3.4.3 Solar PV Thermal Hybrid Technologies

Solar thermal technologies have been overtaken by solar PV, with the majority of new installations utilising solar PV to generate electricity. Thus, as it stands, solar thermal remains most relevant for small scale deployments, such as for domestic heating and cooling and solar cooking systems. However, solar thermal continues to see some large scale deployment when combined with solar PV to form a hybrid CSP and Solar PV facility. This hybrid setup allows for solar thermal to be used to offset some of the key challenges associated with solar PV. For example, the utilisation of CSP can allow for a hybrid plant to provide Round The Clock energy supply, as the heat generated by the CSP system can be stored and used for electricity generation when the solar PV system is not active. Such hybrid installations have been deployed in diverse geographical areas such as South America, Africa, and the Middle East.

Case Studies

a. Cerro Dominador Combined CSP and Solar PV plant, Chile

Background

Chile has some of the highest solar irradiation in the world, with the Atacama Desert having the highest long term solar irradiance of any place on Earth[15]. Chile has set an ambitious target for its energy transition, aiming to obtain 70% of the country's electricity from renewable sources by 2030, and achieve carbon neutrality by 2050[16].

The country also has to meet the significant power demand of the country's large mining sector. The mining sector accounts for ~85% of capacity on the country's northern grid, with power use by copper mines projected to double by 2025[17]. Thus, in order to meet this demand while transitioning towards renewable energy, the country is turning to innovative renewable energy solutions, including Solar CSP and PV hybrid projects.

Project

The Cerro Dominador project located in the Atacama Desert consists of a 110 MW CSP plant which joins a 100 MW photovoltaic plant. The solar field, covering 700 hectares, has 10,600 heliostats that reflect the sun's radiation onto a receiver located at a height of 252 metres[18]. The project began in 2014, and it was completed in 2021 at a total estimated cost of over 1 Billion USD[19]. Financial support was provided by the Chilean Government, the EU, and KFW.

Takeaway

The Cerro Dominador plant is the first project in South America to combine both CSP and Solar Photovoltaics. Despite challenges such as construction delays and high costs, it has shown the benefits of CSP- Solar PV Hybrids. This use case is more relevant than ever as the world tackles the challenge of ensuring grid stability with increasing renewable energy shares being integrated into the grid.

Key Figures

110 MW CSP with 100 MW Solar PV 17.5 hour thermal storage capacity using molten salt Capable of Round The Clock energy supply 630,000 tons of annual CO_2 emissions prevented

[15] https://doi.org/10.1038/s41598-017-13761-x
[16] https://www.statkraft.com/newsroom/news-and-stories/archive/2019/country-series-chile-leads-the-way-with-commitment-to-renewable energy/
[17] https://spectrum.ieee.org/chiles-hybrid-pvsolar-thermal-power-stations
[18] https://www.acciona.com/updates/news/cerro-dominador-csp-plant-chile-officially-opens/?_adin=02021864894
[19] https://www.reuters.com/article/us-chile-energy-solar-idUSKBN1X9132

b. Mohammed bin Rashid Solar Park Phase 4, Dubai

Background

The United Arab Emirates (UAE) is among the world's ten largest oil producers but has recently made its clean energy ambitions clear by announcing plans to achieve net zero by 2050[20]. As part of this target, The Mohammed bin Rashid Solar Park, located around 50 Km. from Dubai, is being developed. The park aims to produce 5000 MW by 2030 and is being developed in phases. The fourth phase of construction involves the development of the world's largest CSP plant, which will be combined with PV capacity to provide solar energy around the clock.

Project

The project consists of almost 1000 MW of capacity across three solar technologies, a world first. The project will consist of CSP (600 MW Parabolic Trough, 100 MW Central Tower), and 250 MW Solar Photovoltaic capacity. The solar tower for the site will also be the tallest of its kind in the world, standing at 260m. The CSP components of the project are currently under commissioning, while a section of the PV capacity is now complete.

Takeaway

As per the project implementer Noor Energy 1 PSC, The CSP-PV hybrid has achieved a new world record of levelised cost of electricity at USD 7.3 cents per KWh under a 35 year PPA, competing with fossil fuel electricity without subsidy for reliable and dispatchable solar energy through the night. It is thus clear that, given the right project circumstances, CSP- PV hybrid technologies can achieve suitably low levelised cost of electricity while maintain reliability for more than half of the day.

Key Figures

700 MW CSP with 250 MW Solar PV 15 hour thermal storage capacity using molten salt Capable of Round The Clock energy supply 2.4 million tons of CO_2 saved

[20] https://economictimes.indiatimes.com/news/international/uae/uae-launches-plan-to-achieve-net-zero-emissions-by 2050/articleshow/86842399.cms?from=mdr

c. Ouarzazate Solar Power Station, Morocco

Background

Morocco made an early decision to position itself as a regional leader in clean energy, and in 2009 announced ambitious targets to achieve 42% of renewable energy in installed power capacity by 2020. A respectable 37% renewable capacity was achieved by Morocco, and the country has further pledged to build no new coal power plants[21].

Project

The Noor Ouarzazate Solar Power Station is being developed in four stages:

- Stage I: 160 MW CSP with 3 hour thermal storage
- Stage II: 200 MW CSP with 7 hour thermal storage
- Stage III: 150 MW CSP with 7 hour thermal storage
- Stage IV: 72 MW Solar PV

The facility covers over 6000 acres and will generate enough clean energy to supply 2 million Moroccans[22]. The total project cost is estimated to be ~USD 2.35 Billion with key funding sources including KfW, AfDB, AFD, WB, EIB, BMZ etc.

Key Figures

510 MW CSP with 72 MW Solar PV Max. 7 hour thermal storage capacity using molten salt Capable of Round The Clock energy supply 760,000 tons of CO_2 saved annually

Takeaway

The commissioning of an ambitious Solar CSP-PV Hybrid project in a developing country such as Morocco shows that with a clear vision for an energy transition can result in meaningful change. Morocco's early commitments to decarbonizing its power capacity may serve as an example to other countries at similar stages of development. Additionally, the project provides further evidence of the benefits of CSP as a method to replace stable generation from coal and other fossil fuels. The project has also employed over 9000 people, with local area employees consisting of anywhere from 23% in Stage II to 59% in Stage IV.

[21] https://www.bbc.com/future/article/20211115-how-morocco-led-the-world-on-clean-solar-energy
[22] https://www.climateinvestmentfunds.org/CIF10/morocco/ouarzazate

3.4.4 Other Applications

3.4.4.1 Solar Integrated with Green Hydrogen Production

Yet another form of energy banking or energy storage is by utilizing solar energy, generated via Solar PV modules, to produce Green Hydrogen. In such a scenario, green power, or in this case, solar power is supplied to water/steam electrolyser, which then, by virtue of electrolysis, generate hydrogen. Since the hydrogen generated is powered by green in nature, it is termed as Green Hydrogen.

This Green Hydrogen is stored in tanks, to be later utilized by fuel cells to generate power during the non-solar hours. The green hydrogen produced can also be used in the Ammonia Industry, Steel Industry, Refineries etc., wherever Hydrogen is a key component for synthesis, to produce green products, hence cutting down on the CO_2 emissions involved in the products value-chain.

Case Studies

a. Cerro Dominador Combined CSP and Solar PV plant, Chile

Parameters	Units	2020				2050			
		Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell Pressure	Bar	<30	<70	<35	<10	>70	>70	>70	>20
System Efficiency	kWh/KgH2	50-78	50-83	57-69	45-55	<45	<45	<45	<40
Lifetime (thousand hours)	Hours	60	50-80	>5	<20	100	100-120	100	80
Capital Costs estimate for stacks > 1 MW	USD/kW	270	400	--	>2000	<100	<100	<100	<200
System Capital Costs	USD/kW	500-1000	700-1400	--	--	<200	<200	<200	<300

Source: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, International Renewable Energy Agency, Abu Dhabi.

[20] https://economictimes.indiatimes.com/news/international/uae/uae-launches-plan-to-achieve-net-zero-emissions-by 2050/articleshow/86842399.cms?from=mdr

Case Study: Standalone Solar PV + Green Hydrogen Microgrid in Andhra Pradesh, India

Background

Green Hydrogen is produced by the splitting of water particles using an electrolyser, powered via a renewable source of energy. Green Hydrogen once produced, can be stored in storage tanks, to be utilized later to generate electricity via fuel cells. Hence, Green Hydrogen can be understood as an energy storage technology as well. To test the reliability of the same, India's State-owned power producer, NTPC Limited has come up with a project to set up a standalone micro-grid project with hydrogen storage at its Simhadri thermal station in Visakhapatnam, Andhra Pradesh. The project is expected to commence in 2022 in Simhadri, Visakhapatnam, India.

Project

The aim of the project is to provide "Round the Clock" power to the Micro-grid set up at Simhadri, Visakhapatnam, India. To do so, NTPC shall be utilizing the energy generated via a nearby Floating Solar PV energy generation plant nearby during the solar hours. This energy shall be used to cater to the electricity needs of the guest house in the daytime, as well as supply power to the electrolyser producing Green Hydrogen.

The hydrogen would be produced using the advanced 240 kW Solid Oxide Electrolyser. The hydrogen produced during sunshine hours would be stored at high pressure and would be electrified using a 50 kW Solid Oxide Fuel Cell. The system would work in a standalone mode from 5 PM to 7 AM.

This will be India's first green hydrogen-based energy storage project. It would be a precursor to large-scale hydrogen energy storage projects and would be useful for studying and deploying multiple microgrids in various off-grid and strategic locations of the country.

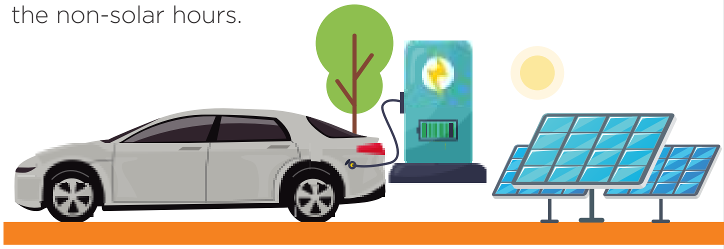
Takeaway

With the rising need for nations to achieve energy security and carbon neutrality, Green Hydrogen is set to become a viable solution for Energy Storage. With the help of such technological solutions, renewable energy, especially solar energy can be used in a much more effective manner to cater to electrical loads during both, solar hours and non-solar hours. Pilot projects like these shall help us understand the feasibility of the same.

3.4.4.2 Solar Integrated with EV charging

With the rising share of energy being used for transportation purposes, the need to shift to cleaner, non-fossil fuel-based energy sources for transportation is necessary. One such energy solution is the use of Electric Vehicles which use batteries as energy source for driving the electric motor of the vehicle. Sales of Electric Vehicles (EVs) doubled in 2021, from the previous year to a new record of 6.6 million. Nearly 10% of global car sales were electric in 2021, bringing the total number of electric cars, globally, to about 16.5 million. Global sales of electric cars have been kept rising strongly in 2022, with 2 million sold in the first quarter, up 75% from the same period in 2021.

With such rising share of Electric Vehicles globally, the electricity demand for the charging of batteries for these EV's is also increasing. In the effort to switch to greener fuels, integrating Solar PV with EV charging carports seems like a feasible solution. The solar PV electricity generation plant, deployed on the roof of such car ports can be used for the direct electrification of charging stations, and battery energy storage systems (BESS) can also be utilized to cater to the energy demands during the non-solar hours.



Rotherham Council Solar PV + Storage deployment for EV Charging Stations

Background

Transportation is one of the key sector driving global GHG emissions, with the vast majority of vehicles operating on fossil fuels. Electric vehicles are thus set to become a major tool in decarbonising the sector. However, although the operation of the electric vehicle does not involve the burning of fossil fuels, it requires charging. Considering that most countries continue to have a significant share of their electricity mix supplied by non-renewable sources, EV's may not be as green as they could be. EV charging may also place a significant load on a consumers electricity demand, resulting in excessive payments and a risk of imposition of demand charges. In this context, the deployment of solar power alongside EV chargers can help ensure that EVs are as green as possible, while also helping to offset the energy requirements for charging. The intermittency and limited availability of solar can also be addressed through the deployment of energy storage, creating an integrated system that can meet charging demand day or night.

Project

The Rotherham Metropolitan Borough Council conducted a scheme to install EV charging points across the borough. In some locations, the council took the opportunity to combine these points with energy storage and solar PV installations. The flagship installation was conducted at a multi-story car park. The location features 5 charge points with dual sockets (for a total of 10 charging connections), 87kW of solar PV capacity, and 3 batteries for a total of 40.5 kWh of energy storage. The solar PV installation was carried out on the top deck of the multi-story car park, as it was noticed that the top deck was not being utilised for parking, leaving it open for conversion to a rooftop solar plant. The location offers free EV charging facilities, and visitors need to only pay for the parking charges at the location. The project cost was supported by funding from the UK Government's Clean Air Fund early measures programme.

Takeaway

The council had initial concerns regarding whether the charging stations would be utilised, considering the relatively high expensive of electric vehicles in the region. However, these fears have been unfounded and the charging points are being widely used. The solar PV generation is being used for on-site consumption, leading to reduced electricity bills, and the battery storage capacity helps address overnight lighting requirements as well. This deployment helps demonstrate how solar can assist with the decarbonisation of non-electricity sectors. Solar has the flexibility to sit at the intersection of technologies, acting as an enabler alongside storage and electric vehicles to drive the decarbonisation of transportation, and further improve the impact of electric vehicles through green charging.

3.4.4.3 Agrivoltaics

Water, energy, and agriculture are the bedrock of modern civilization. And while many technologies have advanced these components separately, few have aimed to address all three components at once. Agrovoltaics targets the issues of energy and agriculture industry. While land is the main concern for setting up of solar PV modules, excess heat and sunlight can ruin the agriculture yield as well. Setting up solar PV modules at a height from the ground level, allows for agriculture to prosper, with adequate heat and sunlight, while at the same time, the same area caters to the generation of solar energy via the solar PV modules. Farmlands have many characteristics that make them desirable from a solar development perspective, including having existing connections to the electric grid, access roads, and relatively flat ground. These characteristics, combined with the growing economic challenges of traditional farming, have led to solar projects being developed on agricultural lands (Walston et al. 2021).

Provided that we have the right conditions and configurations, agrivoltaic installations have the potential to:

- Increase the financial inflow for farmers, agricultural entities and solar developers.
- Provide beneficial ecological services
- Expand opportunities for solar deployment.

Case Study: Agri-PV in Mali and Gambia

Background

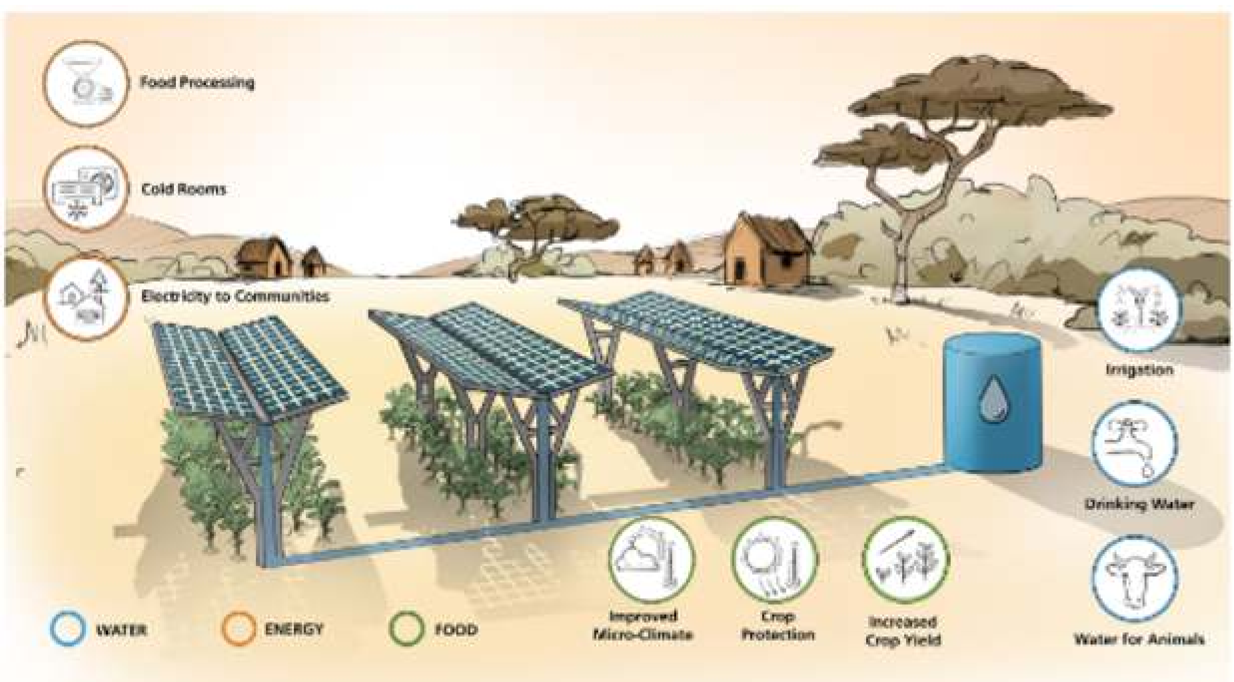
Mali and Gambia are part of the West African Sahel region and have been exposed to extreme climate events such as droughts, floods and heat waves over the past several decades. In both Mali and Gambia, demand for solar power generation through ground-mounted photovoltaic systems is steadily increasing. The limited availability of arable land combined with an increasing demand for land has already led to an intensification of land-use competition. The vision of the APV-MaGA CLIENT II project is to establish Agri-PV (APV) as a sustainable energy system that provides food, water and electricity to the local population while increasing the resilience of the agricultural sector to climate change.

Project

The APV-MaGa project involves the installation of a 200-kWp demonstrator on approximately one hectare of land in Katibougou, Mali. Four demonstrators, each with a capacity of approximately 62.5 kWp, will be installed in selected communities in Gambia. These include an irrigated rice farm; a pilot system with integrated rainwater harvesting; a "transformation platform"; and a cold storage facility for food preservation.

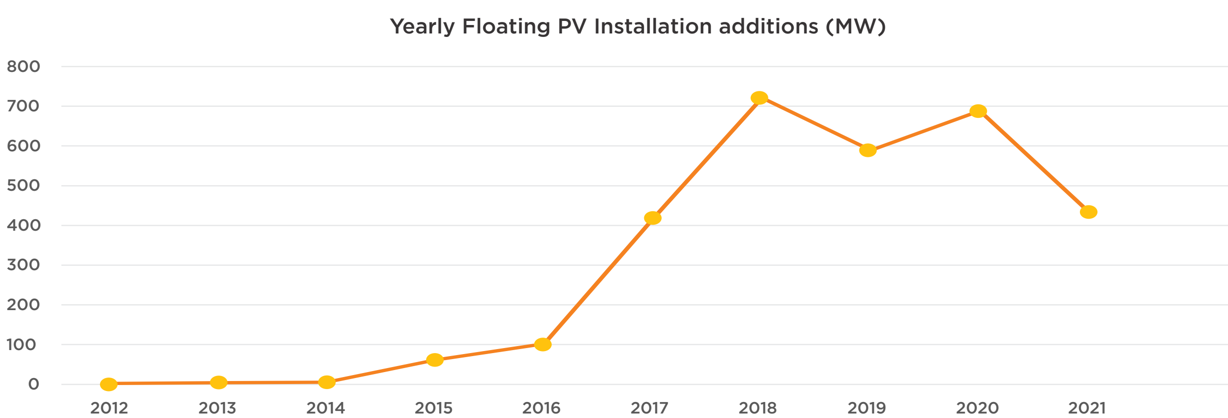
Takeaway

The agrivoltaic project in Mali and the Gambia (APV-MaGa) is a research and development project that aims at proofing the technical and economic viability of an integrated triple land-use system in order to contribute to a more ecological and socio-economic sustainable development of the partner countries. The different pilot projects are installed to optimize the use of the generated electricity and to ensure profitability from crop yields for the local communities.



3.4.4.4 Floating Solar PV

Floating Solar PV is a major upcoming application of solar PV generation systems. With land being a major resource requirement for setting up a solar PV plant for utility scale energy generation, Floating Solar PV saves land by setting up a solar power generation plant over stagnant water bodies. With the same components used, like a ground mounted solar PV plant, the only addition in BoS that floating solar PV systems has is floaters, which hold the majority or the entire PV system on the water surface. Although a floating solar PV is expensive when compared to a ground mounted solar PV, due to the additional cost of floaters, as well as the higher maintenance cost involved for keeping the components functional in humid and wet operating conditions, the power yield from the same is higher as well. The cooling effect of the water helps in maintaining the ideal temperature for the operation of a solar module, leading to a higher generation. While FPV plants solve the issue of land availability, they also help in suppressing the evaporation of water, as well as improve the overall water quality. FPVs can be easily integrated into commercial water bodies such as irrigation and drinking water reservoirs, aquaculture farms and even hydropower generation sites. With the increasing research and development of Floating Solar PV plants, there has been growing installations globally. About 434MW of such plants were installed in 2021 alone, making the cumulative installed capacity of FPV rise to 3.02 GW.



Source: SolarPower Europe

Case Study: Floating Solar PV plant at Banasura Sagar Dam- Kerala, India

Background

Banasura Sagar Dam, situated on the Karamanathodu tributary of the Kabini River, is part of the Indian Banasurasagar Project consisting of a dam and a canal project started in 1979. Though it was originally planned for irrigation, water from this Reservoir is not being used at present. This reservoir was chosen as the site for setting up a floating solar PV plant, to utilize the abundant space available.

Project

The **500 kWp Grid Interactive Floating Solar Power Plant** in the Banasura Sagar dam, Wayanad is the first of its kind in India. The project is designed for Kerala State Electricity Board (KSEB) and the solar photovoltaic array, inverters and 11 kV Sub-station are installed on 18 floating platforms made of Ferro cement floaters with hollow insides which are able to adapt to varying reservoir water levels by means of an innovative anchoring system. This **solar farm floats on 6,000 square metres of water surface** of the reservoir. **Each floating platforms has 115 solar panels and a 33kW solar string inverter.** There is Supervisory Control and Data Acquisition (SCADA) system to control and monitor power generation and the power produced will be evacuated through an **11 kV under water cable to the 11 kV grid of KSEBL.**

Takeaway

The floating solar power plant was commissioned and inaugurated on 4th December 2017. The project generates about 700,000 kWh per year which is fed directly to the grid. Previous studies have proved that floating solar panels generate higher output due to lower ambient temperature existing on the surface of the waterbody. The floating plant also requires less space compared to land-based plants. The area requirement for the Banasura Project is app 1.23 acres for 0.5 MW whereas the land requirement for equivalent land-based system is 2 to 2.5 acres.[23] Apart from this evaporation of water from the reservoir will be minimal as the surface is covered by solar panels.

3.4.4.5 Building Integrated Solar PV

Although with the progress of research and development in the field of solar PV modules, the size of the solar modules per kW of generation has reduced, land usage still poses a major concern in today's era. This issue is solved by the innovative ways in which solar PV modules can be introduced in various facets of our lives. One such innovative method is to use Building Integrated PV modules (BIPV) technology, wherein, apart from just the roof of a building, the solar PV modules can be integrated into the glass facades of the building as well. This in turn also leads to higher generation of solar energy from a particular establishment and also helps buildings into reducing their carbon footprint, moving towards a carbon zero or carbon negative environment.

With the help of case studies, this section shall explore on the various innovative ways in which solar PV can be integrated in buildings, leading to higher generation of solar energy and buildings reducing their carbon footprint.

[23] https://www.energyforum.in/fileadmin/user_upload/india/media_elements/Presentations/20190304_Presentations_CBIP_IGEF_Sudy_tour_floating__solar/20190220_dma_KSEB_500kWp_Floating_solar_power_plant_at_Banasura_Sagar.pdf

Case Study: World's largest BIPV Project- Gao'an, China

Background

The global BIPV market is expected to witness a rapid increase. Photovoltaic building is a new concept of applying solar power generation and is a perfect combination of solar PV and modern building without taking any additional land. With carbon neutrality being a global goal, the manufacturers, especially those labeled as energy- extensive consumption companies are eager to offset their carbon footprint.

Project

The facility being discussed in this case study is the second largest architectural ceramic base in China. In an attempt to revamp the roof of the facility, the company replaced the complete rooftop with a BIPV infused rooftop. The whole project is spread of 665,000 square meters and has a listed capacity of 120 MW, once complete. It consists of 11 individual rooftops[24] and shall supply the facility with 100% renewable electricity.

Takeaway

The BIPV system is an ideal solution to facilitate the decarbonization of ceramic manufacturing facilities and pave their path towards ecological and environment friendly development. Once fully commissioned, this Solar Power generation plant, using BIPV technology shall generate 120 GWh of clean power, eliminating 96,000 Tonnes of Carbon Dioxide.[25]

The Gao'an Factory, Before (Left) and After (Right)

3.4.4.6 Vehicle Integrated Solar PV

Currently, solar Photovoltaic (PV) technology is used majorly in the form of grid-connected systems or in mini-grids, by means of standalone solar PV plants or floating PV plants. A new, innovative application of solar PV technology can be Vehicle Integrated PV (VIPV). Globally, trucks and vans contribute to about 29% of global CO_2 emissions from the entire transport sector. VIPV is a solution that designates the mechanical, electrical and design-technical integration of photovoltaic modules into vehicles.

The output of the solar PV panels, integrated into certain parts of the vehicle, such as a bonnet or a roof, is fed to the electric loads or a drive battery for an Electric Vehicle. Such a solution shall also help in reducing the CO_2 emission of the vehicle, as well as act as a range extender for Electric Vehicles, leading to lesser time spent at the battery charging stations.

[24] https://ieefa.org/articles/worlds-largest-building-integrated-pv-project-completed-china

[25] https://www.saurenergy.com/solar-energy-news/sungrow-sets-up-worlds-largest-bipv-project-in-china

Fraunhofer ISE: Lade-PV- Development of Vehicle-Integrated Photovoltaics for On-Board Charging of Electric Utility Vehicles

Background

Electric vehicles are set to revolutionize the transport sector, replacing fossil fuel powered vehicles. While EVs bring significant environmental benefits, there are a few challenges that can hamper widespread adoption of EVs. One of these is the challenges associated with utilising EVs for longer range transport. EVs have shorter ranges than traditional automobiles before they require charging, and EV charging stations are yet to achieve the widespread availability that the fuel station network for traditional vehicles have achieved. These limitations affect the target market that will consider switching to an EV. In this context, Vehicle Integrated Photovoltaics (VIPV) can help provide a solution. VIPV can help increase the mileage of an EV and reduce the requirement for charging stations. Additionally, the expensive of electricity for EV charging can also be reduced. Thus, VIPV is being explored for freight transport and other utility vehicles.

Project

Fraunhofer ISE in Germany is conducting research into PV applications for mobility. The project on VIPV, Lade-PV, aims to demonstrate PV applications in freight transport. This involves the development of suitable PV modules that can be mounted on vehicles and manufactured cost effectively. The aim of the project is to demonstrate energy savings in freight transport of more than 5% by using PV. The weight and robustness of the modules must be suitable to ensure that they can be deployed on vehicles. The project is unique in that manufacturing and production concepts will be developed alongside the actual system level components themselves. Fraunhofer ISE partnered with industrial clients to develop the modules for freight applications.

Takeaway

The Lade-PV project began in April 2020, and by October 2021, as part of testing, a 3.5 kW PV system was deployed on the roof of an 18 ton electric truck. This truck will now be tested throughout 2022 in Germany. Sensors will take readings of the trucks performance, and it is estimated that 5-10% of the vehicles electricity demand can be met by the PV system. The panels in the truck are equipped with a separation device to help disconnect the panels from each other in case of an accident, to minimize risk of electrical damage. The VIPV enabled truck is the first to be equipped with Fraunhofer’s new modules and has passed technical inspection. As testing continues, it will be interesting to see if the vehicle is able to see tangible benefits arise due to the deployment of solar panels.

3.5 Design and EPC: Innovations are optimizing costs and commissioning times

Solar PV plant design involves a number of considerations, including system sizing, orientation, equipment selection, grid connection etc. A well designed system can help optimize plant generation and keep LCOEs low. Once the plant design is complete, Engineering, Procurement, and Construction (EPC) activities can be carried out by a contractor to ensure that the plant is constructed to specifications and suitably operational before handover to the client.

Insights and Trends

The material requirements for a standard solar PV plant have been discussed previously in this report, but it is important to take into account the timescale and manpower requirements for a project. Construction and installation accounts for 17% of the man day requirements for a typical installation[26]. Further improvements in installation processes and equipment have helped reduce the commissioning time for solar projects, and large scale project development timelines have gone from a timescale of years to months.

Large solar PV plants have been tending to increase their Inverter Loading Ratio significantly, reaching upto 1.35- 1.40. This naturally affects the plant design in terms of solar inverter capacity and also positively impacts plant LCOE. This is because the plant equipment usage is optimized by minimizing expenditure on capacity that can often be left idle due to various reasons (time of day, curtailment, shading, weather conditions etc.) Additionally, the structural design of the solar plant also takes into account soil constraints and weather conditions when determining the method of installation for the plant.

Solar power is a variable renewable energy source and brings inherent challenges to grid integration. At the same time, the technology increasingly occupies more of the worlds generation mix, and the need for stable and round the clock supply of solar energy is apparent. Thus, a number of tenders for solar projects request for solar combined with storage capacity in order to ensure grid integration. Such solar and storage tenders have been at significant scale, including over 1 GW of solar capacity combined with a smaller energy storage capability. This trend in tenders is set to impact how solar plants are designed as developers would seek to meet market needs effectively.

Key Takeaways

- Construction and installation only accounts for 17% of the total time required for EPC activities.
- To achieve "Round The Clock" power, Solar PV EPC projects are being combined with smaller energy storage capabilities as well.

[26] IRENA, Measuring The Socio-Economic Footprint Of The Energy Transition: The Role of Supply Chains

3.6 Operation and Maintenance: Automation and IoT are the future

Solar Operations and Maintenance (O&M) activities are essential in ensuring that plan performance is at par with project expectations and regulations. Quality of O&M is also a major influence on risk and return considerations for investors in utility scale solar applications.

As per NREL, PV operations include the following key areas:

Administration of operations

Ensures effective implementation and control of O&M services including curation of as-built drawings, equipment inventories, owners and operating manuals, and warranties.

Conducting operations

Ensures efficient, safe, and reliable process operations including making decisions about maintenance actions based on cost/benefit analysis

Directions for the performance of work

Specifies the rules and provisions to ensure that maintenance is performed safely and efficiently, including the formalization and enforcement of safety policy [including training for direct current (DC) and alternating current (AC)] safety, rooftop safety, minimum staffing requirements, arc flash, and lockout/tag-out); work hours; site access, laydown areas and parking; and any other stipulations under which work is performed.

Monitoring

Maintains monitoring system and analysis of resulting data to remain informed on system status, metering for revenue, alarms, diagnostics, and security monitoring.

Operator knowledge, protocols, documentation

Ensures that operator knowledge, training, and performance will support safe and reliable plant operation.

PV maintenance includes the following procedures:

Administration of maintenance

A This overlaps with “administration of operations” and ensures effective implementation, control, and documentation of maintenance services and results.

Preventive maintenance

Scheduling and frequency of preventive maintenance is set by the operations function and is influenced by a number of factors, such as equipment type, environmental conditions at the site (e.g., marine, snow, pollen, humidity, dust, wildlife), and warranty terms.

Corrective maintenance

Required to repair damage or replace failed components. It is possible to perform some corrective maintenance such as inverter resets or communications resets remotely.

Condition Based maintenance

Condition-based maintenance is the practice of using real-time information from data loggers to schedule preventive measures such as cleaning or to head off corrective maintenance problems by anticipating failures or catching them early.

Insights and Trends

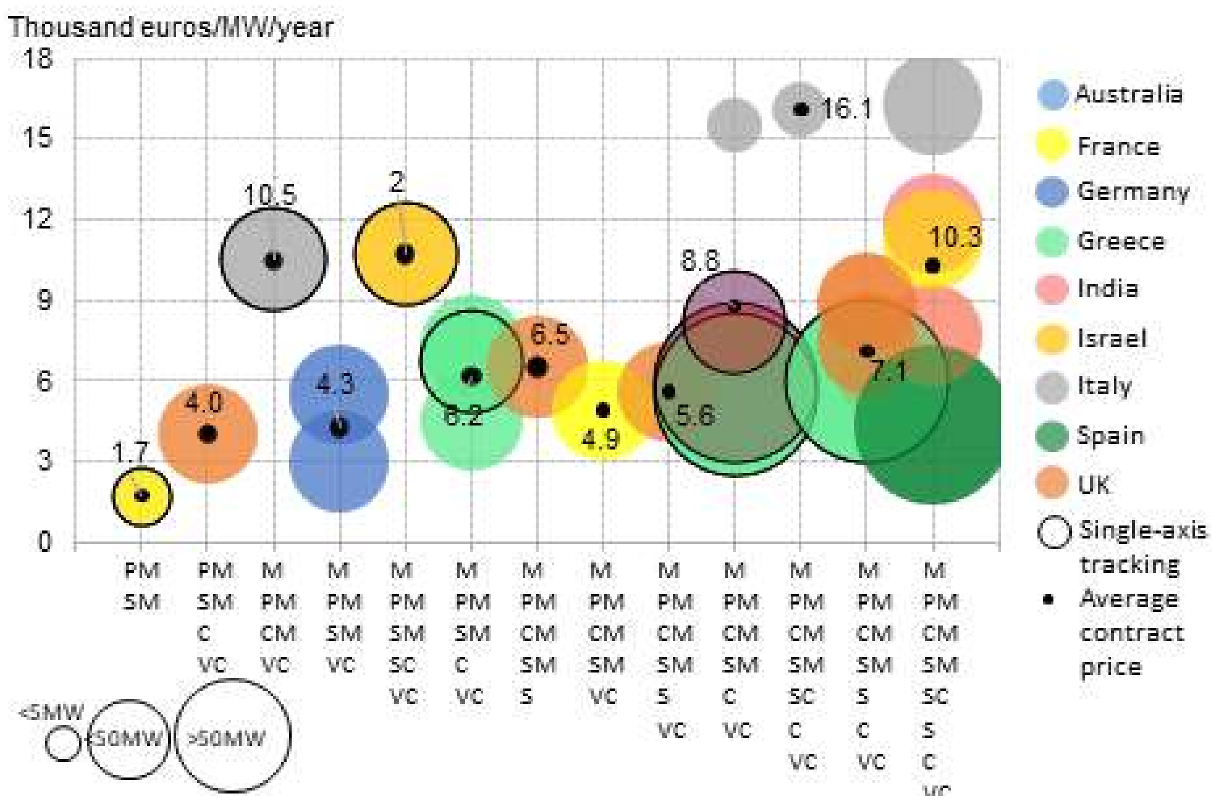
As solar equipment and plants become increasingly optimized, a number of O&M activities such as solar module cleaning, electrical equipment audit and maintenance are seeing increasing use of automation. Some innovative solutions for O&M of solar PV power plants have been highlighted below:

- **Remote Monitoring via Drones:** The usage of drones for surveillance and monitoring can replace the need for manual inspections. Drones are easy to operate and allow for long range inspection. Additionally, drones can be fitted with a variety of sensors and cameras (e.g. Thermal sensors) to identify anomalies in the plant. Finally, the usage of Machine Learning for video analysis can minimize the need for human inspection of captured data/ footage.
- **Power Output forecasting:** The variability of PV generation brings the challenge of accurate forecasting of generation in order to ensure grid stability. Thus, a number of solutions have been created to improve forecasting accuracy. Simulation models and meteorological forecasting for PV plants are well established technologies, and algorithms that match weather forecasts with plant parameters can assist with hourly forecasts for a 48 hour period. With the need for accurate forecasting apparent, the collection and utilisation of near- real time data at significant granularity can improve forecasting capabilities. Solar monitoring systems will thus play a key role in solar plant operations, and further accelerate the deployment of IoT devices at solar sites.
- **Smart plant monitoring for maintenance:** Smart plant monitoring and increased data collection also allows for root cause analysis for failures and underperformance. Smart plant monitoring can thus help with preventive or emergency automated maintenance, intervention management and rescheduling, and algorithms for equipment or plant behavior and reliability predictions based on historical failure data and simulation models.
- **Retrofit Coatings for PV modules:** The deployment of post-production coatings on solar modules can help address challenges that are commonly faced during plant operations. For example, high temperatures affect PV module lifetime and performance. PV coolants and PV-T systems are also utilised but bring cost and complexity related hurdles. In this context, the deployment of a silica based transparent coating can help reduce module temperatures by reflecting non absorbable light wavelengths away from the panel, thus reducing heating while increasing panel efficiency.

- **Anti-Soiling solutions:** Soiling due to dust and grime accumulation on solar panels can significantly impact power generation in plants, especially in regions with limited rainfall. Thus, regular cleaning of solar panels is carried out, and several anti-soiling solutions are being developed. Sprinkler and soap dispensing systems are utilised effectively but require significant water consumption. Robotic panel cleaning solutions have also been developed that required significant investment but utilise less water and are effective in regions with high labour costs. Additionally, Anti soiling coatings have been developed that get dirty less quickly, making panel cleaning easier and allowing for reduced impact to performance.

- **Biotechnology/ Seed Selection for Zero Vegetation Treatment:** Shading due to vegetation at the plant site is a potential drag on plant performance. Although pesticides and other methods exist for vegetation control, safer alternatives are being developed. These include the use of weed control fabrics at suitable locations in and around the modules and plant perimeter to limit weed growth. Additionally, planting of seeds with slow growth and limited height can help reduce the need for maintenance.

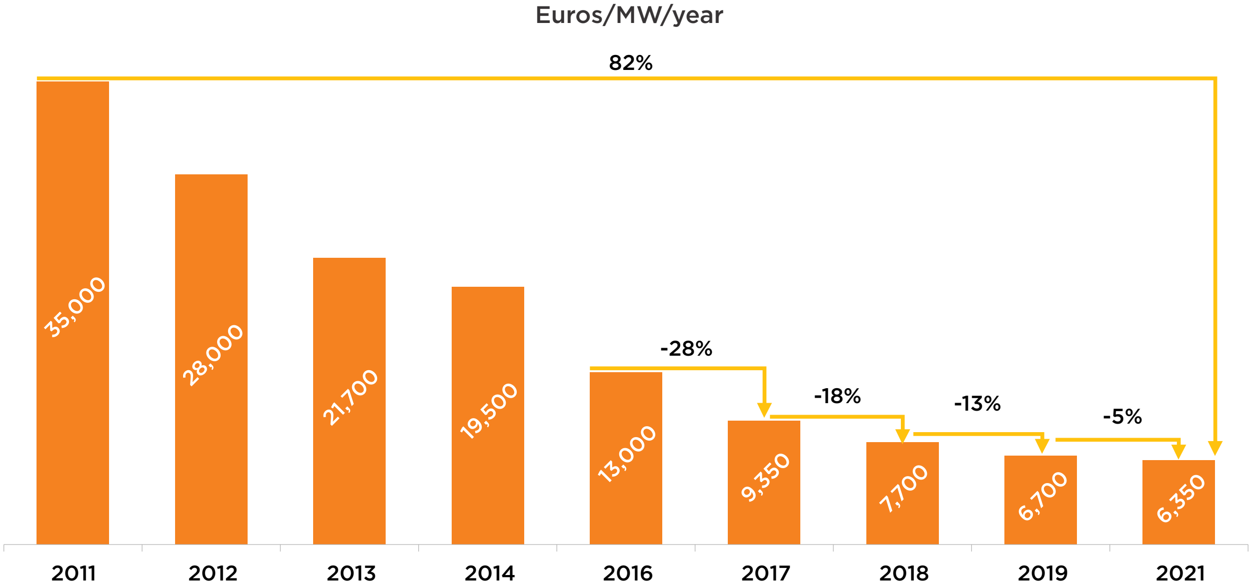
Solar O&M contracts vary significantly in cost and contract scope, with a number of offerings available in the market. It is interesting to note how country level O&M costs vary significantly even for nations in similar regions and with presumably similar labour costs. For example, O&M costs in Italy appear to be more expensive than identical O&M costs in other European countries. Additionally, more comprehensive O&M contracts are undertaken by plants with greater than 50 MW capacity, and these larger plants also show lower O&M costs.



Source: BloombergNEF.

Note: Bubble sizes represent project capacity. M: monitoring; PM: periodic maintenance; CM: corrective maintenance; SM: spares management; SC: spares costs; S: security; C: cleaning; VC: vegetation control.

The cost of PV O&M has declined rapidly over the past decade



Source: BloombergNEF

The average cost of a full scope PV O&M contract in Europe has declined by more than 80% in the past decade. This decline has flattened out slightly in the last 3-4 years but the fall in costs are a testament to the increasing capability of O&M technologies to solve PV plant challenges cost effectively.

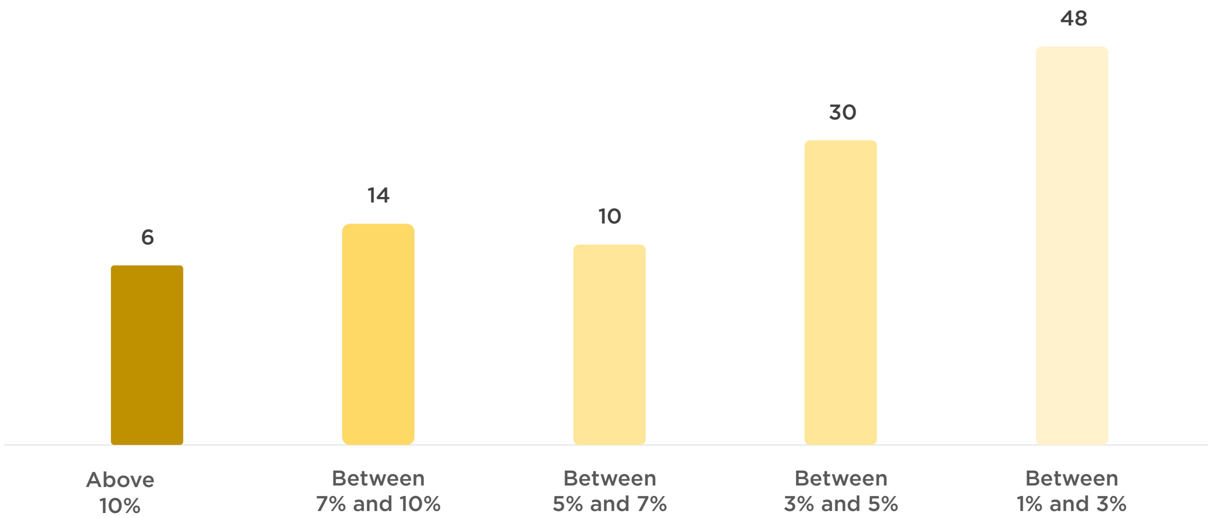
Key Takeaways

- O&M of a solar power plant is essential for ensuring optimum plant performance.
- Modern O&M solutions such as remote monitoring via drones, anti-soiling solutions, biotechnology for Zero Vegetation Treatment ensure minimum human intervention.
- Smart plant O&M technologies allow for a quicker root-cause analysis, resulting in better upkeep of the plant.

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

In the last two decades, the share of solar and wind in the total global energy mix has risen from almost zero to 3.7% and 9.3% respectively. Given that the world is undergoing a clean energy transition, the share of wind and solar is going to increase dramatically in the coming years. There are currently 8 countries that source more than 30% of their total electricity demand via solar and wind energy. Some of these countries such are Denmark, Uruguay, Luxembourg, Lithuania and Ireland. There are 49 countries which have at least 10% of their electricity being sourced from solar and wind energy sources. A few countries have solar energy generation share of greater than 10% of their electricity mix, and this number is all set to grow in the future as installations continue to grow.

Regionwise Penetration of Solar PV in Overall Electricity Mix



Source: BloombergNEF.

New solar PV capacity 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.

Although it is imperative that the world moves towards renewable energy sources, it is not sufficient to simply increase their capacity. With increasing generation, the rising share of solar PV in the grid poses a number of challenges to grid stability. Issues such as voltage instability, loss of power flexibility, frequency mismatch, nonsynchronous generation, harmonics and islanding, to name a few, lead to this potential instability. These challenges get amplified as the variable renewable share in the grid system increases and must be suitably addressed in order to achieve terawatt scale solar installations.

Stage	Characteristics	Challenges
1	VRE has no noticeable impact on the system	
2	Minor to moderate impact on system operation	Minor changes to operating pattern of existing system
3	Determines operation pattern of system	Greater variability of net load and changes in power flow pattern
4	Periods where VRE makes up almost all generation	Power supply robustness during periods of high VRE generation
5	Growing amounts of VRE surplus (Days-Weeks)	Longer periods of surplus/deficit of electricity
6	Seasonal or inter-annual surplus or deficit of VRE supply	Requirements of seasonal storage and use of synthetic fuels or hydrogen

IEA Phases of VRE Integration

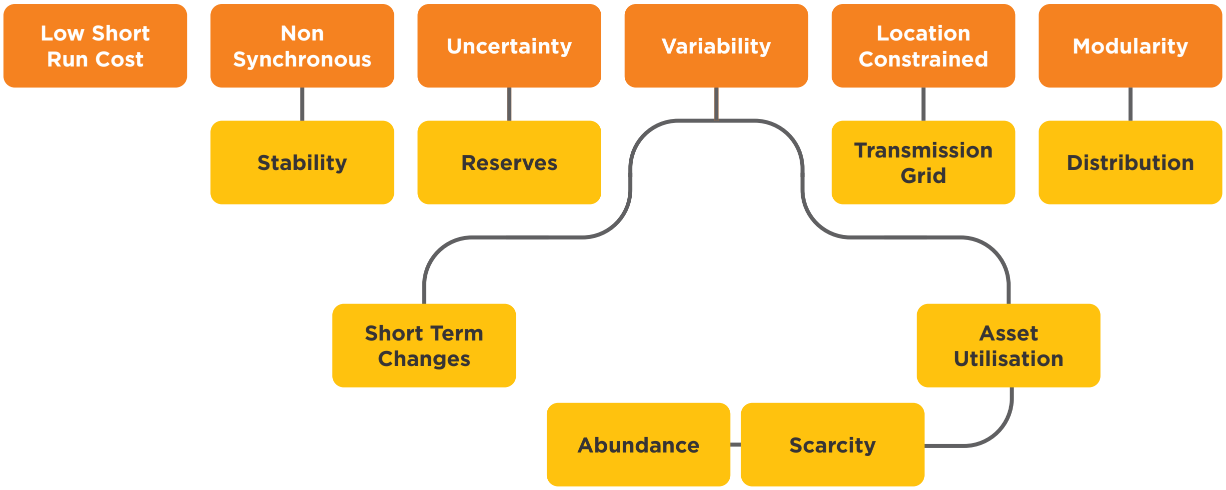
Source: Introduction to system integration of renewables

Key Messages:

- Globally 8 countries source more than 30% of their electricity demand via solar and wind energy.
- Development of new fossil fuel powered capacity is being halted in some regions,
- High penetration of VRE often leads to grid instability due to loss of power flexibility, frequency mismatch, nonsynchronous generation etc.

4.1 Managing high share of solar requires supply and demand side measures

Solar energy, with all its potential upsides, has certain limiting factors. Since solar energy is dependent on the availability of sun, it can only be generated during the daytime, and that too is limited at times due to cloud cover and rain.



Seconds	Years		>100km	<<1km
Stability	Balancing	Profile/ Utilisation	Location	Modularity

Properties of Solar, and their impacts on the electricity grid

The variable nature of solar energy leads to a number of challenges to grid stability, which are barriers to large-scale, cost-effective grid integration. This inability to integrate significant amounts of solar PV generation can in turn reduce the value of solar energy and lead to capacity/generation going to waste. In some cases, the challenge to grid integration may not be simply technical in nature. For example, a grid may be able to accept solar generation but may be unable to do so due to economic considerations and costs. Thus, identifying and understanding the reasons that grid integration is a challenge is important prior to addressing them.

The major challenge areas associated with grid integration of PV systems include:

1. **Forecasting:** In a traditional electricity grid, operational uncertainties in the grid usually occur due to demand fluctuations. However, the large scale integration of variable renewable energy resources such as solar PV with the power grid introduces supply side uncertainties as well. PV generation can be volatile due to varying climatic conditions, which can make generation difficult to predict.

2. **Voltage stability:** A flat voltage profile with minimal variations requires a constant generation source that can adapt to grid demands. However, solar PV generation varies depending on the position of 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.

3. **Frequency response:** Grid integration of PV systems can increase the probability of imbalances between generation and demand due to the inherent intermittent nature of the technology. These imbalances may lead to frequency fluctuations, that can in turn lead to loss of electrical supply.

4. **Reactive power:** Since solar generation is outputted as DC current, it lacks the capability to provide reactive power, which is inherent to AC current. Since variable renewable energy sources are connected to the grid through frequency converters, they are unable to contribute to grid inertia, which in turn leads to susceptibility of frequency shocks.

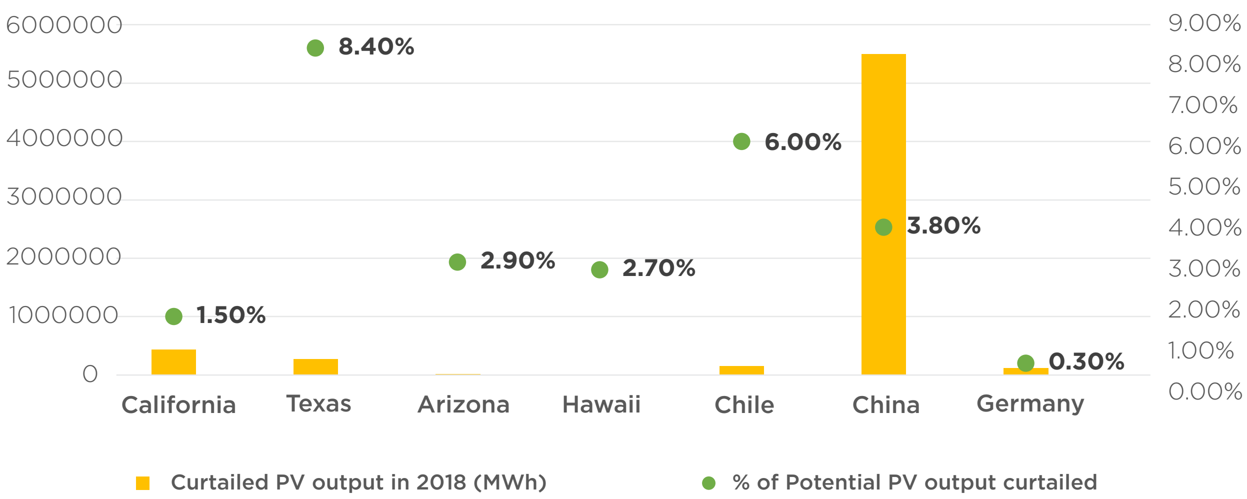
5. **Harmonics/power quality:** The electronic converters employed to integrate PV into the grids introduce harmonics that can damage the equipment connected to the network and reduce their efficiency and lifetime.

6. **Islanding:** Due to the increase in deployment of distributed renewable energy, situations may arise where the distributed generator is powering a system in the absence of an external grid connection due to outages etc. Although intentional islanding may be carried out in some cases (Such as for microgrids in remote locations), unintentional islanding may result in safety hazards and lack of frequency and voltage control.

7. **Grid Security:** The advent of variable renewable energy has coincided with the development of smart grids in order to optimize performance. As grids are increasingly digitized and connected through IoT/smart systems, the new risk of cyber-attacks needs to be addressed. Ensuring that grids are resilient to threats such as ransomware, electricity theft, control disruption, and data theft requires a new focus on hardware and software security.

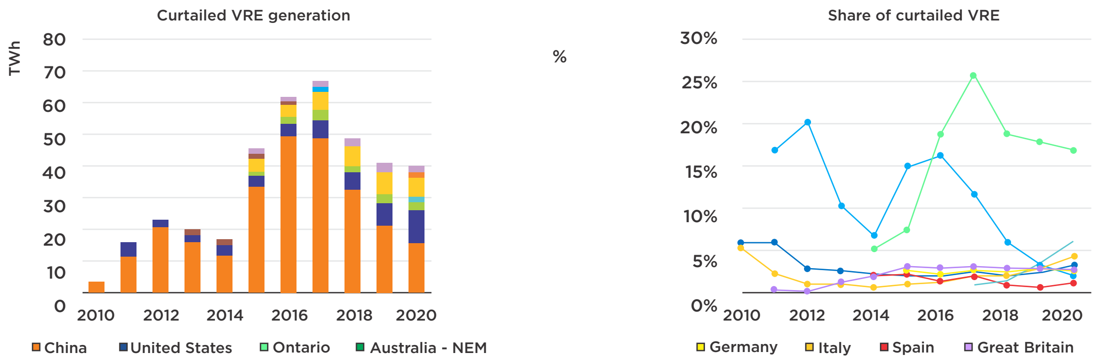
Most modern grids operate under some form of constrained economic dispatch, maintaining system reliability and flexibility at the lowest possible cost. To decrease the instability a grid might face due to above mentioned factors, , curtailment of power via VRE is expected to increase. VRE curtailment 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.

PV Curtailment Statistics in Key Markets (2018)



Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7470769/#:~:text=Recently%2Dpublished%202019%20estimates%20suggest,output%20(CAISO%2C%202019a).

Figure 1.11 Wind and solar PV generation curtailment by country



Notes: NEM = National Electricity Market: VRE = variable renewable energy. The graphs represent officially reported curtailed or constrained energy and also combine various curtailment schemes depending on the country.

Sources: Bundesnetzagentur (2020), Netz- und Systemsicherheit; China Energy Portal (2021), 2020 Wind Power installations and Production by Province; LBNL (2021a), Curtailment Data; IESO (2020), 2020 Year in Review; AEMO (2021), Statistical Reporting Streams; GSE (2020), Rapporto delle Attivita 2019, (2021a), El sistema electrico espanol sintesis; REF (2020), Balancing Mechanism Wind Farm Constraint Payments.

Source: IEA Renewables 2021

It is also important to note that countries in different global regions may differ in the share of solar PV electricity that they are able to integrate into their grid. This variation arises in part due to the differing characteristic of the electricity supply mix across countries. For example, countries in the APAC region relying on significant coal fired capacity may lack the ramp-up/ramp-down capabilities that their counterparts in Europe may possess due to usage of gas fired plants. This in turn may hamper the integration of solar energy in those grids.

Key Messages

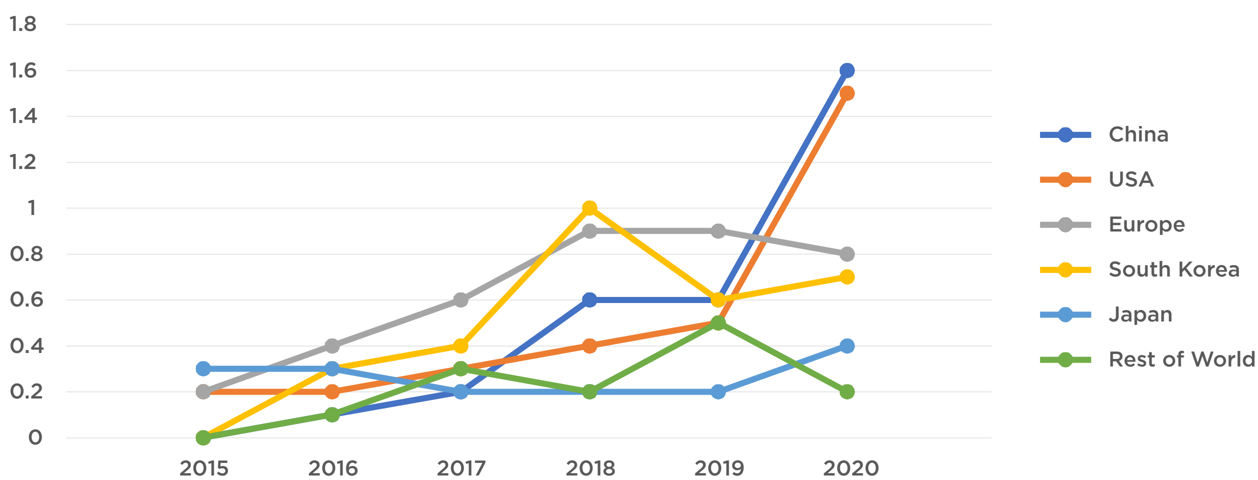
- **Variable nature of solar energy leads to a number of challenges to grid stability.**
- **Power forecasting, voltage stability, frequency response, power quality, reactive power, islanding and grid security ae some of the challenges leading to curtailment of solar PV.**
- **Curtailment of solar energy in grid can be due to technical issues as well as due to economic considerations and costs.**

4.2 Enabling technologies to enhance solar penetration in electric grids: A varied toolbox is in place

Solar energy, with all its potential upsides, has certain limiting factors. Since solar energy is dependent on the availability of sun, it can only be generated during the daytime, and that too is limited at times due to cloud cover and rain.

- **Energy storage deployment:** 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 Battery Energy Storage Systems (BESS) are emerging as a key technology, with potential for both utility scale and distributed deployment. However, many storage technologies, currently entail high up-front costs. Storage additions are being driven by a few key countries, including the USA and China. Utility scale installations dominate the market and account for two-thirds of total added capacity[27].

Annual Energy Storage additions by country (GW)



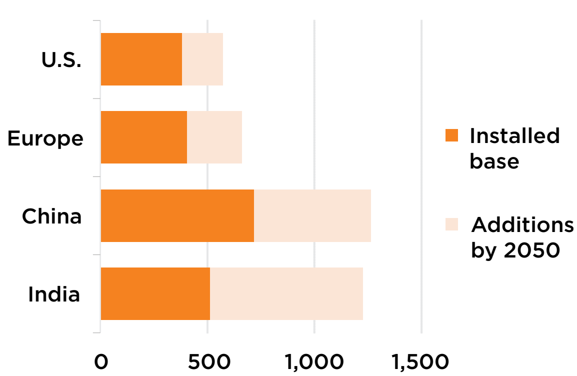
Source: IEA Energy Storage Tracking Report: November 2021

- **Demand side management:** Demand side management initiatives aim to control electricity demand by encouraging consumers to change the amount and pattern of electricity utilised by them. Creating flexible electricity loads can allow for them to be planned or shifted in a manner that best absorbs excess PV output based on generation peaks. This shifting of electricity demands may be achieved through Time-of-Day tariffs and demand charges for peak loads. This can serve as a cost effective solution to ensure solar integration. However, demand side initiatives rely on voluntary enrolment and actions of various grid actors and customers.

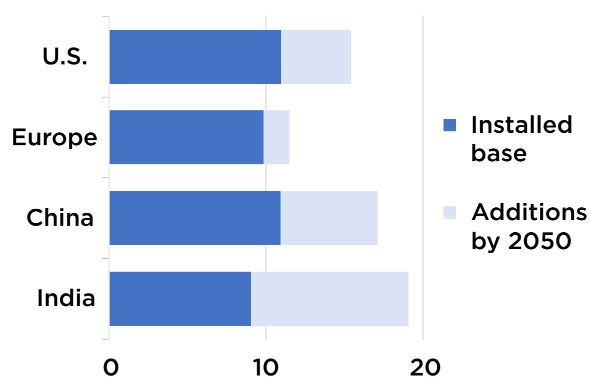
[27]https://www.iea.org/reports/energy-storage

- **Expansion of grid infrastructure and interconnections:** Improving inter and intra-regional grid interconnections help improve supply security, system efficiency, and integration of variable renewable energy such as solar. 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 load 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 for reducing curtailment, such as in Germany. However, it is limited by transmission constraints and challenges associated with building expensive new transmission infrastructure. India and China are expected to lead transmission and distribution grid infrastructure growth in the coming decades.

Transmission Grid Length, thousand km



Distribution Grid Length, million km

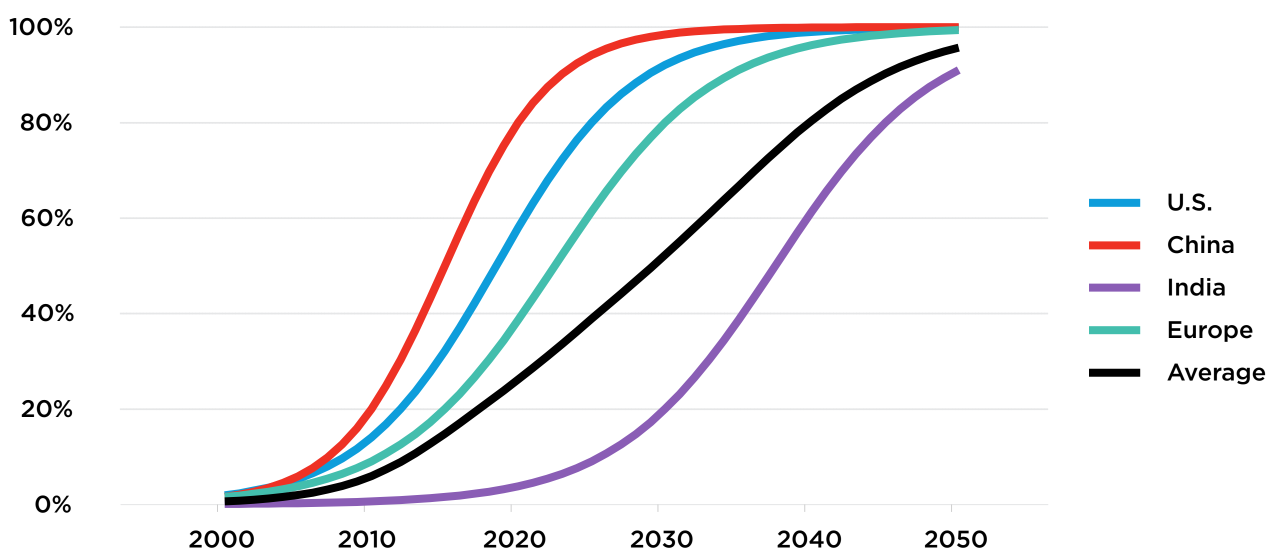


- **Flexible generation capabilities:** Investments in flexible assets that allow the grid to respond more effectively to changes in PV supply can allow for greater grid integration of solar energy. Traditional power plants can also provide the system inertia that is otherwise absent in solar sources. This can allow power grids to leverage existing grid assets. However, some flexible assets using fossil fuels such as coal or natural gas may be incompatible with clean energy mandates.

- **Improved market design:** Electricity markets can be designed in a way to optimize operational efficiencies and give appropriate investment signals. Long, medium, short term markets exist for renewable energy. Of these, short term markets assist variable renewable energy integration significantly, as they can allow players to re-optimize and re-balance their portfolio on a near real-time basis with minimal forecast errors. The ancillary service market can also help provide the required interventions to help maintain demand-supply balance in the grid and ensuring that voltage and frequency fluctuations remain within safe limits. The development of localized energy markets, based on microgrids and distributed solar PV generation, can also help with solar integration in the grid, particularly in locations with network constraints.

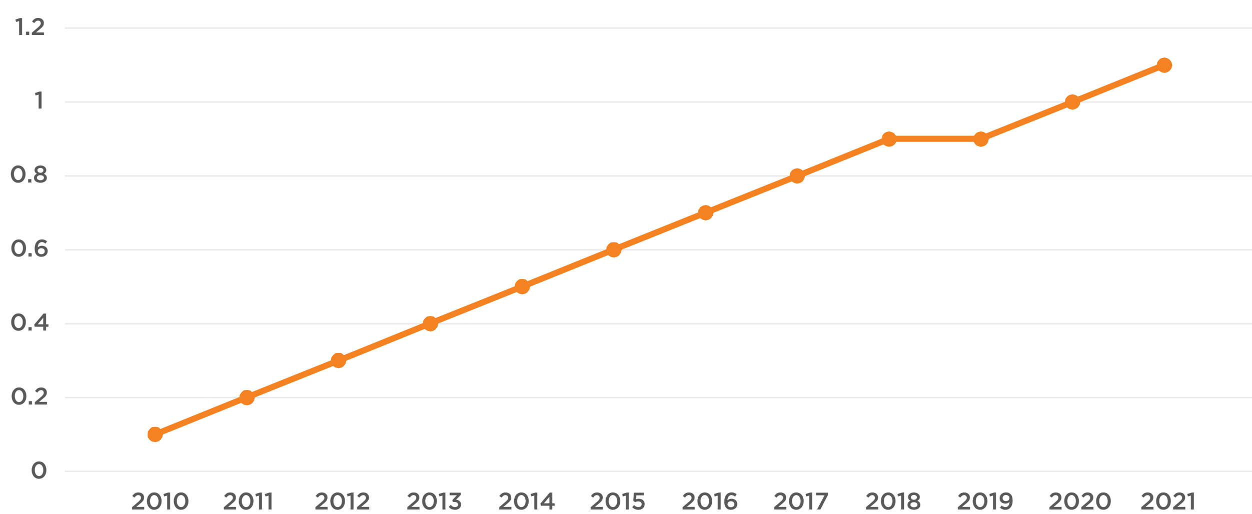
- Digitalization and smart grid integration solutions: Digitalization of grid assets brings a number of benefits, including access to real time data, remote management capabilities, increased efficiency, and enablement of distributed generation. The degree of digitalization in the grid is now also impacting the potential for grid integration of renewables, including solar power. The utilisation of digital technologies and smart grids allows for improved system integration through better demand response capabilities. This can allow for reduced curtailment of variable renewable energy. The presence of a digitalized grid also facilitate the connection of distributed renewable energy resources such as rooftop solar plants, with the wider grid, further improving the share of solar in the grid.

Percentage of asset base digitalised in terms of smart meter adoption rates



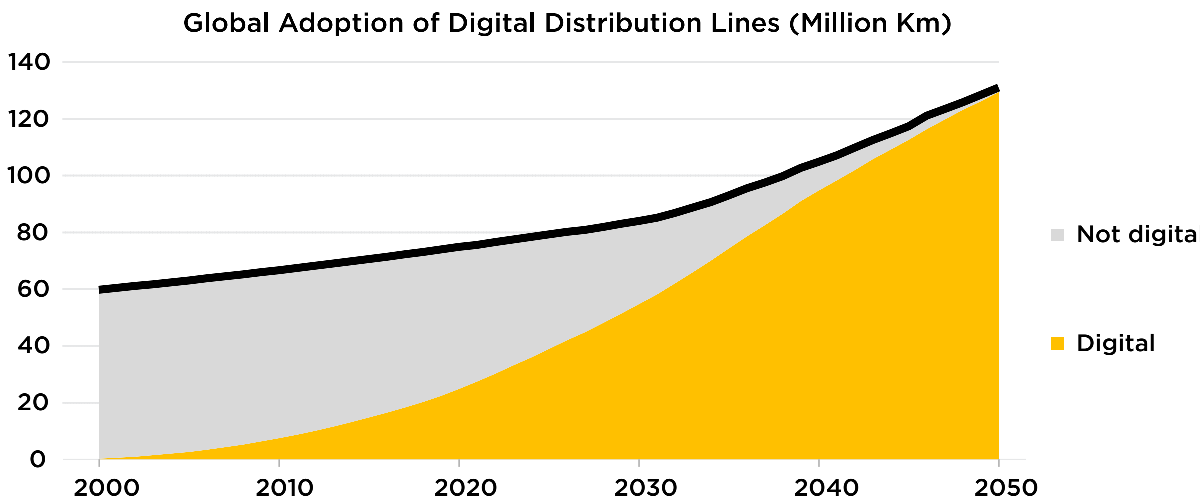
Source: BNEF Power Grid Long-Term Outlook 2021

Global Smart Meter Deployment (Billions of units)



Source: IEA Digitalization Tracking Report 2022

The digitalization of grid assets has begun in earnest, but progress varies significantly across various countries and regions. China has achieved significant digitalization, with over 80% of assets digitalized by 2021. The USA and Europe trail slightly behind, with adoption in India yet to achieve scale. Cost of upgradation/replacement of grid assets, lack of technical knowhow and institutional capacity, and lack of awareness on smart grid benefits are some of the reasons that can hamper adoption of digital assets. However, increasing variable renewable energy generation, greater distributed generation, and imminent widespread adoption of demand side applications such as EV charging, net metering for small scale solar and behind the meter energy storage should help drive smart grid growth around the world.



Source: BNEF Power Grid Long Term Outlook 2021

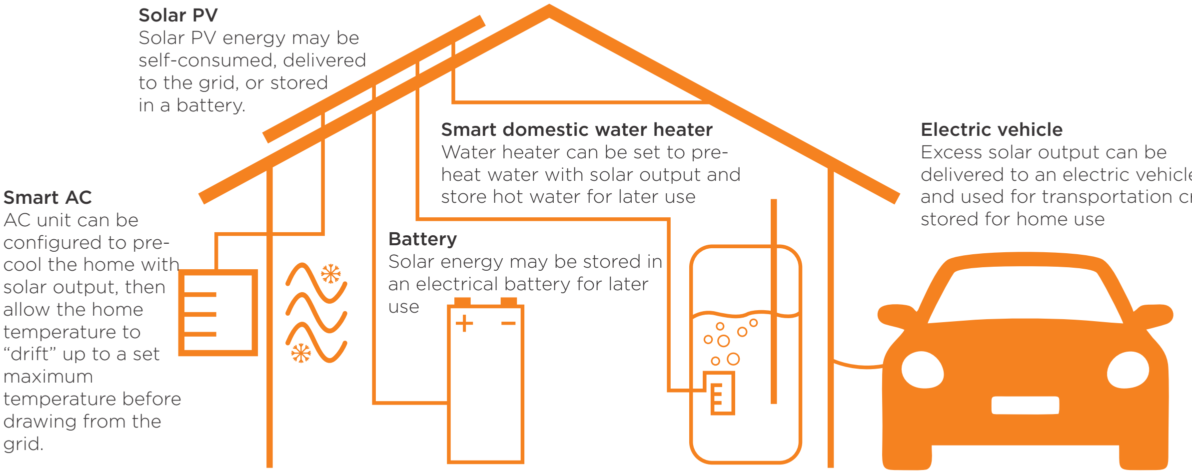
It is important to note that each of the solutions highlighted above exist as part of an overall solution. There is no one single option that can address grid integration challenges. Instead, it is important to utilise the appropriate available solution to tackle a specific grid integration challenge effectively. The technical toolset for large scale grid integration of renewables, and even round the clock renewable energy supply, is in place. However, markets for these solutions need to be developed in order to make solution deployment feasible across different countries.

Key Messages

- **Some key solutions to tackle grid integration issues are- energy storage, demand side management, expansion of grid infrastructure, flexible generation capacities, improved market design and adoption of digitalization and smart grid solutions.**
- **Battery Energy Storage Systems (BESS) are emerging as a key technology, with potential for both utility scale and distributed deployment.**
- **Increasing variable renewable energy generation, greater distributed generation, and imminent widespread adoption of demand side applications such as EV charging, net metering for small scale solar and behind the meter energy storage should help drive smart grid growth around the world.**

Smart Homes

A Smart Home is a bundle of solutions that can include monitoring, automated control and optimisation of the energy consumption of a household, taking into account consumers' comfort while also allowing for demand side management from a grid operators perspective.



Source: NREL

- Deployment of monitoring technologies such as smart meters will allow for homes to monitor electricity data on a near real time basis. Through other IoT devices or Machine Learning analysis of load patterns, appliance level electricity demand and usage can also be tracked. Thus, households are set to have the most ever data on their electricity usage.
- This newfound data and energy management capabilities can dovetail well with the development of residential solar systems for captive consumption, or potential feeding back into the grid through net metering mechanisms. This deployment may be through a variety of applications, including rooftop solar and building integrated Photovoltaics.
- Residential solar can also find synergies with other electricity-based applications such as EV charging (including through solar carports). This also opens avenues for the use of Behind the Meter storage to assist with maximizing solar generation potential, providing demand management or off-peak supply, or avoiding demand spikes during high load applications such as EV charging.

Solar Asset Management

Uses of IoT and data analytics for O&M services:

1. Improved Asset Performance: By combining different data like solar radiation, temperature, wind speed, dust levels and energy outputs of individual panels, grid managers can identify low-performing units and potential causes. This helps optimize reparation and maintenance planning to enhance asset performance.

2. Minimum manual intervention: With granular visibility, technicians can locate and troubleshoot the error sources from their workstations, hence minimum time spent over troubleshooting. With IoT, performance indicators such as String voltage, inverter performance, system output, battery voltage levels etc. are being observed, to identify the exact component where system inefficiency might be taking place.

3. Effective Production Forecast: With multiple data models at hand for sun irradiation, wind patterns, temperature etc., companies can effectively forecast the daily power production, which can then lead to improved grid stability.

4. Theft and Vandalism Protection: An IoT-based monitoring system is also a powerful tool to help protect solar panels against theft and vandalism attempts, especially in rural areas. For example, IoT sensors can detect suspicious movements around a panel or if it is dismantled from the supporting structure. An alarm can then be automatically triggered for operators to timely intervene.

4.3 Country Specific Case Studies

The integration of significant amounts of solar generation have already been seen in select countries and regions. These may be studied in order 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.

Germany

Germany added ~6 GW of solar PV capacity in 2021 and solar PV accounted for around 10% of electricity generation in 2020 . In 2021 renewable energy sources produced more electricity than all fossil fuels (coal, gas, oil) combined together and now provide 41.1%of German electricity demand. Addition of such large quantity of installed solar capacity can lead to a high probability of grid instability. Despite this, Germany has managed to ensure that its grid remains stable through various flexibility measures.

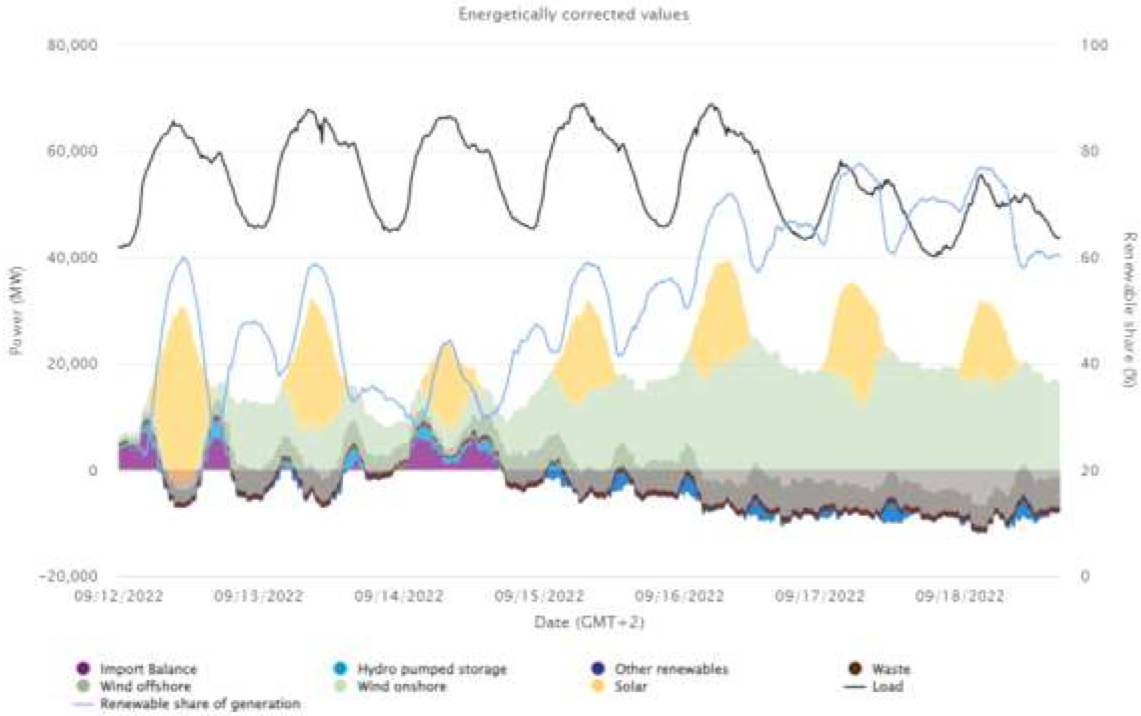
0.3% of potential Solar and Wind output curtailed in 2018

Share in gross final energy consumption reached 19.7 percent in 2021

The interconnected power network in Europe has assisted the German grid by allowing the country to manage both oversupply and undersupply situations. The European grid has sufficiently strong technical infrastructure in place to allow it to handle significant quantities of variable renewable energy. Thus, during the Covid 19 pandemic, the country was a net importer of electricity after being a net exporter for several years . Germany is also the leading European market for energy storage, although emphasis has shifted away from utility scale storage to behind the meter installations in recent years.

The chart below shows net public electricity generation in the country for the week of 12-18 September 2022. It can be observed that apart from a few periods in the early part of the week, the country is primarily exporting energy to the European grid. Additionally, a very high share of renewables can be seen in the electricity generation mix.

[28] https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf
[29] https://www.sciencedirect.com/science/article/pii/S0360544222002067



Source: Fraunhofer ISE Energy Charts

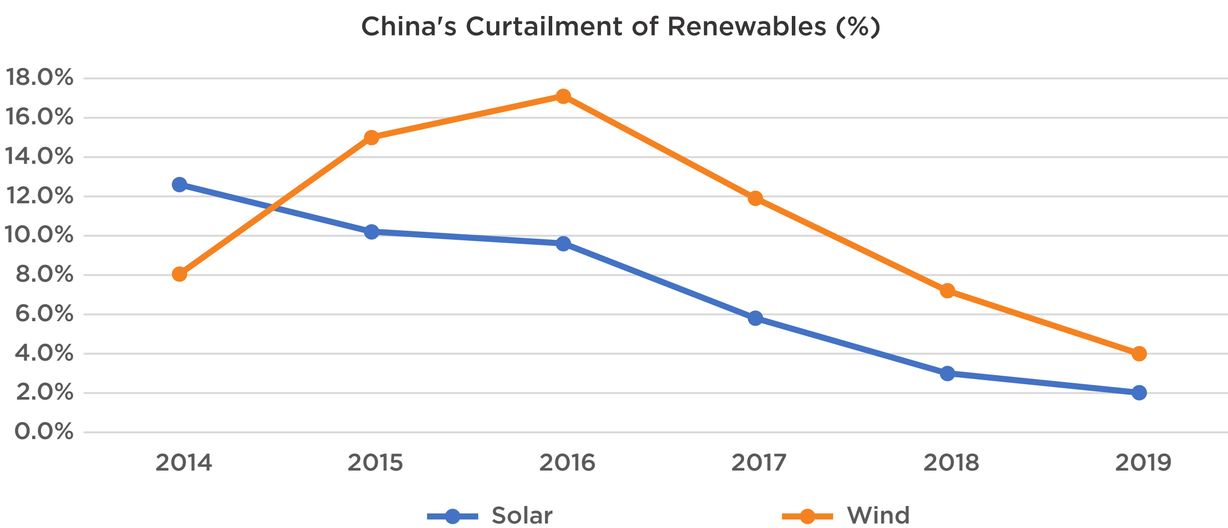
However, there are further challenges for Germany to address. The conflict in Ukraine and associated disruption of natural gas supplies to Germany has made renewables integration all the more vital for the country. However, the planned rapid expansion in renewable energy capacity will require development of suitable enabling infrastructure such as battery capacity, Peaker plants, and high voltage transmission lines. Additionally, Germany already has some of the highest electricity prices in the world, which will make this transition challenging for consumers. Although significant challenges lie ahead, Germany's track record of utilising renewables to meet electricity, heating and cooling demands gives reason for optimism.

China

China has seen significant solar capacity additions in the last decade, culminating in a record 54.8 GW of installed solar capacity in 2021. This annual installation took the country's overall solar capacity to 308 GW by end 2021[30]. China also faces the challenge that its wind and solar resource rich provinces are located in the far west region of the country. 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 if excess power which cannot be transported across the country. The country also lacks sufficient peak shaving capacity within its power system, further increasing the likelihood of curtailment.

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[31]. 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%[32].

Source: BNEF Power Grid Long-Term Outlook 2021



Source: BNEF Power Grid Long-Term Outlook 2021

[30] Solar Power Europe Analysis
[31] https://www.bloomberg.com/news/articles/2022-06-06/china-s-renewable-energy-fleet-is-growing-too-fast-for-its-grid-l425v47z
[32] https://www.solarpaces.org/chinas-curtailments-go-up-as-renewables-growth-explodes/

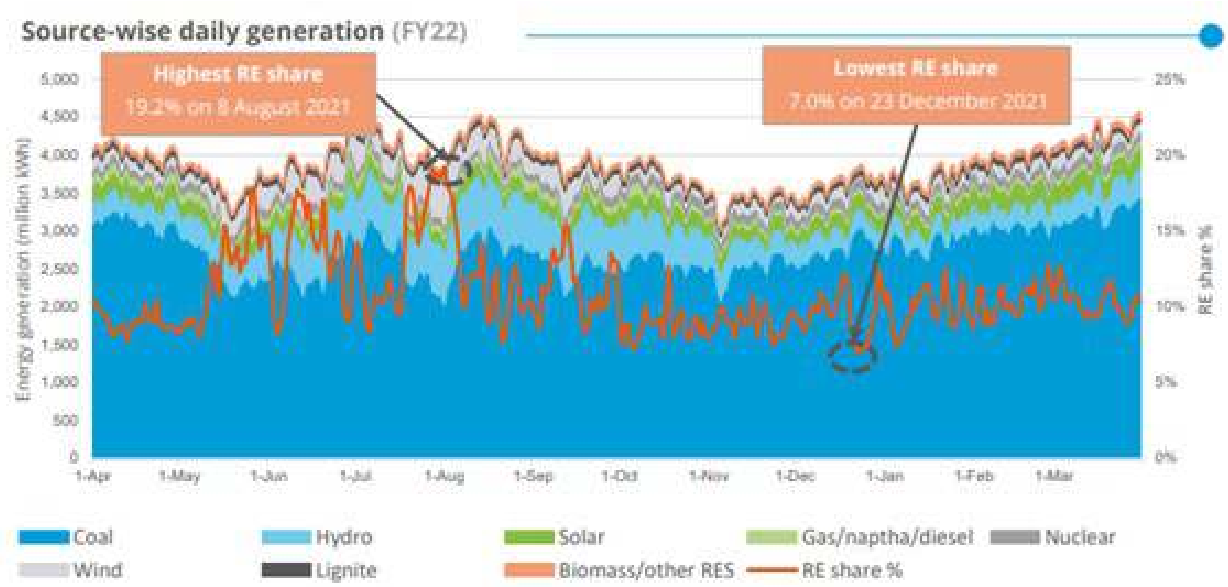
In order to tackle the threat of increasing wind and solar power curtailment, China is developing its long distance power transmission infrastructure to effectively shift excess generation to high electricity load areas. China State Grid is set to begin work on USD 22 Billion of Ultra High Voltage (UHV) power lines to connect solar, wind and hydro plants in far western regions to large cities and load centres. Eight such UHV projects are to be developed with this investment, and a further 11 such UHV projects are already under construction[33]. The country is also investing in new energy storage solutions in order to help manage increasing solar and wind generation. The country aims to install more than 30 GW of "new" energy storage capacity by 2025. This new storage capacity will include technologies such as flywheel storage, battery based solutions, compressed air, and super capacitor systems, but excludes pumped hydro storage[34].

[33] https://www.reuters.com/business/energy/chinas-state-grid-invest-22-bln-ultra-high-voltage-power-lines-report-2022-08-03/
[34] https://www.reuters.com/business/energy/china-aims-install-over-30-gw-new-energy-storage-by-2025-2021-07-23/

India

India has set ambitious targets to achieve 450 GW of renewable energy capacity by 2030, with solar PV capacity expected to reach around 280 GW by the same year[35]. The country has already achieved 114 GW of renewable capacity, of which 57.7 GW is solar.

Despite the significant renewables share in the country's capacity, non-hydro renewables accounted for only 10.8% of total generation during FY22. Thus, the rapid increase in installed capacity has not yet translated into a high share of renewables (which are primarily solar) into the grid due to integration challenges.



Source: CEEW Market Handbook FY22

Several factors constrain the capability of the Indian grid to accept significant quantities of renewable energy. Renewable, and more so solar capacity is concentrated in certain key states, resulting in system integration challenges. Additionally, India's Transmission and Distribution sector lacks the necessary infrastructure and technologies to handle significant amounts of variable renewable energy (VRE). Indian discoms also follow a merit order dispatch system, and will prioritize financial benefits when choosing electricity sources, resulting in an economic rationale to curtail renewable energy.

Measures are being taken to prepare the Indian grid for future VRE projects. An increasing number of tenders for grid scale energy storage are being announced, while future renewable energy tenders will also have storage components. These Round-The-Clock (RTC) tenders will help make solar generation easier to integrate into the grid. Additionally, India has taken market measures to help minimize renewable energy curtailment. The Indian Energy Exchange (IEX) has launched the Green Term Ahead Market (GTAM), a power trading to allow bulk electricity buyers to procure renewable energy on a short term basis. The market supports contracts with timescales ranging from intra-day (at 15 minute intervals) to weekly. The GTAM platform will help in the sale of surplus renewable electricity, further minimizing curtailment. The development of interstate grid connections and green corridors, demand side management through tariff reforms, and improved monitoring, and regulation through smart meter deployment will all contribute to making India's grid stable.

[35] Report on Optimal Generation Mix for 2029-30, Central Electricity Authority (Published January 2020)

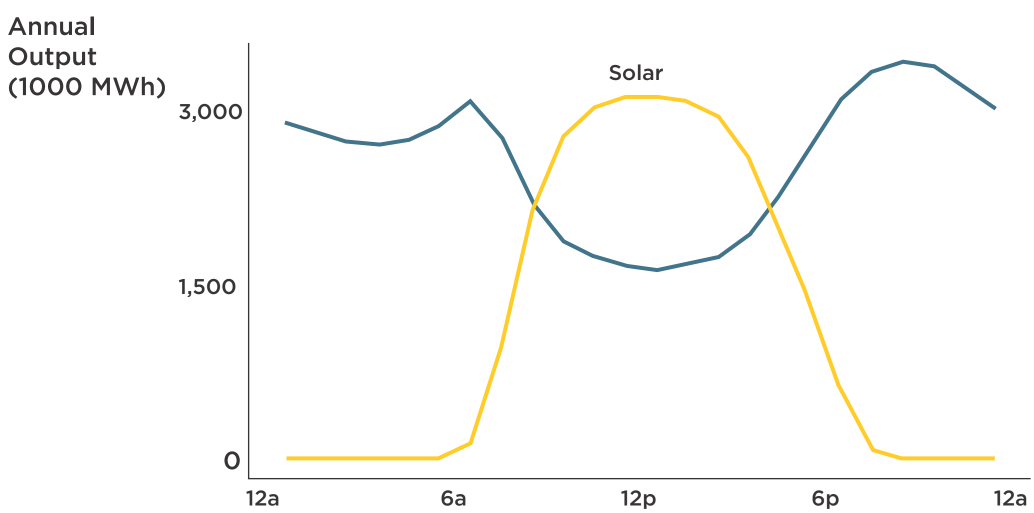
USA (California)

California has the largest solar PV capacity of any state in the country, estimated to be a little under 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 state saw curtailed 5% of its utility scale solar production in 2020, amounting to 1.5 million MWh[36]. Solar accounts for around 95% of the total generation curtailed by CAISO. This curtailment is a function of the large amount of PV capacity in the state. PV curtailment in CAISO is implemented through negative pricing, decremental bids, or manual curtailment when market signals don't suffice.

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 systemwide, and not purely in areas with transmission constraints.

Despite this high solar PV capacity and slight mismatch of peak loads and demand, California is able to 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.



Daily generation profiles in CAISO for PV and other generation resources

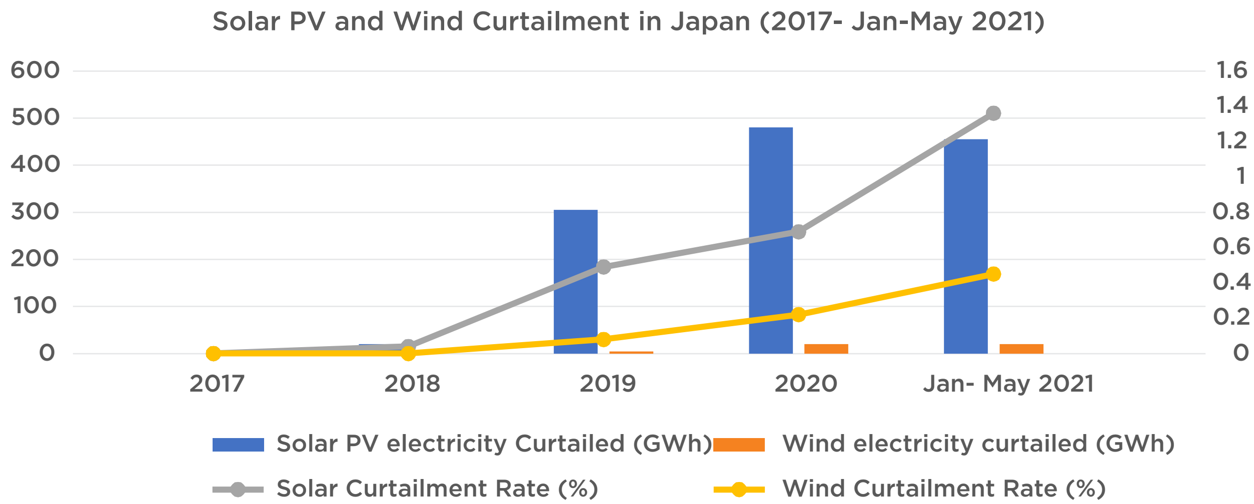
Conceptually, CAISO is using imports as a source of flexible generation, though all of the dispatch is achieved through market pricing. The capability to reduce imports to make room for Californian PV output allows CAISO to reduce curtailment. CAISO estimates that as of 2019, the EIM has avoided more than 800,000 MWh of renewable energy curtailment since its inception[37].

[36] https://www.eia.gov/todayinenergy/detail.php?id=49276#:~:text=In%202020%2C%20CAISO%20curtailed%201.5,total%20energy%20curtailed%20in%20CAISO.
[37] https://www.nrel.gov/docs/fy21osti/74176.pdf

Japan

Japan was an early mover into the Solar PV market and achieved 1 GW of total installed capacity by 2004. Although Japan has an installed solar PV capacity of 74.19 GW[38], as of 2021, 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[39]. 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.

[38] IRENA RE Capacity Statistics 2022
[39] https://iea.blob.core.windows.net/assets/3470b395-cfdd-44a9-9184-0537cf069c3d/Japan2021_EnergyPolicyReview.pdf



Source: UNESCAP presentation by Renewable Energy Institute

A number of measures are being taken to allow Japan to minimize solar curtailment. Currently, as per IEA's Japan 2021 Energy Policy Review, a significant number of solar PV installations in the country are small scale commercial installations in the 10 kW- 500 kW range. These installations primarily aim to sell electricity to the grid due to high Feed In Tariffs for Solar power. By encouraging self-consumption of generated solar power, curtailment can be minimized. It is also important to improve remote energy management systems to enable faster grid response of renewable energy plants. This will help tackle the physical presence requirement for day ahead curtailment.

Solar Manufacturing: Moving towards terawatt scale

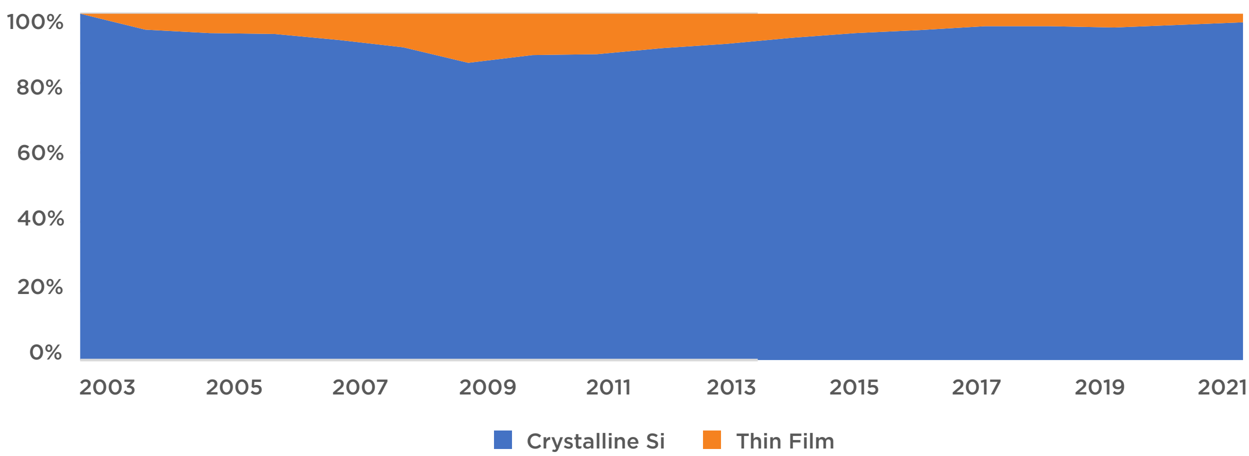
As highlighted in chapter 2, the demand for solar power has multiplied over the past decade. Additionally, the rate of solar deployment is only set to increase as solar technology is coupling with diverse sectors for various applications. For rapid Solar deployment to continue, an enabling manufacturing and supply chain ecosystem is required:

- **Manufacturing of solar modules and BoS equipment at scale will be required to growing global demand**
- **Manufacturers need to drive innovations that improve solar module efficiency and innovate on new applications for solar energy.**
- **A strong manufacturing and supply chain ecosystem is essential for keeping equipment costs down, which reduce solar project LCOE**

Crystalline silicon PV and Thin Film PV, have very different manufacturing processes, and considerations. Crystalline silicon accounts for the majority of manufacturing capacity worldwide.

Thin film technology manufacturing peaked in 2009, when it accounted for ~15% of module manufacturing capacity. Since then, crystalline silicon PV has been the dominant technology for solar modules. Its share in the manufacturing capacity has steadily grown this decade to reach over 95% of total installed capacity.

Share of different module technologies in overall module manufacturing capacity (%)



Source– BNEF Database

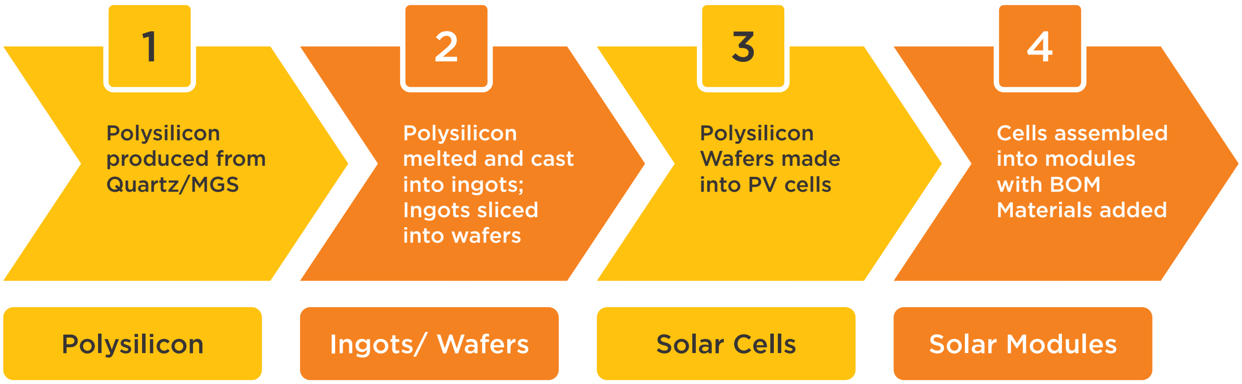
Besides modules, it is also important to scale up the value chain for the Balance of System (BoS) components, including inverters, junction boxes, mounting structures, trackers etc. Several technology and process trends have emerged in BOS component which have increased efficiency/power, reduced material usage, or simply opened up new avenues for PV deployment. Additionally, new segments in the value chain, such as solar recycling may change the value chain as a whole. "End-of-Life" management and potential recycling options available has become an important aspect. Although solar has a smaller footprint than most energy generating technologies, it can be further optimized and even made circular to a degree, thus minimizing the waste from the large capacities that will be installed in the future.

Key Messages

- **The successful transition to Terawatt scale solar is heavily dependent on having an enabling manufacturing and supply chain ecosystem**
- **Crystalline Silicon's dominance in the market is reflected 95% share of module manufacturing capacity worldwide**
- **In addition to direct PV manufacturing, it is important to consider aspects such as BoS supply and End of Life management for modules to have a robust supply chain**

5.1 Silicon Based Technologies:

The supply chain for Crystalline Silicon PV consists of four main stages:

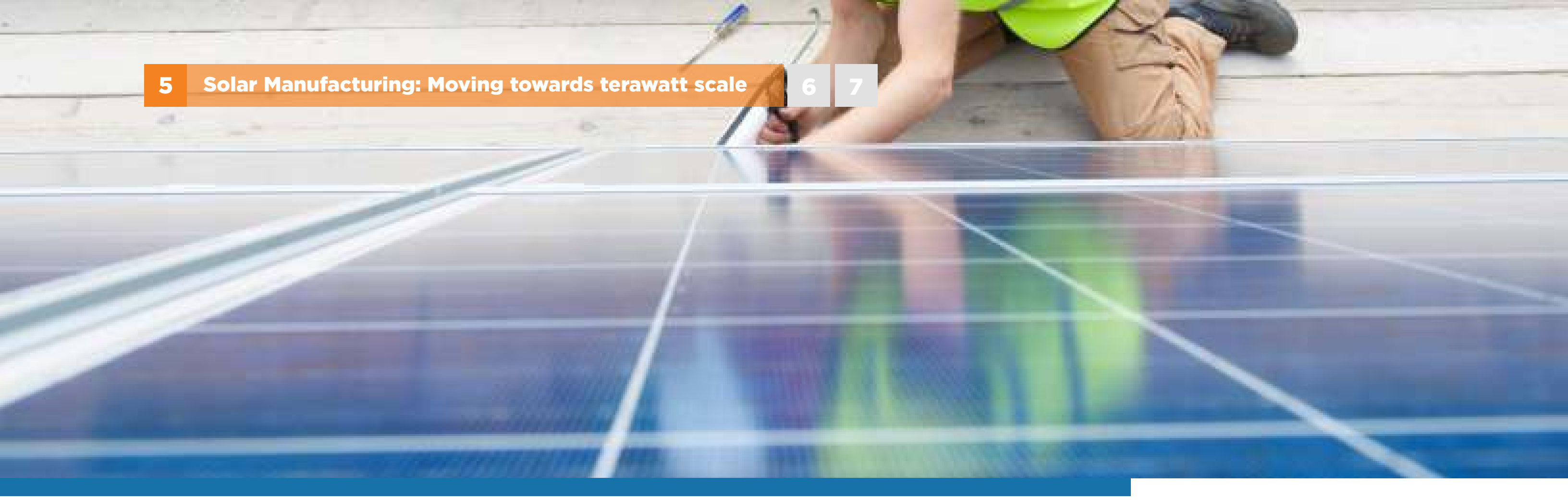


Crystalline silicon PV module production begins with the reduction of high purity quartz into Metallurgical Grade Silicon (MGS). The MGS is subsequently further purified into high grade solar silicon, or Polysilicon. This purified into silicon ingots (either monocrystalline or polycrystalline), which are subsequently sliced and cleaned to prepare very thin wafers. These wafers form the base material for the solar cell, the heart of the PV module system.

Silicon wafers are fabricated into solar cells through various methods, depending on the cell technology used. Steps include texturing, cleaning, doping, etching, and printing silver paste metal connections. Since the output power of a single solar cell is low, several cells are interconnected electrically in series to form a matrix to reach a meaningful output power level.

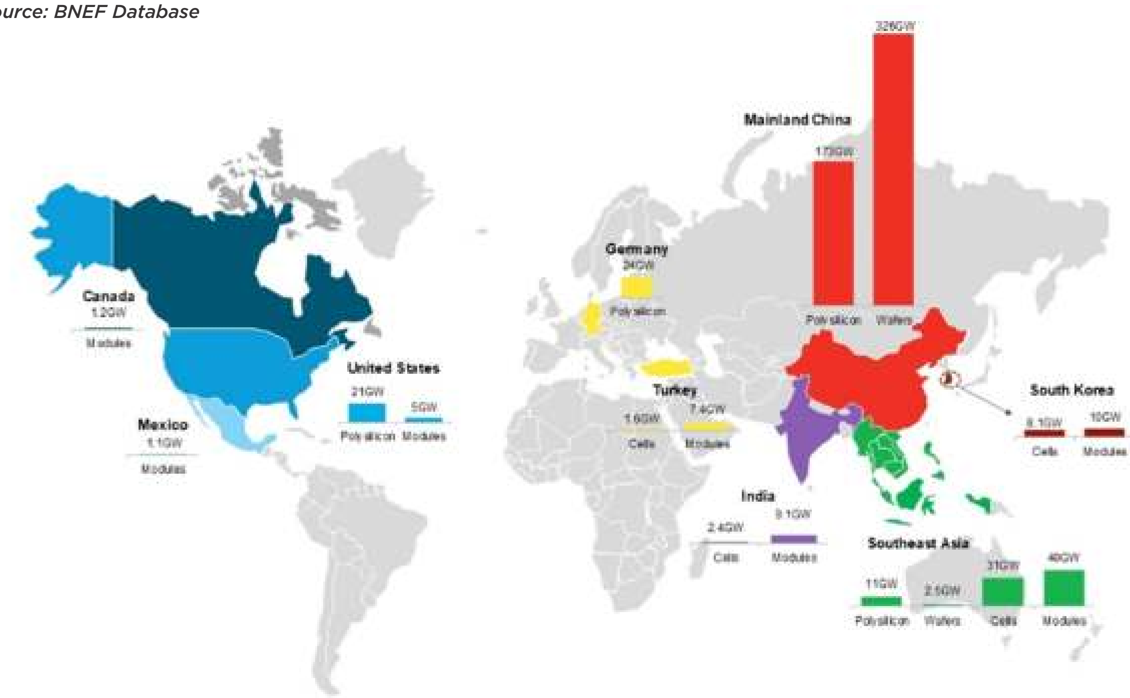
This interconnected matrix is encapsulated with several layers of polymers and glass to protect the electrical circuit from physical damage and weather. The laminate is usually framed and provided with a junction box to collect the power from the cell strings. This assembly process results in the final PV module which can then be deployed in a solar PV system.

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. China has a near monopoly on silicon ingot and wafer production.



Stage	Polysilicon	Ingots	Wafers	Crystalline Silicon Cells	Crystalline Silicon Modules
China's Share in installed manufacturing capacity	78%	96%	96%	86%	80%

Source: BNEF Database



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 range anywhere from 600 GW to 1 TW of manufacturing capacity.

The following subsections will cover the major processes for crystalline silicon solar manufacturing in detail, along with the key manufacturing locations and recent trends observed in each stage

Key Messages

- Crystalline Silicon PV supply chain consists of four major stages: Polysilicon, Ingots/Wafers, Cells, and Modules.
- The crystalline silicon supply chain is heavily concentrated in China, with a near monopoly on silicon ingot/wafer capacity
- A number of non PV specific materials make up the majority of the solar module, including glass, polymers, and aluminum. Additionally, a number of input materials (quartz, MGS etc.) are vital to the C-Si manufacturing supply chain as well. The task of ensuring a secure supply chain for these materials and inputs should not be overlooked as they are vital to the overall manufacturing process.
- Solar PV installations are expected to ramp up in the coming decade, and all stages of solar PV manufacturing will need to scale up to meet this high demand. Around 600-1000 GW of manufacturing capacity may be required to meet this demand.

5.1.1 Non PV specific materials

Non PV specific materials

Although the crystalline silicon supply chain forms the heart of the silicon solar technologies manufacturing process, there are a number of other materials that make up the overall module. Materials such as glass, polymers, and metals such as aluminum form the majority share of the module Bill of Materials. These materials are used to manufacture the non-PV specific components of a module, such as front and back covers, encapsulants, backsheets, and module frames.

5.1.1.1 Glass

Technology Overview

Flat glass is typically used for PV modules assembly. This glass generally has low iron content to ensure suitable transmittivity 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 utilised for solar manufacturing typically uses silica sand as an input material (Heidari and Anctil 2021). The glass used for crystalline silicon modules and thin film modules varies in terms of manufacturing process:

- 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 I c-Si 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.

Industry Overview

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 potential increase in float glass manufacturing capacities in other countries as required.

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 labor costs as compared to float glass, it is much cheaper when produced in areas with low-wage labor, such as China.

Figure 18. Flat glass production by country and number of float lines, 2017.

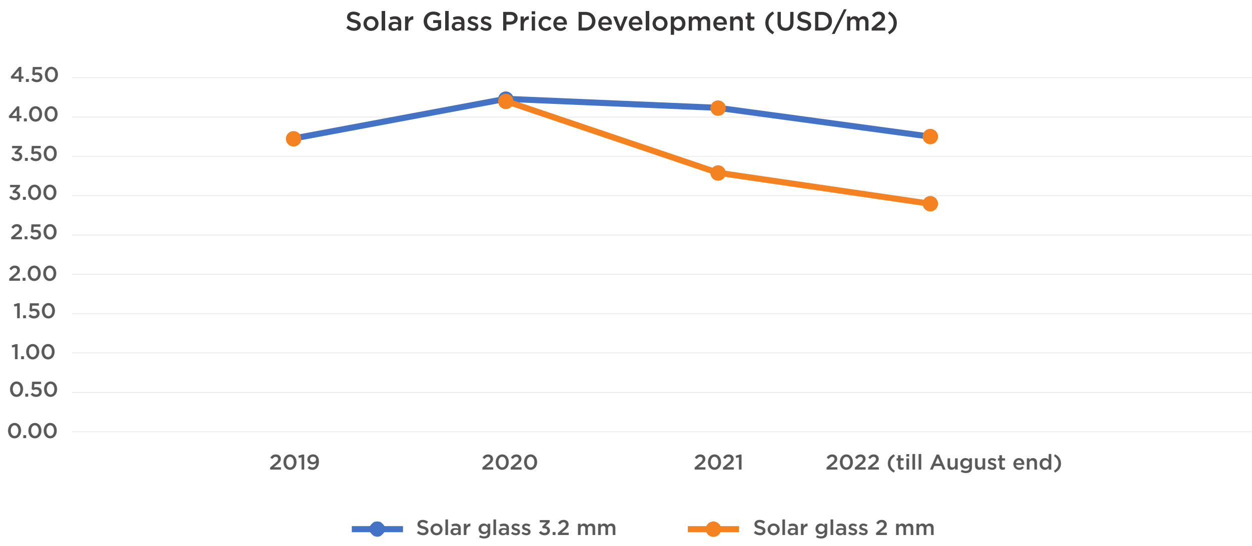
Source: (B. Smith and Margolis 2019)

Float glass is typically more expensive than rolled glass, and thus require larger facilities to achieve the required economies of scale. A single float line is capable of producing approximately 2 GWdc of front glass per year and would require a capital investment of approximately $150 million. PV specific float glass production brings challenges as well- in order 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[40].

Price:

Prices for 3.2 mm solar glass crossed USD 4/m^2 in 2020 as a supply shortage struck the sector. Prices remained above USD 4/m^2 in 2021, before easing slightly and coming down to around 2019 levels. Prices for 2 mm solar glass were almost equivalent to 3.2 mm glass in 2020 but have seen a sharper fall in 2021 and 2022 so far to drop below USD 3/m^2.

[40] NREL Solar Photovoltaic Supply Chain Deep Dive Assessment



Source: ISA Analysis

Key Messages

- **Silica sand based tempered flat glass with low iron content used for the front glass of Solar PV modules.**
- **China has the capacity of producing 448 GWdc of front glass, per year.**

5.1.1.2 Polymers

Different polymers are involved in the manufacture of different components of a PV module. The two major components where polymers serve as input materials include encapsulants and backsheets. A variety of polymer materials can be used for the manufacturing of these components, which can depend on the specific module type in which the component will be used.

Encapsulant

Technology Overview

There are two main resin options that 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 (B. Smith and Margolis 2019). 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.

Industry Overview

The resins for encapsulant manufacturing are produced globally, but extrusion capabilities are concentrated in China. Some Southeast Asian countries also have encapsulant production established by Chinese corporations to support the module industry in those countries. Similarly, encapsulant extrusion exists in India, but is often owned by Chinese companies. Hangzhou First is the largest global encapsulant producer and also supplies backsheets. HIUV, Sveck, and Cybrid are also major encapsulant producers in China, while Borealis is a smaller producer in Austria. The United States has significant capability to produce encapsulant resin, but extrusion capabilities are less common. DOW Chemical is focused on POE resin for PV applications, though it produces EVA resin as well. Natural gas is the feedstock for both POE and ethylene, thus regions with low gas prices can run cost effective manufacturing operations[41].

Backsheets

Technology Overview

Backsheets served as the final back layer of c-Si modules, but clear backsheets are now seeing use as the backing material for bifacial modules as well. Backsheets electrically insulate the module and protect it from environmental damage due to moisture and wind.

Backsheet materials vary significantly across the market. Almost all backsheets 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), polyethylene, or less commonly polyolefin or polypropylene (Chunduri and Schmela 2020).

Similar to the setup used for encapsulants, backsheet materials are typically first produced as resins and are then extruded into films. Backsheets 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 backsheets[42].

Industry Overview

PVDF-based backsheets are reported to dominate the backsheet 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 own resin to produce completed backsheets. Jinko and LONGi, two of the largest PV module producers, use PVF-based backsheets 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 backsheets. Most laminators are located in China, with some appearing in India more recently[43] .

[41] NREL Solar PV Supply Chain Deep Dive Assessment
[42] NREL Solar Photovoltaic Supply Chain Deep Dive Assessment
[43] NREL Solar Photovoltaic Supply Chain Deep Dive Assessment

Key Messages

- The resins for encapsulant manufacturing are produced globally, but extrusion capabilities are concentrated in China.
- Backsheets 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.
- PVDF-based backsheets are reported to dominate the backsheet market

5.1.1.3 Aluminum Frames

Technology Overview

Flat glass isThe aluminum 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 aluminum must be suitably alloyed prior to use. Alloying occurs during the casting stage. The most popular extrusion alloy class, which is typically used in solar applications, is the 6000 series (Werner 2013). 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 aluminum 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 aluminum extrusion industry encompasses production of the desired alloy, extrusion into the desired shape, then 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[44].

Industry Overview

Some countries subsidize aluminum, which would result in PV frames and racking at 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 significant capacity to produce aluminum for frames. China produces more than half the world's aluminum and steel[45].

Global glass, quartz, polymer, Al usage for PV is a data challenge- to be discussed to decide how to address

Key Messages

- The most popular extrusion alloy class, which is typically used in solar applications, is the 6000 series.
- China produces more than half the world's aluminum and steel

[44] NREL Solar Photovoltaic Supply Chain Deep Dive Assessment
[45] NREL Solar Photovoltaic Supply Chain Deep Dive Assessment

5.1.2 Polysilicon: Price increases as demand outpaces supply but new capacity should bring back normalcy

Solar grade Polysilicon is considered the starting raw material for crystalline silicon PV. The primary input material for polysilicon is Metallurgical Grade Silicon (MGS). MGS is a commodity material produced from high-grade quartz.

Thus, polysilicon for solar manufacturing is produced in a two-step process. The silica in the quartz sand is reduced in an arc furnace to metallurgical grade silicon. This metallurgical grade silicon is then purified further into solar grade silicon (6-13N purity) by either a silane (SiH_4) or trichlorosilane ($SiHCl_3$)-based process, typically via a Siemens reactor method[46]. The result of this process is Solar Grade Polysilicon.

[46] Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, IEA PVPS, 2020

Processes and Technologies:

The production of polysilicon to quartz consists of two main processes: The conversion of quartz to metallurgical grade silicon, and the subsequent conversion of metallurgical grade silicon to Polysilicon:

Step 1: Quartz to Metallurgical Grade Silicon

The quartz 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 quartz is relatively inexpensive and accounts for a small share of the input. 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. South Africa, USA, Kazakhstan, and Brazil are among the key countries supplying quartz for PV applications. The silica in the mined quartz is reduced in an arc furnace to metallurgical-grade silicon with coal as the reducing agent. As most silicon production is ferrosilicon production, capacity could be switched over, and even brownfield existing sites could pick up solar demand.

About 6 tons of raw materials are required to produce 1 ton of metallurgical grade silicon (>98% purity). These raw materials consist of 2.7 tons of quartz, 1.5 tons of reductants (low ash coal or charcoal), 1.5 tons of wood. Around 2.7 tons of quartz is required to produce 1 Ton of metallurgical grade silicon[47]

The processing and purification stages involved for converting quartz sand to MGS entails a large amount of energy consumption. The electrical energy consumption to produce metallurgical-grade silicon is 10-15 MWh/ton of MGS produced[48]. The energy consumption per ton of alloy is reduced significantly with increasing iron content in the silicon alloy product[49].

Step 2: Metallurgical-grade Silicon to Solar Grade Silicon

The quartz 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 quartz is relatively inexpensive and accounts for a small share of the input. 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. South Africa, USA, Kazakhstan, and Brazil are among the key countries supplying quartz for PV applications. The silica in the mined quartz is reduced in an arc furnace to metallurgical-grade silicon with coal as the reducing agent. As most silicon production is ferrosilicon production, capacity could be switched over, and even brownfield existing sites could pick up solar demand.

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[47] https://www.crmalliance.eu/silicon-metal
[48] NREL Solar Photovoltaics Supply Chain Deep Dive Assessment
[49] Silicon Processing: From quartz to crystalline solar cells, South African Pyrometallurgy, 2011

Fluidized Bed Reactor (FBR):

FBR technology has been the favorite alternative to CVD technology, mainly due to the potential to reduce cost. FBR has two main advantages – low energy consumption and higher utilization of the precursor – compared to the traditional Siemens-CVD process.

In FBR technology a vertical column functions as reactor, which is filled with tiny silicon particles of less than 100 µm in size. A fluidized gas, like hydrogen or nitrogen, is injected at the bottom of the reactor. At certain gas velocity, the drag force exerted on each solid particle equates to their respective weight. At this stage, referred as fluidized bed, the bed of the particle behaves like a liquid and the flow of gas keeps it in contiguous motion. The reactant gas, mixed with fluidizing gas, is introduced into the bed. The particles are heated to a temperature above the decomposition temperature of the reactant gas by means of external heaters. As a result of the decomposition, silicon is deposited on the particles, which then grow in size. When the particles are large enough, they are extracted from the reactor and the cycle is repeated by adding fresh seeds to the bed.

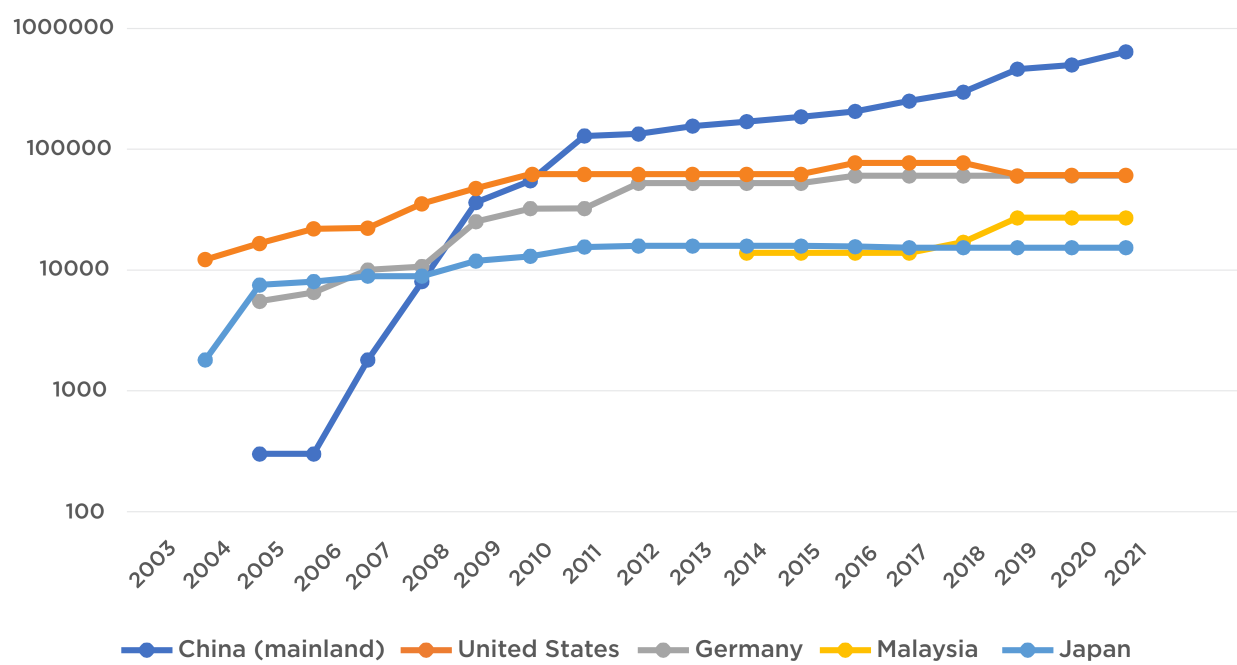
1 ton of polysilicon is produced from around 1.13 tons of metallurgical grade silicon[51].

Manufacturing Status and Key Suppliers

Global polysilicon manufacturing capacity crossed 800000 tons in 2021, with production highly concentrated in a few countries worldwide. China has become the market leader over the past decade, with over 78% of all polysilicon production capacity located there. Chinese polysilicon manufacturing has grown nearly 400% since 2011, and nearly 30% between 2020 and 2021 alone. Countries such as the USA, Germany, and South Korea once had significant capacity, with the USA being the leader until 2010. The top 5 countries in terms of polysilicon manufacturing capacity accounted for over 97% of the global manufacturing capacity for the sector. Rising prices of electricity in other countries have often made polysilicon manufactured outside China uncompetitive. It is telling that no country other than China in the top 5 of polysilicon manufacturing capacity saw any capacity growth between 2020 and 2021, showcasing the difficulty in manufacturing polysilicon without the advantages that Chinese manufacturing enjoys.

50 Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, IEA PVPS, 2020

Polysilicon manufacturing capacities of key countries (Tons/Year)

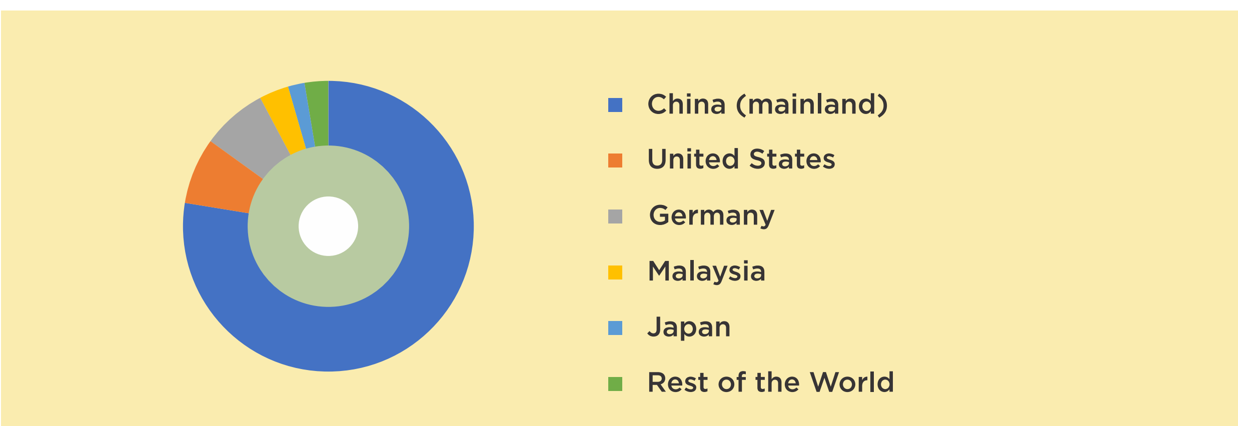


Source: BNEF Database

From 2017 to 2021, the world witnessed a 40% rise in the installed production capacity for polysilicon. With the development of large scale polysilicon plants and associated economies of scale, China is set to remain the leader in polysilicon production for the foreseeable future.

However, several countries such as India are exploring vertically integrated solar manufacturing in order to reduce import dependence and improve energy security as solar power becomes a key component of their decarbonization plans.

Polysilicon Manufacturing Capacity (2021)



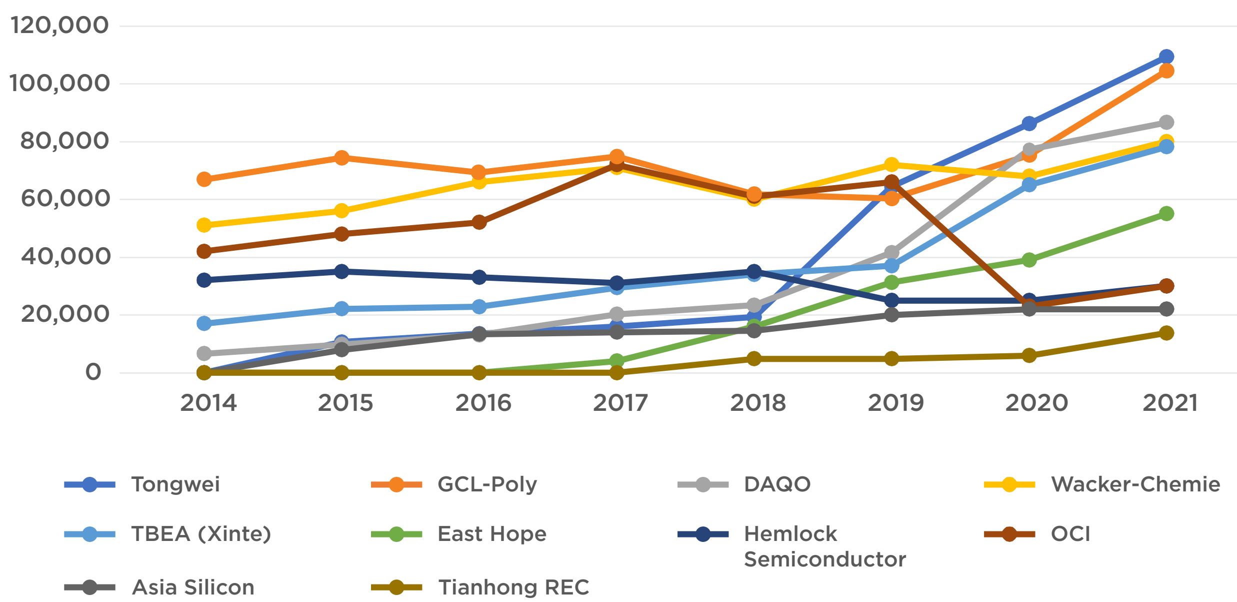
Source: BNEF

Key drivers for setting up polysilicon manufacturing:

for setting up factories include access to reliable and cheap or subsidized electricity, access to cheap and long term debt and new lines of credit, access to transportation infrastructure, and government initiatives and support (such as support with land, cash grants, tax exemptions, assistance with infrastructure development etc.)

Around 90% of polysilicon is supplied by only 8 players (GCL, Tongwei, Daqo, Xinte, East Hope, Wacker, OCI, Asia Silicon), of which only 2 (Wacker, OCI) are not based in China. Like many other raw materials, solar polysilicon is currently in short supply, and prices have increased in recent months, but are expected to come down by 2023. Tongwei, GCL Technology and Daqo New Energy now are the top 3 suppliers of the polysilicon and all of them are from China. Wacker from Germany is now at 4th in the list.

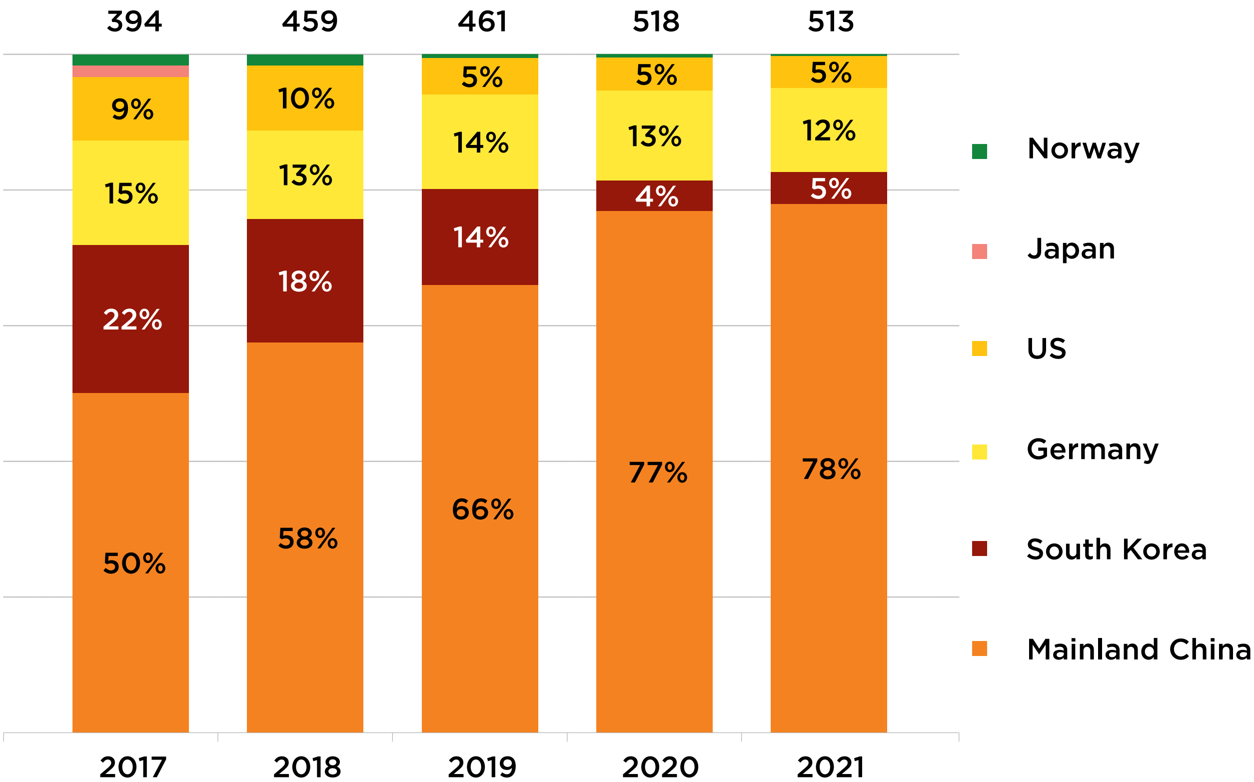
Top ten manufacturers by annual polysilicon production (Tons)



Source: BNEF Solar Manufacturers' 2021 Production

Polysilicon manufacturers have greatly increased production in recent years. Four out of the top 10 manufacturers in 2021 did not have any production in 2014. Production by Tongwei, the leading producer in 2021, has grown over 450% when compared to production in 2018. DAQO, the third largest manufacturer in 2021, saw a similar sharp increase of ~270% over the same time period. Some manufacturers has also seen a fall in production, with production by OCI and Hemlock falling 51% and 14% respectively as compared to their production in 2018.

Percentage of total production in key countries (thousand tons)

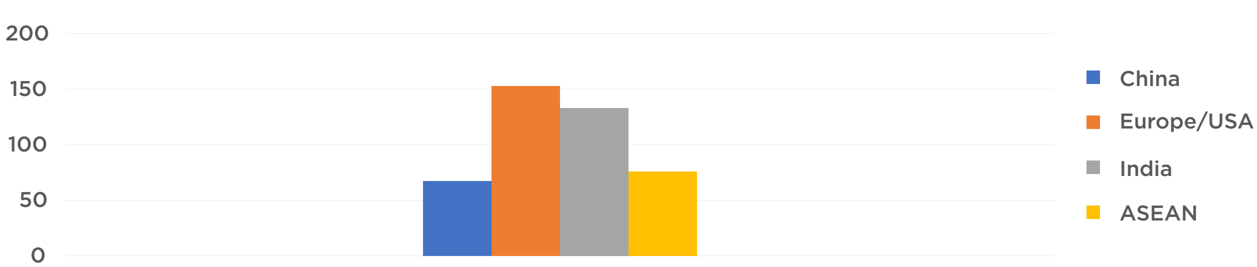


Source: BNEF Solar Manufacturers' 2021 Production

Global polysilicon production in 2021 crossed 630,000 tons. China accounted for 78% of the 513,000 tons of polysilicon produced in 9 major manufacturing countries in 2021, with Germany, the next largest producer, accounting for 12%. Production in these countries has increased from 394,000 tons in 2017, an increase of 30%. Although polysilicon manufacturing capacity is greater than current production, not all production capacity can be operated economically, and supply has been outstripped by demand in recent years.

It is estimated that around 3 grams of polysilicon is required per Wp of solar modules manufactured. Thus, to produce 1 GW of module capacity, approximately 3000 Tons of polysilicon is required. However, manufacturing process improvements and the development of new technologies may reduce specific silicon consumption in coming years.

Regional investment capex costs for polysilicon (USD Million/GW)



Source: IEA Special Report on Solar PV Global Supply Chains

It is estimated that around 3 grams of polysilicon is required per Wp of solar modules manufactured. Thus, to produce 1 GW of module capacity, approximately 3000 Tons of polysilicon is required. However, manufacturing process improvements and the development of new technologies may reduce specific silicon consumption in coming years.

Polysilicon capex is lowest in China as the development of large polysilicon plants upto 100,000 tons allows manufacturers to take advantage of economies of scale. ASEAN countries show similar capex trends as capacities developed there are usually done so by integrated Chinese manufacturers. India and Europe exhibit higher capex requirements due to a number of reasons, including longer development times, higher cost of capital, lack of economies of scale, and limited technical know-how.

After a long oversupply situation, current polysilicon production capacity has not been sufficient to meet demand, which has led to high prices for the commodity. IEA estimates that global nameplate polysilicon manufacturing capacity will reach 400 GW in 2022. Despite this increase, more manufacturing capacity additions are required to be on track to meet solar PV installation demands by 2030.

Key Messages

- Metallurgical grade Silica serves as a raw material for obtaining polysilicon of 6-13N purity.
- China houses 78% of global polysilicon production capacity while Germany catered to 12% of the global polysilicon demand.
- From 2017 to 2021, the world witnessed a 40% rise in the installed production capacity for polysilicon.
- To produce 1 GW of module capacity, approximately 3000 Tons of polysilicon is required.

5.1.3 Ingot/Wafer: Near monopoly by China

Ingot and wafering is the second stage of the PV value chain. While ingot growth and wafering are two completely different processes, the general practice is to combine these two steps when discussing the PV supply chain. Additionally, both stages are typically accomplished by one company. This is due in part to the specific benefits to vertical integration for these stages, such as the avoidance of the complex logistical challenges behind transporting a heavy ingot to a wafering factory. As a result, they can be considered jointly for analysis.

Processes and Technologies:

The significance of the ingot crystallization stage in the PV value chain is that it determines the crystallographic structure of the silicon. The equipment and process employed to solidify molten silicon essentially determines whether the produced ingot is monocrystalline, multicrystalline or even quasi-monocrystalline. To produce monocrystalline ingots, Czochralski (CZ) pullers are widely used in mass production, while the Float Zone (FZ) process is the method of choice for high-quality desired laboratory related applications. For producing multicrystalline ingots, Directional Solidification (DS) furnaces have been the key equipment that is employed. These DS systems are also capable of being tweaked to support the production of quasi-monocrystalline silicon.

- **Czochralski Method:** In the CZ method, polysilicon is loaded into the crucible and melted at temperatures higher than its melting point at 1420 °C in an inert environment. A seed crystal is then lowered until it touches the melt and starts to dissolve in it. Then, the seed is withdrawn from the melt at a defined rate so that the crystal growth continues the molten silicon surface. In this way, an elongated single crystal is grown from the melt. This method results in periodically arranged silicon atoms in a cylindrical ingot. Ingot manufacturing capabilities have advanced, allowing for ingot diameters ranging from 200 mm to 300 mm, and weights ranging from 400 to 800 Kg (at pilot scale)[15].

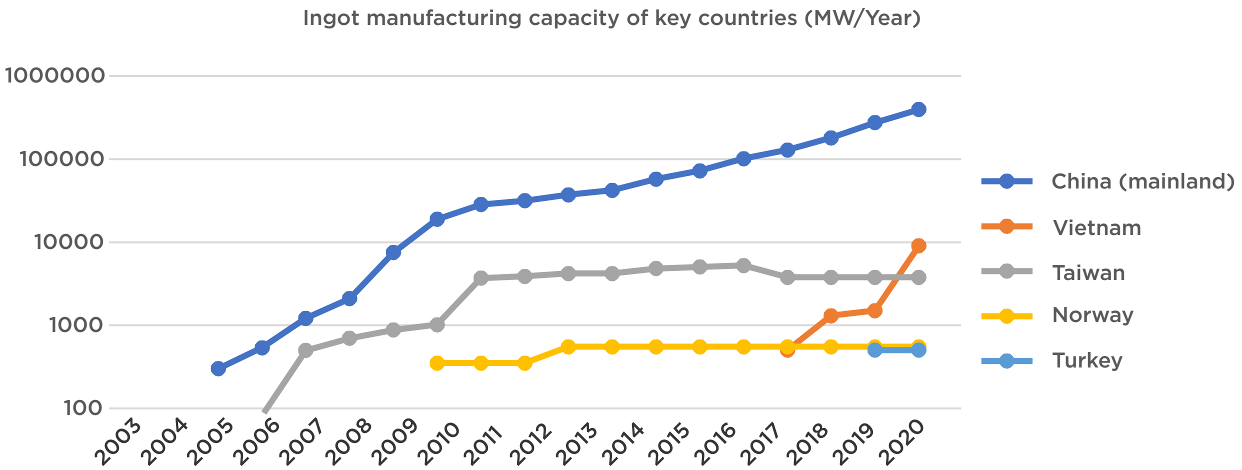
- **Float Zone Process:** A monocrystalline silicon ingot can also be grown directly from a polysilicon rod without using a crucible by means of FZ technology. In this relatively simpler process, a silicon rod is set on top of a seed crystal, while a melt zone is established between the lower seed material and the upper feed material by applying localized heating. The molten silicon adapts to the pattern of the single crystal seed as it cools and solidifies gradually as in a CZ process. This float zone is moved along the rod. The major drawback for commercial usage of this process is the high-quality requirement of the carefully grown polysilicon rods, which are sold at prohibitively high prices.
- **Directional Solidification:** In the DS process, polysilicon melting, and recrystallization take place in the same crucible, very similar to the casting process. The crux of the process lies in the DS furnace design employed to melt the polysilicon effectively and carry out a controlled solidification. After melting, a temperature gradient is established along the molten silicon by means of a power supply to heating elements in various positions. During the solidification process, the heat is extracted through the bottom of the crucible so that the solid-liquid interface moves upwards from the bottom of the crucible. The goal here is to achieve a vertically aligned columnar grain structure in the resultant ingot. With a superior process control and a few hardware changes to prevent melting of the seed, the DS furnaces can also be upgraded to produce quasi-monocrystalline silicon ingots.

Wafering: 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. Diamond-coated wires are typically used for wafering. The wires are wrapped around the ingot multiple times for all of the wafers to be cut in parallel, simultaneously. A significant portion of the ingot is wasted as sawdust in the sawing process, an occurrence known as kerf loss, and minimizing these losses is key to the optimization of the wafering process.

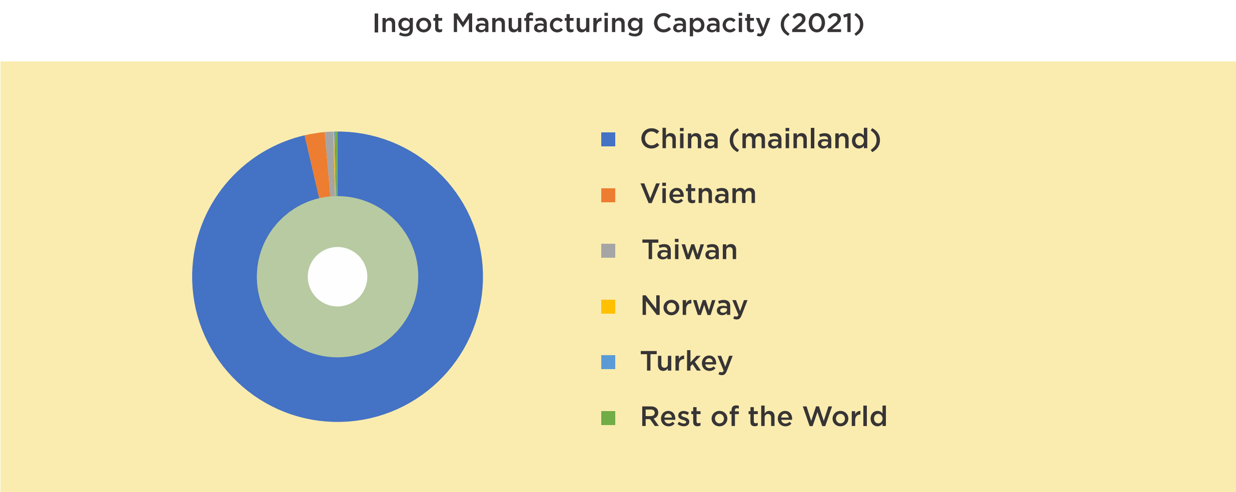
Manufacturing Status and Key Suppliers:

Global ingot and wafer manufacturing capacity stood at ~408 GW and ~442 GW respectively in 2021. China has developed as the hub of crystalline silicon manufacturing across the value chain, and for no stage is this fact more apparent than for the ingot and wafering processes. China hosts ~96% of global ingot and wafer manufacturing capacity. Additionally, most of the announced expansion plans with ingot and wafer production are also China centric, implying that the country will continue to dominate for these segments in the near future. Chinese ingot manufacturing capacity has grown nearly 13 fold in the last 10 years and grew by 44% in the last year alone. The top 5 countries with ingot manufacturing capacity accounted for 99.8% of global manufacturing capacity, with the same figure for wafers sitting slightly lower at 99.2%.

[51] NREL Solar Photovoltaics Supply Chain Deep Dive Assessment



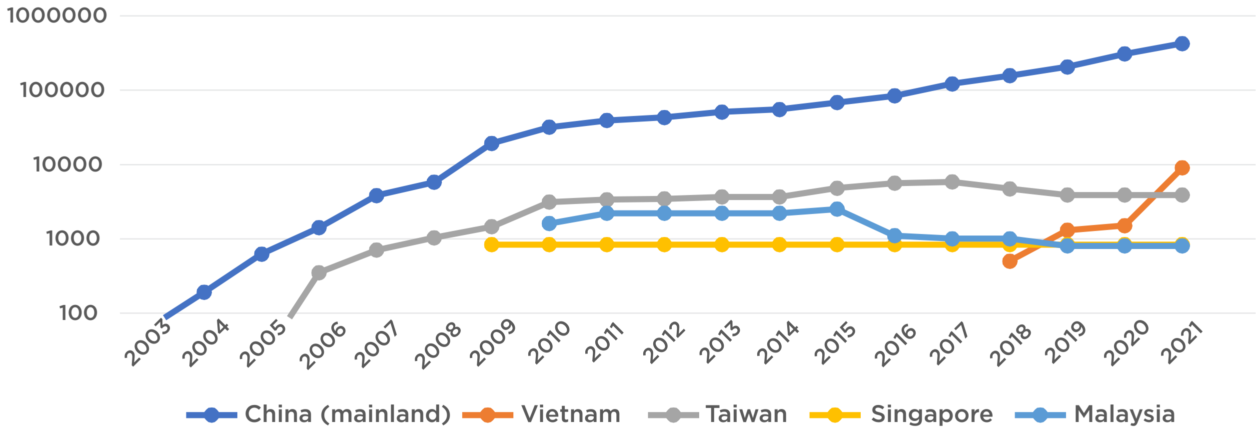
Source: BNEF Database



Source: BNEF

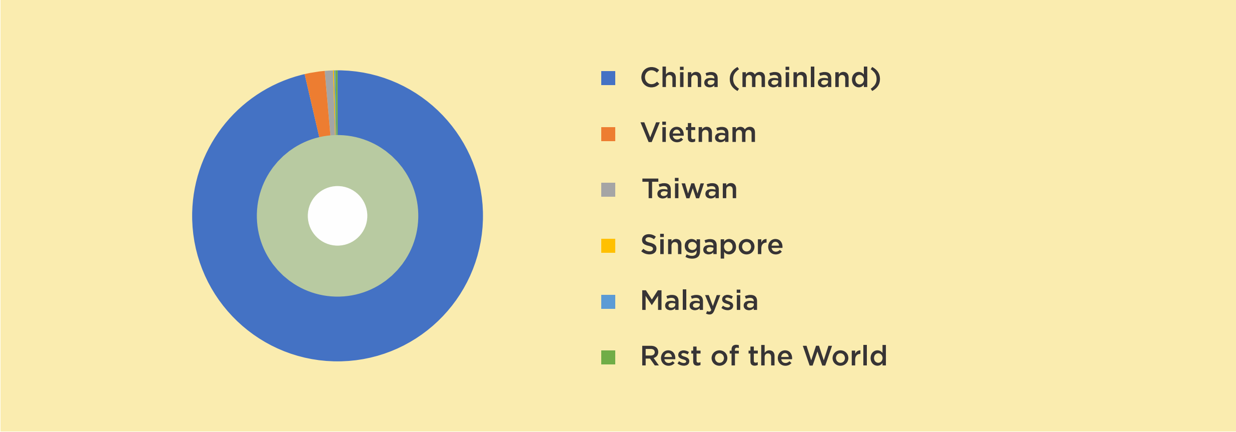
Chinese wafer manufacturing capacity grew nearly tenfold in the last ten years and ~38% in the last year. Amongst the other top countries with ingot and wafer manufacturing, Vietnam has seen significant growth, with capacity growing fivefold in the last year for both stages. It is important to note that ingot and wafer manufacturing capacity in Vietnam is driven by investments by Chinese manufacturers seeking to avoid trade dispute related sanctions and charges.

Wafer manufacturing capacity of key countries (MW/Year)



Source: BNEF Database

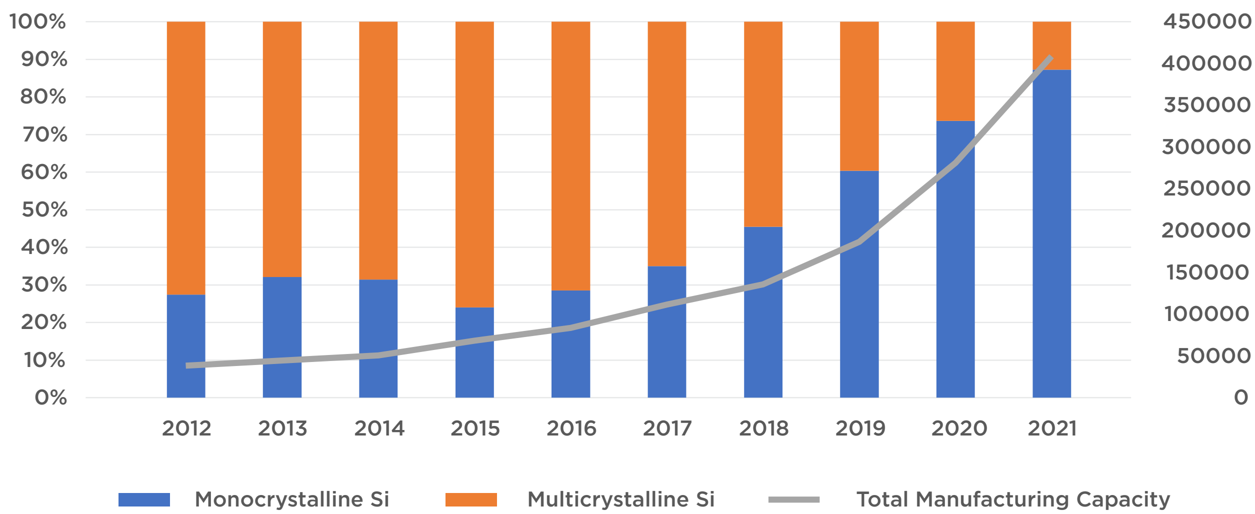
Wafer Manufacturing Capacity (2021)



Source: BNEF Database

The increased preference for monocrystalline silicon-based PV due to their higher efficiencies has resulted in significant growth of manufacturing capacity for monocrystalline ingots. Monocrystalline ingot manufacturing capacity accounted for around 25% of ingot manufacturing capacity in 2015. Since then, coinciding with the development of mono silicon PERC architecture, monocrystalline ingot manufacturing capacity has increased rapidly to account for around 85% of global ingot manufacturing capacity.

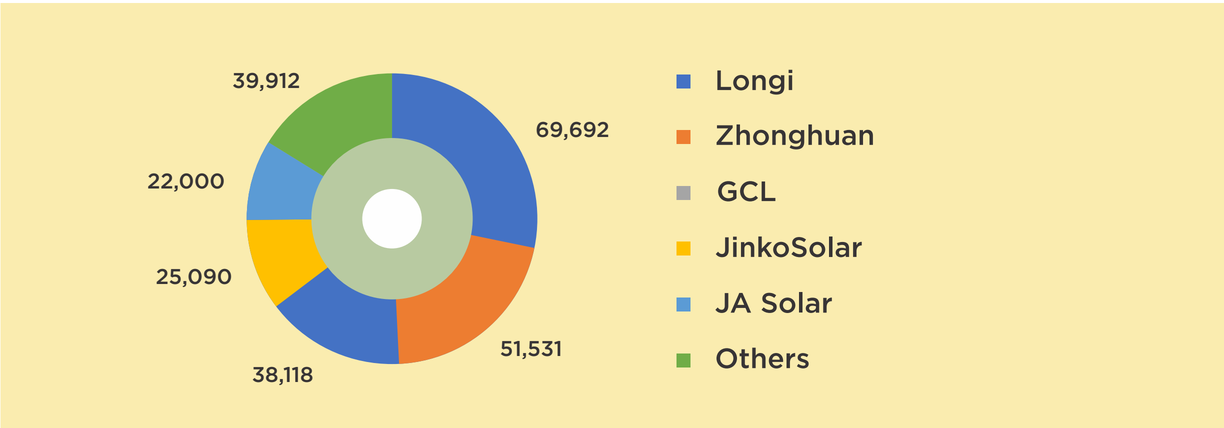
Share of Mono/Multicrystalline Si Ingot Manufacturing Capacity (%)



Source: BNEF Database

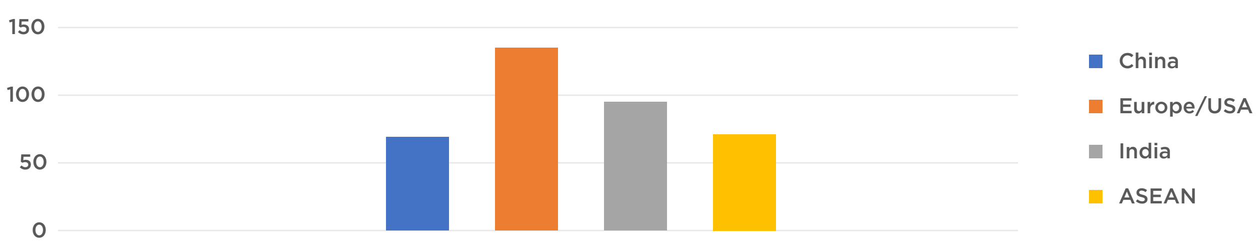
More than 90% of global wafer production in 2021 was accounted by the top 10 companies, and all are Chinese. LONGi and Zhonghuan are the two leading supplier wafer suppliers, while companies such as JinkoSolar, JA Solar, Canadian Solar are the integrated companies that use the wafer capacity for captive consumption.

Top ten solar wafer manufacturers in 2021 by production (MW)



Source: BNEF Solar Manufacturers' 2021 Production

Regional investment capex costs for ingots and wafers (USD Million/GW)



Source: IEA Special Report on Solar PV Global Supply Chains

Low capex in China and ASEAN countries (due to the presence of Chinese manufacturers) is driven by the fact that the most of ingot/wafer manufacturing capacity is located in China. Thus, the country has the technical know-how and practical experience in setting up large scale manufacturing facilities, driving down capex costs.

IEA estimates that global nameplate wafer manufacturing capacity will reach 520 GW by end 2022. While this represents clear growth on the existing capacity in place, the geographical concentration of the capacity raises supply chain stability concerns. Thus, more efforts are required to develop these manufacturing stages in other geographies.

Key Messages

- **Ingot crystallization determines the crystallographic structure of the silicon, i.e., monocrystalline, multicrystalline or even quasi-monocrystalline.**
- **Diamond-coated wires are typically used for wafering the ingots.**
- **Global ingot and wafer manufacturing capacity stood at ~408 GW and ~442 GW respectively in 2021.**
- **Monocrystalline ingot manufacturing capacity has increased rapidly to account for around 85% of global ingot manufacturing capacity.**

5.1.4 Solar Cell: Diverse architectures call for diverse manufacturing processes

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. As covered in the previous chapter on solar technologies, a variety of solar cell technologies exist as options. Different architectures may require different numbers of steps, each with differing complexities. These architectures may vary depending on the type of wafer utilised (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. POCL3 Diffusion
4. Laser-driven selective emitter formation
5. Wet chemical PSG etch, rear side planarization, and isolation etch by rear side Phosphorous removal
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-aluminum 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. Cofire.
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 less processing steps but may require greater process variation due to the broad range of cells available.

Manufacturing Characteristics:

Cell processing is the most impacted from the changes in wafer size that have been observed and covered in the previous section on ingots and wafers. However, equipment makers have played a significant role in ensuring that this trend has not impacted cell manufacturing. Today's production tools can handle all mainstream wafer sizes — M6, M10 and G12. Flexibility aside, tool vendors have also readapted their equipment platforms to improve productivity in parallel.

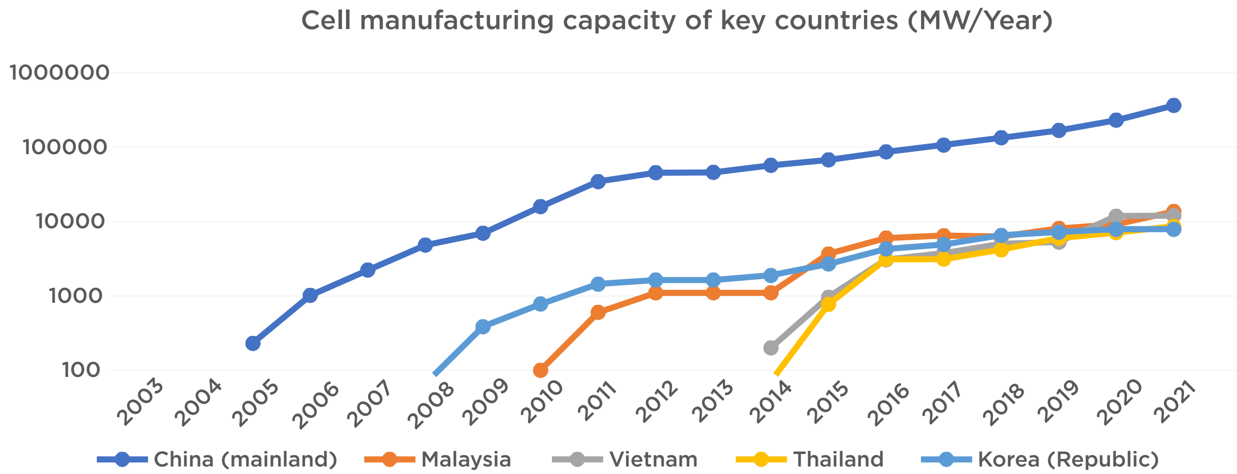
Manufacturing Status and Key Suppliers:

Solar cell fabrication has become a technologically intensive process that is very highly automated. As a result, cell fabrication typically thrives in locations with a few key advantages:

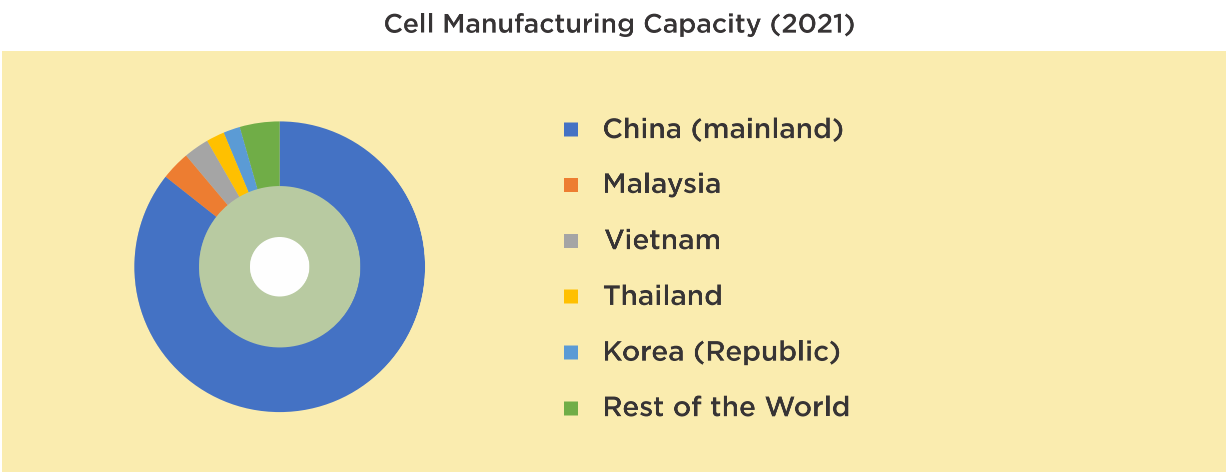
- Locations with a sufficient labor pool of manufacturing engineers and machine laborers
- Government support of manufacturing through cheap land, electricity, and tax breaks to incentivize companies with sufficient access to capital to procure the equipment and land
- Access to a supply chain of affordable machines

Global cell manufacturing capacity stood at ~423 GW in 2021. 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 by 950% since 2011 and saw a 57% growth in the last year. Additionally, as with ingot and wafer production, manufacturing capacity in other Southeast Asian countries such as Malaysia, Vietnam, and Thailand is driven by Chinese manufacturers seeking to avoid trade related restrictions. Malaysia saw a 49% growth in cell manufacturing capacity in the last year, while Thailand saw a 21% growth in the same time period. China's dominance can be attributed to the country having all of the three favorable advantages listed above (quality labor, government support, and equipment supply). Additionally, Chinese manufacturers make significant investments in R&D to drive process improvements (for stages other than solar cells as well). Countries such as India and Turkey are attempting to grow their domestic cell manufacturing ecosystem through policy initiatives and schemes. However, these are in relatively early stages, and China will likely remain a vital player in the PV cell supply chain for the coming years.

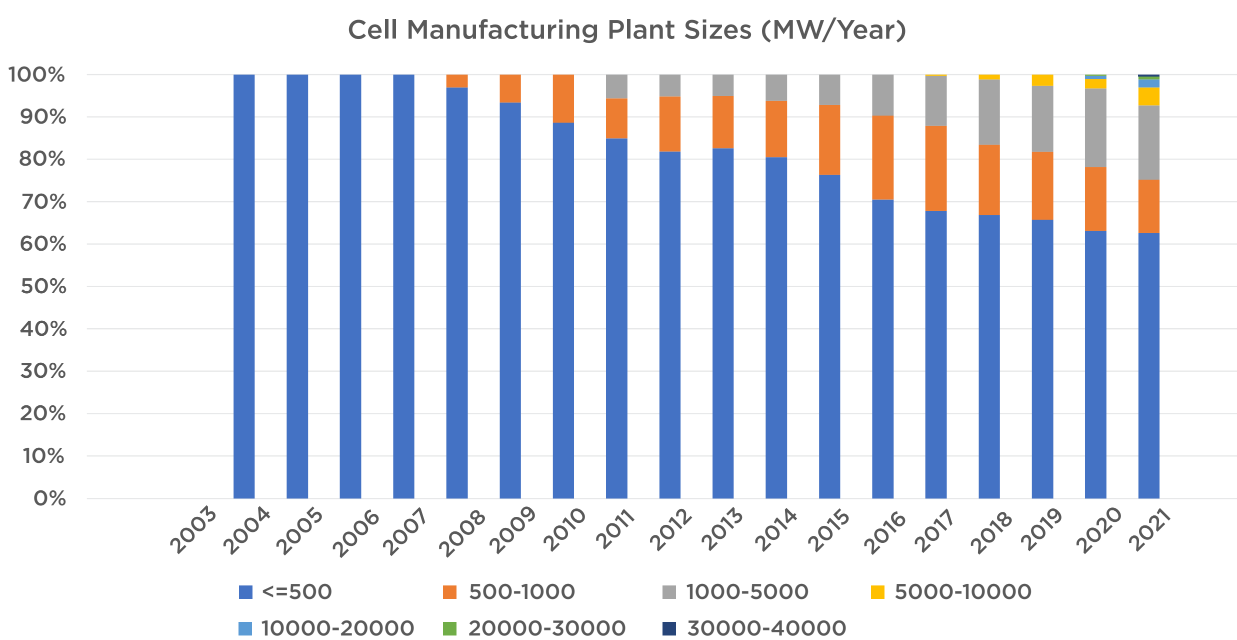
The top 5 countries in terms of cell manufacturing capacity accounted for 95.6% of global capacity in 2021.



Source: BNEF Database



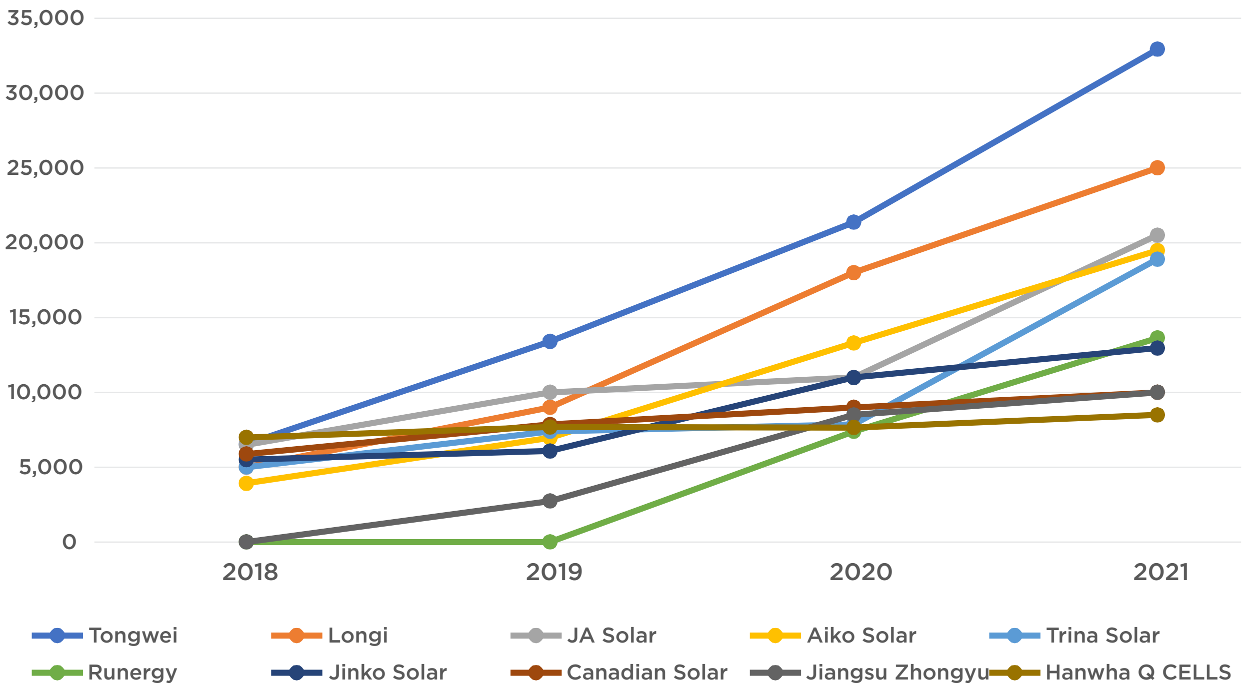
Source: BNEF



Source: BNEF Database

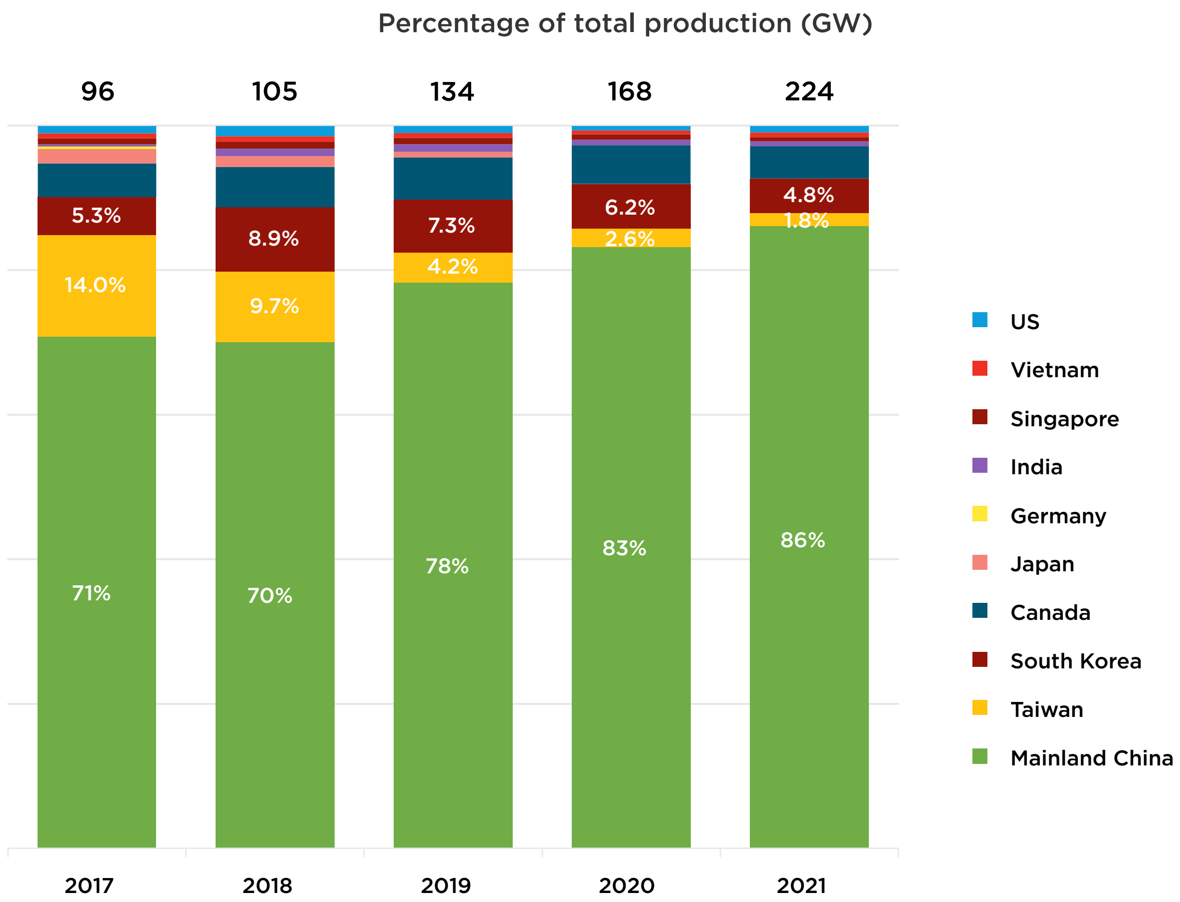
Over the years, with advancement in the manufacturing technologies, and growing demand of solar energy, a number of manufacturing plants have been set up, of different capacities. Plant sizes are increasing to take advantages of economies of scale, that in turn drive down costs and allow companies to compete in the solar PV market.

The top ten cell manufacturers accounted for around 70% of the production for 2021, implying less company level consolidation of manufacturing than polysilicon or ingot and wafer manufacturing. Most of the largest manufacturers are headquartered in China. Three out of the top four manufacturers, Tongwei, Longi, and Aiko Solar, had their 2021 cell production be ~400% greater than their production in 2018. Two out of the top ten manufacturers, Runergy and Jiangsu Zhongyu, had no production in 2018, showcasing the rapid rise of some of the largest solar cell manufacturers in the world.



Source: BNEF Solar Manufacturers' 2021 Production

Solar cell production in 10 major manufacturing countries grew from 96 GW in 2017 to 224 GW in 2021, an increase of ~130%. Production was dominated by China, which accounted for an 86% share of production in 2021. Canada and South Korea were other centres of production but accounted for just a fraction of production.



Source: BNEF Solar Manufacturers 2021 Production

Equipment, land, and construction costs drive up cell manufacturing capex requirements for Europe and the USA, resulting in significant differences of 2.5-3 times when compared to the cost in China. ASEAN countries again benefit from having their domestic manufacturing driven by Chinese companies.

IEA estimates that global solar cell manufacturing capacity will cross 550 GW by end 2022. This shows that the sector is on track to meet the demands of the PV industry, but redundant capacity will need to be upgraded to align with newer technologies with improved efficiencies.

Key Messages

- **Global cell manufacturing capacity stood at ~423 GW in 2021.**
- **China accounted for 86% of the solar cell production in 2021.**
- **IEA estimates that global solar cell manufacturing capacity will cross 550 GW by end 2022.**

5.1.5 Solar Module: Innovation across subcomponents drive power rating growth

Processes and Technology:

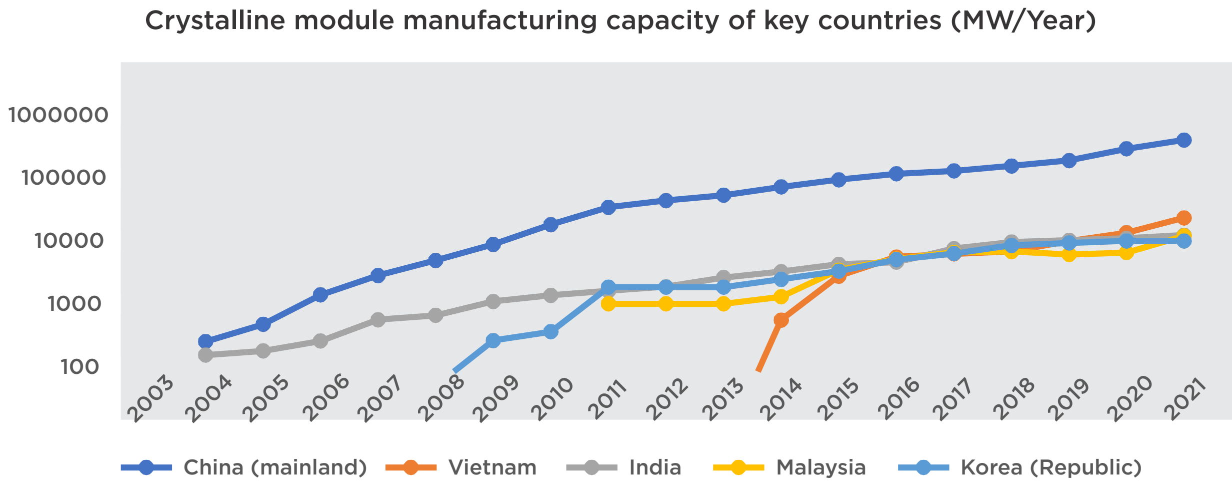
Module assembly entails electrically connecting cells into strings, arranging parallel cell strings into an array, electrically connecting the strings with metallic ribbons, mounting the array onto a layer of encapsulant on top of a sheet of glass or backsheet, and laminating another sheet of encapsulant and front glass onto the whole assembly. 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 backsheet or another sheet of glass on the back.

The ribbons are fed through a hole in the back glass or backsheet 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 aluminum frame is typically put around the perimeter of the module. Some firms have been developing glass-glass modules without an aluminum frame, while monocrystalline and multicrystalline busbar less, 72-cell, 96-cell, frameless, and glass-glass module options (including but not limited to options using bifacial cells) are also available.

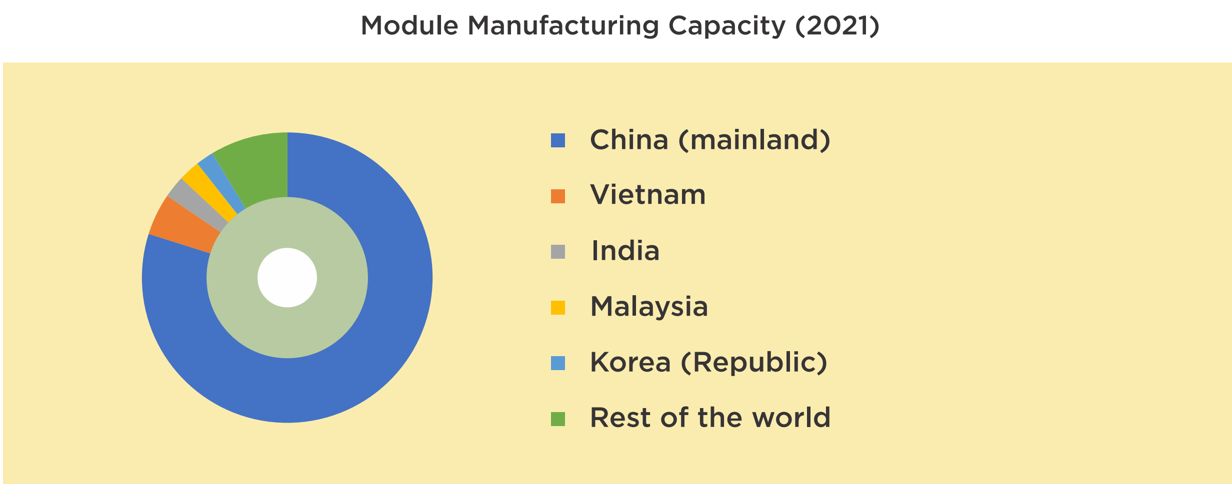
Most of the components are relatively cheap to ship, including the aluminum frame and glass. Therefore, provided a manufacturing site has access to the PV supply chain, they can manufacture modules relatively inexpensively and without much capital expenditure or labor development. While there are economies of scale to this process, many locations around the world, including the United States, have encouraged local manufacturing, and module assembly represents a relatively large part of the cost of a final module, without the need for large government development support.

Manufacturing Status and Key Suppliers:

Global module manufacturing capacity stood at 500 GW in 2021. 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. As a result, the top five countries in terms of module manufacturing capacity account for around 81% of global capacity, implying significantly less geographical concentration than upstream manufacturing stages. However, Chinese module manufacturing capacity is far ahead of other countries, growing more than ten times when compared to its capacity in 2021, and 37% in the last year alone. Vietnam and Malaysia saw rapid growth in the last year as well, with manufacturing capacity growing 72% and 84% respectively.

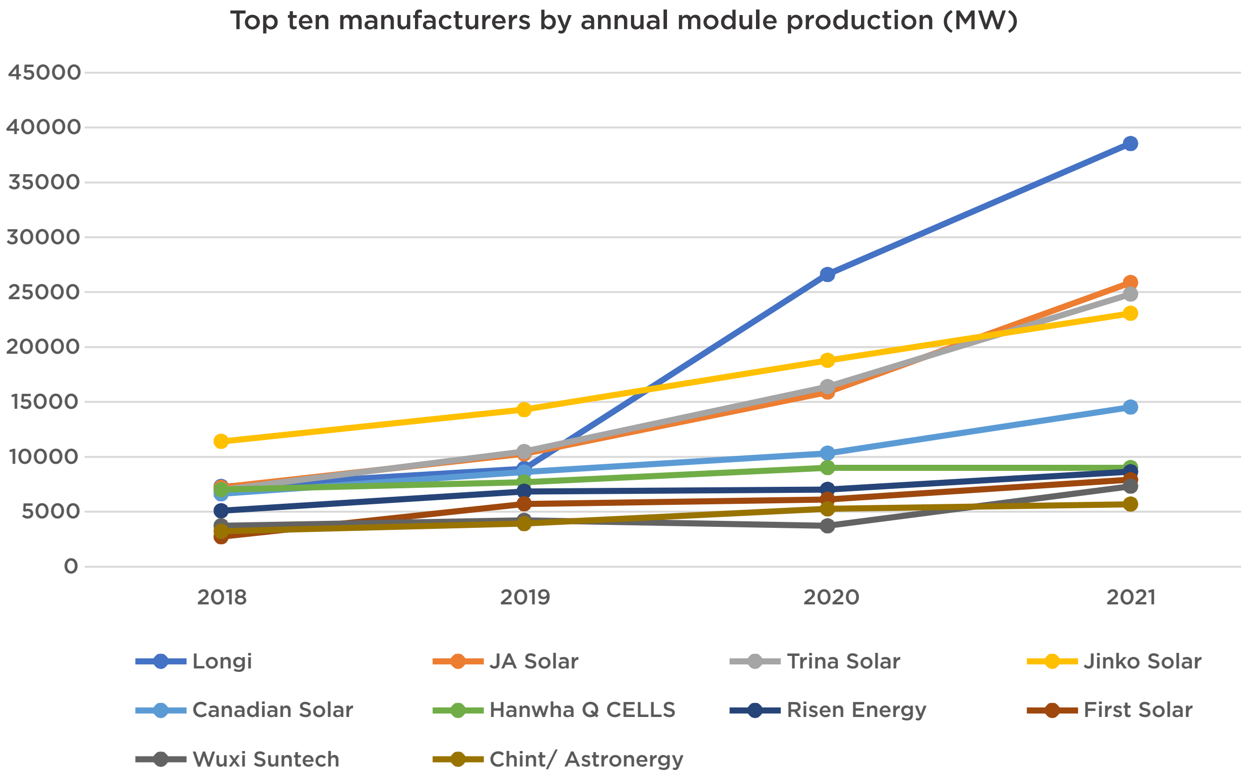


Source: BNEF Database



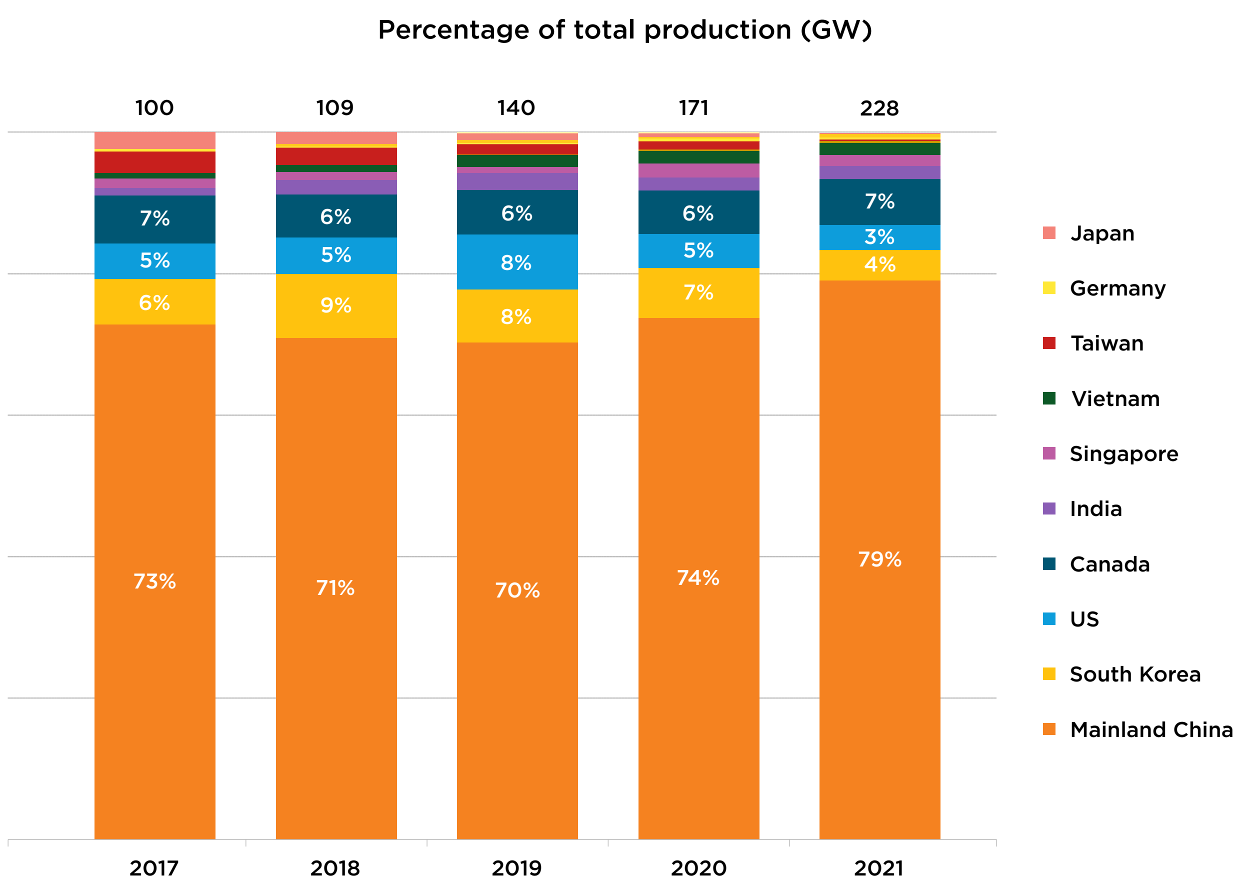
Source: BNEF

Module production is understandably dominated by Chinese companies, which are increasingly turning to larger scale larger scale module production to maintain cost advantages in the increasingly competitive module market. Longi has emerged as the largest module manufacturer with over 12 GW worth of module production than its closest competitor. Longi's module production in 2021 was over 400% greater than its production in 2018. First Solar (USA Headquartered) and Canadian Solar (Canada Headquartered) are the only companies in the top 10 who are not China based.



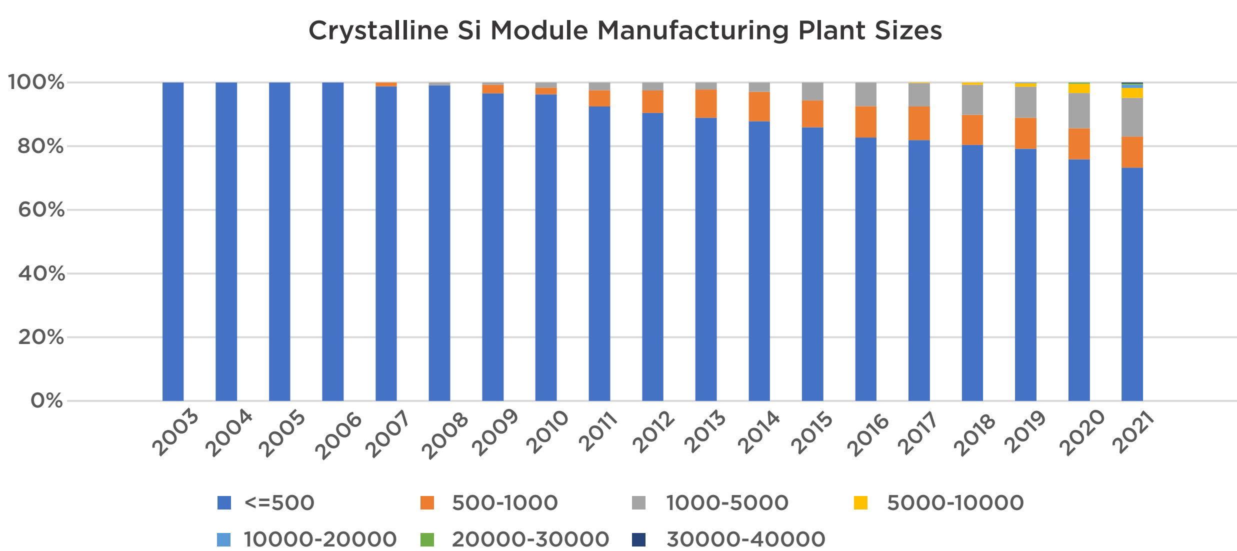
Sources: BNEF Solar Manufacturers' 2021 Production

Module production for 2021 across ten major manufacturing countries stood at 228 GW, an increase of nearly 130% since 2017. China accounted for 79% of global production in 2021, with Canada having the next largest share of production at 7%. Other countries hold smaller shares of the overall global production.



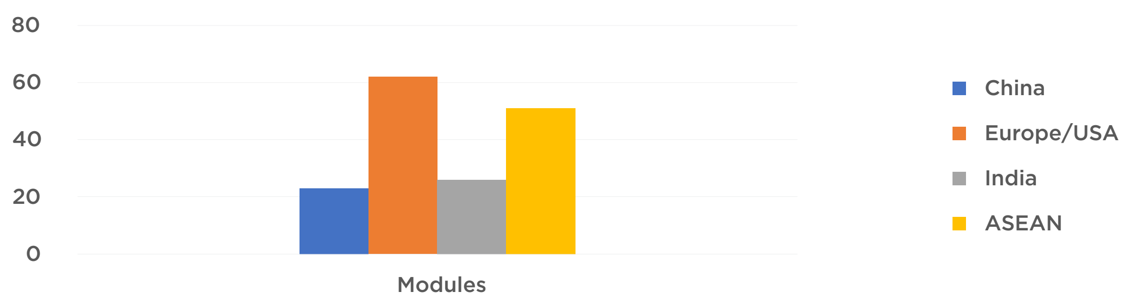
Source: BNEF Solar Manufacturers 2021 Production

As observed with cell manufacturing plants, an increase in manufacturing plant sizes has been the trend, with almost 20% of plants having an installed capacity of greater than 1 GW.



Source: BNEF Database

Regional investment capex costs for solar modules (USD Million/GW)



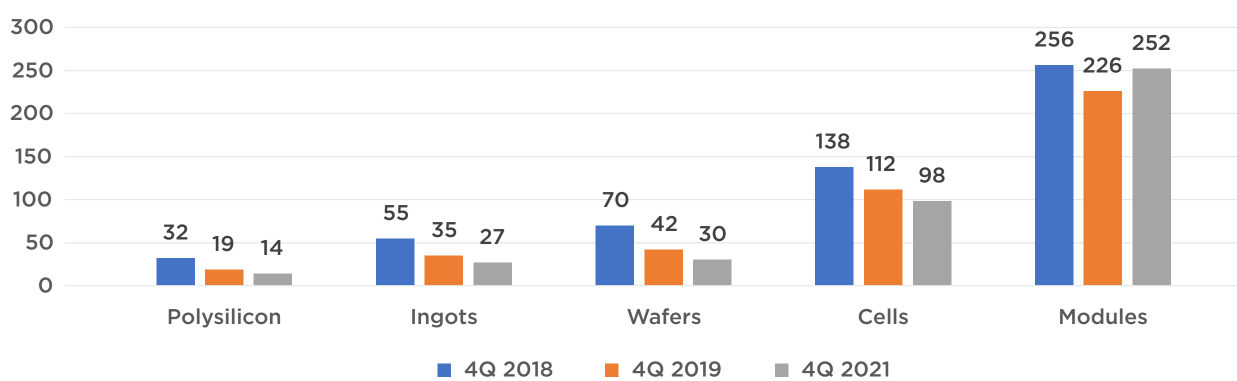
Source: IEA Special Report on Solar PV Global Supply Chains

India has module capex intensity that is similar to like Chinese levels, which is a testament to module manufacturing's relatively lower technical requirements. India and China are ASEAN, European and American manufacturing plants have a higher capex requirement.

IEA expects global nameplate module manufacturing capacity to cross 600 GW by end 2022. As one of the most geographically diverse manufacturing stages with low entry requirements, capacity can be considered to be on track to meet the demands of the solar PV industry.

In general, 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 entrenchment of existing manufacturers. 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 being more than 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.

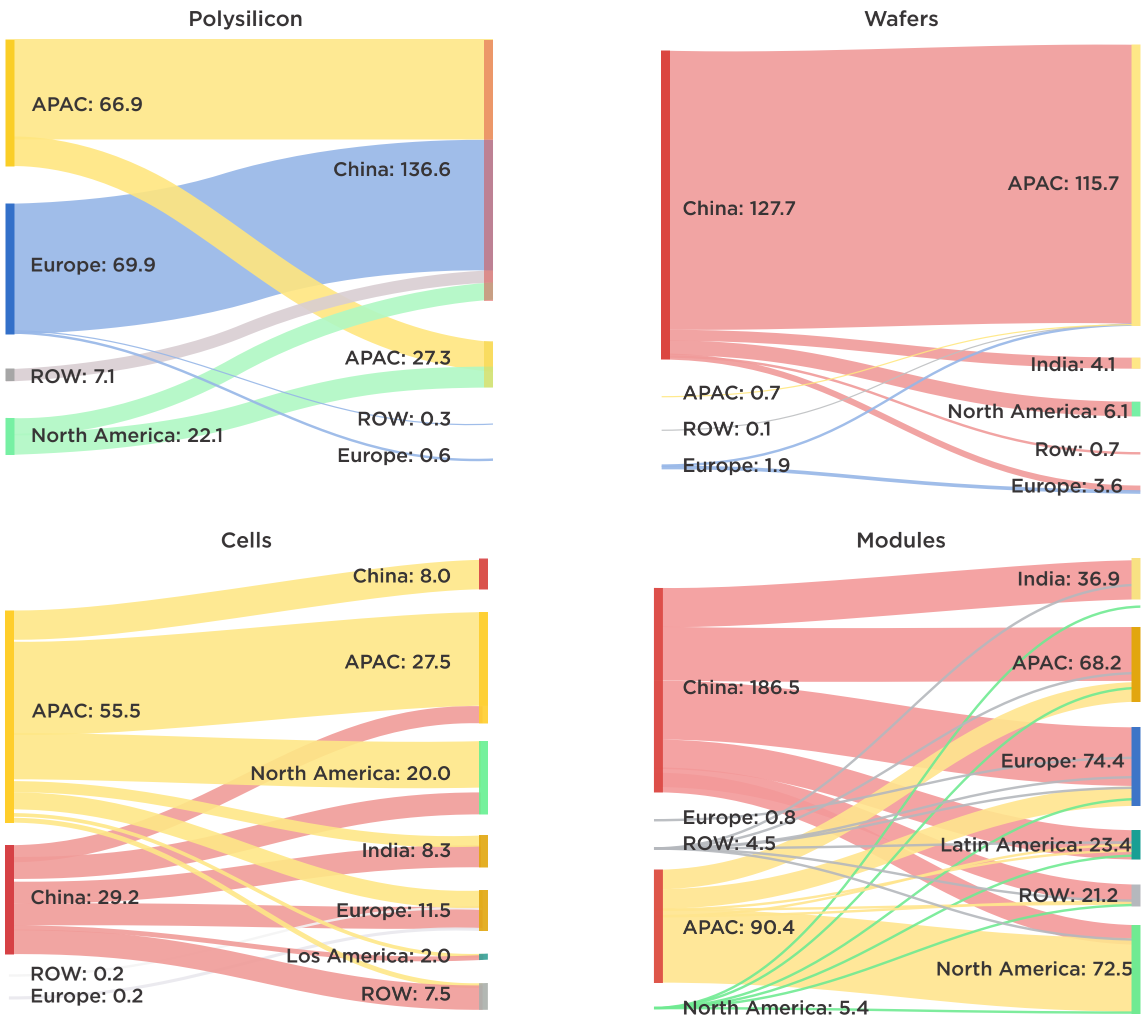
Number of c-Si PV makers along the value chain (4Q 2021)



Source: BNEF 2021 PV Manufacturing Capacity Review

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) or 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

Cumulative international shipments of PV-grade polysilicon, wafers, cells and modules in GW-equivalent by region, 2017-2021



Note: APAC= Asia-Pacific. ROW = rest of world. The figure provides data for international shipments only. Diagrams were created using the SankeyMATIC system.

Source: IEA Special Report on Solar PV Global Supply Chains

Key Messages

- Global module manufacturing capacity stood at 500 GW in 2021.
- China accounted for 79% of global production in 2021, with Canada having the next largest share of production at 7%.
- IEA expects global nameplate module manufacturing capacity to cross 600 GW by end 2022.

5.2 Non-Silicon Based Technologies: Emerging as an alternative to Si PV

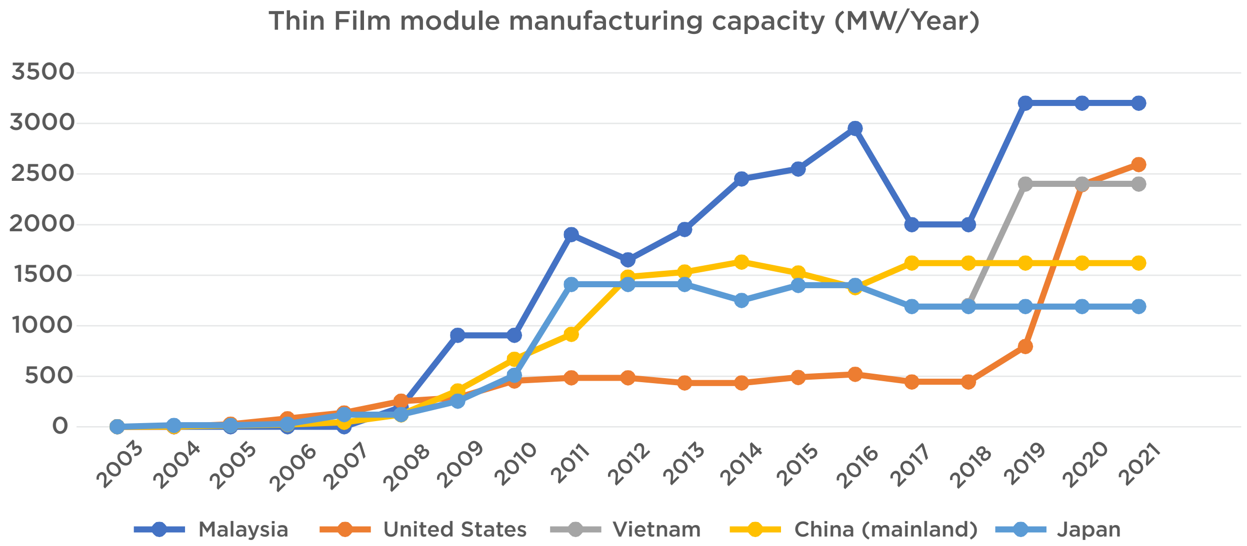
The process for manufacturing the key thin film technology in the market-Cadmium Telluride PV- is fundamentally different than that followed for crystalline silicon modules.

CdTe thin-film PV technology does not use polysilicon as its main material. The process starts by extracting and refining cadmium and tellurium, and then proceeds to deposit a series of thin layers (transparent conductive oxide, an absorber layer, back contact, etc.), each a few micrometres thick, on a substrate, usually glass.

Cells are then delimited by laser scribing or etching before being encapsulated, framed and covered.

Manufacturing of thin film silicon-based technologies such as amorphous Silicon have remained stagnant and even reduced over the past 9 years.

Malaysia has become the leading country for thin film module manufacturing capacity, with the United States increasing its capacity 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.



Sources: BNEF Database

Non Silicon thin film modules may retain some of their appeal as CdTe modules do not rely heavily on Chinese suppliers, unlike the Crystalline Si 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. Pilot manufacturing lines for perovskite-silicon tandem solar cells are being set up, while GW scale manufacturing facilities are in place for CIGS PV modules. 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.

Key Messages

- **Cadmium Telluride, the key thin film technology in use today, follows a completely different manufacturing process as compared to the widely used Crystalline Silicon PV**
- **Thin film manufacturing capacity is significantly smaller than Crystalline Silicon PV and growth has been stagnant in most countries**
- **Interest in thin film technology manufacturing may increase if countries want to explore a manufacturing ecosystem with lesser external dependencies**

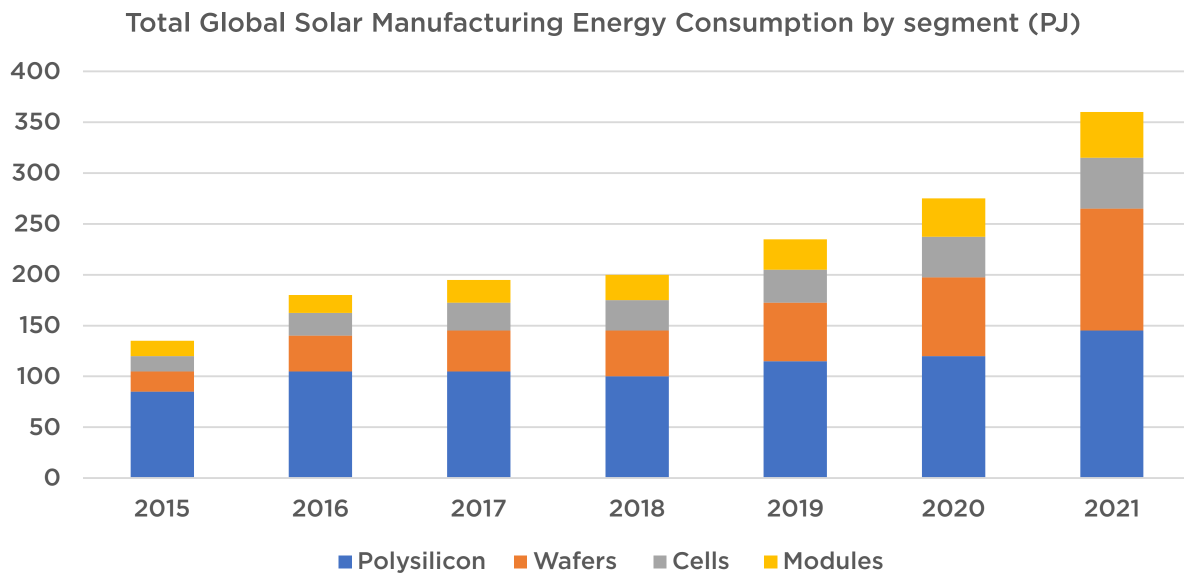
5.2.1 Solar Manufacturing Energy Usage and Emissions: Critical to address green the Energy Source

Energy Consumption

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 in 2021. At current production levels, however, this consumption is low compared with other large industries and makes up less than 0.2% of global industry energy use.

Polysilicon production accounts for 40% of all energy consumed to manufacture solar PV modules, the largest portion of all supply chain segments. Polysilicon is the most energy-intensive segment due to the high temperature and the time that needs to be applied to melt quartz, extract silicon and refine it to the level of purity required for solar cells. MGS production requires the use of an electric arc furnace with 10–15 MWh of power required for each ton of MGS produced.

Ingot and wafer production is also electricity-intensive because it requires high temperature heat for long periods of time; in fact, it has the second-highest energy consumption after polysilicon production. Energy use for wafer manufacturing has been growing since 2015 because of rising demand for monocrystalline wafers, which i three times more energy-intensive to produce than multicrystalline cells. Cell and module manufacturing capacity account for a limited amount of energy usage, around one-third of the overall requirement.



Source: IEA Special Report on Solar PV Global Supply Chains

Emissions

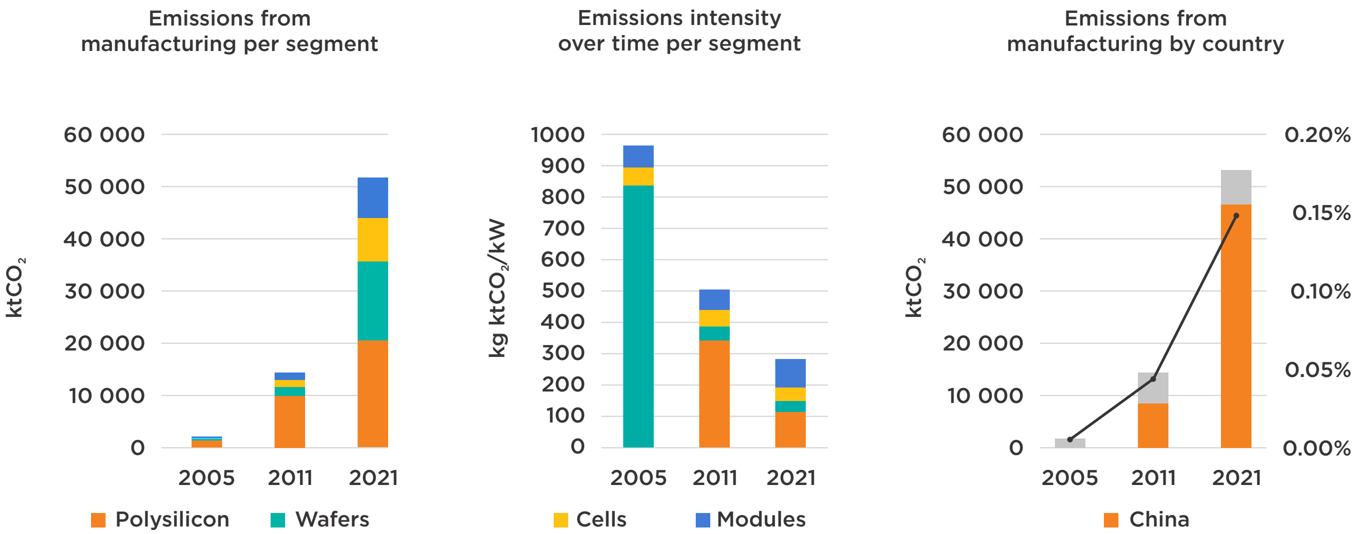
Electricity supplies over 80% of total energy consumed in solar PV manufacturing.

Coal fuels 62% of the electricity used for solar PV manufacturing, significantly more than its share in global power generation (36%), largely because production is concentrated in China – mainly in the provinces of Xinjiang and Jiangsu. In these provinces, coal often accounts for more than 75% of the power supply, partly because the government offers favorable tariffs. Reducing the carbon intensity of manufacturing could thus be a prime opportunity for the PV sector to further decrease its carbon footprint. Using renewables-based electricity in production processes could reduce emissions from PV manufacturing significantly.

CO_2 emissions from solar PV manufacturing have almost quadrupled over the past decade in response to a near seven fold production increase over the same time, as well as the industrial shift to manufacturing in coal dependent China. Emissions increases have, however, been counterbalanced by energy and material efficiency improvements and declining electricity generation emissions intensity in many countries.

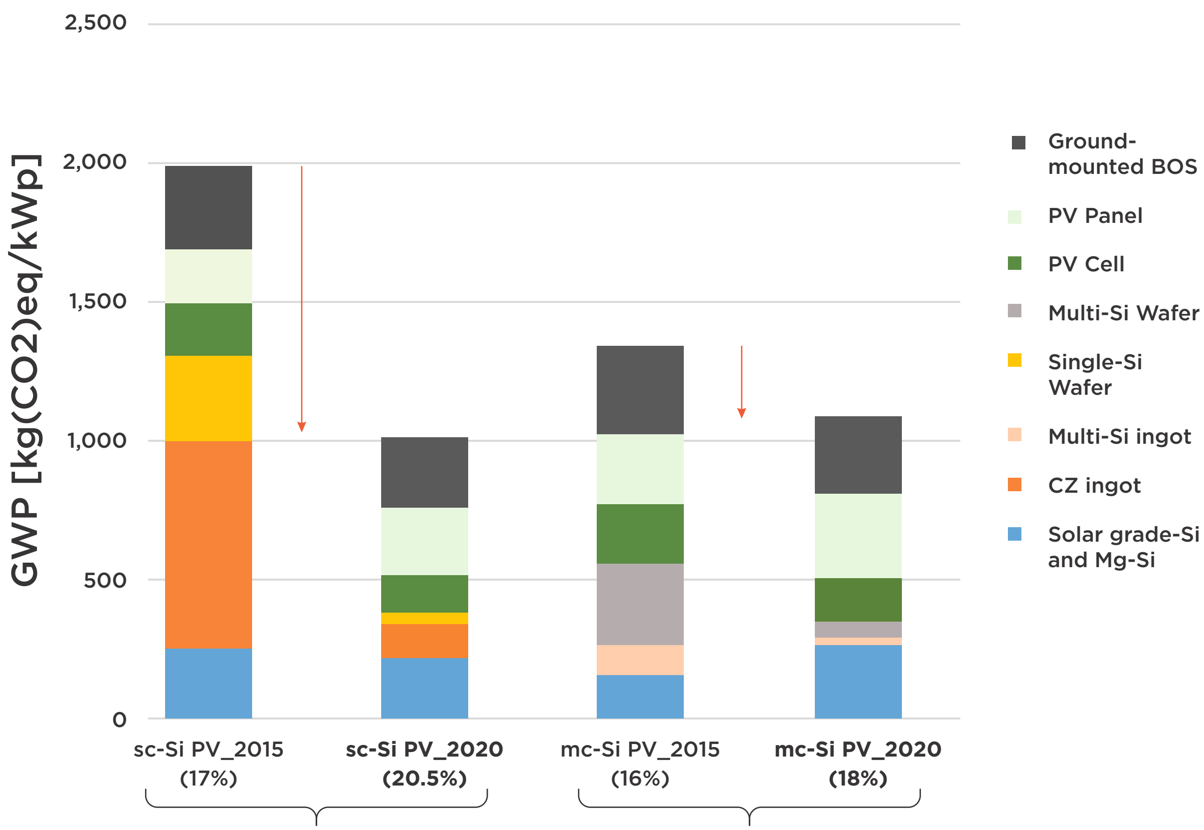
Today, China is responsible for 87% of global emissions from solar PV manufacturing involving polysilicon, ingots, wafers, cells and modules, compared with only over 59% in 2011. In the last decade, China's increase in production capacity surpassed global growth in all segments. As a result, enlargement of its production and CO_2 emissions shares outpaced even global expansion. Nevertheless, the amount of CO_2 emissions PV plants is able to displace during their operational lifetime far outweighs the volume emitted during module manufacturing. For instance, 1 GW of installed solar PV capacity could offset 1.5 million tons of carbon dioxide (Mt CO_2) annually from coal-fired generation.

Absolute emissions and emission intensity of PV manufacturing globally



Source: IEA Special Report on Solar PV Global Supply Chains

Efficiencies in solar PV manufacturing are already being seen. Increasing module efficiencies and efficient manufacturing processes have led to the reduction of per Kw emissions from C-Si PV modules.



Source: Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends

Key Messages

- The amount of energy consumed globally for PV manufacturing makes up less than 0.2% of global industry energy use
- China's dominance in the PV manufacturing sector coupled with its reliance on Coal power plants have underlined the need for efficient manufacturing and greener energy supply for the same
- The amount of CO_2 emissions PV plants is able to displace during their operational lifetime far outweighs the volume emitted during module manufacturing.

5.3 Solar Balance of System Manufacturing: Fragmented production with limited vertical integration

Solar PV energy generation system are made up of wires, mounting structures, junction boxes and inverters, 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 System". Their manufacturing costs account for a significant chunk of the overall solar PV systems cost. Although 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 and Mounting/ Racking systems.

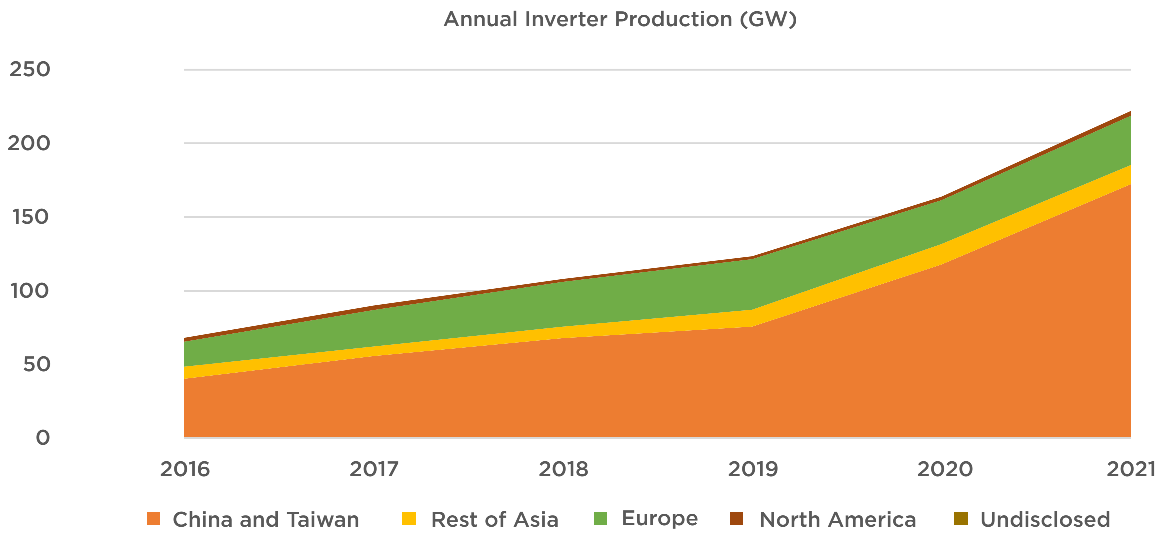
5.3.1 Solar Inverters: disaggregated manufacturing

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 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 input is done by an inverter. PV inverters have varying levels of capacity and functions, each with its own sets of advantages.

Manufacturing Insights

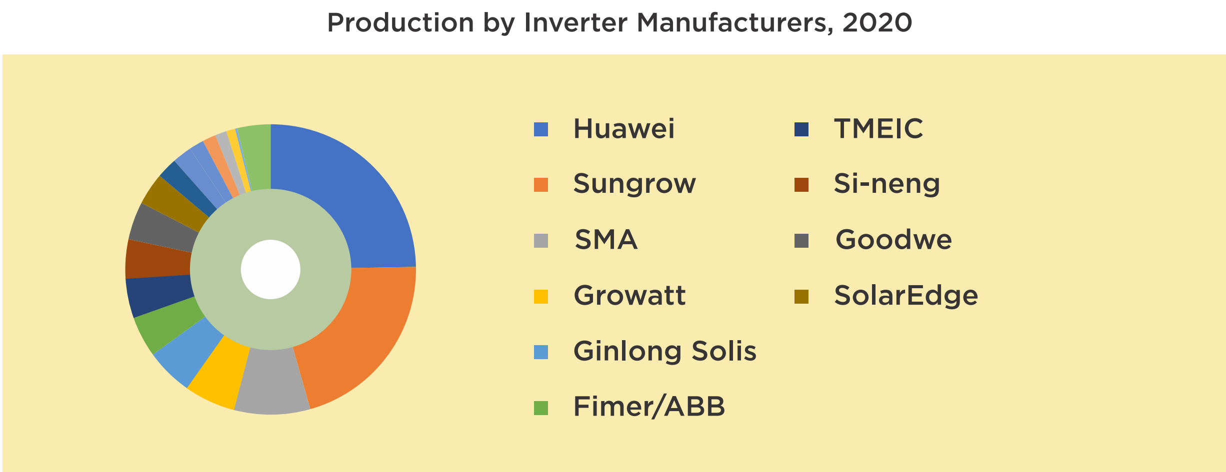
Solar inverter manufacturing is currently scattered in a manner that the power electronics and other components are manufactured in a standalone manner, and later assembled into an inverter casing. There are very few companies, which have 100% vertical integration of the solar inverter value chain. As per Bloomberg NEF 2021 update, solar inverter manufacturing is dominated by Chinese companies, with some production also being carried out in parts of Europe- Italy and Germany.[52]

[52] BloombergNEF: Solar Manufacturers' 2021 Production



Source: BloombergNEF: Solar Manufacturers' 2021 Production.

As can be seen in the above figure, the overall solar inverter production has tripled from 2016-2021 as solar installations continue to soar. The major share still lies with China, rising from 62% in 2016 to 78% in 2021. Some of the key solar inverter manufacturers, globally, as per their production capacity, can be seen in the below image.



Source: BNEF: Solar Inverter Market Update, 2021

With the increase in production of solar inverters, and the advancement in inverter technologies as well as production technologies, leading to lesser material consumption, there has been a significant reduction of inverter costs.

Key Messages

- China occupies the major share of solar inverter manufacturing industry
- Costs have fallen across all inverter types over the year with improvements in technology and efficiency in material consumption

5.3.2 Solar Mounting and Racking: Limited re-assembly and direct shipment to tracker site

Another essential part of a solar energy generation system is the solar module mounting and racking system. A solar PV mounting structure holds PV panels in place, in accordance with the sun's angle of incidence leading to efficient performance of the solar PV module. These mounting systems are at times coupled with motors, allowing for the adjustment of solar PV module's position as per the movement of the sun, throughout the day. Such systems are known as Solar PV trackers and have either 1 degree of freedom (single-axis system) or 2 degrees of freedom (dual axis trackers). Today's utility-scale solar PV plants almost exclusively use single axis devices. Although there are different types of tracking systems, horizontal-single axis-trackers (HSAT) are opted for by most power plants implementing trackers.

While single-axis tracking systems attach the modules to a horizontal torque tube that is oriented on a north-south axis that rotates the modules from east-facing in the morning to west-facing in the evening, fixed-tilt systems typically orient the modules facing towards the south tilted at an angle above horizontal equal to the local latitude. Rooftop systems for flat roofs typically orient the modules between southwest and southeast at a tilt angle of 10 to 20 degrees above horizontal. Rooftop systems for pitched roofs are typically coplanar with the roof.

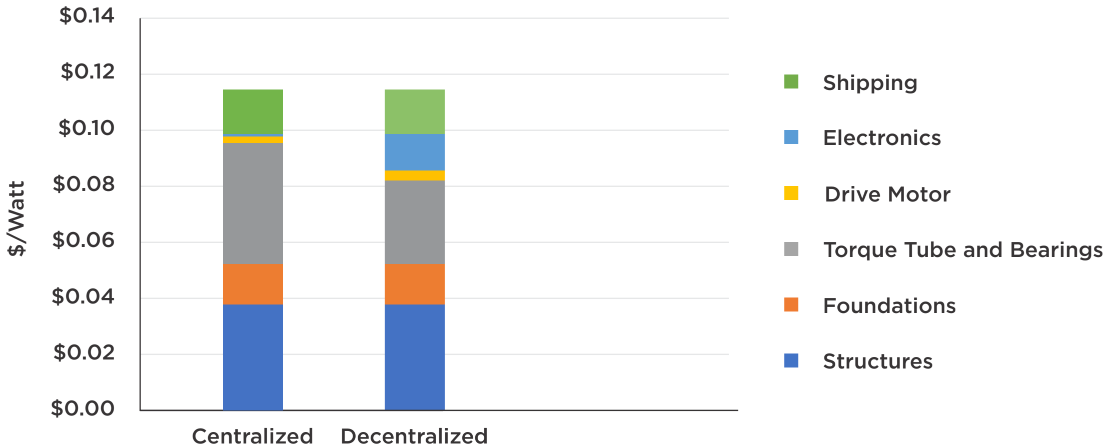
Single axis tracker architecture is typically either centralized, with equipment designed to move multiple rows of PV modules at a time (typically 15 to 30), or decentralized, with equipment designed to move one row of modules at a time (Figure 53). Approximately 42% of 2020 tracker shipments used centralized trackers, while 58% used decentralized architecture.[53]

While a single-axis tracking system has a motor for ideal module positioning, a fixed-tilt mounting system typically consists of rails connected to the rear and front legs (or single leg), with clamps present to hold the modules in place. The legs of the structure are usually driven into the ground or fixed at a high position, with concrete. Virtually all components of such a system are made of steel or aluminum.

Similar to a fixed-tilt mounting system, most of the rooftop racking system component are either made of galvanized steel or aluminum and consists of rails and clamps. They also have splice plates to connect the rails, which can be used for grounding, and either a ballasted foundation (used with concrete as the weight) or a roof penetration system is used for sufficient anchorage.

53 Solar Photovoltaics: Supply Chain Deep Dive Assessment, NREL

Figure: Indicative Cost Breakdown of a Tracking System

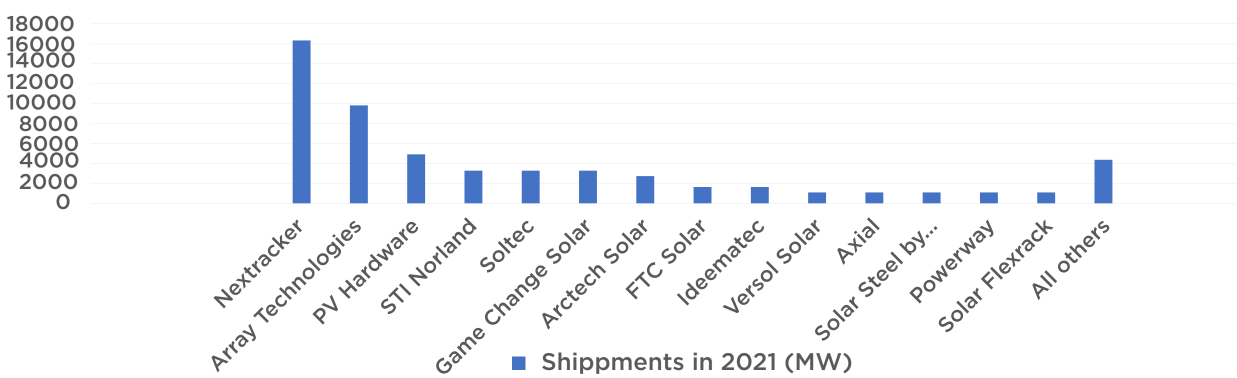


(Source: Solar Photovoltaics: Supply Chain Deep Dive Assessment, NREL)

Manufacturing Insights

Solar tracking manufacturing is a scattered industry, with very limited amount of pre-assembly at the manufacturer's facility. Almost all the parts of a tracking system are directly shipped to the deployment, from different manufacturing units, and assembled on site. This is done since the components of a tracking system are manufactured at separate locations and companies rarely have a single manufacturing unit. Some of the key global players of solar trackers are mentioned in the below graph.

Global PV Tracker Market Share as per shipments 2021



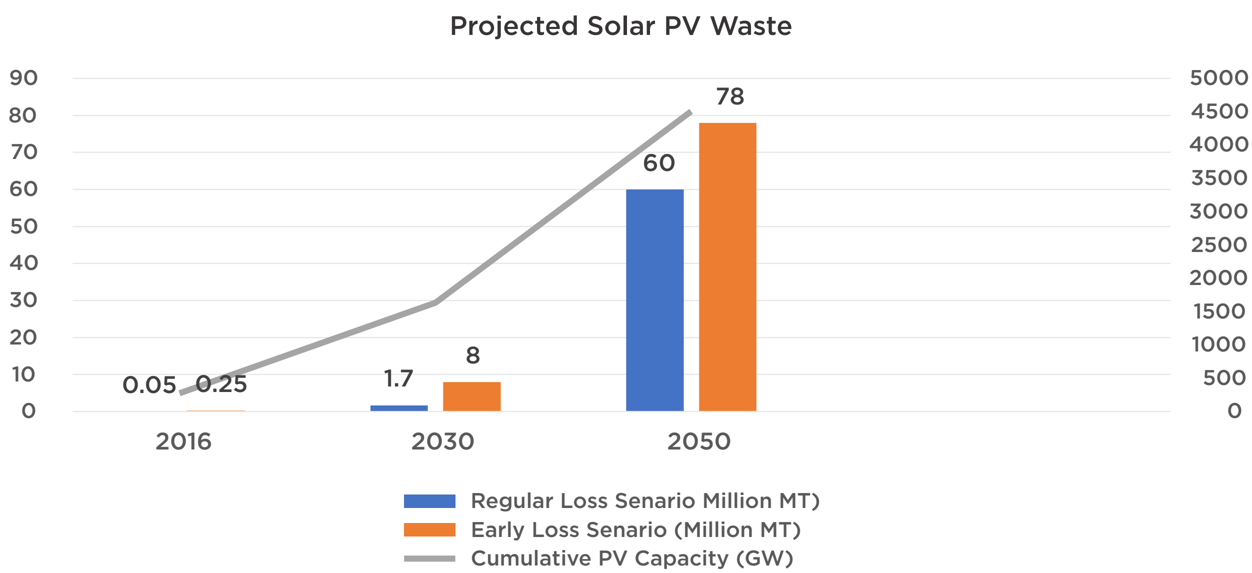
Source: BloombergNEF

Key Messages

- Horizontal-single axis-trackers (HSAT) are favored for by most solar power plants using trackers
- Cumulatively, solar trackers for 54 GW of solar PV capacity were shipped globally in 2021
- The tracker manufacturing industry is fragmented, with assembly of components being done at the deployment site

5.4 Solar waste management will gain importance as PV installations begin decommissioning

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).**



Source: IRENA: End of Life Management- Solar Photovoltaic Panels ,2016

With the rapid developments in solar PV module technologies, and considering the efficiency drop of solar PV modules after the 25-year time period, more and more solar PV plants shall be decommissioned and replaced with newer, advanced and much 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, which shall exceed 10% of the total global electronics water (e-waste) at that time.[54]

Addressing the Challenges:

Policy action and technological solutions are required to address the challenges ahead, with 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 efficiency and manufacturing improvements, material demand will increase, eventually resulting in waste as deployed modules reach 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

[54] https://doi.org/10.1038/s41560-020-0645-2

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.

Projected Solar PV Waste in 2050, Top 5 Countries

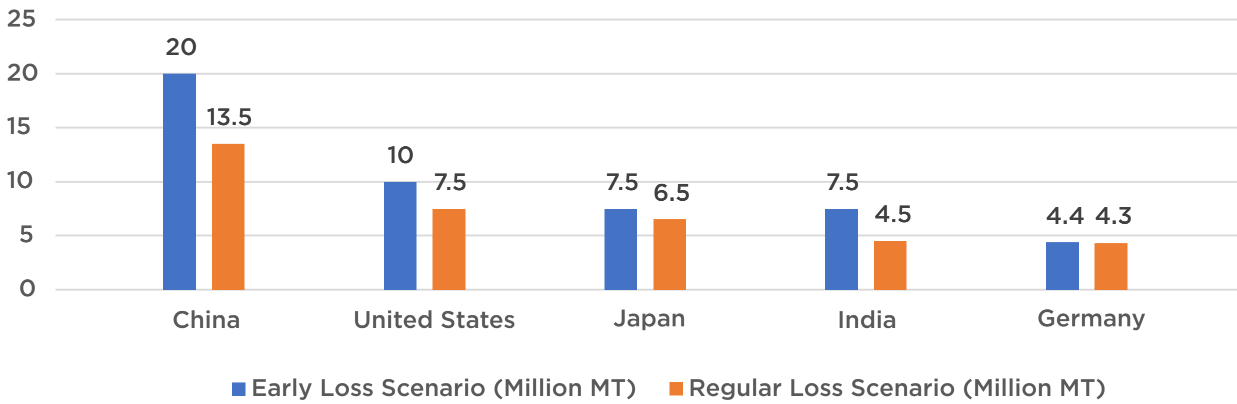


Figure: Solar PV Recycling Value Chain

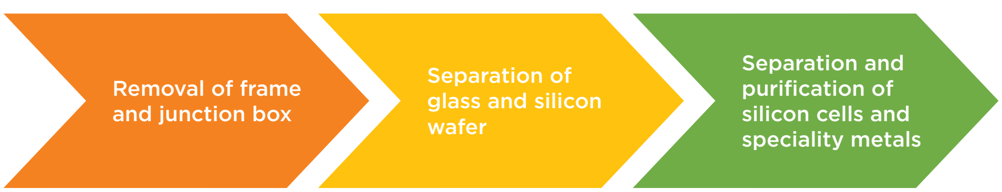
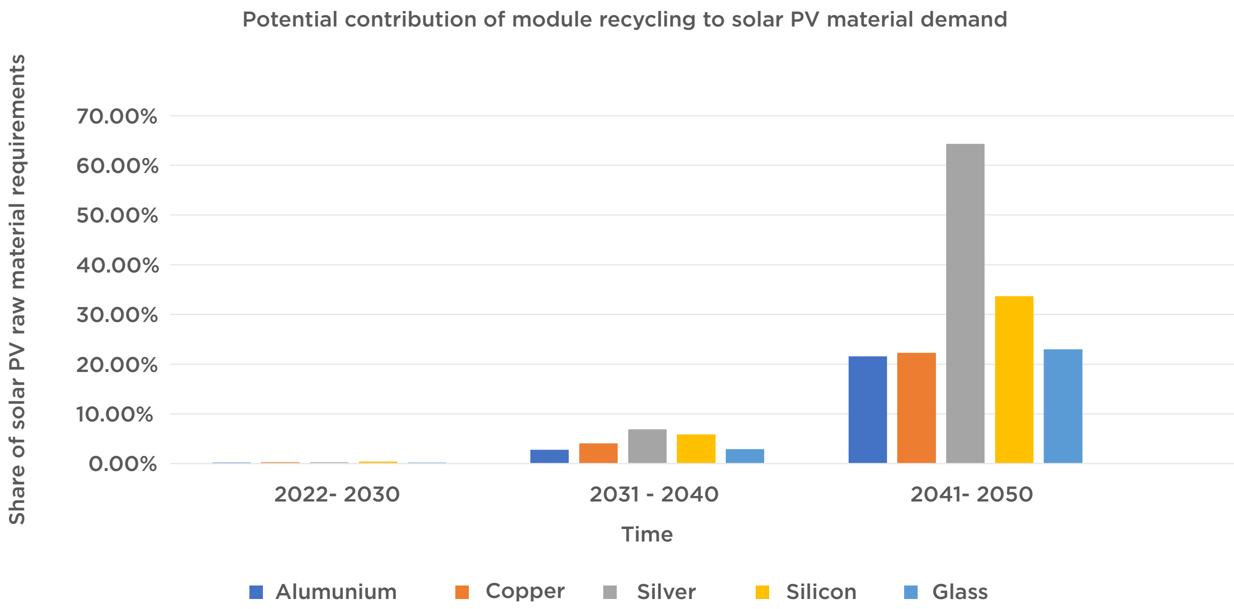


Figure: Solar PV Recycling Value Chain
(Source: https://www.epa.gov/hw/solar-panel-recycling)

An ideal solar recycling value chain is described in the above figure. Assuming proper and systematic collection of End-of-Life 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 for production of new solar PV modules by 2031-2040.[55] 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.

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



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

Key Messages

- Around 80 million Tons of solar PV waste may be generated by the year 2050.
- Recycled material from solar PV waste can cater to approximately 3%-7% of industry's material demand for production between 2031-2040
- Solar PV recycling can alleviate energy security concerns for countries heavily dependent on imports.

Fostering Solar Technology Development: Addressing the key gaps

Solar power, more specifically solar PV, has all the ingredients to become the key technology of the energy transition. There is significant captive demand, a vibrant technology environment with constant R&D driven improvements, large manufacturing ecosystem, governmental focus and support, and significant potential for sectoral linkages for decarbonization. However, to achieve its potential, several concerns need to be addressed. These concerns range across manufacturing, project development, quality, technology, R&D, geopolitics, policy, and environmental topics, to name a few.

6.1 Solar Value Chain: Important to consider all requirements from start to finish

6.1.1 Manufacturing: Improving supply chain resilience is key

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 solar supply chain is heavily dependent on China. The country has at least 75% 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. Thus, there is an urgent need for diversification and development of other manufacturing hubs. These new facilities will compete with large Chinese manufacturers who benefit from economies of scale, government support, and access to cutting edge technologies. Thus, supportive policies and mandates 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 helps de-risk the solar supply chain, while also providing potential cost reduction benefits. 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.

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). Thus, these countries are reliant on imports of polysilicon and wafers, leaving their supply chain vulnerable to external shocks. Consequently, there are significant benefits to the development of vertically integrated manufacturing facilities, 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 vertical integration must also take into account the additional components that are required to prepare a solar module. Glass covers, back sheets, encapsulants, metallization pastes, and interconnection materials 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 increase in costs.

- **Overcapacity across the crystalline PV supply chain for all stages except polysilicon**

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. This is true for all stages of the supply chain except polysilicon, which has seen severe capacity shortages in recent times, coinciding with restricted supply and a sharp increase in costs. Additionally, the development of new polysilicon capacity, while underway, will require some time to ramp up to production close to nameplate capacity. Thus, polysilicon shortages will ease, but not completely. Meanwhile, wafer, cell, and module manufacturing capacity are nearly double the global demand. Though globally there is overcapacity, there are cases of regional shortages as all regions apart from Asia have to import huge quantities from China which has 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 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.

- **Reduction of Capital and Operations expenditures**

Capex requirements vary significantly across different geographies, depending on past installations in the region, presence of cheap labor and machinery, cost of construction etc. However, relative to the cost of plant operation, these capex requirements are relatively lower. Opex costs are primarily driven by labor and electricity costs, both of which vary across regions. For example, China benefits from subsidized electricity and cheap skilled labor, while an equivalent plant in Europe or the USA would be significantly more expensive to run due to high costs of electricity and labor. As a result, 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 polysilicon supply chain, primarily for upstream stages such as polysilicon or ingot/wafer, production is dominated by the top 10 or so companies, in some cases providing over 90% of manufacturing capacity. While this concentration can result in reduction in costs for the end consumer, it 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 supply.

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 of solar waste**

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 is set to change as global installations reach Terawatt scale. As elaborated in Chapter 4, with an expected material recovery rate of 85%, cumulative secondary supplies from recycling all End-of-life solar PV modules could help meet 3%-7% of the solar PV industry's material demands for production of 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. 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. 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**

The solar industry has been focused on scaling up its production capacity, technology capabilities, and plant installations. Accordingly, government policies and schemes have also been focused on these segments, providing incentives for manufacturing and solar installations. However, as solar capacity increases at record rates, it is also important for policymakers to consider the end-of-life processes for solar modules. 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. The long life of solar plants, with

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

Solar modules, due to their relatively 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 to 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 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.

- **Clarity on responsibility for waste disposal or recycling**

Proper disposal of PV modules and equipment comes with an associated cost. Recycling is currently an expensive proposition, as cost-effective methods for recycling of the valuable materials in modules have not yet been perfected. Additionally, there are a wide variety of stakeholders involved in the production of solar modules and equipment, with varied manufacturing stages, points of sale, and end users (Utility, Commercial and Industrial, Residential consumers etc.) Thus, due to the cost considerations involved and for clarity to the market, it is important to identify to whom the responsibility for proper end of life management is attributed. This responsibility may be shared across various key members of the supply chain to mitigate the financial impact of recycling or EoL management.

Policy and Regulatory Interventions from Select Countries

S. No.	Region	Description	Features
1	European Union	The EU was the first to develop regulatory guidelines to handle PV module waste. The EUs Waste Electrical and Electronic Equipment (WEEE) Directive provides guidelines for all electrical and electronic waste management in EU member countries. the directive was modified in 2012 to include PV panels as one of the categories in electronics. Member countries can adopt parts of the directive to suit their national laws.	EU's WEEE directive is based on extended producer responsibility (EPR). A producer is responsible for taking back, recycling, and disposing of the modules they sell in the EU member countries. Other producer responsibilities include financing waste collection, ensuring finance availability for future recycling, sensitising users, informing consumers, maintaining records of waste weight at various stages, and updating on recycling targets. The UK, Germany, and France are some of the early adopters that have included sections of this directive into their national laws.

S. No.	Region	Description	Features
2	USA 	There are currently no specific central regulations in place to handle PV waste. At present, the waste is disposed of as per the general waste management framework under the Resource Conservation and Recovery Act (RCRA). Certain states, such as California, Washington, North Carolina, and New Jersey have enacted PV module recycling policies	PV Waste under the RCRA is treated as per the usual hazardous waste method to assess if the sample contains contaminants beyond the regulatory levels. • California's regulations allow for discarded PV modules that exhibit toxicity characteristics of hazardous waste to be managed with requirements that are less stringent than hazardous waste regulations. • Washington has created a Photovoltaic Module Stewardship and Takeback Program. which requires PV module manufacturers to finance and implement a takeback and recycling or reuse stewardship plan for PV modules sold after July 1, 2022, at no cost to the owner. • North Carolina General Assembly passed a House Bill to study and consider the adoption of regulations to govern the management of EoL PV modules used in utility-scale projects. • New Jersey has created a Solar Panel Recycling Commission to investigate options for recycling and End of Life management.
3	Japan 	Japan doesn't have any formal regulations to manage PV waste. At present, PV waste is treated under the general regulations for industrial and construction waste.	Trading and Industry, and The Ministry of Environment have released a roadmap to manage PV waste. The roadmap includes: • Providing guidelines to decommission, collect, transport, reuse, recycle, and dispose of waste modules • Supporting research in recycling technologies • Investigating the market for reused modules • Promoting environmentally benign module designing
4	China 	China does not have a dedicated PV module waste recycling policy in place. Moreover, they are not covered under the general waste electrical and electronic product regulations.	Currently, The Waste Electrical and Electronic Product Recycling Management Regulation of 2009 authorises manufacturers to manage and recycle their produced electrical waste. However, these regulations do not apply to PV module waste.

S. No.	Region	Description	Features
5	South Korea 	Currently, South Korea has no regulation in place to manage PV waste. However, the government is planning to introduce a new EPR scheme in 2023.	The proposed method identifies manufacturers as the responsible entity for module recycling. Unlike other countries, the manufacturers need not recycle waste and collect and transfer it to a recycling facility although they have to pay a recycling fee to support recycling facilities.

Source: CEEW and SSEF: How India can Manage Solar Photovoltaic Module Waste Better: Learnings from Global Best Practices; NREL Solar Photovoltaic Module Recycling: A Survey of U.S. Policies and Initiatives

In addition to the above government led initiatives, certain countries have also developed industry led initiatives for solar recycling.

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

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**

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. The consequences of a skilled labour shortage is 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 demand been met[57].

- **Use of improved processes to reduce material consumption**

As highlighted earlier in the report, solar requires relatively small 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.

[57] https://www.bloomberg.com/news/articles/2022-09-27/solar-panels-piling-up-in-warehouses-in-energy-starved-europe#xj4y7vzkg

- **Link usage of high efficiency technologies to public procurement tenders**

Currently, there are no regulations regarding the efficiency of solar modules to be installed for solar energy generation plants. Developers, depending upon the overall cost of the project, often procure low efficiency technology, to save on the capital costs. This ultimately results in larger land requirements, more modules per MW of generation, to be installed. This can be changed by mandating a minimum efficiency of solar modules accepted globally, as per the nature of application. For example, the PLI scheme for solar manufacturing in India aims to promote advanced solar technologies and favors high efficiency technologies.

China's Technology Top Runner Program

The Technology Top Runner Program in China aims to develop technologically advanced high efficiency solar panels. The program works by setting aside an amount of solar capacity that can only use panels that meet certain efficiency standards. This creates a market for high efficiency products and may have helped promote the development of n-type solar cells.

6.3 Quality Standards: Crucial to ensure a sustainable ecosystem

Standards pertaining to manufacturing, performance and integration plays a vital role in adoption of solar energy in a sustainable manner. Since various enabling applications are evolving, there is 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.

Guidelines for using these standards are key, as they may be complex and difficult to understand for manufacturers.

- **Significant disparities in quality across manufacturers**

Solar modules are not created equal. There may be significant quality variation between two modules 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 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 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 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 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 of 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.

- **Quality testing infrastructure**

In certain countries, the lack of sufficient testing facilities can lead to issues in introducing new modules to the market. Additionally, lower quality of testing infrastructure can result in modules that do not measure up suitably to international standards. Thus, the development of quality testing infrastructure can help develop and maintain high quality standards of solar modules.

6.3.1 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 that 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.

Guidelines for module selection for different applications

S. No.	Application	Features to consider
1	Residential Solar	High efficiency to make use of small available area for installation (usually on rooftops). Aesthetic considerations are relevant for houses, including use of black-black modules.
2	Ground Mounted Utility Scale	Low cost per watt due to high quantity of modules required. Potential for deployment of high power and bifacial modules, as well as tracking systems
3	Floating Solar	Humidity resistant, lead free, water and dust resistant, limitations on weight of module
4	Agrivoltaics	Limitations on use of bifacial modules, trackers etc. depending on type of system. Addressing increased soiling and module cleaning challenges through use of automated cleaning
5	Building Integrated PV	Use of flexible and lightweight solar modules- Thin Film technologies

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 central 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 has been described in section 4, the various steps involved in the solar module manufacturing value chain are highly energy intensive. While solar manufacturing is being ramped up, given the emphasis on more and more deployment of solar power generation plants for clean energy, the reserves for materials being used for the 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.

- **Promotion of R&D for newer technologies**

Heightened focus on R&D for newer high efficiency solar technologies such as TOPCon, HJT, 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 are using solar energy as a primary energy source for Round The Clock power. Integrating solar panels in vehicles, building facades, or via agrovoltaics, enable 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. (This point shall further discuss the various policies/programmes in countries that promote such technologies, such as "Green Hydrogen" policy of India provides fee waiver for inter-state transmission charges for solar etc.)

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 a very 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 single 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.

- **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.

India

- **Modified Special Incentive Package Scheme (M-SIPS)**

A scheme launched by Ministry of Electronics & Information Technology, the scheme provides subsidy for capital expenditure – 20% for investments in Special Economic Zones (SEZ) and 25% in non-SEZ.

- **Production Linked Incentive (PLI) Scheme for High Efficiency Solar PV Modules**

For enhancing India's manufacturing capabilities and exports, India has issued the Scheme Guidelines for Production Linked Incentive Scheme 'National Programme on High Efficiency Solar PV Modules', with an outlay of Rs. 4,500 crores. The Scheme has provisions for supporting setting up of integrated manufacturing units of high efficiency solar PV modules by providing Production Linked Incentive (PLI) on sales of such solar PV modules.

- **Preference to 'Make in India' in Public Procurement in Renewable Energy Sector**

For public procurement of items in respect of which there is sufficient local capacity and local competition, only Class-I local supplier shall be eligible to bid. Class-I local supplier means a supplier or service provider, whose goods, services or works offered for procurement, has local content equal to or more than 50%. Solar PV modules are one of the products identified as having sufficient local capacity and competition.

- **Domestic Content Requirement (DCR)**

Under various schemes for solar energy development, such as CPSU Scheme Phase OII, PM-KUSUM and Grid-connected Rooftop Solar Programme Phase-II, wherein government subsidy is provided for projects, it has been mandated to source solar PV cells and modules from domestic sources.

- **Basic Custom Duty (BCD)**

The Indian government has imposed 25% BCD on solar cells and 40% BCD on solar modules to reduce import of solar modules and push local manufacturing of the same.

- **Anti-dumping Duty**

The Indian government levies ani-dumping duty on Solar Module BoM such as glass and EVA backsheets, to promote local manufacturing of the same.

Turkey

- **Import Duty on Solar Modules:**

Since 2020, Turkey has started imposing import duty on solar modules, to be charged as per the weight of the solar module, instead of the area. This shall promote local manufacturing and procurement of solar modules since the newer, higher efficiency solar modules are heavier in weight, thus attracting higher import duties.[59]

[59] https://www.pv-magazine.com/2020/04/15/turkey-sets-new-rules-for-solar-module-imports/

USA

- **Defense Production Act**

To increase the domestic production of clean energy technologies, including solar panels, U.S.A recently authorized the defense production act. Under the act, the Department will encourage recipients of federal support to use strong labor standards, including project labor agreements and community benefits agreements that include local hire provisions.[60]

- **Super Preference Status of Solar Manufacturing Projects**

Put the full power of federal procurement to work spurring additional domestic solar manufacturing capacity by directing the development of master supply agreements, including "super preference" status.

- **Make More in America Initiative**

The Export-Import Bank of the United States (EXIM) Make More in America Initiative, approved by the EXIM board in April, will prioritize investments to expand clean energy manufacturing. The U.S. International Development Finance Corporation supports building resilient clean energy manufacturing supply chains in allied nations around the world, reducing global dependence on China[61].

[60] https://www.energy.gov/articles/president-biden-invokes-defense-production-act-accelerate-domestic-manufacturing-clean
[61] https://www.energy.gov/articles/biden-harris-administration-announces-56-million-advance-us-solar-manufacturing-and-lower

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.

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.

- **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 centers. 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.

- **Benefits to users in remote/impoverished regions**

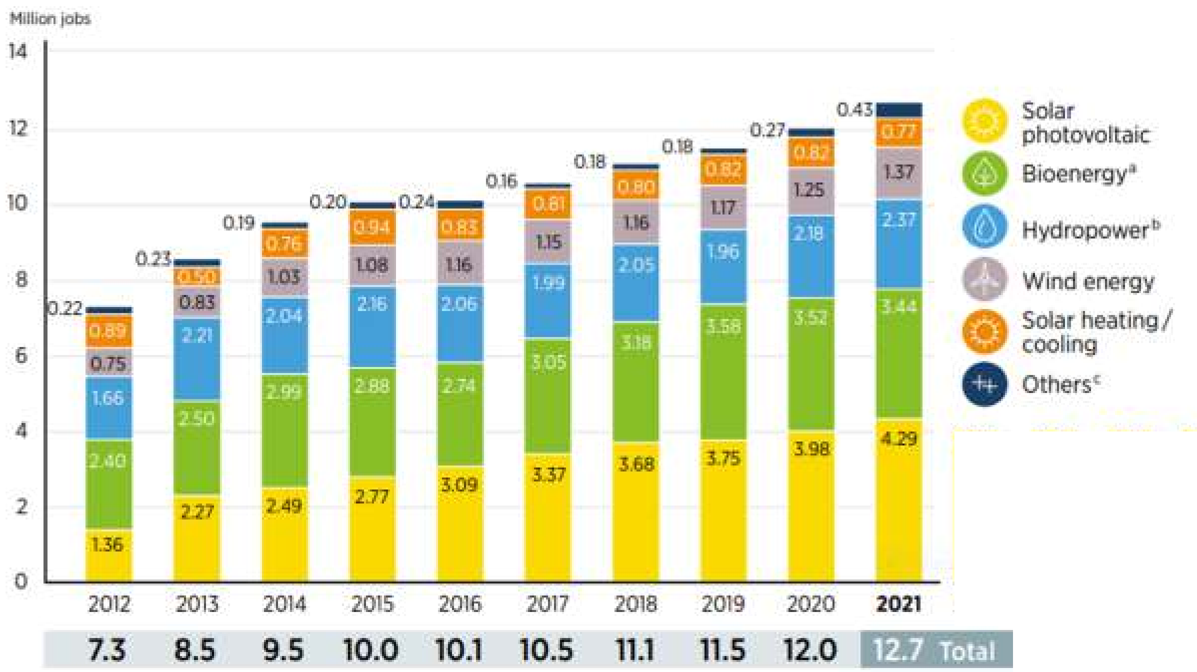
The impact of distributed solar power can be significant in remote or impoverished regions. Small scale applications of solar such as cooking or lighting can open doors to significant improvement in quality of life, safety, and even education. Additionally, the solar power often replaces fossil fuel burning, which brings further health benefits. Additionally, the development of micro grids can help bring power to remote and inaccessible locations.

Economic

	Polysilicon	Ingot/Wafer	Cells	Modules
Direct Manufacturing Jobs at 1 GW scale	35-70	400-800	150-450	500-700

Source: NREL Solar Photovoltaics Supply Chain Deep Dive Assessment

Solar is the largest source of renewable energy jobs worldwide. The number of jobs in solar have grown over 3 times in the last 9 years, crossing over 4 million jobs in 2021.



Source: IRENA and ILO: Renewable Energy and Jobs: Annual Review 2022

Country	2020 Jobs	2021 Jobs	Jobs per total installed capacity (per MW)	New Jobs per annual capacity installed in 2021 (per MW)
USA	231,474	255,000	2.08	0.86
China	2,300,000	2,682,000	8.71	6.96
India	163,500	217,000	3.61	3.77
Europe	239,000	268,000	1.36	1.00
Global IRENA and ILO	3,980,000	4,290,000	4.56	1.85

Source: IRENA and ILO: Renewable Energy and Jobs: Annual Review 2022 and 2021; SolarPower Europe Analysis

China has by far the most jobs in solar, thanks to its significant capacity installations as well as 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.

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 dependance of non-fossil fuel producing countries. For example, solar deployment can help reduce the need for coal, gas and oil imports. 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. This in turn can have significant benefits to foreign trade balance, especially in times of volatile fossil fuel prices due to geopolitical disturbances.

Environmental impacts

- 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 that coal fuels ~62% of the electricity used for solar PV manufacturing, disproportionately more than coal's share in the global generation mix (~36%)[62]. This leads to an avoidable increase in the CO2 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.

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

AA 100 MW solar project is estimated to avoid 139,000 MT of CO2 emissions each year. Additionally, a further 90 MT of NOx, 80 MT of SOx, and 6 MT of PM2.5 particles are prevented as well. 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. It is estimated that the reduction in NOx, SOx, and PM 2.5 can prevent ~30 work loss days each year.

- **Benefits to 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 decarbonisation of a number of linked sectors, including transport, buildings, agriculture, chemicals, and more. A 100 MW solar plant also saves ~303 million litres of water that would've otherwise been used in a thermal power plant, which further underlines Solar's credentials as a green technology.

[62] IEA Special Report on Solar PV Global Supply Chains

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 emissions while meeting the energy demands of the world. Solar technologies are well placed to serve as this clean energy source, thanks to their modularity, flexibility, and technical and commercial maturity. The sector is seeing rapid technological innovation, a growing manufacturing supply chain, and a suite of technologies to ensure grid integration. Additionally, solar energy is well placed to combine with energy transition solutions across sectors.

Although solar is emerging as the preeminent renewable energy source worldwide, further work is required to help achieve terawatt scale installations.

1. **A number of promising solar 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. **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 allowing solar to provide Round the Clock power.**

3. **Plant design, EPC, and O&M activities are helping in eking out greater generation and cost reduction throughout the lifetime of a solar plant. Developments in these activities will help ensure that solar plants are able to meet generation requirements in a cost effective manner.**

4. **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.**

5. **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 as a whole from geopolitical tensions and trade conflicts.**

6. **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.**

7. **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.**

8. **Solar capacity deployment provides a number of socioeconomic and environmental benefits that must be recognized when planning the future energy mix.**

This annual World Solar Technology Report will serve to raise awareness of solar energy's capabilities, and track trends across the sector.

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