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ABBREVIATION LIST

BAPV	–	Building Apposed Photovoltaics
BIPV	–	Building Integrated Photovoltaics
c-SI	–	Crystalline Silicon
CIGS	–	Copper indium gallium selenide (type of solar photovoltaics cells)
CdTe	–	Cadmium Telluride (type of solar photovoltaics cells)
EPC	–	Engineering, Procurement and Construction
FiT	–	Feed in Tariff
HTJ	–	Heterojunction
IBC	–	Interdigitated back contact
MG-Si	–	Metal-grade silicon
Mono c-Si	–	Monocrystalline silicon
Multi c-Si	–	Multicrystalline silicon
PERC	–	Passivated Emitter and Rear Cell
Poly-Si	–	Polysilicon (or solar-grade silicon)
PV	–	Photovoltaics
SG-Si	–	Solar-grade silicon (or polysilicon)
TOPCon	–	Tunnel Oxide Passivated Contact
USD	–	US Dollar

SUMMARY FOR DECISION MAKERS

The unique momentum for local PV manufacturing in the world can be leveraged, even in emerging markets, but multiple barriers still need to be overcome

The extreme concentration of the solar PV supply chain presents multiple risks, geopolitical and economic. The development of local solar PV manufacturing across the globe would bring advantages to the entire sector, from end customers to project developers as well as public authorities. Even if local solar PV manufacturing is unlikely to be as cost competitive as China's, there are many other sources of value. In addition to reducing geopolitical supply or economic risk, developing regional supply chains can increase energy independence and reduce the cost and emissions of logistics around the world.

But the road to a more diversified and more resilient global solar PV supply chain remains full of obstacles. Firstly, investments on the order of $150B globally by 2030 will be needed to develop the hundreds of GW of production capacities required along the value chain. Therefore, creating the conditions to unlock financing will be a major consideration for decision makers. Secondly, the labour needs associated with the estimated production capacities' expansions are enormous. Depending on the considered step of the value chain, the level of qualification of this required workforce can vary from unskilled labour such as for warehousing purposes, to highly skilled labour, e.g. in the case of R&D or production supervision. In countries where the available workforce is limited, or if lacks the necessary skills, the ambitions in terms of local manufacturing could be heavily constrained. This employment-related aspect is a very powerful lever, as the creation of local jobs can also help increase social acceptance, triggering a virtuous circle where local manufacturing and local market deployment can reinforce each other.

To overcome these obstacles, best practices can be implemented:

- Decision makers need to design holistic national strategies for solar PV, targeting both upstream and downstream parts of the value chain with specific measures, with inputs from all stakeholders. It must include long term objectives, with intermediary milestones and clear indicators allowing to measure and verify their achievement..
- Different policy tools exist to help unlock investments, as shown by the analysis of study cases:
  - ➢ As part of direct upstream measures, grants can be given, or other support mechanisms such as low-cost loans, production-linked incentives, direct tax rebates, or equity investments by public entities
  - ➢ As part of indirect upstream measures, state guarantees can be provided, as well as preferential tax regimes. Public authorities must also invest in infrastructures that will be essential for factories, should they be energy-related (electricity, water or gas networks) or transportation-related (roads or ports). This core infrastructure must first be developed prior to developing the solar PV value chain
  - ➢ Downstream measures can also help reduce the level of risk associated with local solar PV manufacturing, especially for first entrants. For instance, tenders with strict local content requirements (within WTO limits) and conditions on the origin of the installed equipment can help ensuring the off taking of a part of the production by guaranteeing a certain demand level. For the same purpose, trade agreements with neighbouring countries can be enacted.

- Develop programs to train the local population and create a pool of employment-ready workforce, supporting the demand of the local industry. Regional and international collaborations can also support skill development, including curriculum development, trainings, etc.
- Invest in Research & Development to support technological innovation and the solar PV ecosystem

The booming solar PV market will create opportunities to develop local PV manufacturing industrial ecosystems, if accompanied by adequate measures to support this development. But not all countries will have the ability or the interest to establish all steps of the PV manufacturing value chain locally. If sufficient scale cannot be reached, or if some requirements are not met for a certain step, it is preferable to focus on existing strengths, specialize in a specific domain and evolve progressively.

The solar PV market remained robust in spite of recent price shocks and delivery delays, while the leadership shifted from Europe and U.S. to Asia in the last decade, especially China

In the last two years, the global PV market grew 64%, in spite of the turmoil created by the Covid-19 pandemic, including price and delivery tensions across the supply chain. Around 175 GW of solar PV capacity were installed globally in 2021, while first estimations indicate a market of nearly 240 GW in 2022, bringing the cumulative installed capacity close to 1.2 TW. This represents significant growth rates and proves the resilience of the solar PV market, with 18.6% year-on-year between 2021 and 2020, 38.3% between 2022 and 2021, after six consecutive years of annual markets above 100 GW.

With around 55 GW installed in 2021 and 106 GW in 2022, China continues to dominate the global PV market, as it has now been the leading market for 10 years in a row. This last year, it represented nearly half of all installations. The next two biggest markets are the United States of America with approximately 27 GW in 2021 and 18.6 GW in 2022, and India, with 13 GW in 2021 and an estimated 18 GW in 2022. In 2022, the rest of the top 10 were: Brazil (9.9 GW), Spain (8.1 GW), Germany (7.5 GW), Japan (6.5 GW), Poland (4.9 GW), Australia (3.9 GW), South Korea (3.1 GW).

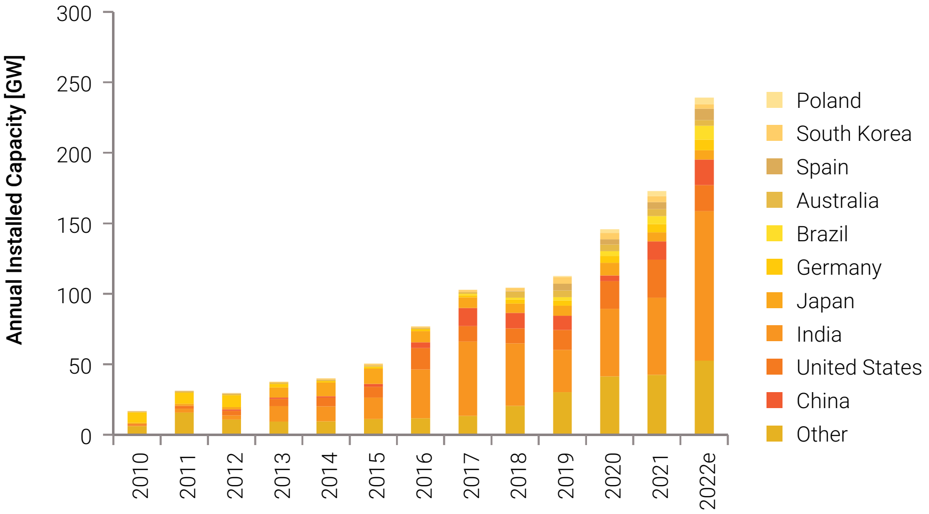


Figure 1 - Market evolution of the top10 solar PV markets from 2010 to 2022

(***Sources:*** IEA PVPS, Becquerel Institute)

China has been dominating the solar c-Si PV value chain for a decade, enabling tremendous cost reductions and setting global technological mainstream trends at all steps

The PV industry has been dominated in the last decade by China. This is true at all steps of the solar PV value chain. At the first stage, metallurgical-grade silicon, 71% was produced in China in 2021. All other producers represent below 10% of the total (Russia, USA, Brazil and Norway).

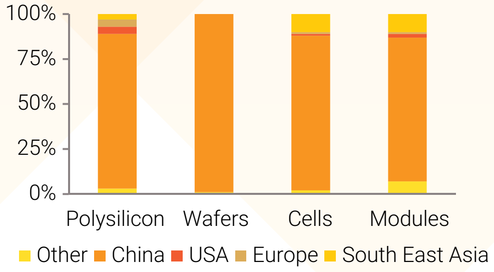


Figure 2 - Production capacity's geographical distribution for the main steps of the PV value chain, 2022

(***Sources:*** Becquerel Institute analysis based on RTS Corporation, AECEA, BNEF)

The next stage, polysilicon production, surged from 31 GW in 2012 to 224 GW in 2021. China represented a 79% market share in 2021, while both Korean and Japanese production had almost vanished by 2021 and European as well as North American production had stagnated. It is worth highlighting that the 2022 price surges occurred at this step of the supply chain, which negatively impacted downstream steps and triggered massive production capacities' expansion.

The next stage, global wafer production, was almost exclusively (99%) located in China. The remaining 2% were located in other Asian countries and Norway. Note that in 2012, this segment of the value chain was already dominated by China with over 70% of the global production of 36 GW. In 2021, the global wafer production amounted to 233 GW.

In terms of cell production capacity, China represented 86% of the total (estimated at 580 GW in 2022) while the rest of the world, mostly in the rest of Asia, shared the remaining 14%.

Finally, module production capacity shows slightly less geographic concentration compared to the previous steps. This can be mainly explained by the lower energy intensity and complexity of this last step, as well as capital intensity. China represented ~80% of the total production capacity in 2021 while the remaining 20% are mainly located in Asia (10%).

Direct upstream policy measures integrated in a long-term holistic sectorial strategy are the most efficient to support the development of local solar PV manufacturing.

The following analysis of successful cases of industrial development in various sectors and regions of the world identifies public or private measures that worked well or not, and most importantly which one are replicable in other regions willing to develop a local solar PV industry.

Despite very different contexts and varying successes, some similarities emerge from these case studies. In general, holistic plans, which are often indirect support to supply, are obviously more effective since they allow the whole ecosystem to develop on the long term with better training of the workforce and better infrastructure. Such plans bring together different stakeholders such as public officials, large production companies and local suppliers to make them successful. On the other hand, if the entire ecosystem does not grow at the same time, bilateral agreements between a government and a company may be effective in the short term but do not promise sustainable development over time if the entire ecosystem does not grow with them.

The best way to support the development of solar PV manufacturing projects is direct support to upstream actors, for instance through financial incentives such as tax exemptions, low-cost financing or direct subsidies (e.g. for land or infrastructure investments). Triggering demand, therefore stimulating downstream players is also an efficient way to develop the industry but it must necessarily be followed by further investments upstream. On the contrary, local content requirements, which have been tested in many regions, have a subpar effectiveness, especially if non mandatory, while restrictive import rules are often circumvented, thanks to loopholes.

The global solar PV market will keep on growing and should cumulatively increase by a factor of 10 between today and 2030 in order to reach Paris Climate Agreement objective

To analyse the potential of local solar PV manufacturing, future production capacities have been estimated. The first of the five steps of this quantitative analysis was to select PV market development scenarios.

Many scenarios exist, produced by various organizations. For the purpose of this study, scenarios depicting three different level of ambition in terms of PV deployment have been selected. The chosen projection scenarios may seem daunting But the solar PV market is already strong with nearly 1.2 TWp of cumulative installed capacity worldwide at the end of 2022. Thus, to reach 5 TWp in the year 2030, as envisaged in the "Minimum Transition" scenario, an additional 4 TWp would have to be installed in about ten years. Considering the development of the current market, this seems feasible.

In any case, the industry is ready to absorb such a demand, as the total annual production capacity of PV modules already stands above 250 GWp. The other two scenarios, especially the "Total Transition" with very large capacities and which would allow to respect the objective defined in Paris Climate Agreement, appear to be hardly feasible without a deep awareness and full support of the population and political decision makers. Indeed, in this scenario, the cumulative PV capacity would have to be multiplied by more than 10, from approximately 1.2 TWp by the end of 2022 to more than 12 TWp by the end of 2030. From a geographical distribution point of view, Asian countries, mainly China and India, are expected to maintain or increase their share of annual world production in 2035, while the current major European and American players are expected to see their market share slightly decrease.

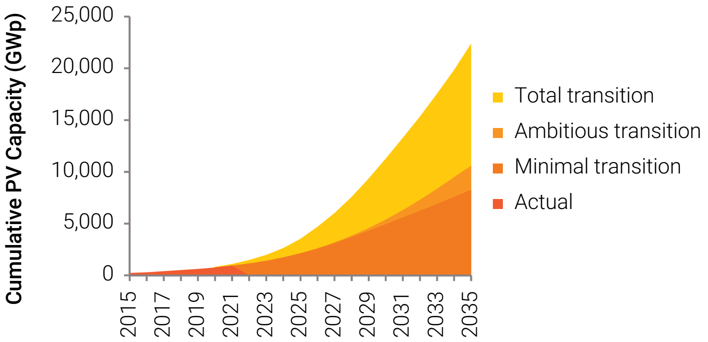


Figure 3 - Overview of the global cumulative installed PV capacity for each selected scenario until 2035 (***Sources:*** LUT, IEA, BNEF, BI Analysis)

This booming global solar PV market will create opportunities for new industry players, but these opportunities will not be distributed evenly across solar PV value chain's steps

The PV market scenarios were converted into production capacities' estimations using assumptions on PV technologies, market segmentation, factory-related parameters and geographical distribution.

First of all, starting at the very beginning of the solar PV value chain (see Chapter 2.2), the required quantity of quartz to be extracted each year in order to cover the demand of the (c-Si) solar PV value chain would have to significantly increase in order to keep up with the growing demand of the solar sector, at least until 2030, especially in the case of the "Total transition" scenario. As the global annual production of quartz (and quartzite) is estimated to amount to around 5,000 to 6,000 kilotons today, the competition for this resource will increase. On the other hand, it creates opportunities to develop mining sites in new locations or expand ones. Plus, as prices will probably be impacted upwards, sites that were previously profitable might become so. This step might be the real bottleneck for the industry. The analysis of metal-grade polysilicon's production step tells the same story.

The estimations of future required production capacities from polysilicon to modules show that overall, the solar PV industry already is on a path that could allow the sector to achieve defined scenarios. It also means that incumbent actors are well positioned and that the opportunities for new entrants would be much more limited in the "Minimal transition" scenario and, to a lesser extent, in the "Ambitious transition" scenario. Especially as most of the growth is expected to occur prior to 2030, which leaves limited time for new actors to prepare and act. This is particularly true for polysilicon to wafers, while the field would be more open in the case of cells and modules, where the technology turnover is higher (useful lifetime of equipment of 5-7 years), which will create opportunities, especially after 2025. On the other hand, the "Total transition" scenario, which might appear to be extremely challenging, would create massive opportunities for new entrants at all steps of the value chain, as the production capacities to develop are enormous.

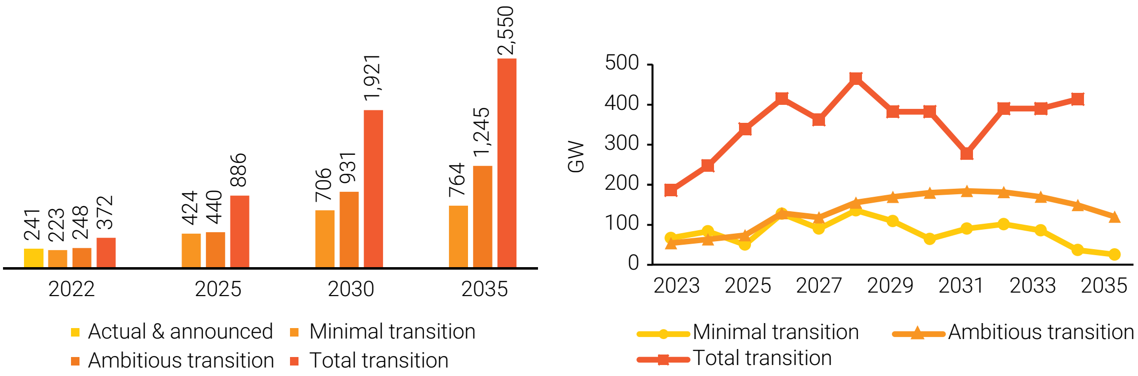


Figure 4 - Required total production capacity (left) and annual production capacity additions (right) in GW for modules for the three solar demand scenarios until 2035

(***Sources:*** Becquerel Institute Research & Analysis)

Even in the least ambitious scenario, the demand for input materials, components and consumables would be multiplied by a factor 3 within less than 10 years. In more bullish scenarios, this factor could grow to 4 or even 9, depending on the considered component. Thus, the industry, also in terms of supply of somewhat less crucial inputs, will have to adapt extremely fast. While there already have been evidences of shortages, for instance in terms of glass or encapsulant supply. This demonstrates that shortages and competition could arise, which could have negative impacts, both in terms of cost and market deployment. Even if efficient recycling largely develops in the future, it will fail at easing tensions, as decommissioned capacities are far from the levels of capacity to be installed in the coming years. On a more positive note, this can be seen as an opportunity for new actors to enter the field of photovoltaics.

There is also a tremendous opportunity for new entrants to leverage emerging technologies to gain market share in Solar PV. For example, emerging technologies such as TOPcon (expected to be the largest form of Solar PV by 2035) requires new equipment/processes relative to existing technologies, so creates an opportunity for countries to directly "leapfrog" into the most efficient technology. Similarly, investments in R&D to increase stability and efficiency of Perovskites/tandem cells could create an opportunity for technology leaders to carve out new niche in the market.

The assembly of solar cells into modules appears to be the easiest entry point among the four main steps of the c-Si solar PV value chain, thanks to reduced constraints, e.g. in terms of capital-intensity.

To evaluate the potential to develop solar PV manufacturing in a specific region, it is crucial to understand the most influential factors. For this purpose, a list of essential requirements to consider when discussing the potential of establishing local PV manufacturing has been defined. The essential requirements have been divided into four main categories, namely:

- Baseline requirements
- Key requirements for CAPEX-intensive steps
- Key requirements for OPEX-intensive steps
- Key requirements for competence-intensive steps.

The defined key requirements have been analyzed for the four main steps of the c-Si solar PV value chain (Table 1). For each step, a score from 1 to 3 for every requirement is given. A score of 1 means that the listed requirement is of limited importance for the concerned step, while a score of 3 means that it is of high importance.

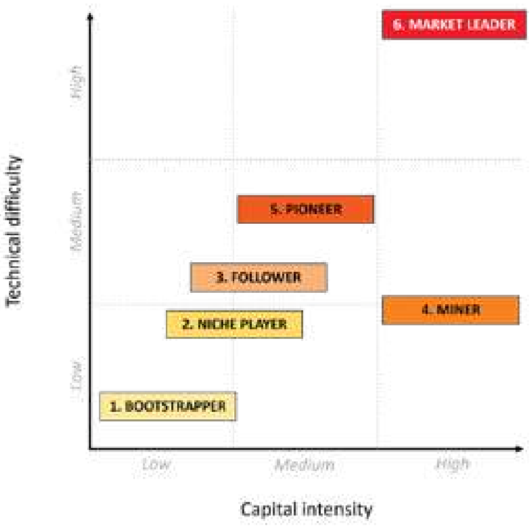
Table 1 - Overview of the importance of requirements for different step of the solar PV value chain (Source: IEA, NREL, U.S. Department of Energy, Becquerel Institute Analysis) [1] [2]

	Polysilicon	Ingots/Wafers	Cells	Module
Baseline requirements				
Existing industrial ecosystem	3	3	2	1
Domestic solar demand	2	1	3	3
Status of existing upstream PV actors	3	3	2	1
Infrastructure	3	3	3	3
Raw material availability	1	1	1	1
Ease of doing business	3	3	3	2
Key requirements for CAPEX-intensive steps				
Access to capital	3	2	2	1
Interest rate	3	2	2	1
Key requirements for OPEX-intensive steps				
Electricity cost	3	3	2	1
Electricity carbon intensity	3	3	2	1
Labor cost	1	1	2	3
Key requirements for competence-intensive steps				
Qualified labor	3	3	3	1
R&D centers	2	2	3	2
IP availability	2	2	3	2

New entrants in the PV manufacturing field facing multiple constraints should start with least complex steps, using mainstream technologies, and progressively integrate vertically

The strategy to apply in order to enter the solar PV manufacturing field and the associated recommendations vary in function of the characteristics of the concerned region or country as well as the pursued objectives. To provide an overview of this diversity, typical "profiles" have been designed. They have been ordered according to their degree of complexity, from the lowest to the highest.

The first profile, "1. Bootstrapper", is of limited technical difficulty and capital intensity, which is crucial for some developing countries, and focuses on the production of simple components (cabling, frames, mounting structures). For a limited



initial investment, such activities will allow the domestic industry to get started while rapidly while creating jobs requiring low qualifications.

The second profile, “2. Niche player” can be vertically integrated or not, e.g. focusing only on modules. Such strategy can be implemented by targeting special features or customization. This type of profile requires an efficient R&D to be able to differentiate on the market. Local content requirements are useful if well designed, i.e. leveraging the specificities of local products as well as in addition to (rather than instead of), existing solar tenders, mandates, etc. so as to avoid slowing the energy transition.

The third profile “3. Follower” is slightly more technically complex and capital intensive, while still being suitable for developing countries. As an entry point to the industry, it focuses on assembling steps such as modules and inverters, using mainstream technologies, with limited scale at first. It can be an opportunity to start developing a local solar PV expertise while supporting the local PV market, with the objective to evolve to more complex steps in the long term.

Profile “4. Miner” is very specific and is suitable for a country where valuable raw materials are largely available. Technical difficulty remains manageable, particularly for countries with some experience in mineral extraction. The required capital to take advantage of the available natural resources is enormous and can be provided through joint venture agreements. This type of activity must be carefully regulated so as not to negatively affect the environment or the inhabitants.

Finally, the last profiles are quite similar in terms of constraints, both requiring a well-developed industrial ecosystem and leading-edge R&D to maintain their dominant market positions. Profile “5. Pioneer” relies particularly on its innovative and efficient R&D to make the difference, should it be in terms of manufacturing cost or in terms of LCOE. It obviously requires extensive support to R&D, but also upstream direct measures to support small- to medium-scale actors. The “6. Market leader” profile prioritize vertical integration. It requires a holistic long-term strategy including all stakeholders. Furthermore, direct upstream measures to create a favorable environment are crucial, but also downstream measures to stimulate the local market and thus securing market opportunities, which are crucial to help reduce the risk of initial investments in manufacturing.

There is significant opportunity and value for new entrants in the solar manufacturing space, though training of the workforce, equipment and financing must be addressed

The rapid increase in production will create a strong demand for a trainer workforce, with total direct employment of 500,000 in the minimal transition and up to 2.5 million in the total transition scenario by 2025. However, 30-40% are expected to require training and a specific diploma, which creates a huge need to rapidly scale and train the workforce.

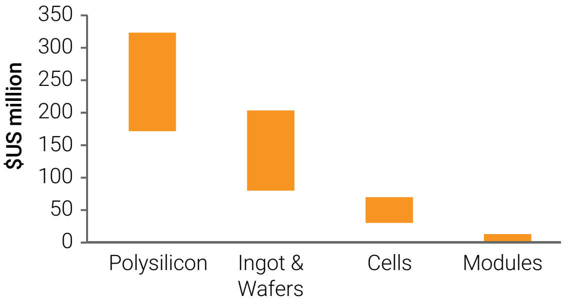


Figure 5 - Average mnimum investment required per value chain step (Becequerel Institute analysis based on IEA data)

There is also a risk of bottlenecks in the equipment suppliers, particularly for the ingot and wafering stages. The performance and scale of Chinese equipment is unparalleled, which the Chinese Ministry of Industry has recognized as a strategic advantage, and have launched a public consultation on limiting the export of key manufacturing equipment abroad. Therefore, it is crucial for other regions to redevelop local expertise and rebalance the distribution of the solar PV value chain across the globe.

Finally, the scale of investment required to set up solar manufacturing is significant, as shown below. At less than $50 Million, module manufacturing may be an appropriate first step, particularly for emerging markets with less access to capital.

The total capex required is about $110 Billion between 2026 and 2030. This may be a challenge, especially for emerging markets. However, relative to the scale of capital investments in the fossil fuel industries, this figure is quite achievable. In a diversified supply chain scenario, investments would be much more evenly spread across regions, as shown below.

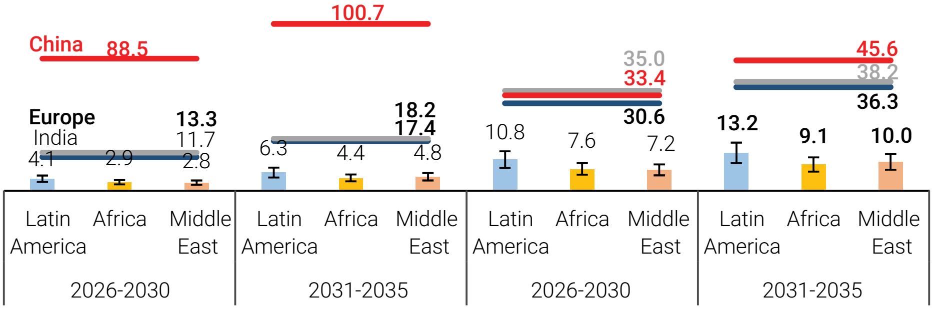


Figure 6 - Investments in billion USD required in production lines by region until 2035 according to BAU (left) and FDi (right), Ambitious Transition scenario

(***Sources:*** Becquerel Institute Analysis based on IEA, BNEF, LUT, ITRPV, CPIA)

FOREWORD

We anticipate that the global manufacturing capacity of solar panels will increase by a factor of 4 to 5 in the next 7 years, upto 2030 - and this in turn necessitates a large increase in solar manufacturing capacity as well. We have also seen a lack of global solar resiliency in the past year leading to price surges (of about 50% in 2022, compared to 2021, though the price increase has since declined) and to temporary supply disruptions. Together, these suggest that we need to diversify the global solar manufacturing value chain - and have a unique opportunity to do so.

It is within this context that the International Solar Alliance is delighted to present this analysis and assessment on building resilient global solar supply chains. The findings of this study will inform our work towards fostering international collaboration in dispersing emerging technologies and solutions around the world, including to developing countries.

We intend this report to be a conversation starter with our member countries and global actors around the world, on how we can work together to boost investment and capacity in solar manufacturing. We look forward to this report also serving as a basis for dialogue to help policymakers, manufacturers and developers create robust solar manufacturing ecosystems within their countries and around the world.

The International Solar Alliance thanks its partners, the Becquerel Institute and RTI, in preparing this report and looks forward to engaging with countries in developing globally resilient solar manufacturing ecosystems. In particular, I thank my colleague, Mr. Alexander Hogeveen Rutter for ably and knowledgably coordinating the preparation of this report.

METHODOLOGY

To achieve the defined objectives, the methodology to develop this report is based on six main pillars, combining a quantified evaluation and qualitative analysis:

- Future Demand Scenario: Three solar PV market scenarios have been selected, depicting three different level of ambition in terms of PV deployment.
- Technology Scenarios: Estimations on the future cells and modules technologies based on recognized sources in the sector
- Regional Distribution: Geographical distribution of the solar PV market
- Localization hypothesis: In terms of industry distribution across the World, two pathways have been defined, depending of the level of diversification of the value chain, concentrated in the case of business as usual, or fully diversified
- Factory Assumptions: To finalize the estimation of production capacities based on market demand, assumptions such as the useful lifetime of equipment have been made
- Definition of Key Assessment Criteria: Requirements evaluating the suitability of a region or country have been defined, followed by a discussion on the potential of establishing local PV manufacturing in selected emerging PV markets

This quantitative analysis was then supplemented by case studies, analysis and recommendations for specific policy measures, as well as a framework to support countries and regions in developing their solar PV supply chains.

Scenarios		Regional Distribution		Analysis	
PV Market	**PV Technologies**	**Market**	**Industry**	**Manufacturing Capacities**	**Key Assessment Criteria**
1. Selection of PV market development scenarios to be used as a basis for the analysis. **2.** Definition of the future performances of cells and modules technologies as well as their respective market share.		**3.** Estimation of the distribution of installed PV capacities across regions **4.** Assumption on the distribution of PV factores in the World, with two pathways defined: Localized value chain & Concentrated value chain		**5.** Evolution of required local manufacturing capacities along the value chain based e.g. on equipment utilization rates and lifetime **6.** Review of requirements evaluating the suitability of a region or country and how to improve it: ▪ Policies ▪ Economics ▪ Market	

I.INTRODUCTION

1. The solar PV market at a glance

1.1. Market evolution

Since 2010, when the solar PV sector started to transform into a global market, the annual PV market has grown from 17 GW in 2010 to 240 GW by 2022. This equals to an impressive compound annual growth rate of 24%. But this decade of development was a bumpy road.

In 2011, the capacity almost doubled compared to 2010, as the solar PV market exploded in Western Europe, especially in Germany and Italy, mainly thanks to generous support schemes. While Europe remained the absolute leading region in terms of installed PV capacity from the 90's until 2012, when it represented almost 70% of the global cumulative installed capacity, European PV installations decreased after 2011. This led to a very disappointing year in 2012, with a global market contraction of approximately 5%; as the PV market collapsed in multiple European countries due to a support schemes' phaseout.

This regional decreasing trend continued in 2013 and 2014 but was offset at the global level as other national markets started developing, especially China, the USA, and Japan which witnessed rapid growth. This allowed us to put the global PV market back on a robust growth path, as 2012 would prove to be the only year of the decade during which the annual PV market would decrease.

The year 2015 saw PV market growth in all markets except Europe, leading to a growth of 26% of the global annual PV market compared to 2014, and the 50 GW point was reached for the first time. Then, 2016 was even more impressive. Indeed, the Chinese market exploded, from 15 GW to 35 GW, and so did the market in the USA, jumping from 8 GW to 15 GW. With other GW-scale markets developing all over the globe, this led to a 77 GW PV market, equivalent to an astonishing 52% year-on-year growth.

This increasing trend was confirmed in 2017, when the global PV market broke the 100 GW threshold for the first time, reaching 103 GW of installed capacity. Many regions of the world contributed to this expansion, but the highest contributions came from Asia. China, especially, was a massive contributor, with 53 GW of solar PV capacity installed that year alone. By 2017, Asia represented 58% of the cumulative installed capacity worldwide, followed by Europe which accounted for 28% of the total capacity installed.

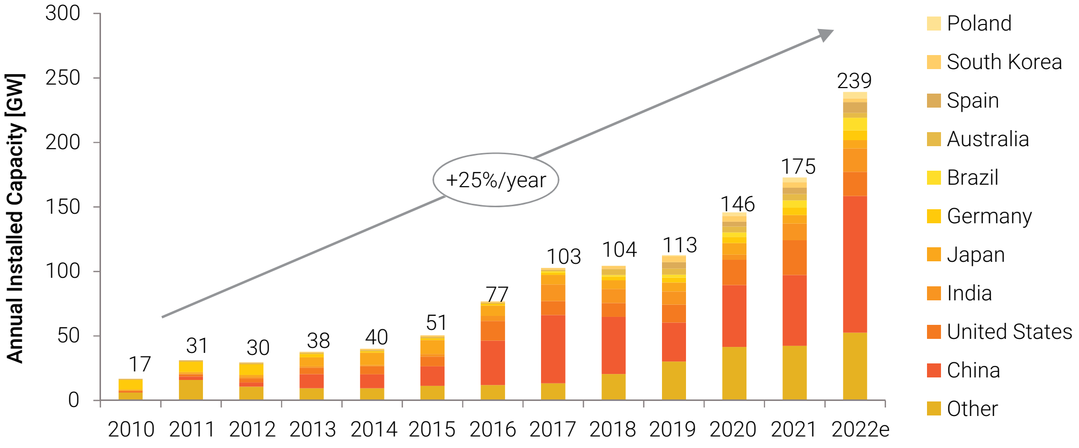


Figure 7 - Market evolution of the top solar PV markets from 2010 to 2022

(***Sources:*** IEA PVPS, Becquerel Institute)

The share of the Americas was equal to 14% of the global market, thanks to the US and few leading Latin American countries, while the 2% remaining covered the Middle East and African region. In 2018 and 2019, the global market stagnated, as annual installed capacity contracted in leading markets, such as China and India. Nonetheless, this was compensated by growth in other regions of the world, such as Australia, Latin America, or Europe, which finally bounced back after a few gloomy years.

In the last two years, the global PV market tremendously grew, in spite of the turmoil created by the Covid-19 pandemic, such as price and delivery tensions on the supply chain. These tensions can be illustrated with the evolution of average shipping costs, as shown on the left. Still, around 175 GW of solar PV capacity were installed globally in 2021, while first estimations indicate a market of nearly 240 GW in 2021, bringing the cumulative installed capacity close to 1.2 TW. This represents important growth rates and proves the resilience of the solar PV market, with 18.6% year-on-year between 2021 and 2020, 38.3% between 2022 and 2021, after six consecutive years of annual markets above 100 GW.

With around 55 GW installed in 2021 and 106 GW in 2022, China keeps on dominating the global PV market, as it has now been the leading market for 10 years in a row. This last year, it represented nearly half of all installations. The next two biggest markets are the United States of America with approximately 27 GW in 2021 and 18.6 GW in 2022, and India, with 13 GW in 2021 and an estimated 18 GW in 2022. In 2022, Brazil (9.9 GW), Spain (8.1 GW), Germany (7.5 GW), Japan (6.5 GW), Poland (4.9 GW), Australia (3.9 GW), South Korea (3.1 GW) and also make up the top 10 and must be mentioned as important contributors to the global PV market growth.

Smaller emerging markets are also worth mentioning, such as the Middle East and North African region, with an estimated installed capacity of 10.2 GW, mainly thanks to large-scale ground-mounted PV plants developed through to tenders. Other markets out of the top 10 which are important are countries in Europe like France (2.9 GW) and the Netherlands (3.9 GW).

Overall, this is the confirmation that solar PV truly is a global market, developing in all regions of the world, thanks to its economic competitiveness, flexibility and versatility.

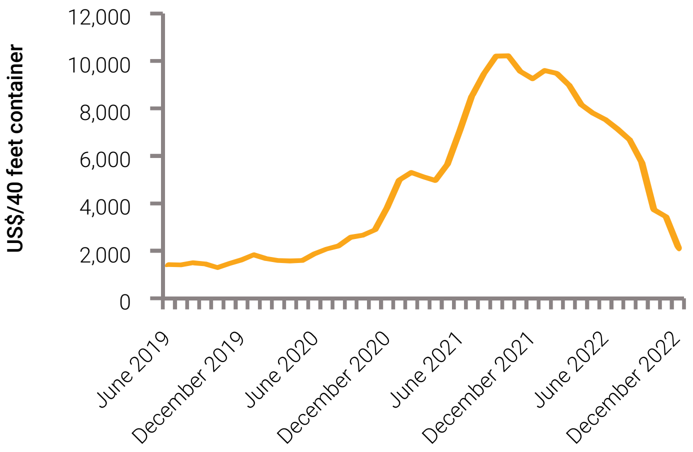


Figure 8 - Evolution of shipping costs

(***Sources:*** Drewry)

1.2. Market segmentation

The solar PV market can be split into two main segments, the distributed PV (including "rooftop PV" and the centralized PV segments (also called "utility-scale PV"). Historically, the separation was mostly based on the PV system's installed capacity, with distributed PV systems being associated with "smaller-scale" PV systems installed on rooftops, the definition of "small" being country-dependent. Typically, three types of distributed rooftop systems are defined: residential (<10 kWp), commercial (<250 kWp), and industrial (up to 5 MWp). It is worth noting that with the PV market's diversification, rooftop PV systems can be found with a bigger installed capacity than some ground-mounted systems, in some extreme cases. Then, centralized PV systems usually refer to ground-mounted PV installations, ranging in size from a few MWp up to hundreds of MWp. This also encompasses installations such as floating PV. It is worth noting that these two main segments are both grid connected, and that a third segment could be mentioned, i.e. off-grid PV systems. Nevertheless, this segment remains limited in volume on the global PV market and uses the same equipment as grid-connected PV systems, thereby depending on the same supply chain. Thus, it will not be treated separetely here.

A segmentation solely based on the installed capacity of PV systems appears as not fully relevant today, considering the evolution of the PV market. Thus, further explanations need to be provided. The "centralized" refers to the fact that these systems are connected to the medium to the high voltage transmission grid, in line with the conventional trend of having centralized electricity generating plants, as opposed to smaller "distributed" or "decentralized" PV installations that are spread across multiple buildings, connected to the low voltage distribution grid.

To complete this distinction based on the type of grid connection, a differentiation based on the business model appears more relevant today and can be regarded as a reference. With this definition, distributed PV systems gather all PV systems from which a part of the production is self-consumed. Even if this business model-based definition prevails, it is still often closely tied to the installed capacity-based definition. Indeed, in some countries, the possibility to do self-consumption is limited to a certain installed capacity range only. In other countries, there is no strict installed capacity threshold used to classify a PV system into the distributed PV segment and the classification depends on whether self-consumption is done or not.

It is crucial to have in mind this segmentation of the solar PV market when analyzing the potential of local manufacturing, as the targeted segment can impact the characteristics of the products to be developed. Indeed, primary requirements such as cost or efficiency of produced modules will vary in in function of the targeted segment, and so will secondary features such as size, weight or aesthetics.

As observed in the figure on the right, the annual PV market was dominated by distributed PV systems in 2010, with over 75% of the market. This market domination of distributed systems lasted until 2012. This trend changed in 2013, as centralized PV has evolved faster, e.g. in terms of cost, and most of the major PV developments in emerging PV markets are coming from utility-scale PV. The success of utility-scale installations is mainly coming from the fact that the installation time and cost per W for utility-scale are lower than for distributed PV plants. This makes it the most suited strategy to kick off a PV market at the most competitive price, which is a crucial factor in emerging PV markets. This increasing number of tenders organized significantly stimulated the installation of utility scale projects. This has been one of the main aspects that have characterized the market in the last decade, and it has strongly contributed to increasing the share of utility-scale installations on the market.

This growing trend lasted from 2011 to 2016, when a peak was reached with around 70% of the PV capacity installed that year coming from the centralized PV segment. Since then, the market has been more balanced, with a slight dominance of the centralized segment (55% to 60% against 45% to 40% for the distributed segment). The increase in the share of distributed PV installations installed annually can be explained by the fact that the European and North American markets, which have been growing, are more balanced, and that China, the world's leading market, has been shifting from a fully utility-scale focused market towards a more balanced market, with rapid growth of distributed rooftop PV installations.

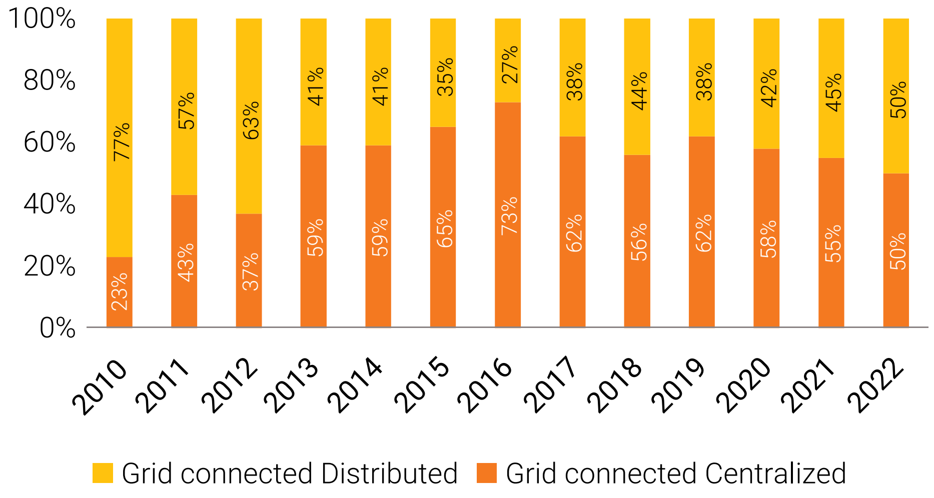


Figure 9 - PV market segment distribution from 2010 to 2021

(***Sources:*** IEA PVPS, Becquerel Institute)

1.3. Socio-Economic Aspects of Solar PV Manufacturing

The solar photovoltaic (PV) sector is the largest employer within the renewable energy sector, accounting for some 4.3 million jobs in 2021 – one-third of all renewable energy jobs, growing from 1.36 million jobs in 2012 [3]

The share of women working in full-time positions in the solar PV industry is 40%. This is almost double the share in the wind industry (21%) and the oil and gas sector (22%). The solar PV industry also compares well with the 32% share across the entire renewable energy landscape. Solar PV manufacturing performs even better than the average, with women accounting for 47% of the share [4].

In an energy transition pathway consistent with the Paris Climate Agreement, the solar PV sub-sector will remain the largest source of employment, accounting for almost 14 million jobs by 2030 – 37% of the total for the renewable energy sector [5].

Solar PV offers employment prospects for people with a wide range of experiences and occupations. There is demand for individuals with training in the STEM fields (science, technology, engineering and mathematics) and with high-level qualifications in non-STEM fields (such as lawyers), as well as people with lower formal skills (such as construction) who could be leveraged from different industries with minimum training. The variety of skills required for many of these jobs opens doors to employment for many people. In manufacturing, for example, The technical workforce forms the bulk of the labour requirements for the manufacturing of every component.

More than 64 percent of the labour required (31,920 person-days) to manufacture components is factory labour and technicians with low to medium technical skills. Industrial engineers account for another 10 percent (5,180 person-days). Many of these workers can be sourced from similar industries, such as semiconductors, electrical equipment and automobiles. Technical education and training offered by dedicated institutions or as part of university curricula can also help equip the workforce with adequate skills. Non-technical experts in marketing and sales, administration, logistics and regulation play a small (each at around 5 percent of the total person-days) but important roles (see Figure 8). Policy makers need then to match skills demand and facilitate the supply of an adequate workforce through active labour market policies [6].

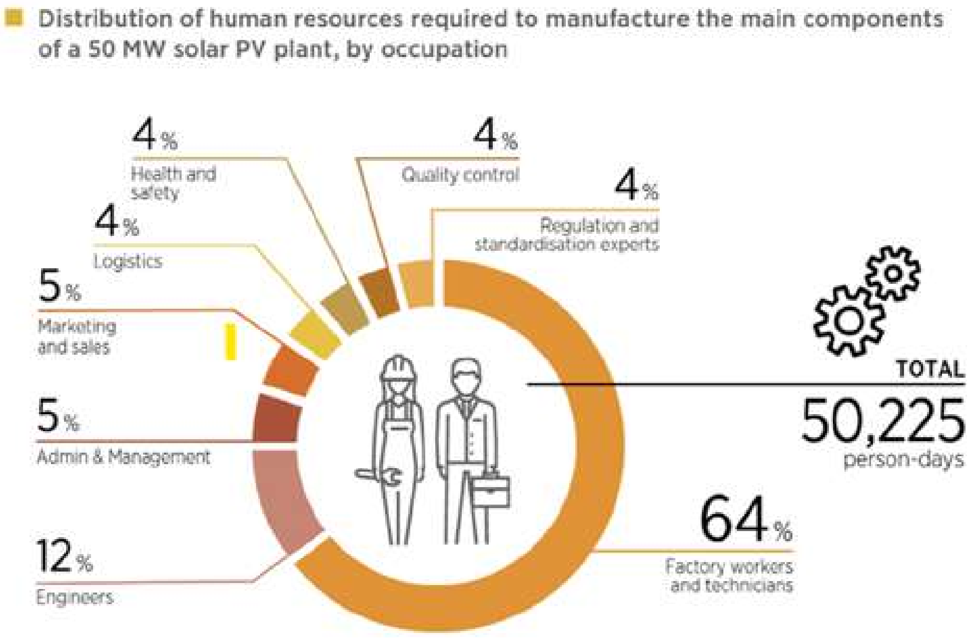


Figure 10 - Human resources required for solar PV Manufacturing (IRENA)

2. The solar PV industry at a glance

2.1. Solar value chain overview

The solar value chain is highly fragmented, with many actors of various expertise. The way the value chain is organised is also dependent on the type of technology considered, in particular at the cell level. Solar PV cell technologies are generally classified into three main categories: wafer-based crystalline silicon, thin film, or organic. Note that the latter remains anecdotical and is often combined with thin-film technologies. Thus, it will not be discussed here.

Crystalline silicon PV represents the bulk of the market by far, encompassing around 97% of the annual market in 2022. It is a complex field, encompassing a broad range of technology variants. These are distinguished by doping (p- or n-type), by whether they are cast in multi-crystalline or quasi-mono form or drawn as a mono-crystalline ingot, as well as by the type of contact used to extract current. Mainstream crystalline silicon (c-Si) cell technologies cover (1) p-type aluminum back surface field (Al-BSF) cells (mono- or multi-crystalline), which are now exiting the market, and (2) p-type passivated emitter rear contacts (PERC) cells (mono- or multi-crystalline), that are by far the most common on today's market. Advanced c-Si cell technologies are all n-types (mainly TOPCon, HJT, and IBC), aiming at overcoming the efficiency limits of conventional p-type. Efficiencies are promising and production capacities are slowly ramping up, but cost remains a problem.

Thin film technologies despite of a growing absolute market have been gradually losing market share to crystalline silicon PV, eventually only representing a couple of percent in 2021. They represent the second main type of solar PV cells and are numerous. Among the mainstream ones, amorphous silicon (a-Si) and micro silicon (μ-Si) have almost disappeared from the market, while CdTe is the most mature of all, thanks to First Solar's industrialisation. CIGS have long been existing on the market, but no industrial actor has so far been able to ramp up production capacities, due to cost and efficiency issues. Advanced thin film technologies are all unmatured emerging technologies. The most promising of them are perovskites, in particular, if used in combination with other technologies as "tandem" cells, such as c-Si or other thin films like CIGS.

Focusing first on the crystalline silicon value chain, five major steps can be highlighted. These are usually named in a simplified way as follows: polysilicon, ingots, wafers, cells and modules.

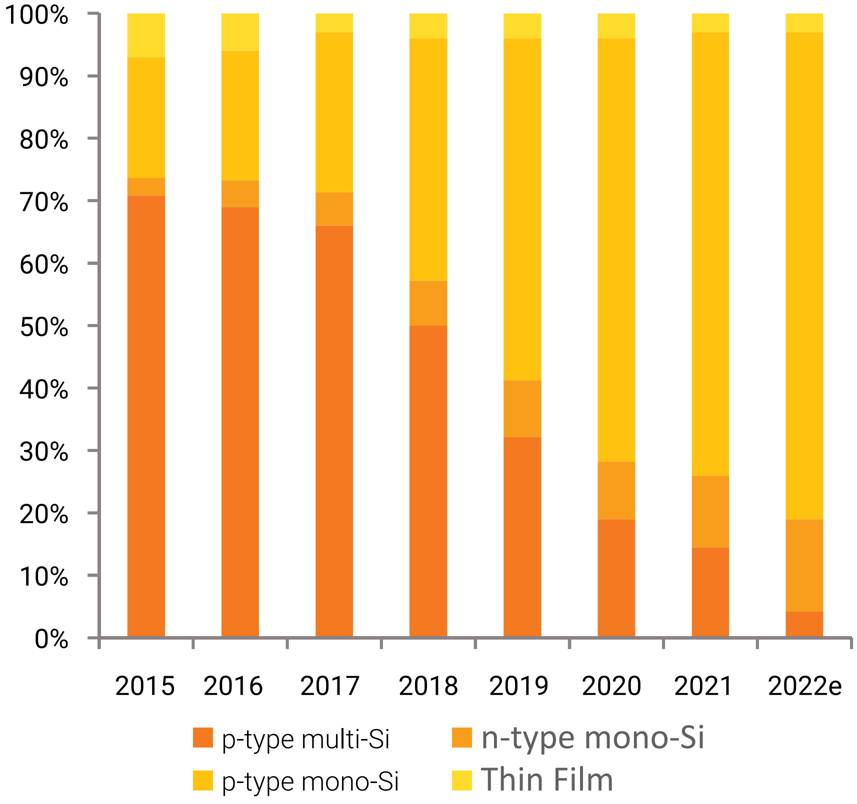


Figure 11 - Annual market share of different cell technologies (Becquerel Institute analysis based on ITRPV & Infolink)

Everything starts with the production of solar grade polysilicon (SG-Si), the main constituent of c-Si solar PV cells. This first step of polysilicon manufacturing is very energy intensive. Starting from silica quartz, metallurgical grade silicon (MG-Si) is obtained by reduction with a carbon source. This MG-Si is then purified into SG-Si, through various chemical processes.

Solar-grade Si is then crystallized into ingots and doped with gallium (p-type) or phosphate (n-type) to cast massive monocrystalline silicon ingots (>300 kg each). Ingots are cropped, then sawed into wafers of 160 to 180 µm with diamond wire. These wafers will be further treated, going through various chemical processes, to obtain photovoltaic cells. First, they are cleaned and their surfaces treated, after the application of a doped layer which will create the necessary p-n (or n-p) junction, followed by further cleaning, passivated, and anti-reflecting layers, among others, depending on the technology considered. The cells are then laminated and connected to form a multi-cell string. Several multi-cell strings are encapsulated, i.e., assembled with a sheet of glass, two foils of EVA resin, and a backsheet to make a module that is consequently framed and equipped with a junction box to form a solar PV module. These modules can then be installed on the field, in combination with other key components such as mounting structures, inverters, and other power electronics in order to obtain a solar PV system.

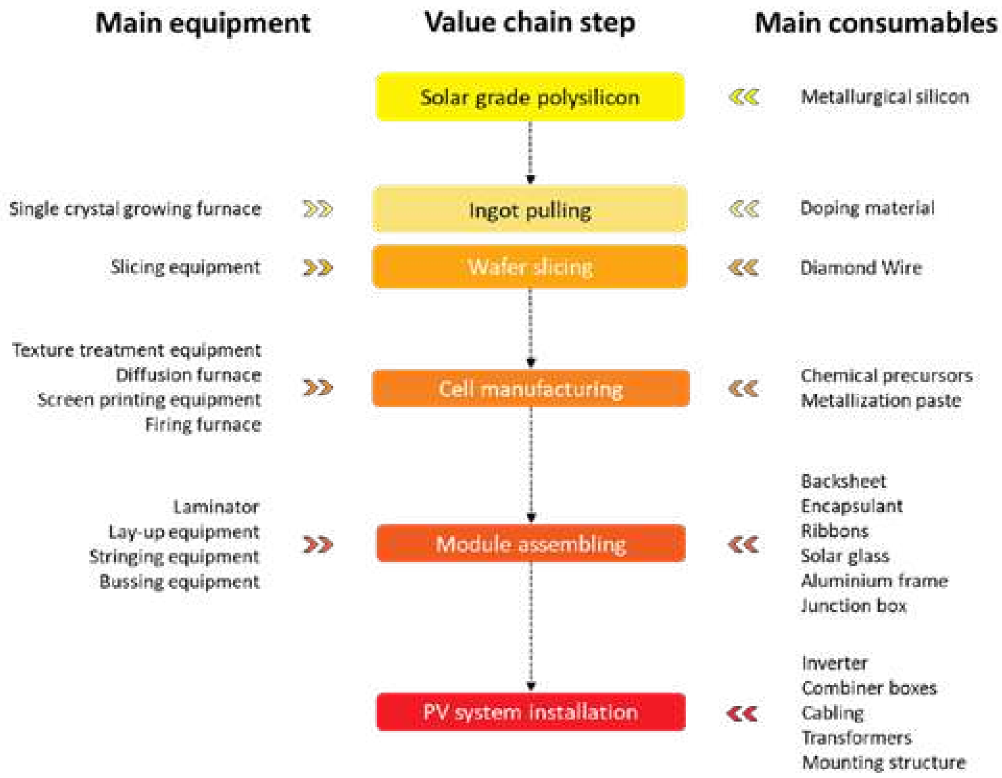


Figure 12 - Schematic view of the main steps of the c-Si PV module value chain

(***Sources:*** IEA PVPS, IEA, Becquerel Institute)

The production of solar PV modules using thin film technologies (e.g. CI(G)S, CdTe or the upcoming perovskites) is simpler than c-Si modules because of the fewer steps required. The diagram on the right shows in a simplified way the main steps, from raw materials to final module assembly and PV system installation.

In the case of CdTe, the process starts with the deposition of the transparent conductive oxide on the substrate of glass followed by an intermediary layer. Then, the absorbent layer of cadmium and tellurium is deposited, followed by the back contact layer. Cells are delimited by laser scribing, and isolated cells are encapsulated. The second glass sheet is then applied and framed to form the PV module. As for CIGS module, the production process is very similar to the production process of CdTe PV modules. The main difference in the process is the order of the different steps. Note that perovskites, the new generation of thin film technology that has gained much traction recently, relies on the same process. In case of "perovskite-c-Si tandem" solar PV cells, i.e. a layer of perovskite on top of a c-Si cell, the "cell deposition" step of the thin film process is added after the "cell manufacturing" step of the c-Si process, before proceeding to the assembling of these tandems cells in modules.

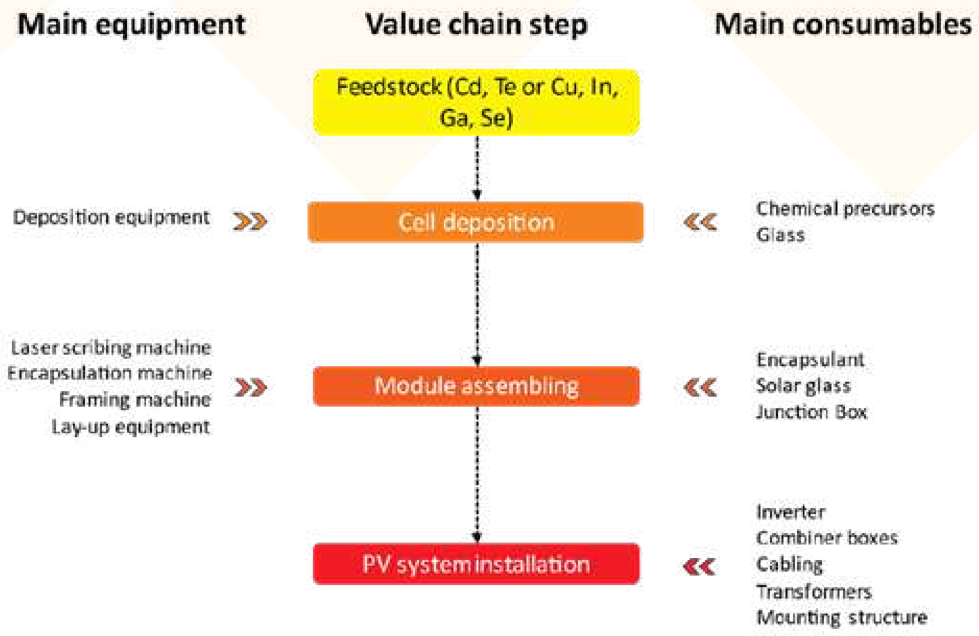


Figure 13 - Thin film PV module value chain
(***Sources:*** IEA PVPS, IEA, Becquerel Institute)

2.2. Solar industry

This section will provide a brief overview of the latest developments that occurred in the solar PV industry and highlight regional differences, which will be discussed in detail in the next section.

Overall, the global PV industry has been dominated in the last decade by China. This is true at all steps of the solar PV value chain, with China representing 79%, 97%, 82%, and 76% respectively of polysilicon, wafer, cells, and modules production capacity in 2021.

Focusing first on the production of polysilicon, China's PV industry relied for a long time on imports of polysilicon from other countries, such as Germany, Norway, South Korea, or the United States of America. But local investment rapidly took off and since 2014, China has become the first producer of polysilicon in the world. Even if China's position as a polysilicon top producer should remain unchanged in the coming years, some production locations outside of China might develop. Indeed, in 2021, the United States of America decided to ban some polysilicon imports based on forced labor allegations, which could stimulate the re-birth of factories in North America or Europe or the development of new ones. It is worth mentioning that this step of the value chain has been heavily disturbed in the last months, because of the shockwave generated by the Covid-19 pandemic as well as energy restrictions and an overall undersupply, leading to an explosion of prices.

Further down in the value chain, the production of ingots and wafers in the last years has almost always exclusively been a Chinese business, with 97% of the ingots and wafers produced in China in 2021. Then, as far as cells and modules are concerned, one can mention that even if historically manufacturing was initially dominated by manufacturers from Europe, the USA, and Japan, it has been gradually moving to Asia and China in particular, especially from 2013 on. Currently, China, is the main cell and module producer, as for other main steps of the value chain. However, it is worth noting that the contribution of other countries in Asia is higher compared to the previous value chain steps. Almost half of this non-Chinese contribution comes from Thailand and Vietnam. This can be explained by the fact that multiple tier 1 Chinese manufacturers started to develop factories in Southeast Asia to avoid import restrictions put in place in Europe (until 2019), the USA,

or India. Malaysia also saw factories develop, for the same reasons. Then, South Korea remains a relatively important cell and module producer thanks to major domestic actors, especially Hanwha. The contribution of the remaining regions of the world remains highly negligible in comparison, for instance, Europe (0.2% for cell production and 1.8% for module production) or the United States (1.2% for cell production and 3.2% for module production). Impacted by the rising price of polysilicon previously mentioned, the price of modules has also been on an upward trend for the past few months. This is not expected to change before 2023 and will be further discussed in the following sections.

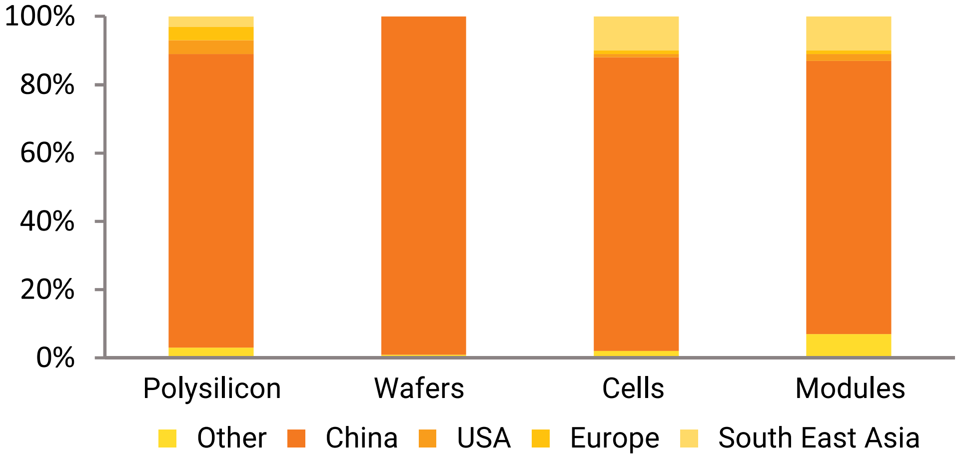


Figure 14 - Production capacity's geographical distribution for the main steps of the PV value chain, 2022

(***Sources:*** Becquerel Institute analysis based on RTS Corporation)

II. STATUS OF THE GLOBAL SOLAR MANUFACTURING SUPPLY CHAIN

1. Silicon metal: less concentrated than following steps of the value chain

Silica or silicon dioxide (SiO2) exists under different forms and is the most abundant component in Earth's crust. Quartz is among them, and it is used as the key input material of the polysilicon-based solar PV value chain. The use of this mineral is growing in demand, due to the central role in many mature and emerging industries such as solar PV, after energy intensive transformation process. A wide range of products can be manufactured out of quartz, in 2019 the overall quartz production reached 4 million tons. Of these, 76% was used to produce metal-grade silicon, while the remaining 24% was used to produce micro-silicon. Of all the end uses of quartz, 7% was used for PV applications. However, if we include the losses in between the steps of the value chain, the PV industry was responsible for around 12% of quartz consumption in that given year. As for the representation within the metal-grade silicon, the PV industry demand for metal-grade silicon was 15% (including losses) of the total. Then, 42% of the metal-grade silicon supply was used to produce aluminum alloys, 33% for silicon and silanes production, less than 1% to the semi-conductor industry and 9% had other usages.

Silicon metal, or metallurgical grade polysilicon, is the first intermediary material obtained from quartz. The manufacturing process begins with a reduction process by melting quartz and coke in a furnace, to remove oxygen, leaving silicon behind. The next step involves cooling the material, when it reaches a certain temperature, the material is crushed to reduce it to the intended size. The metal-grade silicon is ready to be packaged. Polysilicon, also called solar-grade (poly)silicon is then obtained through the purification of metal-grade silicon. There are different chemical and thermal processes to produce solar-grade silicon, the most used is the Siemens process (more than 90% of the industry), this process is complex and carries some environmental risks.

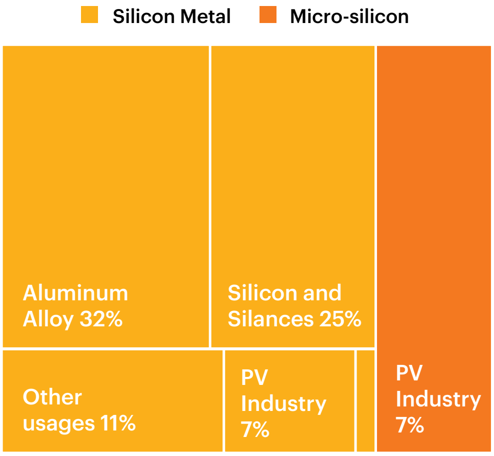


Figure 15 - Usage of quartz production per segment in 2019

(***Sources:*** BRGM 2019)

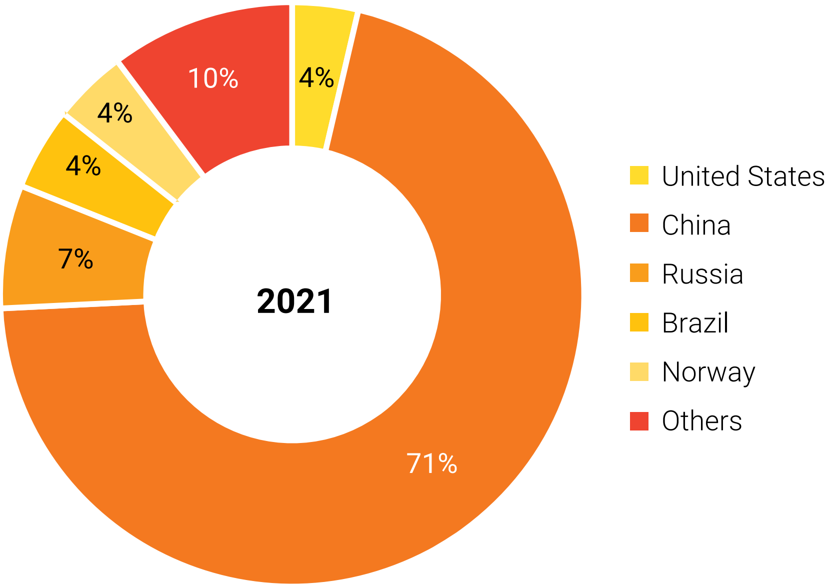


Figure 16 - Metal-grade silicon production per region in 2021

(***Sources:*** U.S. Geological Survey, Mineral Commodity Summaries 2022)

Most metal-grade silicon was produced in China, with 71% of the total, in 2021. Around 7% of the silicon metal was produced in Russia, in 2021, while the United States, Brazil and Norway each produced 4% of silicon metal in the same year. Other producers accounted 10% of the global production.

2. Polysilicon: After soaring in 2021, prices reached a plateau in 2022 and have started to decrease slowly at the end of the year, as additional manufacturing capacities started to be operational. This trend is expected to accelerate in 2023 and 2024.

Polysilicon production marks the beginning of the solar PV supply chain. Over the past decades, polysilicon spot prices have experienced gradual decrease, driven by increasing polysilicon manufacturing capacities that enabled economies of scale, as well as by technological innovation.

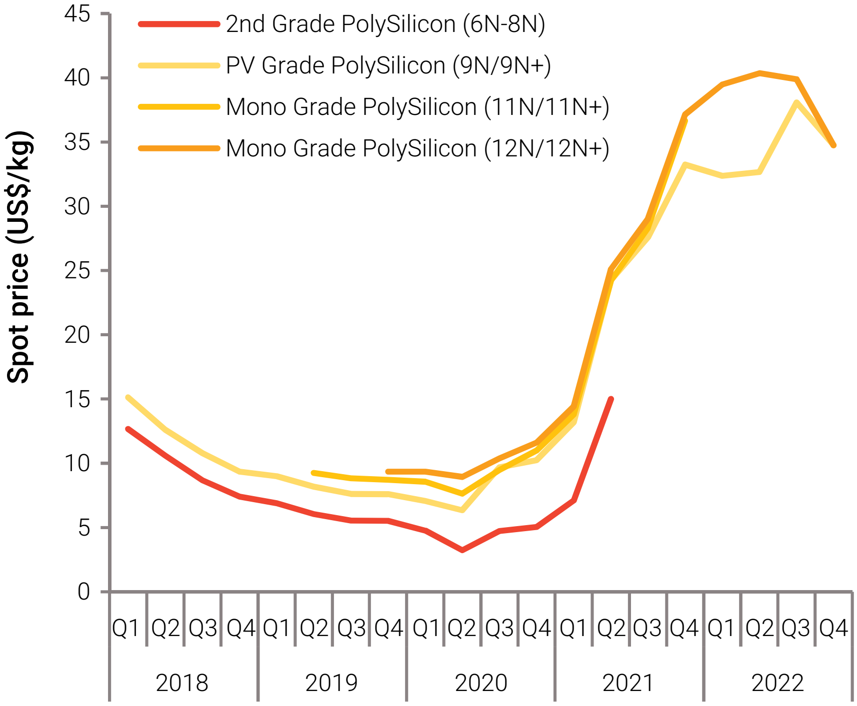


Figure 17 - Quarterly evolution of Polysilicon spot prices by technology (2018-2022)
(***Sources:*** Energytrend, Infolink, PVinsights, Becquerel Institute analysis)

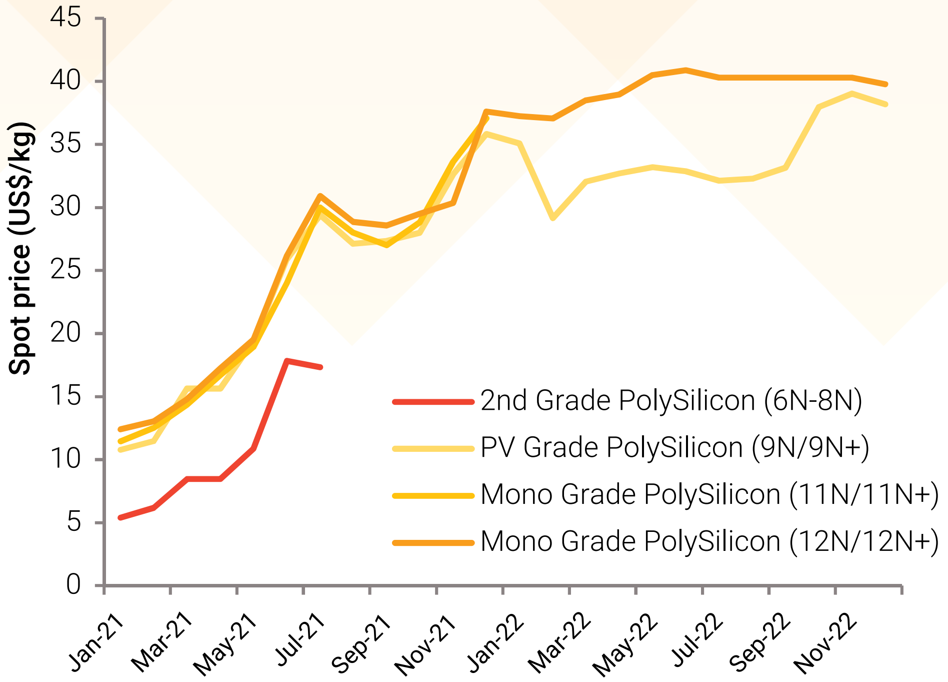


Figure 18 - Monthly evolution of Polysilicon spot prices by technology (2021-2022)
(***Sources:*** Energytrend, Infolink, PVinsights, Becquerel Institute analysis)

However, a combination of conjunctural events marked the end of this downwards path by the end of 2020, with effects lasting until now. Due to lockdowns in China, which concentrates the bulk of polysilicon production, as well as fire outbreaks and natural disasters (e.g., floods) impacting production in multiple factories, the global polysilicon production stagnated (3.8% increase in 2020 compared to 2019). In parallel, polysilicon demand continued to increase at high rates leading spot prices to increase as much as 4-fold, from less than 10$/kg in 2020 to more than 40$/kg in 2022.

Polysilicon production surged from 2012 with 216.6 kt, equivalent to 31.2 GW to 644.1 kt, a threefold increase, equivalent to 224.0 GW in 2021. Over time, the polysilicon production in China kept growing, while both Korean and Japanese production had almost vanished by 2021 and European and North American production had quite stagnated.

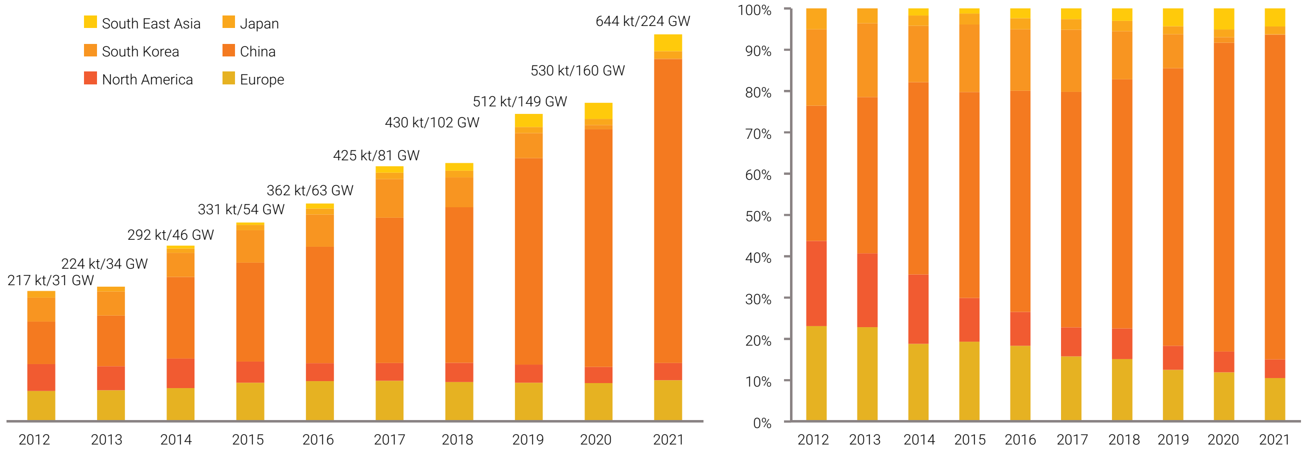


Figure 19 - Evolution of the global polysilicon production in kilotons per region (left) and relative share of the evolution of polysilicon production per region (right), for the period 2012-2021
(***Sources:*** Source: RTS Corporation)

This imbalance between polysilicon demand and supply triggered a surge in the number of announcements of production capacities' expansion and new factories. Some of these new production capacities are expected to come online, a large majority of which in China, before the end of 2022 as well as in subsequent years, which should ease the pressure on prices. Yet, most of these new production lines are becoming operational in 2023, and polysilicon prices have started to decrease.

As of 2022, China dominated the sector in terms of polysilicon production capacity, representing 86% of the global production capacity, while North America represented 4%, Europe 4% and the rest was spread across the world (Southeast Asia, Korea and Japan). In 2021, Tongwei was the leader among polysilicon manufacturers with an estimate of 109 kilotons produced in. Daqo New Energy and GCL followed, both with a production of 105 kilotons/year and 87 kilotons/year in the same year, respectively. Wacker Chemie, a German company closes the top 5.

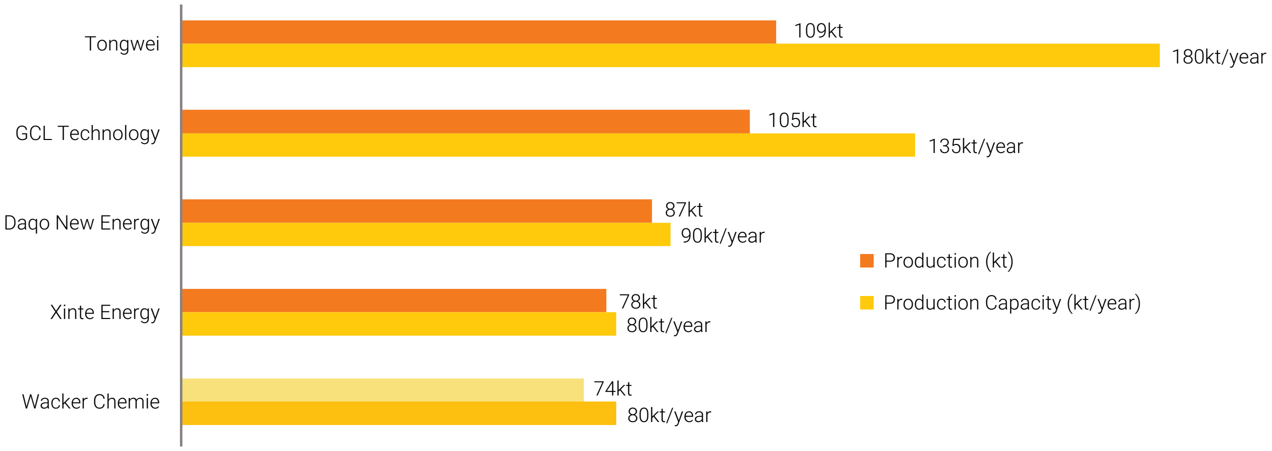


Figure 20 - Manufacturing capacities and production per manufacturer top 5 in 2021
(***Sources:*** RTS Corporation)

It is worth noting that polysilicon production is a complex step, based on heavy chemical industrial processes, which requires technical knowledge. Reaching high purity levels is challenging and has always been the key competitive advantage of Germany-based Wacker Chemie, allowing them to stay among top suppliers in the world. Moreover, this step of the PV value chain has been the last one targeted as part of China's strategy to reach industrial independency. This explains why concentration for this value chain step is not as high as following steps in the solar PV value chain. Nevertheless, thanks to subsidies and subsidized energy prices, among others, Chinese companies have now managed to reach more than three quarters of the global manufacturing capacity for polysilicon.

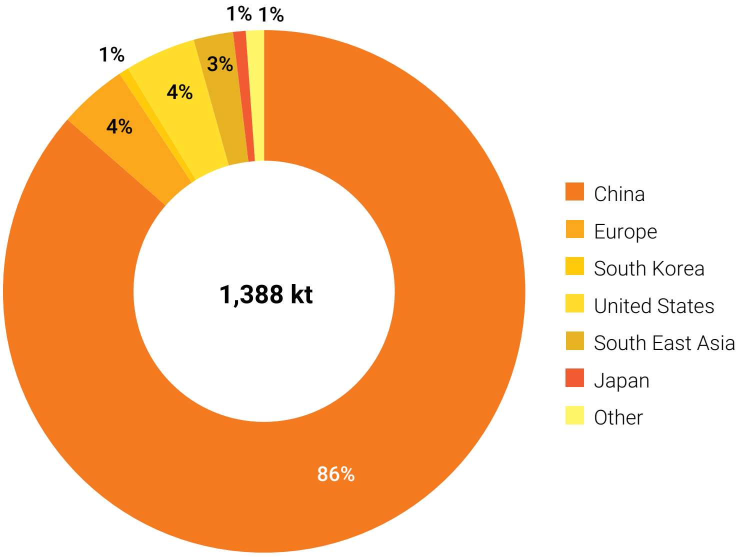


Figure 21 - Manufacturing capacities for polysilicon per region in 2022
(***Sources:*** Becquerel Institute analysis based on AECEA, BloombergNEF, RTS Corporation)

3. Ingots & Wafers: Standards for wafers' sizing dramatically changed in just a few years. As of 2022, p-type Mono PERC is dominant but expected to progressively decline, as n-type c-Si market share is increasing.

The following step in the c-Si PV module manufacturing process is the transformation of polysilicon into ingots, which are then sliced into wafers. As evoked in the introduction, these ingots can be of different types, depending on type of dopant as well as the manufacturing process applied, leading to multicrystalline or monocrystalline silicon ingots.

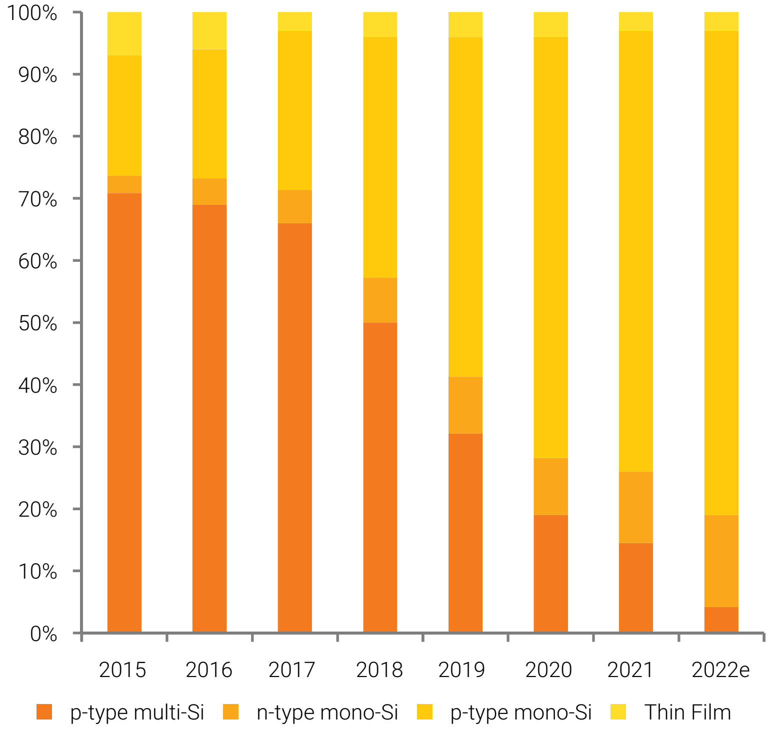


Figure 22 - Evolution of relative shares of different wafer technologies

(***Sources:*** ITRPV, Infolink, Becquerel Institute analysis)

Technologies in the ingots (for mono c-Si), bricks (for multi c-Si) and wafer production sector proved very dynamic in the recent years. Mono-c-Si technology has long been considered a premium technology, and for most of the 2010's, multicrystalline Si-based modules have been the preferred choice of many project developers for their lower price, in spite of their lower efficiency. Then, as all stakeholders across the sector looked for ways to improve efficiencies, and with the development of PERC technology at industrial scale as well as the increase of the average purity of polysilicon, monocrystalline silicon gained traction. All the more so as the price gap shrunk, mainly thanks to economies of scale reached through a massive increase in PERC manufacturing capacity in China, pushed by a minimal efficiency requirement included in tenders launched in across the country ("front runner program"). Eventually, the price gap between multi-cSi and mono-cSi no longer compensated the efficiency difference. As a result, the industry transitioned away from multi-cSi, which only represents 15% of the market today while p-type mono-Si dominates the market with over 70% market share.

As for wafer sizes, M2 wafers (156.75*156.75mm²) prevailed in the industry for a few years as the sole reference, but from 2019 multiple unusual formats entered the market, pushed by wafer manufacturers. At first, there was no consensus on which of these new formats would become the standard, but the shift from G1 (158.75*158.75mm²) to M6 (166x166mm) was rapid, and the second adoption round from M6 to M10 (182*182mm²) and G12 (210*210mm²) seems even quicker. In 2021, the wafer size share for M2 wafers was less than 5%, while both M6 and M10 make up 60%, combined. Larger wafer sizes' advantages are not limited to upstream (reduced production cost

at same throughput). Downstream, larger wafers and thus higher rated power per modules can contribute to decrease the total expenses on some module-associated BoS components. On the contrary, large wafers imply higher current which deteriorate performances at module-level due to increased temperature and resistive losses. This explains why larger cells are in half-cut or even tri-cut formats. Furthermore, at system-level, larger modules may require reinforcement of mounting structures (due to the increased weight) and can compromise container filling optimization (especially for G12-based modules). Consequently, while the advantages of larger wafers are manifold, the most optimal size between M10 and G12 is yet unclear. Some manufacturers have opted for M10 (Jinko, JA Solar, LONGi) while others chose to go for the largest size, G12 (Trina, Risen) and both groups are pushing for their implemented size to enable standardization. Both sizes are suitable for multiple applications (residential, commercial, industrial or ground-mounted), as manufacturers simply reduce the number of cells for applications for which size and weight matter, such as rooftop applications.

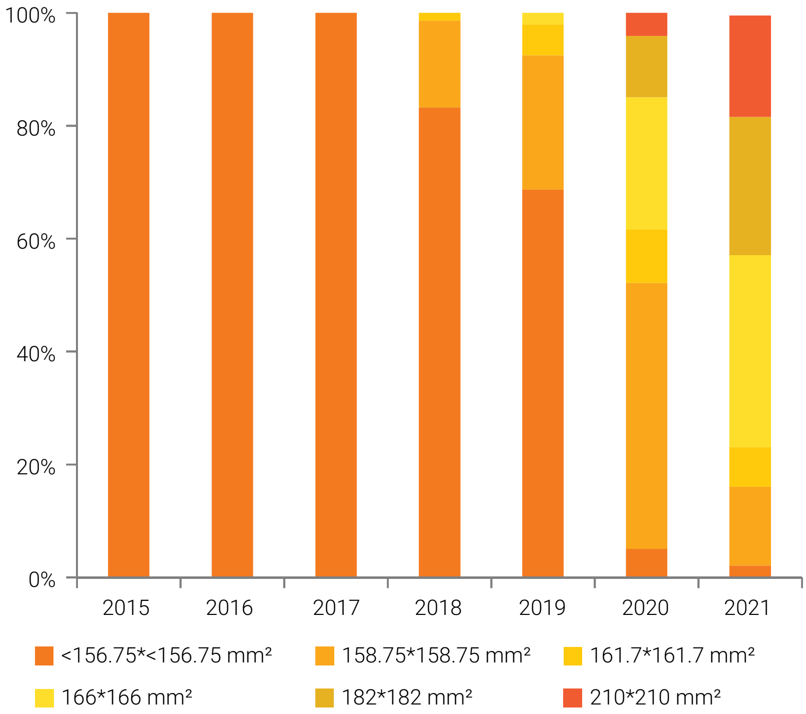


Figure 23 - Evolution of relative shares of different wafer sizes (2015-2021)
(***Sources:*** ITRPV, Infolink, Becquerel Institute analysis)

Similarly to the polysilicon spot price evolution, after years following a downwards path, wafer spot prices have been increasing since the beginning of 2021 and are now stabilizing. This increase is a direct consequence of the bottleneck existing upstream, although with a less pronounced increase. While the prices for polysilicon quadrupled, the prices for wafer production more than doubled.

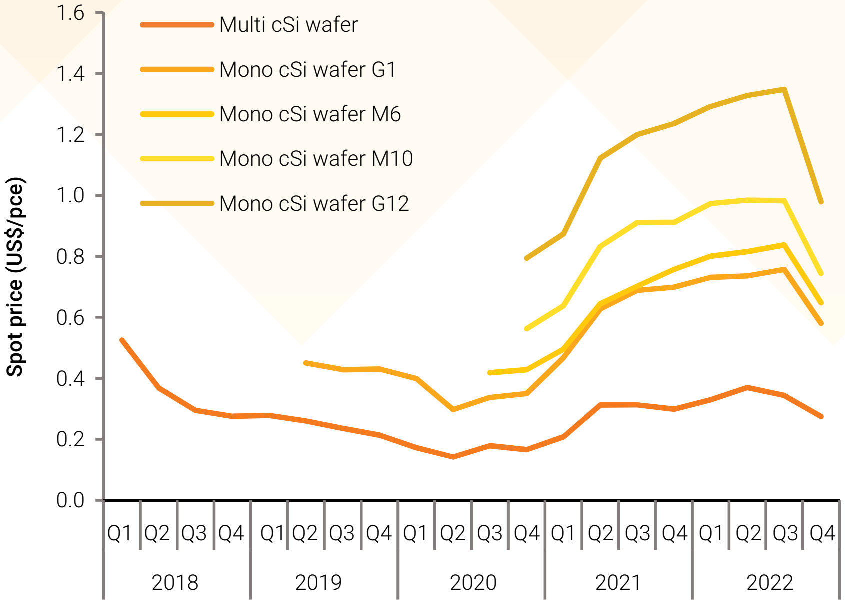


Figure 24 - Quarterly evolution of Wafer spot prices by technology
(***Sources:*** Energytrend, Infolink, PVinsights, Becquerel Institute research & analysis)

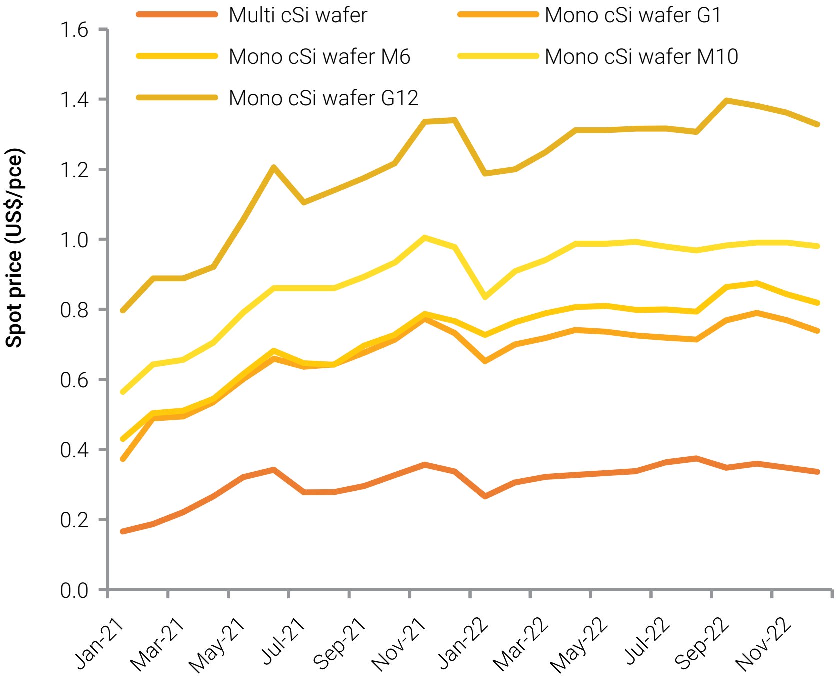


Figure 25 - Monthly evolution of Wafer spot prices by technology (2021-2022)
(***Sources:*** Energytrend, Infolink, PVinsights, Becquerel Institute research & analysis)

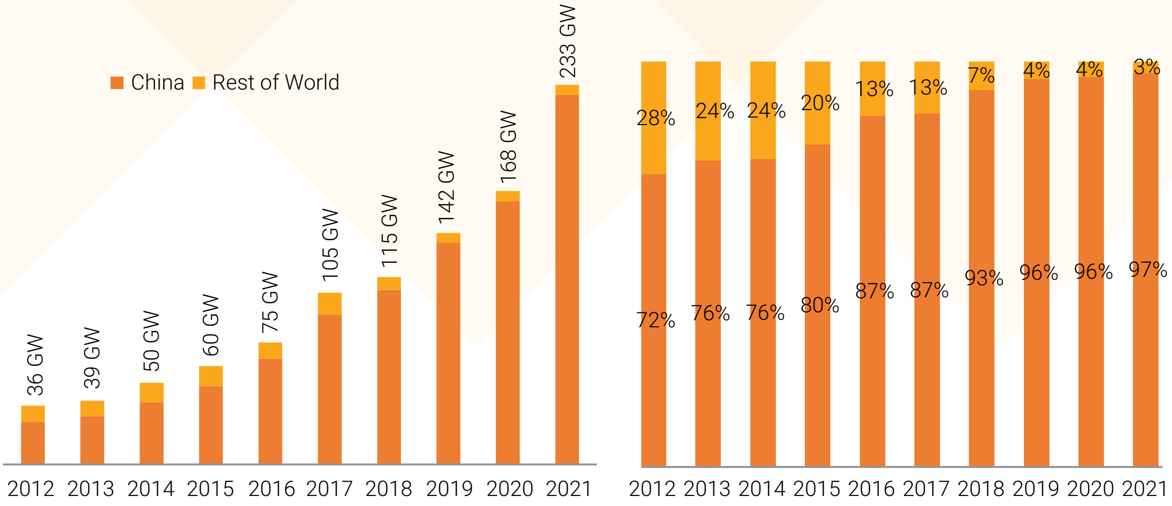


Figure 26 - Evolution of annual production per region by capacity (GW) (left) and relative share of annual production per region (right), for the period 2012-2021

(*Sources:* RTS Corporation)

In 2022, the global production capacity was almost exclusively (99%) located in China. The remaining 1% were located in other Asian countries, mostly. As shown on the previous chart, in 2012 this segment of the value chain was already dominated by China with over 70% of the global production of 36 GW. In 2021, the global production amounted to 233 GW.

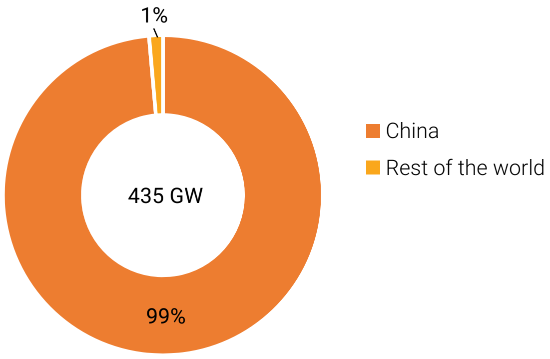


Figure 27 - Wafer manufacturing capacities in 2022 per region

(*Sources:* Becquerel Institute Research & Analysis, RTS Corporation, Bloomberg NEF)

The large dominance of China on this value chain step can be explained by multiple factors. First, this step of the value chain can be considered less technologically challenging than polysilicon manufacturing for example. Moreover, Chinese companies have been positioning themselves on this value chain step earlier compared to polysilicon manufacturing. Finally, Chinese manufacturers benefit from subsidies and very advantageous electricity prices in some regions, that are part of a larger long-term strategy to be technology and energy independent.

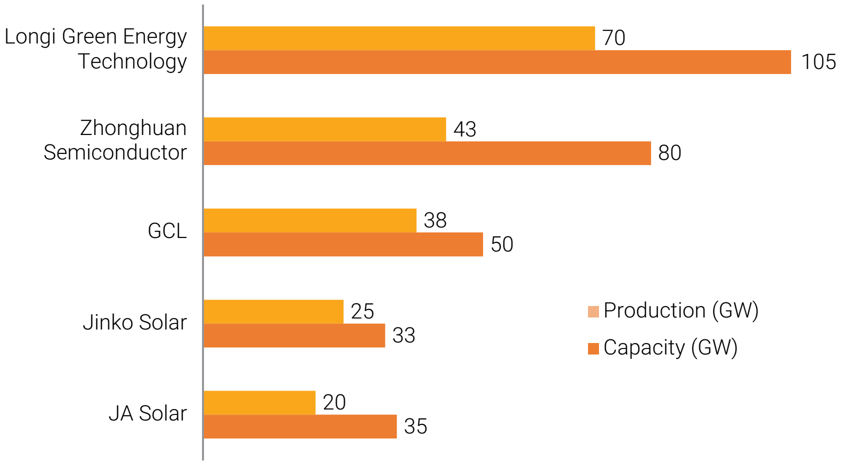


Figure 28 - Manufacturing capacities and production of top 5 per wafer manufacturer in 2021 (GW)

(*Sources:* RTS Corporation)

The main wafer manufacturers by production capacity, which is the manufacturing output a company could theoretically produce in a year, are by far Longi and Zhonghuan Semiconductor, the first with a yearly manufacturing capacity of 105 GW in 2021 with, plans to reach 150 GW by the end of 2022, the latter with a production capacity of 80 GW in 2021 with plans to achieve 140 GW by the end of 2022. The order of the ranking remains unchanged if, instead of considering manufacturing capacity, we consider the production, in other words, the actual amount of GW produced, in 2021. In 2021, Longi produced 70 GW of wafer capacity.

Note that the difference between production capacities and actual production levels is explained by the fact that these are end-of-year number. Hence, some production capacities that are commissioned at the end of the year did not produce during the year. Also, because of interruptions of the production, should they be planned (e.g., for maintenance) or not (supply problems), the production rarely equals nameplate production capacities.

4. Cell: IBC and HJT have the highest efficiency commercially available in 2021, while tandem cells threaten to revolutionize the market upon entry.

Cell production is the next step in the PV manufacturing value chain. The various existing cell technologies yield different results in terms of cell efficiency. Looking at the Si-based solar cell technologies which are mass produced today, there is a clear disparity between n-type and p-type cells, with p-type cells showing on average lower efficiencies than n-type cells. In 2021, p-type mono PERC showed the lowest efficiency (23.0%) while n-type IBC cells demonstrated the highest efficiency overall with 24.4% on average. In the coming years, the commercial efficiency gap between n-type cell technologies is expected to narrow, in particular between n-type HJT and n-type IBC, which could be a sign of the technology reaching its limits.

One important breakthrough we might witness this decade is the dawning of commercially available and competitive tandem cells. Tandem solar cells are stacks of individual cells, one on top of the other, that each selectively convert a specific band of light into electrical energy, leaving the remaining light to be absorbed and converted to electricity in the cell below. By doing so, tandem cells can surpass the theoretical energy conversion efficiency of any single cell acting on its own. The most known tandem cell technology today is perovskites on top of crystalline silicon cells, typically a heterojunction cell, but has been demonstrated with TOPCON and IBC. This technology is rapidly developing as a high-efficiency photovoltaic technology and is expected to reach 28.5% efficiency for commercially available cells by 2032.

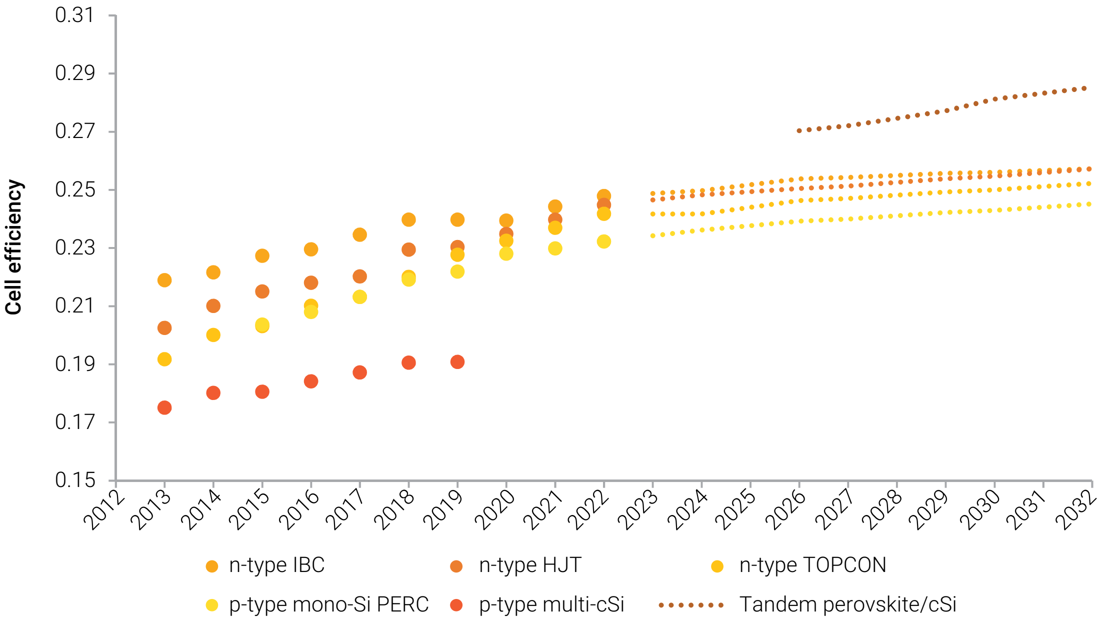


Figure 29 - Evolution of industrial cell efficiencies per technology, historical and forecasted (2013-2032)
(***Sources:*** ITRPV, Becquerel Institute analysis)

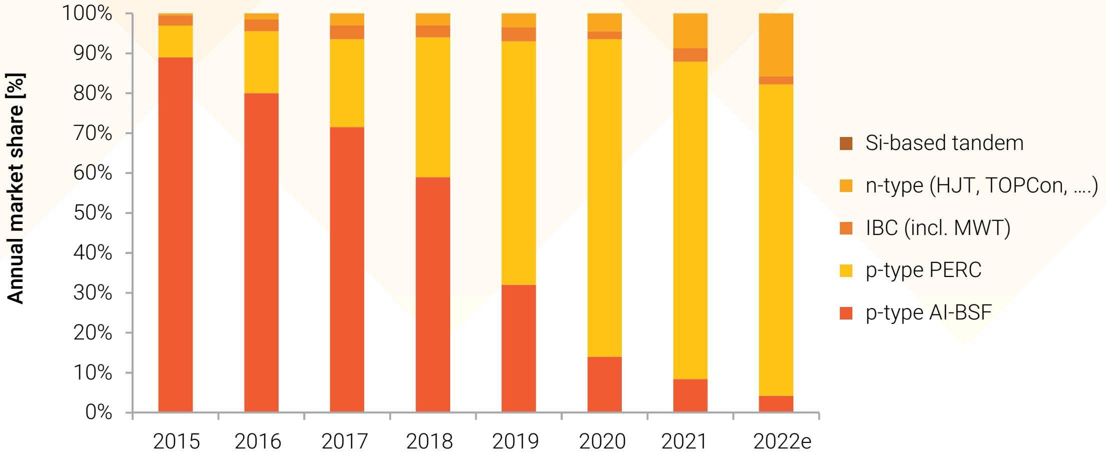


Figure 30 - Evolution of relative shares of different c-Si technologies (2015-2022)
(***Sources:*** ITRPV, Infolink, Becquerel Institute analysis)

The Al-BSF cell technology dominated the market until the emergence of PERC, but this older cell architecture is expected to entirely disappear from the market by 2025. The market share of PERC is expected to decrease for the first time in 2023, after peaking in 2022 with 87% of the market share, after many years of continuous and high-paced growth. The PERC technology will, however, remain the dominant cell technology in the market at least until 2025. N-type technologies, such as HJT, TOPCon and IBC, are expected to slowly become more and more relevant in the market and might challenge PERC dominance in the coming years. By 2021 these n-type technologies represented a combined 12% market share.

Figure 31 - Quarterly evolution of cell spot prices by technology (2015-2022)
(***Sources:*** Energytrend, Infolink, PVinsights, Becquerel Institute Analysis)

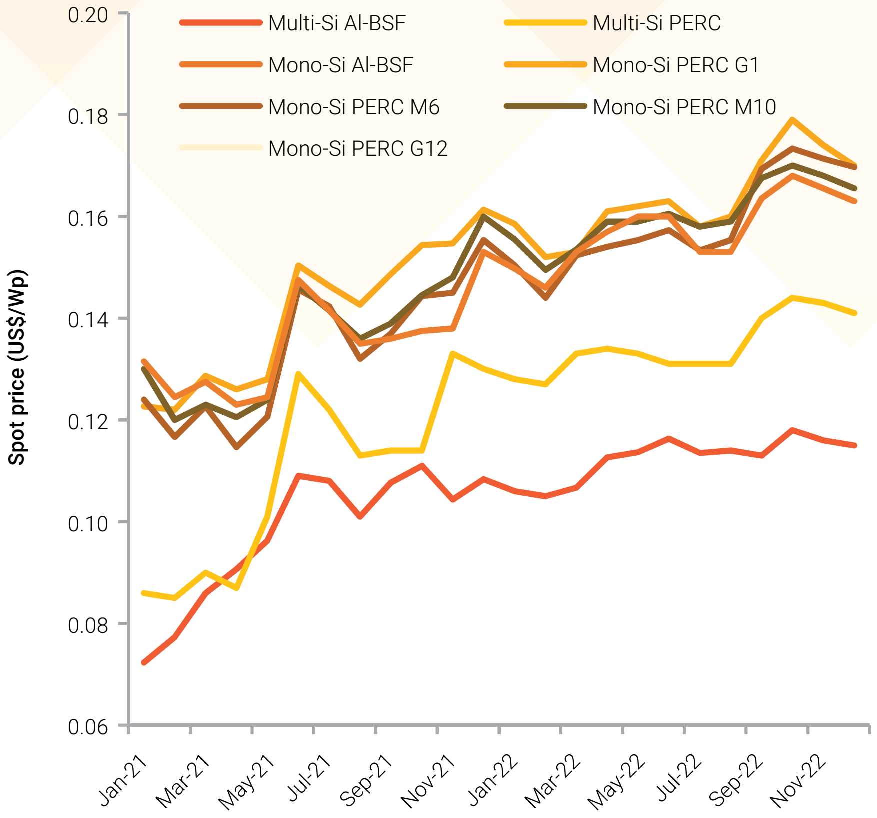


Figure 32 - Monthly evolution of wafer spot prices by technology (2021-2022)
(***Sources:*** Energytrend, Infolink, PVinsights, Becquerel Institute Analysis)

The evolution of solar cells' spot prices is highly correlated with the trends observed for polysilicon and wafers. Prices experienced a drop in the beginning of the pandemic in Q1 2020, to a price below 0.10 US$/W, for the technologies monitored. Then, the prices increased, resuming their pre-pandemic level by the end of 2020. Eventually, mono c-Si technologies reached 0.16 US$/W at the end of 2021, where they appear to increase slowly to 0.17 US$/W by the end of 2022.

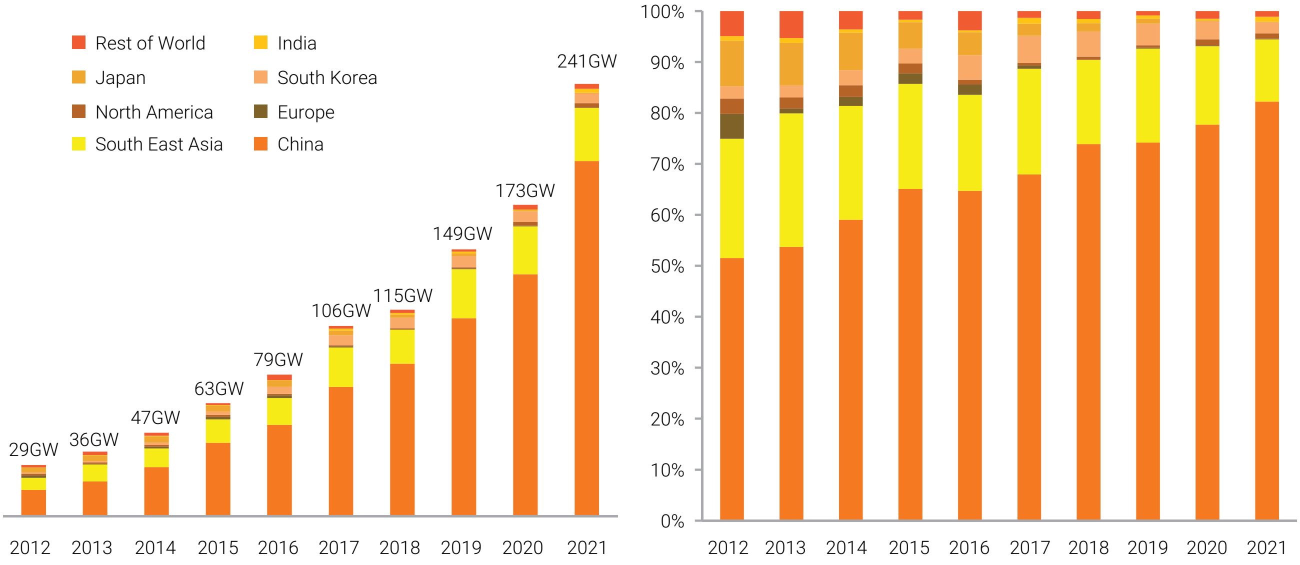


Figure 33 - Evolution of annual cell production per region by capacity (GW) (left) and relative share of the evolution of the cell production per region (right), for the period 2012-2021
(***Sources:*** RTS Corporation)

The cell production capacity distribution across the world resembles that of polysilicon. China represents 86% of the total (estimated at 300 GW in 2021) while the rest of the world (mostly in the rest of Asia but also to a very limited extent USA and Europe) shares the remaining 14%. Among the top 5 manufacturers, Tongwei comes in first place followed by Longi and Aiko Solar, with 40 GW/year, 37 GW/year and 36 GW/year, respectively, by the end of 2021. Some regional differences in terms of cell technologies manufactured are worth mentioning. The USA has established itself as a leader in thin film (CdTe) thanks to massive R&D both from the public and the private sides. Moreover, n-type technologies such as IBC and HJT have historically been mainly manufactured outside of China, as HJT has for many years only manufactured by Panasonic in Japan, owner of the related IP (from Sanyo, another Japan company), and IBC has long been the specialty of SunPower in the US. But this trend is changing as Chinese manufacturers are also investing in R&D to become technology leaders rather than followers and have been able to scale up processes to manufacture these technologies, allowing to reduce costs. Note that this cost reduction is also permitted by the larger availability of n-type wafers and their reduction in cost, led by economies of scale as well as technological innovation.

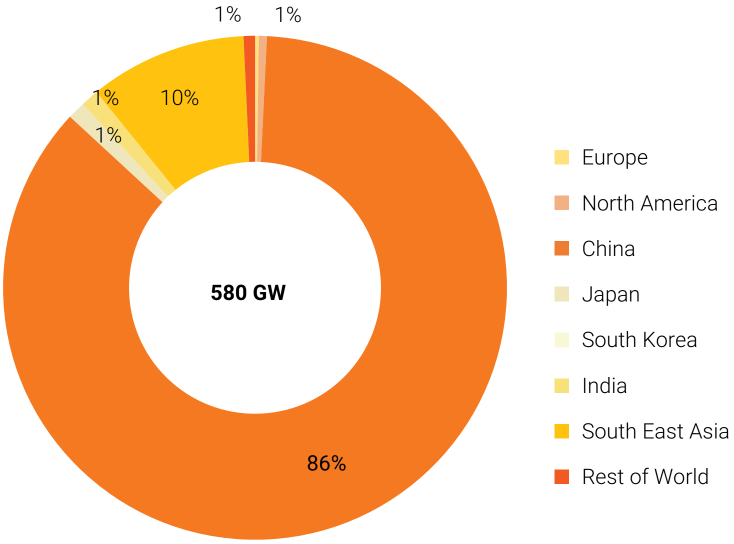


Figure 34 - Cell manufacturing capacities in 2022 per region
(***Sources:*** Becquerel Institute Analysis, AECEA, RTS Corporation)

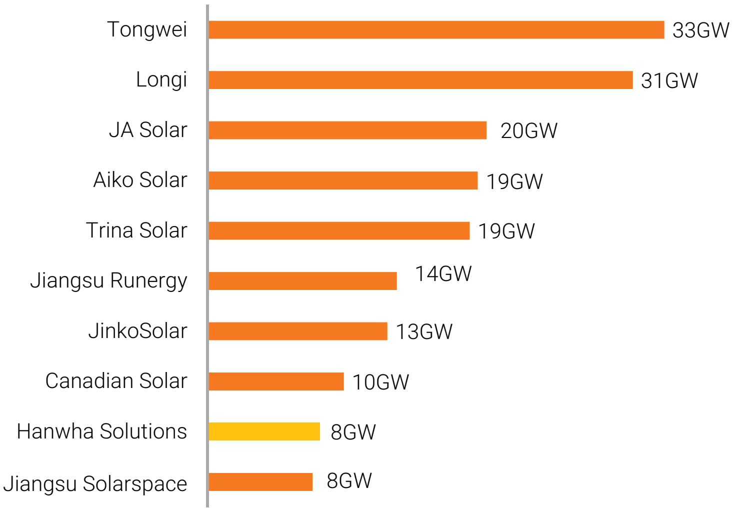


Figure 35 - Manufacturing capacities of top 10 cell manufacturers in 2021 (GW)
(***Sources:*** RTS Corporation)

Silver is one of the most expensive materials used for cell manufacturing. Thus, one technological focus in the PV cell manufacturing has been the reduction of the usage of silver paste. This has enabled price reductions of PV cells over the last years and is expected to continue pushing prices down in the future. Although also following a downwards trend, n-type cells' silver consumption is on average higher compared to p-type cells'. In particular, for a same cell size, silver consumption for HJT is more than double that of a monofacial p-type cell. With the growing market share of n-type technologies, this might become an economic challenge, as the weighted average silver consumption per cell might increase, despite silver use reduction per technologies. Nonetheless, companies like Meyer Burger have drastically reduced silver while companies like SunDrive are pioneering the use of replacing silver with copper, without impact on efficiencies.

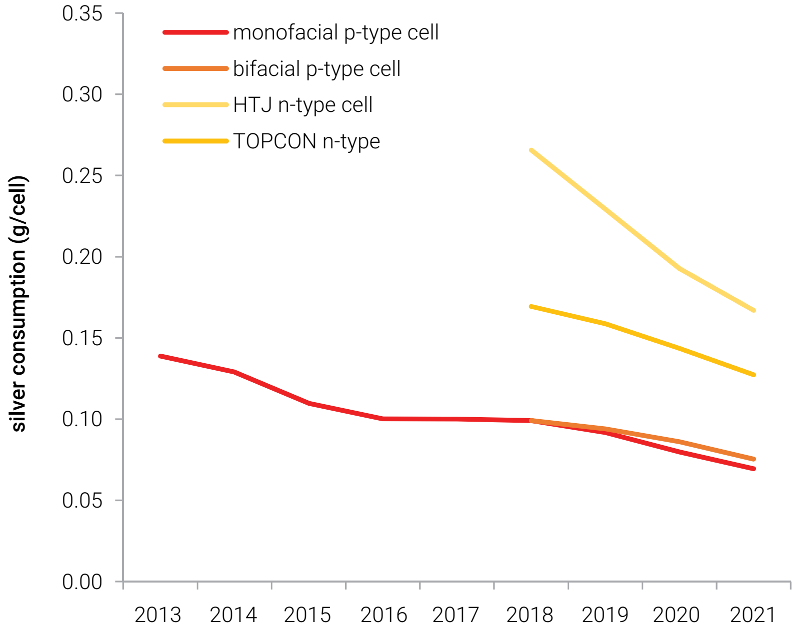


Figure 36 - Evolution of average silver paste consumption per technology for a theoretically assumed constant cell size (M2) (2013-2021)

(***Sources:*** ITRPV, Becquerel Institute analysis)

Figure 37 - Quarterly evolution of silver prices (2018-2022)

(***Sources:*** tradingeconomics.com)

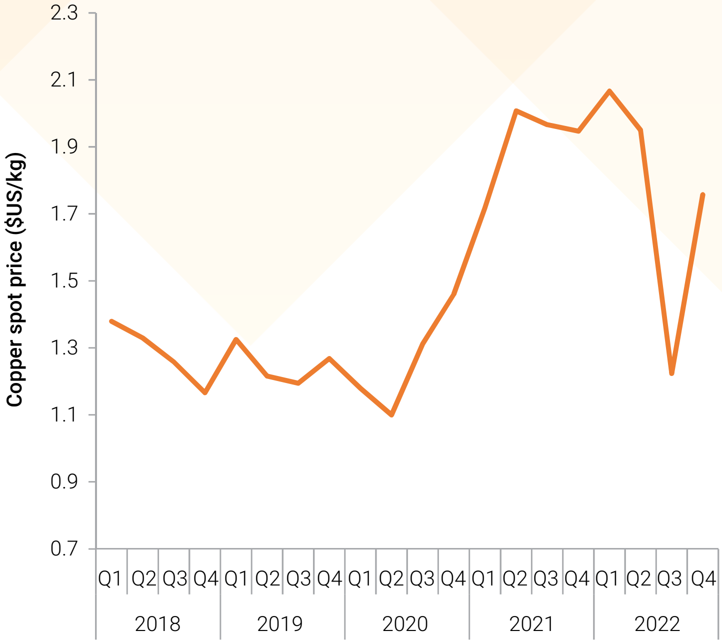


Figure 38 - Quarterly evolution of copper prices (2018-2022)
(***Sources:*** tradingeconomics.com)

The elements silver (Ag) and copper (Cu) are consumed nowadays in two distinct manufacturing steps of PV modules, silver is used for cell metallization in silicon cells as a paste deployed in layers. This silver layer is responsible for providing conductivity to cells given its electrical properties, namely low electrical resistance. Meanwhile, copper use is key to the PV sector for wiring, i.e. in ribbons connecting cells and strings of cells. However, electrical properties of both copper and silver are similar and from a technical point of view, if mastered correctly this substitution could be feasible without diffusion risks. This leads to the opportunity of replacing the costly and scarce element of silver for a more abundant and currently cheaper metal as copper. The direct economic advantage seems straightforward considering the prices differences between the two metals. This substitution would not put at risk copper supply for PV given the difference of scale in demand arising on one hand from PV cell metallization and from PV cabling. However, competition for copper is bound to increase in the future given the important demand for copper which will come from the exponentially growing electric vehicle market. Eventually, this could lead to diminish the cost advantage of copper over silver.

We observe in both figures below the continued increasing in demand for both metals, while the global demand for silver in 2021 was of 3,223 metric tons, the global demand for copper was of 684 million metric tons, for the same year, which is 212,224 times more.

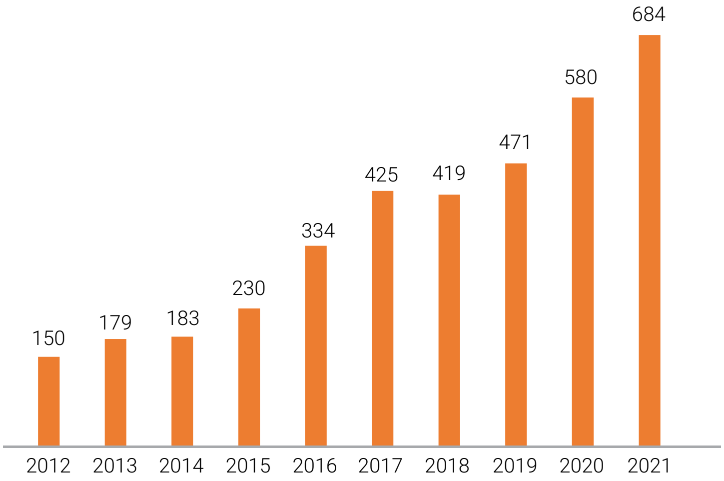


Figure 39 - Evolution of annual copper demand (millions of tons) in 2012-2021
(***Sources:*** RTS Corporation, Becquerel Institute analysis)

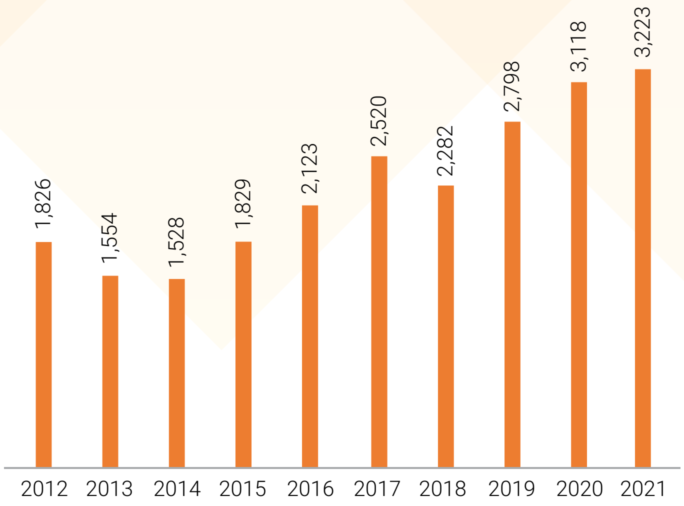


Figure 40 - Evolution of annual silver demand (in metric tonnes) in 2012-2021

(***Sources:*** RTS Corporation, Becquerel Institute analysis)

5. Module: Sharp increase of nominal power outputs thanks to the rise of cells' efficiencies and module-level innovations, as well as the increase of module sizes. Prices rebounded from Q1 2021 after years of decline and remained high until Q4 2022.

Module assembling is the final step in the PV manufacturing value chain. The cells are laminated and connected to form a multi-cell string. Several multi-cell strings are encapsulated, i.e., assembled with a sheet of glass, two foils of cell encapsulant, typically Ethylene Vinyl Acetate (EVA) or polyolefin (POE) resin, and a backsheet to make a module which can be consequently framed and is then equipped with a junction box. The module production capacity in 2020 stood at 326.7 GW, in 2021 it was estimated to be of around 482 GW.

Modules using mono-Si cells (first p-type Al-BSF, then mono-Si p-type PERC and now mono-Si n-type) show the highest module efficiency values. The efficiency of modules using mono-Si p-type PERC cells grew from 17% in 2014 to 19% in 2019 leading them to represent the bulk of the market. More recently, new technologies have emerged: modules using monocrystalline silicon n-type cells such as IBC, HJT and TOPCon which respectively yielded average module efficiencies of 22.0% and 21.9% and 21.3% in 2021. The module efficiency of existing technologies on the market is expected to keep growing in the coming years but this growth will happen at a slower pace as these technologies approach their efficiency limit. Indeed, n-type IBC, n-type HJT and n-type TOPCon modules are expected to converge to an efficiency between 23.8% and 24.0% by 2032, while p-type PERC efficiency is expected to stand at 22.4% by the same year. New technologies with higher efficiency yields are expected to enter the market in a few years such as tandem cells.

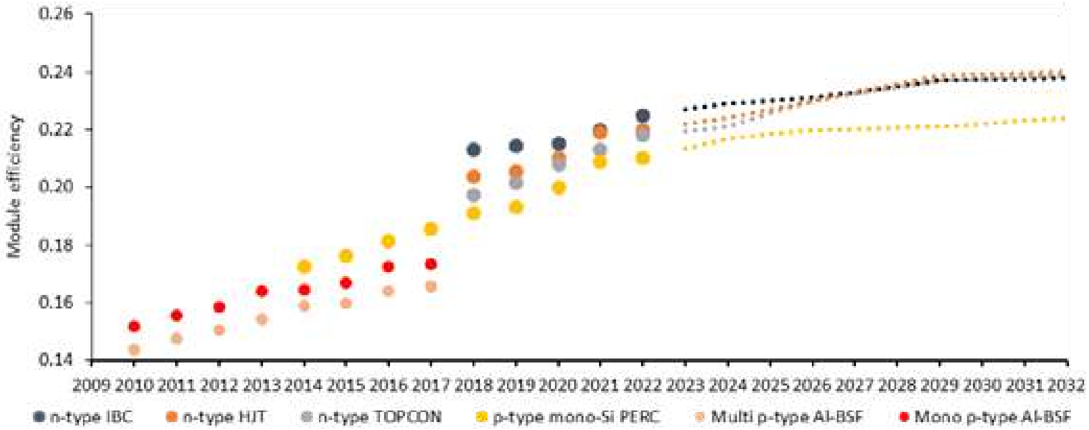


Figure 41 - Evolution of industrial module efficiencies historical and forecasted (2010-2032)

(***Sources:*** Photon, ITRPV, Becquerel Institute database and analysis)

Looking on the graph below at today's commercial modules for ground-mounted applications, i.e., with sizes of 1.8 m² and bigger, multiple PERC-based modules can compete both in terms of efficiency and nominal power with n-type-based modules (HJT or TOPCon). This can be achieved when using high-end PERC cells and combining different module optimisations (multi busbars, half-cut cells, reduced spacing between cells, …). Nonetheless, the modules with the overall highest efficiency are using n-type cells.

The figure below also shows that the wattage and module area increase with cell size, as the modules typically are built with the same number of cells. As a rule of thumb, the bigger the cell size, the cheaper the module per unit of power and the cheaper the system price (as fewer modules are required to meet the same system size, reducing the cost of labour and structural materials).

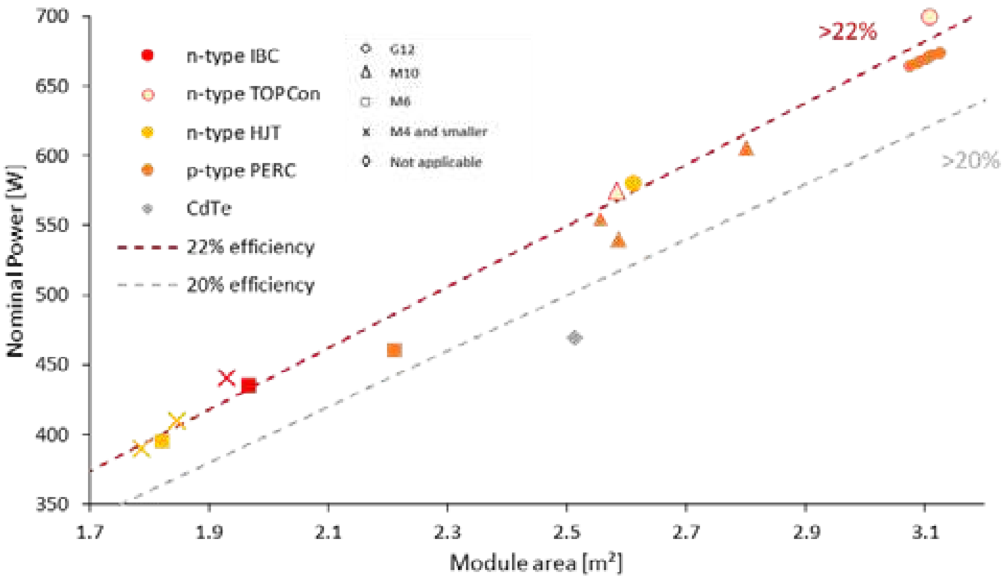


Figure 42 - Comparison of the TOP 20 commercially available modules per technology, cell size, area, and nominal power
(***Sources:*** Manufacturers' datasheets, Becquerel Institute analysis)

Module spot prices evolution follows a similar trend as the upstream components even if at this step of the value chain, variations were slightly attenuated. Modules using multi-Si cells have the lowest spot prices suffering from declining demand. On the other end of the price range, modules using cells with sizes M10 or G12, can still be seen as high-end products and are thus available at higher spot prices.

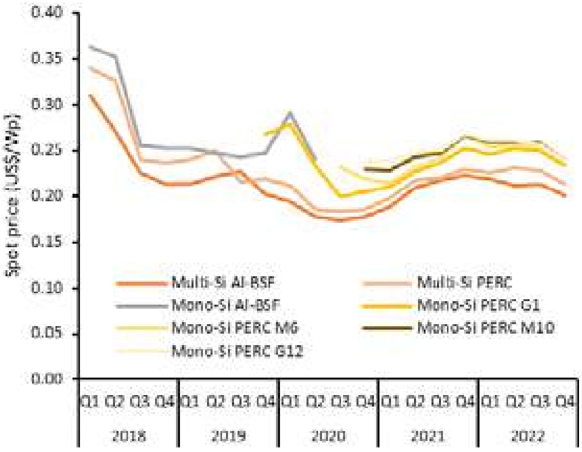


Figure 43 - Quarterly evolution of module spot prices by technology (2015-2022)
(***Sources:*** Becquerel Institute Analysis based on Energytrend, PVinsights, Infolink)

The Drewry World Index measuring the average cost of freight of a 40-foot container over 7 different major shipment routes, provides an excellent indicator of average shipment cost in the world. Since September 2020, due to a shortage of containers as well as an increased demand for transport, because of the restart of many economies, imbalance between supply and demand appeared on the market and transport costs exploded. The situation was further worsened by extreme zero covid-cases restrictions in China and by sanitary restrictions at the ports. Higher shipping costs, on top of higher component prices, have led on the short term to some delays in PV installations. On a longer timescale, if these shipment prices maintain, they could also create a favourable environment for local production. After peaking around September 2021, the shipping cost are on a downwards path again. The shipping cost have recently reached again the pre-pandemic level.

The module production follows closely the same trend and approximate values in capacities to those of cells. The module production increased by 35.8% from 178 GW in 2020 to 242 GW in 2021.

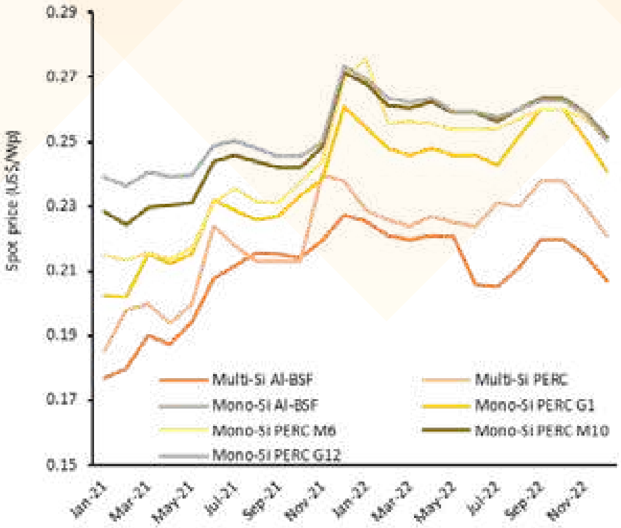


Figure 44 - Weekly evolution of module spot prices by technology (2021-2022)

(***Sources:*** Becquerel Institute Analysis based on Energytrend, PVinsights, Infolink)

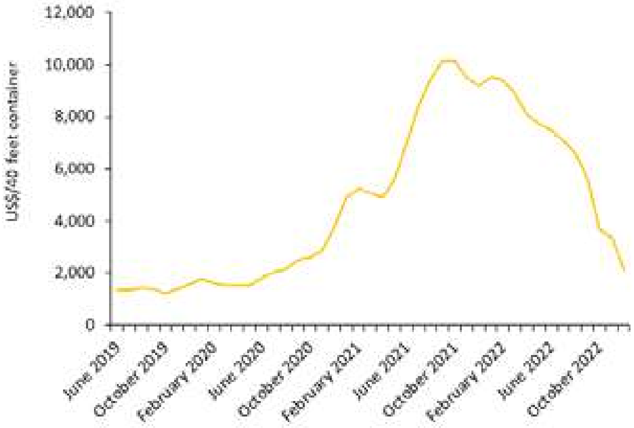


Figure 45 - Evolution of shipping costs

(***Sources:*** Drewry)

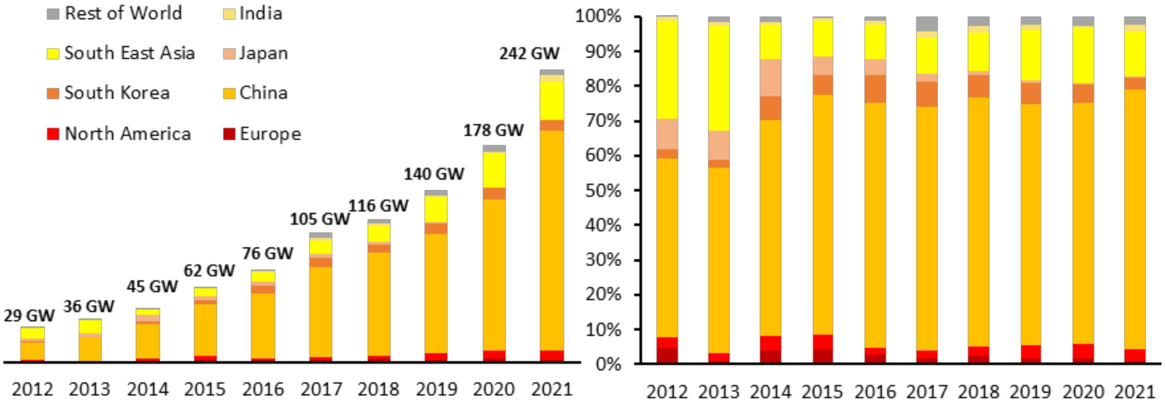


Figure 46 - Evolution of annual module production per region by capacity (GW) (left) and relative share of the evolution of the annual module production per region (right), for the period 2012-2021

(***Sources:*** RTS Corporation)

Module production capacity shows slightly less geographic concentration compared to the previous steps. This can be mainly explained by the lower energy intensity and complexity of this last step, as well as capital intensity. China represents 74% of the total production capacity while the remaining 26% are located in Southeast Asia (12%), North America (3%), India (3%), other Asian countries such as Japan (1%) and South Korea (2%), and Europe (2%). The dominance of Chinese companies is illustrated by the ranking of companies by the quantity of modules shipped, where seven out of ten have their headquarters in China. The list is led by Longi with 39 GW in 2021, followed by JA Solar and Trina Solar with 26 GW and 25 GW, respectively, in 2021.

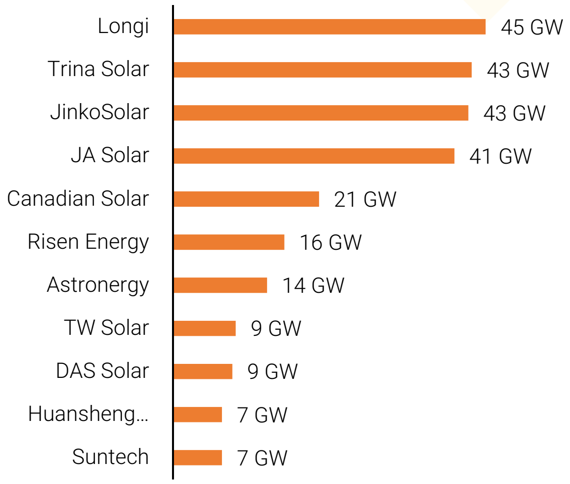


Figure 47 - TOP 10 Module Shipment per Manufacturer in 2022 (GW)

(***Sources:*** Solarbe Global)

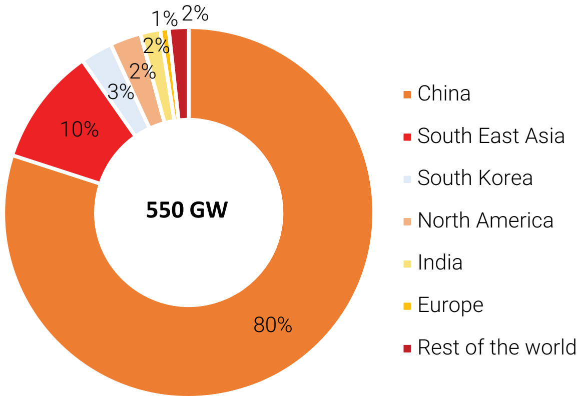


Figure 48 - Geographical Distribution of PV module manufacturing capacity in 2022

(***Sources:*** Becquerel Institute Research & Analysis, RTS Corporation, Bloomberg NEF)

In line with was shown previously for solar PV cells, the technology landscape for PV modules changed dramatically over time. the market was once dominated by multi c-Si, but since 2018 the market share of mono c-Si has been overshadowing the market share of other PV technologies. The market for multi-Si is expected to cease to exist completely in a few years. The only other relevant technology is CdTe, although its market share is relatively small compared to c-Si. However, the US Inflation Reduction Act and Indian PLI scheme has spurred new capacity investments from First Solar in thin film.

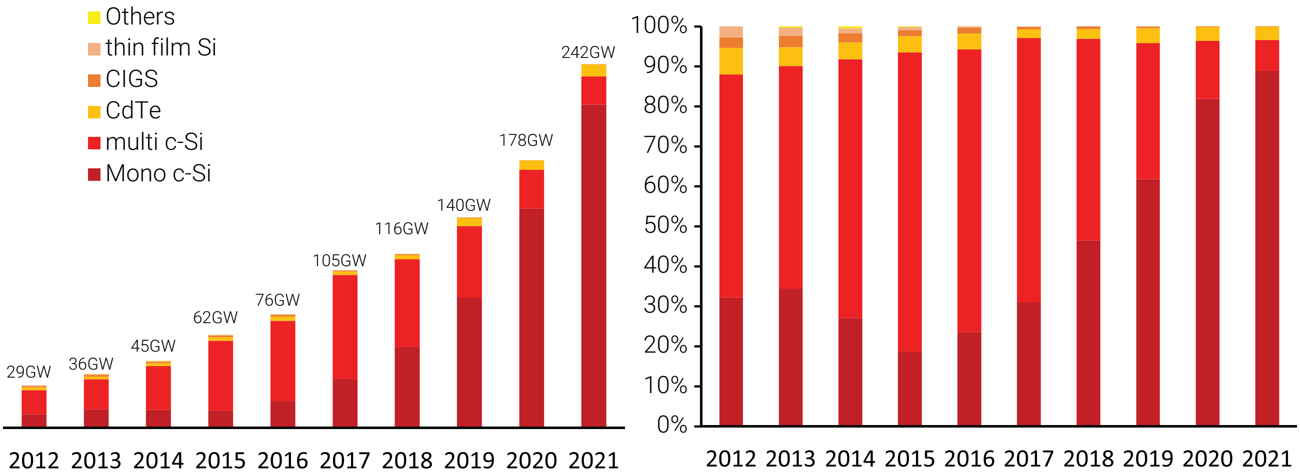


Figure 49 - Evolution of annual module production per technology (GW) (left) and relative share evolution of annual module production per technology, for the period 2012-2021

(***Sources:*** RTS Corporation)

Looking more specifically at the modules' components that are assembled in addition to the cells, such as glass, frames or encapsulants, some technology trends are worth mentioning.

The amount of glass used in a module is related both to the size of the module and the thickness of the glass. While module sizes' evolution has suggested a trend of increasing average module area, the opposite trend is observed for glass thickness. The thickness of the glass impacts the transmission of sunlight to the cells. Therefore, thinner glass improves the amount of sunlight reaching the cells, thereby improving efficiency. While the decrease of glass thickness contributes to the reduction of the average weight of modules, it does not compensate the potential extra weight from glass used as back cover instead of a polymer-based backsheet.

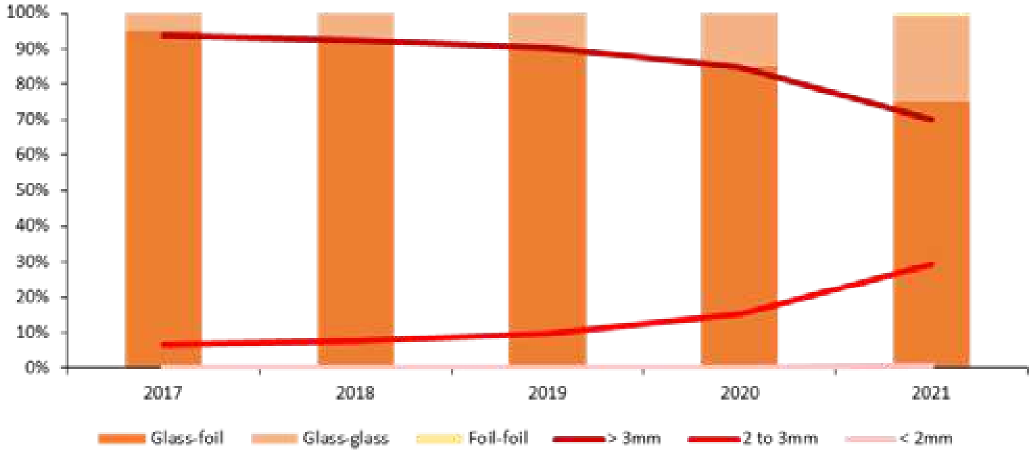


Figure 50 - Share of different front and back cover for PV modules and market share of front glass thickness (2017-2021)
(***Sources:*** ITRPV, Becquerel Institute analysis)

Even if monofacial modules remain on the market predominant, the last years saw an increase in the deployment of bifacial module technology, representing a market share of 15% (this share is higher when considering only utility-scale applications). As a consequence, the glass-glass configuration, which also benefits from several advantages when used with monofacial modules (e.g., improved mechanical stability) and from decreasing glass costs (before recent glass prices increase) has gained market shares in the recent years and represented around 25% of the market in 2021. The trends should continue (with glass-glass modules expected to represent half of the market in ten years) and drive the demand for solar glass.

In December 2020, China alleviated the quota on glass production. In a context of rising demand for solar glass, these quotas had created an important imbalance supply and demand leading to soaring glass spot prices. Once the quota was abolished spot prices decreased and went back to their 2019-level. After dropping considerably in mid-2021, prices bounced back slightly at the end of 2021 and have been stable since then.

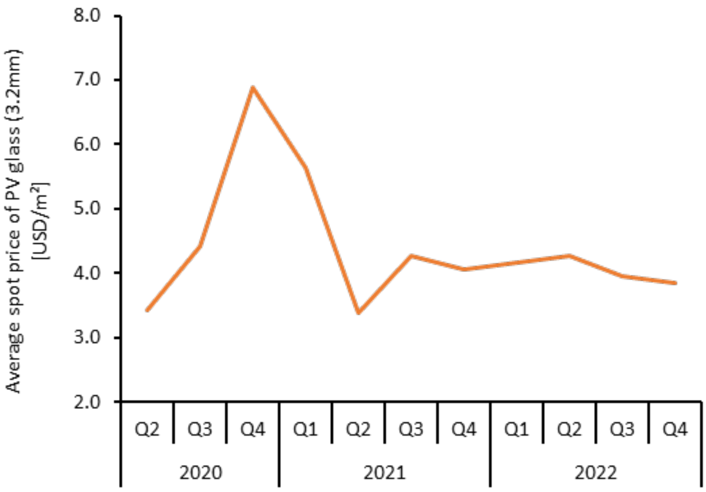


Figure 51 - Quarterly price evolution of 3.2mm PV glass (Q2 2020-Q2 2022)
(***Sources:*** Energytrend, Infolink)

The encapsulation material plays a role in protecting the cells and ensuring long durability to the modules. EVA, the mainstream encapsulant is cheap, widely available and easy to process and has well established itself in the PV value chain. One downside of EVA is that over time it decomposes and produces acetic acid. While with the use of backsheet as back cover, the acetic acid can escape the module, this is not the case when glass is used as back cover which is a configuration gaining traction. This has left opportunity for alternatives to develop such as polyolefin for instance. However, in the future, EVA is expected to continue to have the largest market share, despite EVA breakdown problem in glass-glass modules. Indeed, this mechanism is enhanced by moisture which is limited in the case of glass-glass modules. Moreover, EVA stabilizer additive exist and can limit the formation of acetic acid.

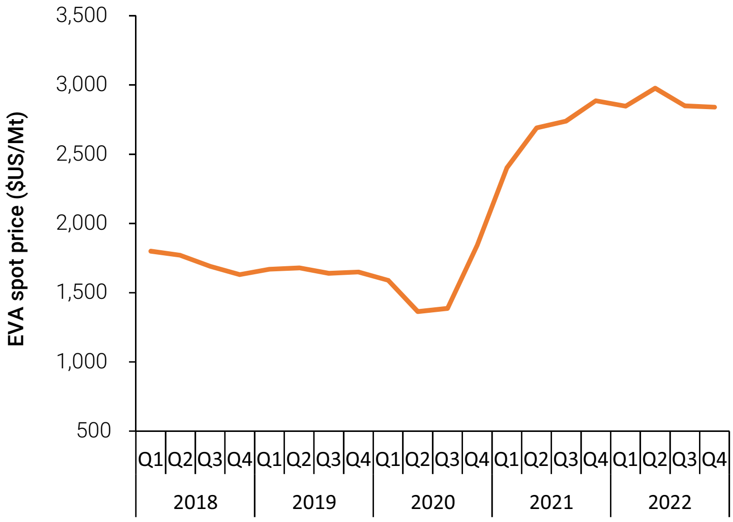


Figure 52 - Quarterly price evolution of EVA (2018-2022)
(***Sources:*** Energytrend, Infolink)

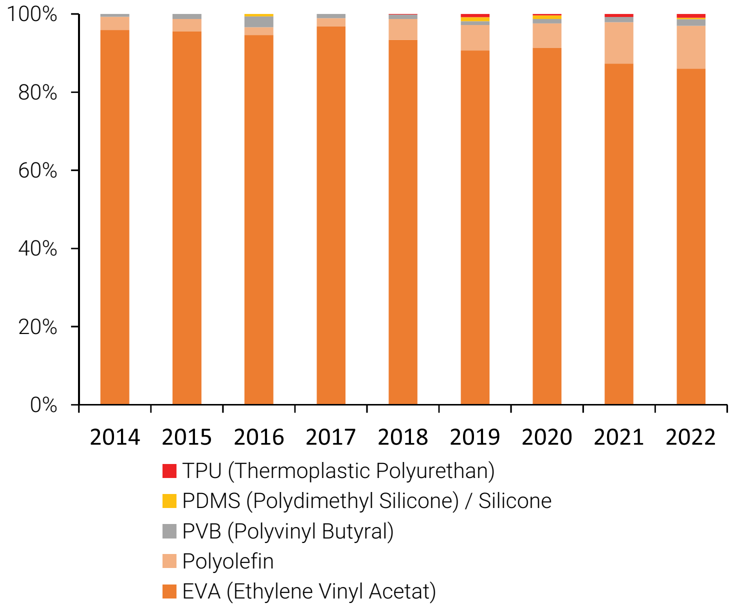


Figure 53 - Evolution of relative market shares of different polymer types used for encapsulation (2014-2022)
(***Sources:*** ITRPV, Becquerel Institute analysis)

The annual demand of encapsulants has been growing, from 1,640 Mm² in 2020 to 2,100 Mm², which represents a 28.0% increase in the demand of encapsulant. China's demand of encapsulant represented 81% of global demand.

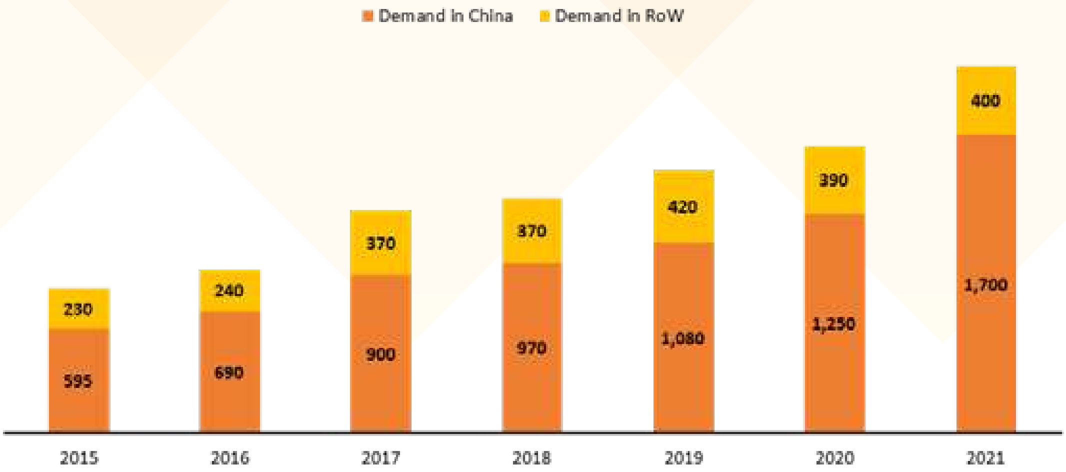


Figure 54 - Evolution of annual demand of encapsulants (2015-2021) in Million m² (Mm²)

(***Sources:*** RTS Corporation, Becquerel Institute analysis)

The main material used for modules' frames is aluminum (plastics remain anecdotal with less than 1% market share). Frameless modules are also an option but have a limited, yet growing, market share. Within the next decade frameless modules could represent around 15% of the market. These later are mainly used in utility-scale applications. The absence of a frame is particularly interesting for glass-glass modules to be installed in order to maximize bifacial gains, as the absence of a frame reduce the risk of self-shadowing on the back side, which could hinder the energy generation. Nonetheless, even if these modules are often priced at the same level as framed modules, opting for frameless modules can have negative cost impacts at the next steps of the value chain. For instance, in terms of logistics, special packaging -therefore more expensive- might be needed as in most cases the module frame is leveraged to maintain the position of the modules in the wooden transportation boxes. Furthermore, in terms of installation, special clamps with an additional layer of rubber might be needed to fix the modules on the mounting structures.

The aluminum prices decreased from at least Q1 2018 until Q2 2020, from then the prices increased considerably, peaking in Q1 2022 and decreasing slightly in the following quarters, contributing to pushing the bill of materials and the manufacturing cost of modules up.

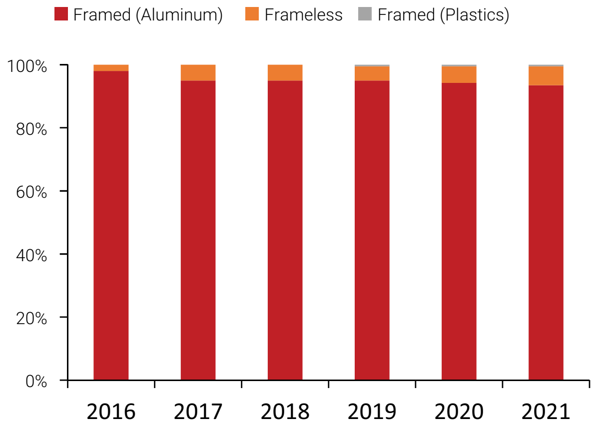


Figure 55 - Share of framed and frameless modules (2016-2021)

(***Sources:*** ITRPV, Becquerel Institute analysis)

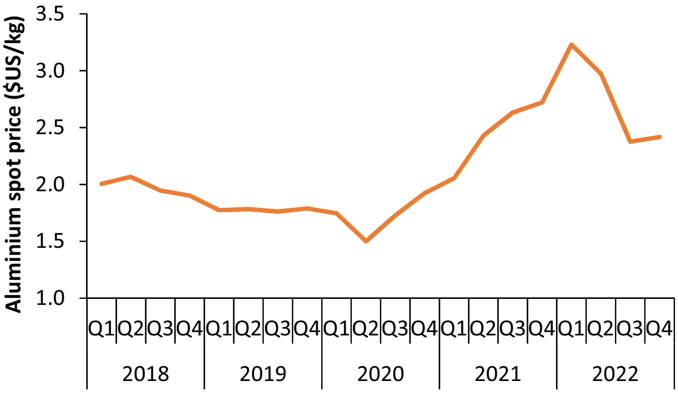


Figure 56 - Quarterly price evolution of aluminum (2018-2022)

(***Sources:*** Energytrend, Infolink)

6. Inverters

Inverters constitute the core of the PV plant, converting the direct current of the PV modules into alternating current.

Three main technologies exist: microinverters, string inverters (single-phase string inverter and multi-phase inverters) and central inverters. Today, central inverters and multi-phase string inverters make up the bulk of the market.

The final application (residential, commercial, industrial or utility-scale) motivates the choice of one technology over another. Microinverter or single-phase string inverters are typically used for residential or small commercial application while multi-phase string inverters and central inverters are commonly used for large commercial, industrial and utility-scale applications. Additional elements such as initial investment costs, operation and maintenance costs and system performances are also important to consider in the decision process. While central inverters demonstrate the lowest costs per Wp, multi-phase string inverters have other advantages such as reduced DC cabling losses, reduced string mismatch losses or improved performance in case of partial shading.

In terms of inverter transistor, for many decades, these have been made of silicon (MOSFET (metal–oxide–semiconductor field-effect transistor) and IGBT (insulated-gate bipolar transistor)). But in recent years, thanks to their multiple advantages such as higher efficiency, lower footprint or higher operating temperatures, the use of compound semiconductors (Gallium Nitride (GaN) and Silicon Carbide (SiC)) has become more common.

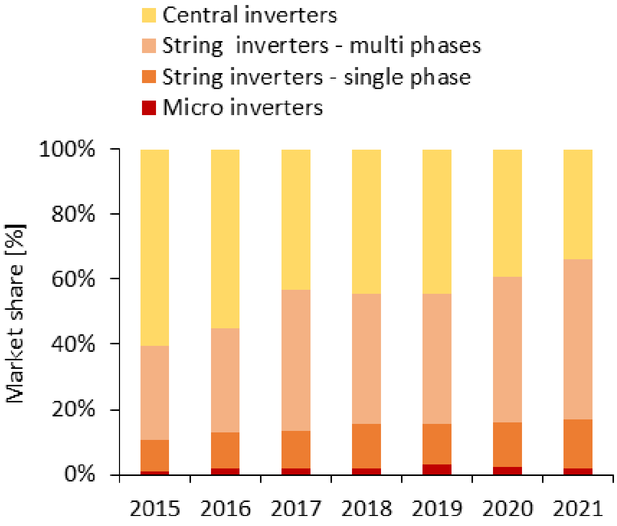


Figure 57 - Market share of different inverter technologies (2015-2021)
(Sources: Fraunhofer ISE, Becquerel Institute analysis)

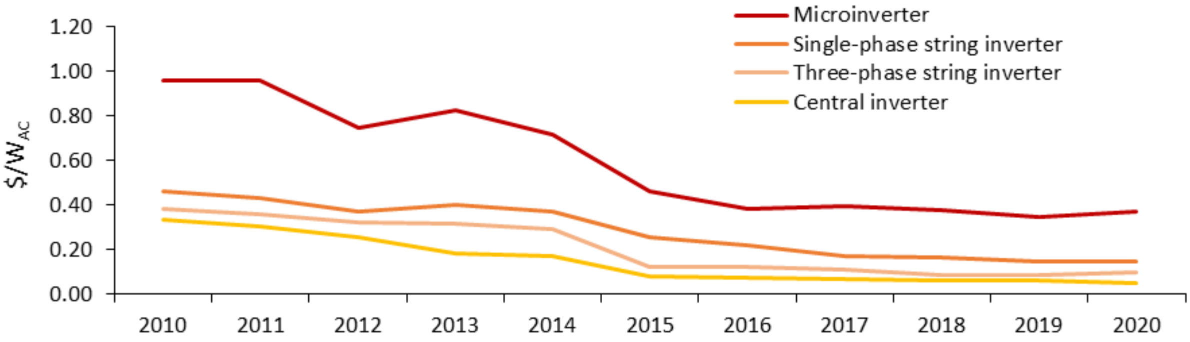


Figure 58 - Price evolution of different inverter technologies
(Sources: NREL, IEA PVPS, Becquerel Institute database and analysis)

Prices of inverter have been steadily decreasing, with sharp decreases for micro inverter, even though it has slowed down in the recent years. Other inverters' type appears to reach plateaus, especially central ones.

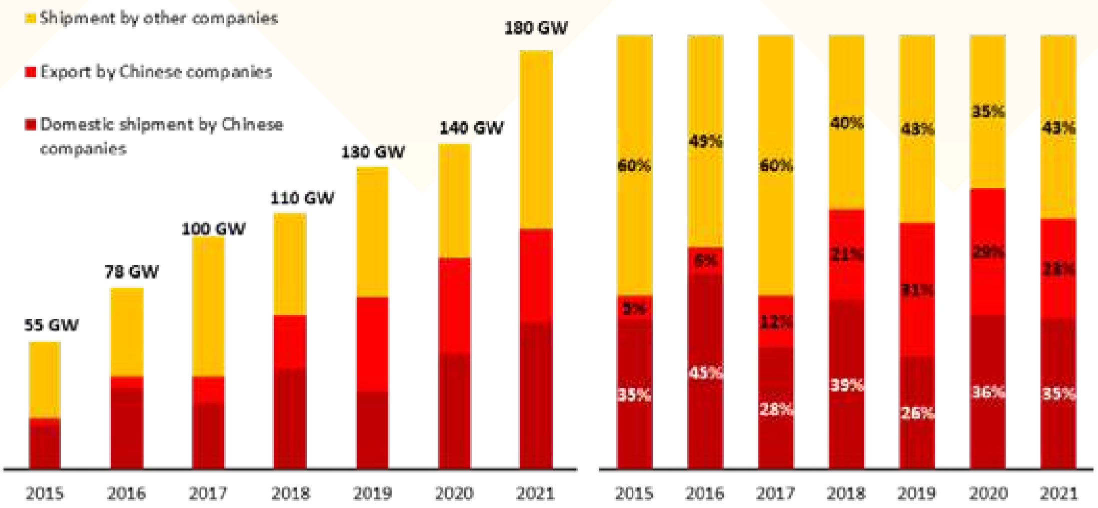


Figure 59 - Evolution of annual inverter shipment by company origin (GW) (left) and relative share of evolution of annual inverter shipment by company origin (right), for the period 2015-2021

(Sources: RTS Corporation, Becquerel Institute analysis)

The global demand for inverters grew, in line with the general growth of PV, it grew 22.2% to 180 GW, in 2021. Shipment for both Chinese and non-Chinese companies grew from 2020 to 2021, and the majority of inverter shipment by Chinese companies is domestic.

The inverter suppliers' landscape is relatively concentrated with the two largest manufacturers by shipment making up close to half of global shipments in 2021. While for this PV system component, China and Asian countries in general represent the bulk of the production capacity, European countries are well positioned as well with 16% of global inverter shipment manufactured in Europe in 2021.

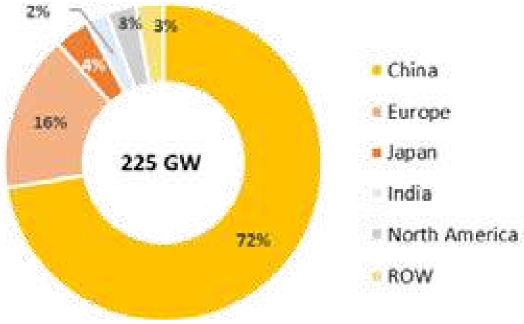


Figure 60 - Inverter shipment per region in 2021

(***Sources:*** RTS Corporation, Becquerel Institute analysis)

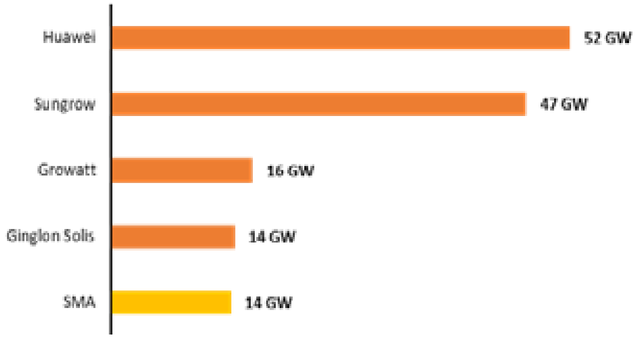


Figure 61 - Shipments per manufacturer in 2021 (GW)

(***Sources:*** RTS Corporation, Becquerel Institute analysis)

III. STUDY CASES

7. Introduction

In this section, the case of four industries (not necessarily photovoltaic) that have been able to develop with the key support of public policies is analyzed. These four case studies are: the automotive industry in North Africa, the gigafactories for batteries in the EU, the PV industry in Türkiye and the Production-Linked Incentive (PLI) program in India.

For each case, we have identified what has been put in place in a certain region of the world to develop/support an industry, what has worked well, what has not, and most importantly what is replicable in other regions that would like to develop a local photovoltaic industry. The emphasis is on both public (regulatory) measures and private initiatives.

Public regulatory measures can be either upstream, concerning the production part of the value chain, or downstream, regarding the distribution of assembled products. They can also support projects directly through targeted measures or support their development indirectly through comprehensive measures. Below are some examples of public regulatory actions divided into four categories as described above:

	UPSTREAM	**DOWNSTREAM**
DIRECT	▪ Tax credits for factories ▪ Grants, e.g. for land or infrastructure investments ▪ Low-cost financing (debt or equity) ▪ Lower energy prices ▪ Lower income tax rates ▪ Lower import tariffs and VAT rates ▪ Labour charges' reductions ▪ Incentives for exportations	▪ Local content or jobs requirements ▪ Tenders for new manufacturing facilities ▪ Public procurement policies
INDIRECT	▪ Import tariffs & trade duties ▪ Import bans on non-sustainable products ▪ Import tax regarding carbon footprint ▪ R&D funds ▪ Tax incentives for skilled labour ▪ Public funds to train skilled labour ▪ Public funds to upgrade infrastructure	▪ Tax credits, FITs or auctions to stimulate demand ▪ Local content or jobs premiums ▪ Low-cost financing for locally manufactured products ▪ Carbon footprint standards in tenders ▪ Environmental rules (Eco-design, ecolabel) ▪ Favour less competitive segments ▪ Communication campaigns

Sources: *IEA Global Solar PV Supply Chains Report, Becquerel Institute Research & Analysis*

Automotive industry in North Africa

Gigafactories for batteries in the EU

Solar PV industry in Türkiye

Measure focus: PLI scheme in India

8. Automotive industry in North Africa

Summary

This study case focuses on the recent development of the **automotive industry in North Africa**. This region recently became a vehicle manufacturer hub as many **multinational manufacturers** decided to develop their production in these growing markets. This region notably benefits from its **location close to European markets** and the **free trade agreements** signed with the main actors on the global market. Thanks to supporting targeted measures, they also provide an attractive environment in terms of **infrastructures, skilled workforce** or **financial incentives**. The recent success story of the French manufacturer **Renault** in Tangier (Morocco), with production of entry-level vehicles for export, has paved the way for further investments in the region.

Key take aways

In a context of liberalization of the automotive sector in the end of the 20th century, historic automotive industry leader **Egypt** implemented **local content requirements (LCR)** to save their industry. These measures combined with high import taxes partially succeeded to save the local industry threatened by the free trade agreements signed during this period. This situation was not specific to Egypt and at the time most African countries **banned the importations of second-hand vehicles** in an attempt to maintain the local production industry. Then, to support local suppliers' competitiveness in terms of skills, infrastructure or cost in a globalized automotive industry, Egypt introduced a **National Supplier Development Program (NSDP)** which provided investment support to allow local suppliers to align with foreign companies' technical requirements. This measure effectively contributed to better integrate local suppliers in the value chain and to strengthen their bilateral agreements with main actors (e.g., Mansour Automotive Group, General Motors).

- **LCR** combined with **taxes on imports** and **support to suppliers** helped Egypt preserve its local automotive industry on the podium of African manufacturers. However, most of these measures and agreements were short- or medium-term solutions taken in reaction to foreign competition and sometimes lacked consistency over the long term.

Morocco's approach is more recent and built on a long-term vision. Industrial development has been shaped by consistent plans: the **National Pact for Industrial Development (PNEI)** during the period 2009-2015, followed by the **Plan for Industrial Acceleration (PAI)** from 2014 to 2020. Both aimed at providing a holistic support based on **financial incentives, provision of industrial facilities and training for major industrial projects.** With such plans, Morocco succeeded in providing an attractive environment for foreign companies to set-up manufacturing in Morocco. In particular the French manufacturer Renault took advantage of these measures to launch a plant in Tangier in 2012, which is now a key site for the company. This success inspired another French manufacturer, **PSA**, to invest and build a plant in Kenitra, near Rabat. **Tunisia** now tries to follow this path with their **Projects of National Interest (PIN)** plan implemented in 2017, similar in terms of measures to the Moroccan plans.

- With a robust and holistic plan combining direct (grants, tax credits, …) and indirect (facilities, training, …) support to suppliers, Morocco recently became the first carmaker in Africa in front of the historic leader South Africa.

Most African countries started their national production business in automotive industry with assembly plants at the end of the value chain. It is considered a short-term way of creating jobs without requiring too many investments since most of the production is imported. If combined with a broader national strategy, assembled products can aim to use a high percentage of local content, like Renault which now use more than 60% of local supplier content in their plant in Morocco.

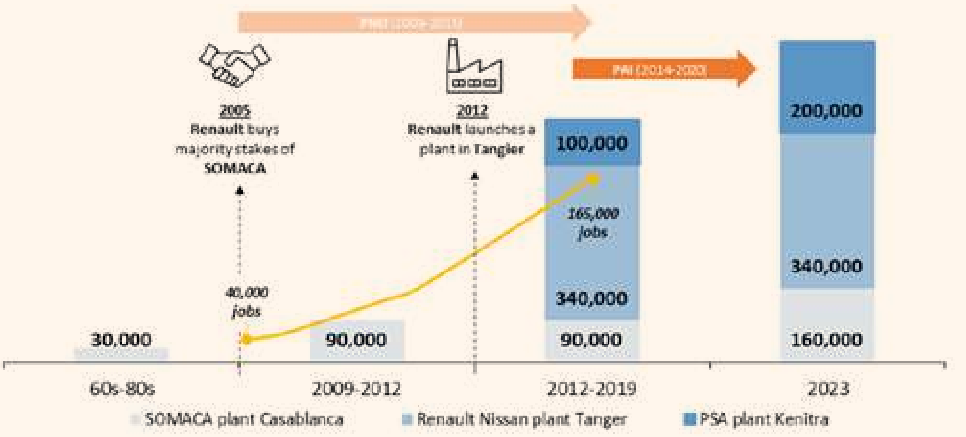


Figure 62 - Automotive industry development in Morocco [average number of cars produced per year]

(Sources: Ministry of industry, commerce and the green and digital economy)

Replicability potential

First of all, since most measures taken by North African countries are not only aimed at the automotive industry, the local PV industry could also take advantage of such measures to start developing assembly lines. Of course, the costs of Chinese PV players will be difficult to match but the financial incentives provided by North African governments could be an attractive entry point for the region.

Then, this strategy could be replicated if the targeted solar PV market is located nearby, as this is one of the key success factors along with the proximity of experienced local suppliers. In case this targeted market is foreign, trade agreements should exist to facilitate exports. Finally, this strategy must be coupled with comprehensive national plans that include workforce training, provision of facilities and financial incentives so that the entire supplier ecosystem can flourish. The starting point of this strategy would be to start with assembly plants before trying to diversify.

Local Content Requirements (LCR)

Egypt

NSDP: 2005-2012

Laws, suppliers support

Requirements

Direct support to demand
Indirect support to supply

To boost local industries, **local content requirements (LCR)** can be implemented, either as a direct law (mandatory) — provided that it does not clash with free trade treaties — or as an indirect incentive (non-mandatory), like for example a condition for public subsidy eligibility. In practice, such policy is often complemented with importation taxes for products that do not meet these requirements. However, despite the incentives in favor of local industry, such policy can also reduce the potential returns on investment and refrain foreign investors. In order to avoid such reluctances, Egypt implemented a National Supplier Development Program (NSDP) in 2005 that grants local suppliers up to 85% of the investments required to meet the technical requirements of foreign investors and reduce the risks associated with these investments. Countries should create additional demand (eg. Auctions) to designate for local content requirement, rather than taking from the existing trajectory, so as to avoid slowing the energy transition.

Industrial Development Plans

Morocco Tunisia

PNEI: 2009-2015
PAI: 2014-2020
PIN: 2017-now

Financial support, facilities, skilled workforce

Requirements

Direct & indirect support to supply

Morocco and Tunisia announced plans to develop their national industries in the medium and long term, in which automotive has a particular place. The plans implemented have similar patterns and timelines: it consists in a combination **of direct financial support** on investments, provision of **lands** for production facilities, **training** program support for employees and students, and **tax incentives**. To ensure some returns on investment, the governments set eligibility conditions for these plans, such as a minimum number of jobs created, a minimum investment cost or sustainability conditions.

Renault success-story example in Morocco

Morocco

From 2005

Attractive context

Requirements

Direct & indirect support to supply

Renault bought the majority stake (54%) of Somaca (Société marocaine de constructions automobiles) in 2005, at a time when they decided to focus on their successful entry model. As 90% of the vehicles produced by Renault in Morocco at the time were exported, they were allowed corporate **tax exemptions** for five years and **reduced value added tax (VAT)**. The Renault plant in Tangier was then inaugurated in 2012. For this investment, Renault took advantage of the national policies implemented: they were granted a **public loan** of 200 million euros as well as the provision of 300 hectares of **land** and the construction of a **training center**. This plant produced its 1,000,000th vehicle in 2017, and the annual production peaked at 318,000 a year in 2018. Even without any mandatory requirements on this point, local content already accounts for more than 60% of the final products and Renault and the Moroccan government have jointly aimed to reach 65% by 2023 through the development of the local automotive ecosystem, as part of an extension of their agreement. Following this success, other multinational car manufacturers decided to invest in North Africa, such as **PSA** in Morocco, **Volkswagen** and **Nissan** in Algeria or **Mercedes-Benz** in Egypt.

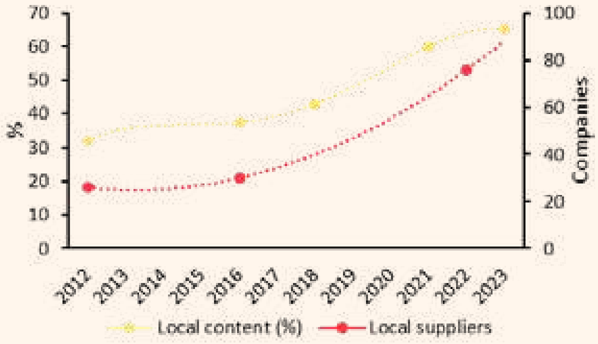


Figure - Evolution of local content in Tangier Renault plant and their number of local suppliers
(Sources: Renault)

9. Gigafactories for batteries in the EU

Summary

This study case focuses on the skyrocketing development of **gigafactories for batteries** in the European Union. As part of the 'Fit for 55' package to reduce CO_2 emissions in the EU by 55% by 2030, only **carbon-free** new cars will be allowed to be registered. Attracted by the expected **massive growth in market demand**, many actors wanted to position themselves on the battery production market in Europe by creating gigafactories, aiming at positioning themselves as **technology leaders** with **sustainable** products. The EU regulatory framework for batteries as well as public support like **Important Projects of Common European Interest (IPCEI)** helped some of these projects to emerge. There are now more than 40 gigafactories scheduled to begin production for a total of around 1 TWh produced per year by 2030, which should meet demand while respecting the criteria of **local production, sustainability** and **recycling**.

Key take aways

In October 2017 Maroš Šefčovič, the Vice-President of the European Commission, created the **European Battery Alliance (EBA)** to gather stakeholders around Europe's plan to create its own "competitive and sustainable battery cell manufacturing value chain", with the help of **EIT InnoEnergy's** expertise. EBA adopted a **Strategic Action Plan for Batteries** in May 2018, with high-priority actions to reach the goals set in different fields like access to raw materials, recycling, energy systems, education or funding.

In accordance with this plan, the European Commission decided to approve **Important Project of Common European Interest (IPCEI)** provisions to battery projects, respectively €3.2 billion in 2019 and €2.9 billion in 2021. These grants have directly contributed to **derisking R&D projects** for more than 50 companies and have globally helped to develop the whole European ecosystem with more than 200 partners indirectly involved.

In parallel, the **European Investment Bank (EIB)** adopted in 2019 a new set of ambitious targets for climate action and environmental sustainability guided by their **EIB Group Climate Bank Roadmap 2021-2025**. To this end, the EIB plans to **invest €1 trillion** in climate-related projects by 2030 and has already granted **low-cost loans** for major battery-related projects like a €480 million loan for LG Chem gigafactory in Wrocław, Poland, three loans counting for more than €380 million for Northvolt Ett gigafactory in Sweden, €49 million loan for Verkor gigafactory in France and a €125 million loan for Umicore battery component production plant.

- The various **stakeholders** have taken the initiative to work **together** on a **holistic strategy** to rapidly develop the battery industry in Europe, as this was a strategic **turning point** that should not be missed. This European strategy was backed up by **large financial supports** through **low-cost loans** or **claw-back fundings** leading to **rapid** implementation.

Along with European organizations, some countries also developed their own strategies to support the battery industry. For instance, **German government** dedicated a **€1 billion fund** available for German companies **to accelerate large-scale battery production** in their country, as well as an additional **€500m to support research**. These funds are granted as **direct subsidies** to gigafactory projects, depending notably on the **region of implementation** and **job creation** criteria.

Many other countries have similar plans as part of a more comprehensive national strategy for low-carbon transformation, such as **Spain**, which has just proposed their **Strategic Project for the Recovery and Economic Transformation of the Electric and Connected Vehicle (PERTE_VEC)** partly financed by the **Next Generation EU funds**. This project includes a comprehensive development of the national industrial environment, including both **direct** and **indirect support** to **suppliers**. Thanks to this plan, the Spanish government has created the conditions for the realization of the gigafactory project near Valencia in collaboration with **Volkswagen** and **SEAT**.

Hungary has a slightly different approach to developing its battery manufacturing industry. Despite a highly developed **network of suppliers**, Hungary cannot count on a major national car manufacturer to develop this industry and must therefore rely on foreign players to establish themselves. Therefore, the Hungarian government is going to finance the gigafactory of the South Korean company **SK Innovation** up to €209 million with the support of the **Regional State Aid** of the European Commission thanks to the creation of jobs especially under the pretext of the **job creation** that will result from it.

- With its early **grant-based financial support** to manufacturers starting in 2019, Germany has already managed to develop **a dozen gigafactory projects** that will allow them to secure **a significant share of the battery market** by 2030. Most governments also feel the **necessity to rapidly position themselves** in this **strategic market**.

In addition to European and national incentives, one of the main **explanatory factor** for the establishment of gigafactories seems to be **access to low-carbon energy** in order to meet the current sustainable production criteria imposed by the European Union regulation, as well as to anticipate future more restrictive measures. Another important factor is the **proximity to the automotive industries**, major partners of battery manufacturers, which explains why Germany is a preferred location.

Replicability potential

In many ways, the growing demand for batteries may benefit the PV industry. The electrification of the European car fleet must necessarily be accompanied by a decarbonized electricity production to be meaningful. On the other hand, gigafactories are themselves very energy-intensive and must therefore be supplied with renewable energy to meet the criteria for sustainable production.

Nevertheless, all the conditions were met for the development of battery factories to take place under the best possible scenario, all that was missing was the trigger for demand. In practice, these conditions are difficult to find in other industries, including PV. The demand will require a strong stimulation to hope for such a development.

EU Green Deal & 'Fit for 55' package

EU Green Deal: 2019-2050 'Fit for 55' package: 2021-2030

Laws

How?

Indirect support to demand

'Fit for 55' package is an intermediate plan and set of policies to reach the net-zero emission by 2050 targeted by the **EU Green Deal**. It notably includes adjustments to the **Emissions Trading Scheme** and the **Carbon Border Adjustment Mechanism** which aims to provide financial incentives to reduce CO_2 emissions. It also sets the objective of reducing CO2 emissions from cars by 55% by 2030 and by 100% for new cars by 2035. These plans triggered the explosion of the demand for batteries for the next decade.

EU regulatory framework for batteries

2019-

Laws

How?

Indirect support to demand

The EU has regulated battery manufacturing with a series of laws. The key features of these regulations are on the **sourcing of battery materials**, the incentives for **low carbon battery production** and the promotion of a **circular battery value chain**. These regulations tend to indirectly promote the production of batteries in Europe rather than importing batteries from Asia or the USA.

Important Projects of Common European Interest (IPCEI)

2019, 2021

Financial support

How?

Indirect support to supply

Two **IPCEI** provisions were granted by the European Commission, one in 2019 and one in 2021. The first one granted **€3.2 billion** to 17 direct participants in 7 EU member states. The participants were mostly industrial actors cooperating with more than 70 external partners like small and medium-sized enterprises (SMEs) and public research organizations. This provision is designed to financially derisk **R&D projects** or **first industrial deployments** and requires "extensive dissemination and spillover commitments of new knowledge throughout the EU".

The second IPCEI fund financed 42 direct participants in 12 EU member states to the tune of **€2.9 billion**, and indirectly over 150 partners through more than 300 collaborations. The projects financed here took into account the **Sustainable Batteries Regulation** proposed by the European Commission in December 2020 to design batteries that are more sustainable through their life cycle.

These provisions are granted through a **claw-back mechanism**, which means that if the projects turn out to be successful beyond expectations, the **extra benefits** must be returned to the respective EU States.

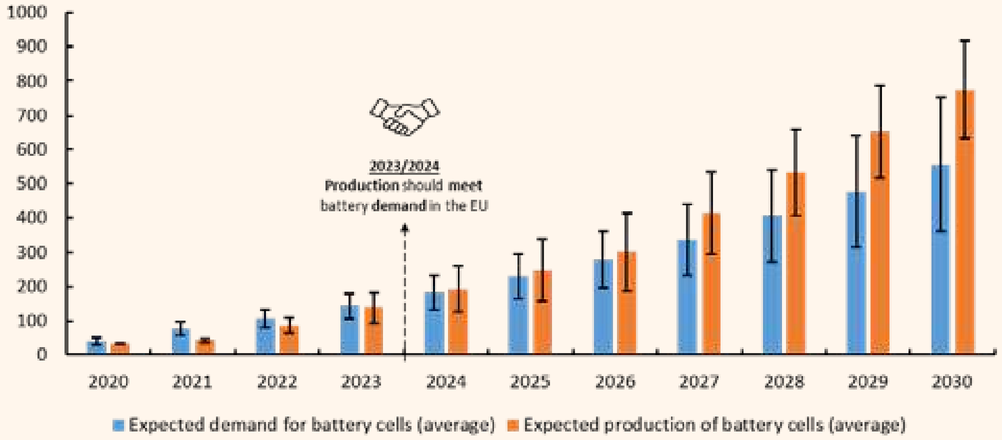


Figure 55- Battery demand and production predictions in Europe by 2030 [GWh]
(Sources: VDI/VDE Innovation)

10. Solar PV industry in Türkiye

Summary

This study case depicts the case of a country which **starting from a close to nonexistent industry** (500 MW PV manufacturing capacity in 2012) was able **in just a decade to multiply local PV module manufacturing by 14** (7 GW estimated module production capacity in early 2022) driven by **regulatory mechanisms** such as **direct downstream support** (i.e., local content requirements (LCR)) and **indirect upstream support** (i.e., financial and tax incentives (FTI)). The Turkish strategy can be decomposed into three axes which have been implemented in combination and/or consecutively between 2013 and today: **YEKDEM**, **YEKA** and **GÖZETIM VERGISI**.

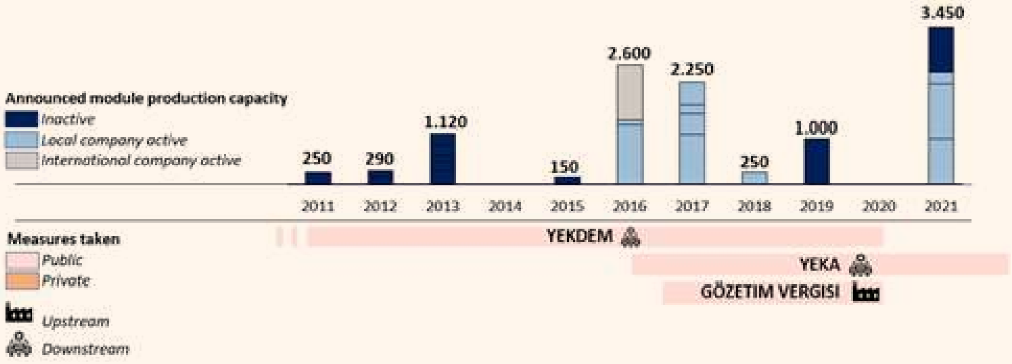


Figure 63- Turkish PV industry development and the public regulatory measures associated
(Source: SHURA Energy Transition Center)

Key take aways

As observed with the rise in module production capacity announcements in the last decade when the Yekdem, the Yeka and the Gözetim vergisi schemes were implemented, Türkiye has succeeded in triggering local manufacturing. The strategy relied on implementing direct downstream incentives such as the mandatory and non-mandatory local content requirement as well as indirect upstream incentives such as new import duties on imported modules. It is difficult to attribute the development of local module production capacity to one of these incentives specifically, and it is rather the combination of measures tackling both the downstream and upstream sector which are responsible for the creation of a favoring regulatory and investment context for local PV manufacturing industry in Türkiye today. Still, some strengths and weaknesses of the different incentives could be observed.

The YEKDEM and YEKA both rely on local content requirement (LCR), but the YEKA by being mandatory and by offering a more attractive remuneration (in particular the 15-year duration) can be seen as more efficient than its predecessor YEKDEM. Eventually, YEKA and to a lesser extent YEKDEM, enabled to provide a favorable investment context for upstream actors by lowering their investment risks by securing a substantial offtake agreement downstream.

- LCR schemes can be effective, if and only if they are mandatory and sufficiently strict. As they are focusing on the downstream part of the value chain, they should be linked to additional mechanisms, such as training and promotion of business interconnections and measures to support other stages of the value chain. In addition, while they support local manufacturing, they can also endanger the development of solar PV projects (and thus the achievement of renewable energy deployment targets) if local manufactured products are uncompetitive or insufficiently developed and available yet or if the necessary additional paperwork to prove local content represents a hurdle for project developers.

The GÖZETIM VERGISI relying on upstream financial and tax incentives (FTI) has effectively led to relatively high import duty (VAT on custom amount is almost double for imported solar modules). Eventually, it enabled to drive down the market share of imported modules in Türkiye.

- TFI schemes can be effective, if and only if they are sufficiently strict (i.e., if they prevent from circumventions of import rules by importing from countries (partially) exempted from import duties). Again, while they provide a competitive advantage for upstream actors compared to foreign products, they can also endanger the development of solar PV projects (and thus the achievement of renewable energy deployment targets) if local manufactured products are more expensive or insufficiently developed and available yet leaving the project developers with higher investment costs.

In addition to these public measures, private actions by upstream stakeholders can be mentioned. An example of such action is the decision of some manufacturers to also position themselves further downstream in the value chain such as engineering, procurement, and construction (EPC) service providers, independent power producers (IPP) or investors.

Replicability potential

LCR and FTI schemes are relatively easy to set up. Moreover, they are associated with limited direct public expenses (almost inexistent for GÖZETIM VERGISI) compared to direct upstream support. They both rather aim at providing a more stable and favorable framework for nascent local manufacturing allowing it to strengthen and blossom. Thus, they should not be implemented as first measures in locations with inexistent local manufacturing. Finally, the results of these measures should also be seen in the light of market trends: Turkey has taken advantage of the US ban on Asian modules to increase its exports.

YEKEDEM

2005-2020

Local Content Requirement

(non-mandatory)

How?

Downstream

YEKDEM, in place between 2005 and 2020, consisted in a non-mandatory local content requirement taking the form of a 10-year feed-in premium bonus for PV generation facilities if they use a minimum of 55% local content for PV panel integration and solar structural mechanics productions (PV modules, cells, inverters and material focusing the solar rays onto the PV module). This bonus can reach up to 6.8 US dollar cent/kWh for 100% local content.

Pros: The bonus feed-in premium is an attractive incentive and encouraged PV installations using local content.

Cons: The bonus was only attributed for 10 years which is a rather short period compared to other countries where feed-in premiums are typically allocated for 20 years. In addition, the local content requirement was non-mandatory and thus had only limited impact.

GÖZETIM VERGISI

How?

2017-today

Financial & Tax Incentive

Upstream

GÖZETIM VERGISI, in place since 2017, consists in a new import duty targeting imported PV panels (25 US dollar/kg) from anywhere outside Türkiye (with a higher value for Chinese imports).

Pros: The incentive drives down the market share of imported modules in the Turkish PV market (favoring local solar panel manufacturers). The import duty is relatively high (VAT on custom amount is almost double for imported solar modules).

Cons: The duty being lower for countries outside of China (Vietnam, Thailand, …) the incentive has mostly triggered imports from these countries rather than local manufacturing until now.

11. Measure focus: PLI scheme in India

Summary

This study case depicts the case of the **Indian Production-Linked Incentive (PLI) program** for manufacturing covering 13 different fields including high-efficiency solar modules. The Solar PLI scheme is overseen by the Ministry of New and Renewable Energy (MNRE) and started in April 2020. It is meant to provide **direct upstream support to gigawatt-scale solar modules manufacturing with a focus on fully-integrated and high-efficiency products manufacturing.** With this, the government aims to achieve 48 GW solar PV manufacturing capacity (including 24 GW fully integrated) while India is currently dependent by more than 85% on foreign imports. This target could be already achieved with the first three winning companies if announced capacity is effectively commissioned. Additional positive effects are also expected with regards to direct and indirect employment, development of micro, small and medium companies in the sector of solar glass, EVA, backsheet, junction boxes, etc. as well as to research and development stimulus on high efficiency modules.

Production-Linked Incentive (PLI)

How?

2020-today

Direct support

Upstream

The support is granted through a competitive bidding process during which interested private companies submit a bid for a certain manufacturing capacity and a certain integration level. The selection of beneficiaries is made with consideration of:

- The overall PLI budget limit of 2.54 billion dollars. The initial allocation was ~600 million dollars but was recently extended as part of the 2022-2023 budget and is distributed as follow: about 1.5 billion dollars for companies setting up vertically integrated capacities of polysilicon, wafers, cells and modules, of about 600 million dollars for companies setting up wafers, cells, and modules capacity, and about 400 million dollars for cells and modules manufacturing capacity.
- The respect of eligibility conditions. In order to qualify for the bid, applicants were required to set up a minimum of 1 GW manufacturing unit. Different capacity was set aside for module + cell and module + cell + wafer, but the major focus was on fully integrated systems. Moreover, manufactured modules should an efficiency greater than 20.5% and certain levels of indigenisation, with an incentive for greater efficiencies and indigenisation. The bidder can be a single company or a joint consortium of multiple companies. In the case of a consortium, the partners will be allowed to join their manufacturing capacity (of any stage) for one bid.
- The applicant's mark. The highest marks are attributed to the bidders offering the highest manufacturing capacity and the highest local value addition (i.e., the highest integration level).

Support is provided for a period of 5 years after the facility commissioning and consists in a certain amount received for each MW of module sold (only 50% of the bided capacity is eligible) and is all the more important as high module efficiency and high integration levels are achieved.

Key take aways

Between the two rounds, 14 companies received funding with an overall support of ~$2.25 Billion and overall manufacturing capacity of nearly 50 GW, which according to the PLI scheme guidelines have to be commissioned within 3 years. Overall, the government support is expected to "crowd in" over $12 Billion in private investment.

- The incentive was positively welcomed by Indian solar manufacturers with an important number of applicants, largely exceeding the initial foreseen budget. By focusing on high-efficiency product manufacturing and integrated manufacturing, India is aiming at reaching a level playing field for Indian actors and multiplying the added value for the country. In addition, the incentive may also attract foreign companies (such as First Solar which was one of the successful bidders in Tranche-II). However, this push for large and integrated actors could make it hard for micro, small and medium manufacturers to compete, and component manufacturers (eg. Glass, EVA) had hoped for drect support as well.

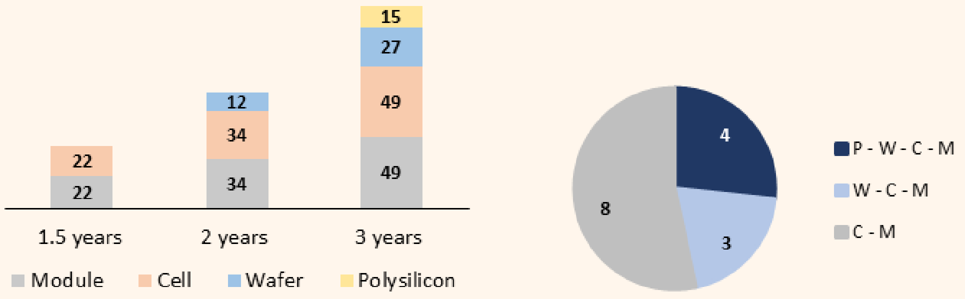


Figure 64- Selected companies per integration level and expected manufacturing capacity [GW] to be commissioned per PV value chain step

(Sources:)

Replicability potential

The PLI program being a direct upstream support has a relatively high direct impact on government expenditure. However, the various expected positive outcomes by the government should largely compensate the investment and reduce energy dependency.

This program is rather tailored in contexts where some incumbent actors are already positioned on some value chain steps but are needing support to do the transition towards becoming both large-scale and integrated actors.

Direct upstream measures integrated in a long-term holistic sectorial strategy are the most efficient

Despite very different contexts and varying successes, some similarities emerge from these case studies. In general, holistic plans, which are often indirect support to supply, are obviously more effective since they allow the whole ecosystem to develop on the long term with better training of the workforce and better infrastructure, for example. It is important that such plans bring together the different stakeholders such as politicians, large production companies and local suppliers to make them successful. For instance, bilateral agreements between a government and a company may be effective in the short term but do not promise sustainable development over time if the entire ecosystem does not grow with them.

Then, the best way to trigger the development of such projects is direct support to upstream actors through financial incentives like for example tax credits for factories, low-cost financing or grants for land or infrastructure investments. Triggering demand and therefore downstream players is also a very efficient way to develop the industry but it must necessarily be followed by further investments.

IV. OUTLOOK FOR THE GLOBAL SOLAR MANUFACTURING SUPPLY CHAIN

12. Scenarios for the future of solar PV until 2035

12.1. Methodology

One of the key preliminary steps of this study is to select PV market development scenarios that will be used as a reference. The total energy demand and its distribution by energy vector are important elements to pay attention to, during the analysis and scenarios selection. In particular, the solar PV penetration in the overall electricity mix, and thus the installed PV capacity at a given time horizon are essential information to estimate the demand for resources and production capacities. Many scenarios exist, produced by organizations with various characteristics. For the purpose of this study, three scenarios depicting three different level of ambition in terms of PV deployment have been selected.

It is important to highlight that the figures presented in the following sub-section and used as a quantified basis are scenarios and not forecasts. In other words, they do not intend to predict what will or should happen. They rather intend to provide a range of possible pathways for the future global solar PV market that could be achieved if a range of conditions are met.

12.2. Market scenarios until 2035

Historical actors in the energy market (Total, Shell, British Petroleum) are among the first to have developed this type of projection, in order to guide their investment strategy. However, publicly available figures are often only partial. Indeed, in these scenarios few precise figures are provided on the amount of energy produced or the installed capacity per technology. They are mainly relative data, which limits the possibilities to exploit them directly [3] [4] [5].

In order to find more exploitable estimations, it is advisable to refer to the scenarios developed by other organizations, e.g. intergovernmental, or researchers. We can mention for example those of the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA) or Greenpeace, which are among the best known. The IEA scenarios, updated annually as part of their flagship publication "World Energy Outlook", have been criticized for their lack of vision and the fact that they consistently underestimate the role of renewable energies [6] [7] [8]. However, the international organization has recently introduced new scenarios, including the Net Zero by 2050, whose estimates are more ambitious, for example with more than 8 TWp of cumulative photovoltaic capacity installed in the world in 2035.

Other organizations also publish the results of their modelling and simulations of the global energy system. Among these energy specialists are the market research firms Bloomberg New Energy Finance, a reference due to the reputation of its parent company, and DNV GL, which has a European anchor and benefits from an international reputation as well. Their results are made available in their annual publications, the New Energy Outlook for BNEF and the Energy Transition Outlook for DNV GL. In particular, BNEF predicts a higher installed PV generation capacity than the IEA forecast. [9] [10]

Researchers have also attempted to assess the role of PV in the energy system of the future. Based, among other things, on an empirical study of decreasing costs and rapid market growth, which can be summarized in a learning curve, they estimated that solar PV will naturally become the world's leading source of electricity generation in the future, already in the medium term [11] [7]. Some researchers have taken a more global view, simulating the entire global energy system. They come to a similar conclusion, i.e., that solar PV, alongside wind power, will naturally play a major role. According to a 2018 study, a global energy system based primarily on renewable energy is possible. Other researchers have gone even further by considering a 100% renewable energy system, using different simulation models [12] [13] [14] [15]. Also, in recent years researchers from Lappeeranta University of Technology (LUT) in Finland and the Energy Watch Group have simulated and analyzed in detail the energy system of different regions of the world and the feasibility of a transition to 100% renewable energy. Their results have been published in a series of studies and papers [16] [6] [17] [18] [19] [20]. In the case that the entire global energy demand would be covered by renewables, about 11 TWp of solar PV would have to be installed by 2030, rising to almost 80 TWp by 2050. Indeed, due to its characteristics, solar PV appears in their simulations as the most suitable solution to cover the global energy needs, covering them at about 70% in 2050 [13]. This percentage is made possible by a flexibilization of the demand, a massive electrification, an increasing interconnection of the electrical networks and the use of storage via batteries but also hydrogen produced from renewable electricity, for seasonal storage or for industrial use.

Among all available scenarios, three have been selected, each presenting a specific point of view on the future of the energy transition and the role to be played by solar PV. All these scenarios are aiming at showing viable pathways towards the achievement of Paris Climate Agreement goals. The main differences between the scenarios, sources to the substantial gaps in terms of solar PV deployment, can be explained by the variety of assumptions in terms of cost and performances of the energy technologies, the rapidity and penetration of electrification, or the evolution of the energy demand by the different sectors of the economy, among others. Overall, they allow to consider a large variety of possible outcomes.

The Net Zero scenario by the IEA is the least ambitious of the three in terms of solar PV development. In this scenario, the electrification of energy demand would rapidly increase, energy intensity of the global economy would decrease, and behavioral changes would also lead to CO2 reductions. Solar PV along other renewables would play a crucial role, even if fossil fuels would still be used.

The second scenario, developed by Bloomberg New Energy Finance, is significantly more ambitious in terms of renewables' deployment. In this scenario, nuclear energy would account for 5% of primary energy supply in 2050, fossil fuels for 15% and renewables for the remaining 85%. Among these, wind energy would be the favored technology, in front of solar PV.

Finally, the scenario by LUT is by far the most ambitious, being very bullish about solar PV's role in the energy transition. The strongest assumption in this scenario is the full reliance of the global economy on renewables, also in the industry, including the production of chemical products.

Note that these three selected scenarios are among the most recent available and allow to consider the point of view of different types of stakeholders, as the first is an international intergovernmental institution, the second one is a private consulting firm and the last one is a group of researchers from a university. A comparison of the scenarios selected in this study is presented in the table and graph below.

Table 2 Presentation of selected scenarios with cumulative solar PV capacities installed by 2030 and 2050 in GW

Scenario's name	Organisation	Scenario's official name	Publication	2030	2050
Minimal transition	IEA	Net Zevro by 2050	2021	4,956	14,458
Ambitious transition	BNEF	NEO 2021 (Green Scenario)	2021	5,400	20,000
Total transition	LUT	100% Renewable Energy Systems	2021	11,300	79,800

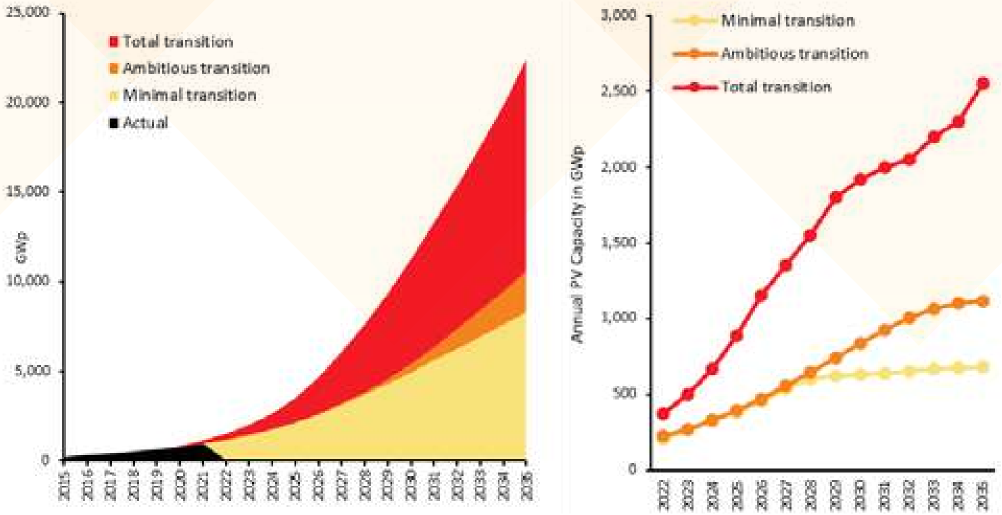


Figure 65- Overview of the global cumulative (left) and annual (right) installed PV capacity for each selected scenario until 2035

The chosen market projection scenarios may seem out of the ordinary at first glance and the figures enormous. But the solar PV market is already strong with nearly 950 GWp of cumulative installed capacity worldwide at the end of 2021 [21]. Thus, to reach 5 TWp in the year 2030, as envisaged in the "Minimum Transition" scenario, 4 TWp would have to be installed in about ten years. Considering the development of the current market, this seems feasible. In any case, the industry is ready to absorb such a demand, as the total annual production capacity of PV modules already stands above 250 GWp [22]. The other two scenarios, especially the "Total Transition" with very large capacities, appear to be hardly feasible without a deep awareness and full support of the population and political decision makers [23]. Asian countries, such as China and India, are expected to maintain or increase their share of annual world production in 2035, while the current major European and American players are expected to see their market share slightly decrease.

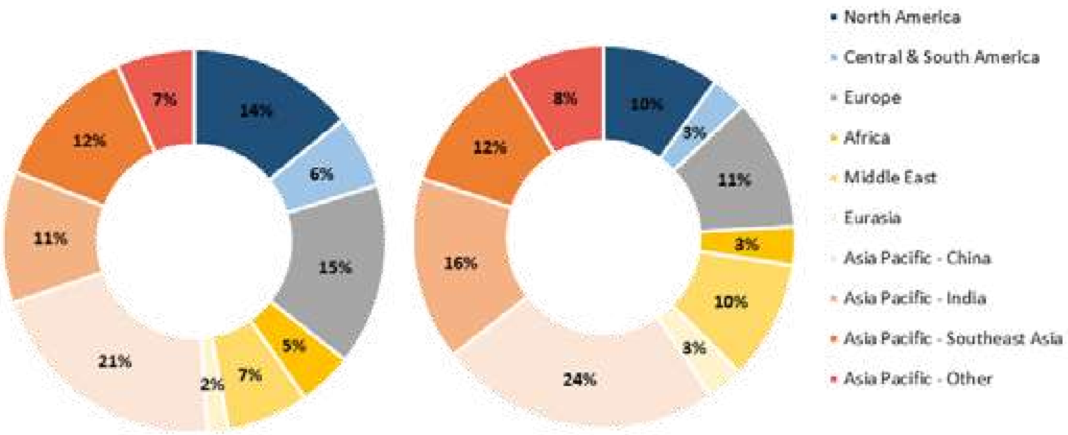


Figure 66- Geographical distribution of annual PV installed capacities in 2022 (left) and 2035 (right) according to Total transition scenario

(Source: LUT)

12.3. Technology scenarios until 2035

To estimate the necessary production capacities at each step of the value chain, it is necessary to make assumptions on the evolution of solar PV (sub)technologies and their respective market shares. To do so, two main sources have been used. First, the International Technological Roadmap for crystalline silicon-based solar photovoltaics sector (ITRPV), developed by an association regrouping a majority of the production equipment manufacturers active on the market, as well as the publications of the Chinese PV Industry Association (CPIA). These sources allowed us to make assumptions up to 2035 on the types of solar PV cells produced and installed, among others. The technology scenario developed based on these sources and presented below can be interpreted as a "business-as-usual" scenario. It reflects the consensus among key stakeholders of the solar PV sector, i.e. what will most probably happen in the future. Nonetheless, deviations from this scenario are possible. These will be mentioned and discussed further in the document when deemed necessary.

In terms of market share of the different solar PV cells' technologies, the dominance of monocrystalline silicon PERC is expected to progressively decrease, while multicrystalline silicon is expected to disappear from the market before 2024. From 2027, the market share of mono c-Si p-type PERC will drop below 50%, and mono c-Si n-type technologies should start their era of domination, especially thanks to TOPCon. Conventional thin-film technologies (CIGS and CdTe should see their market shares remain negligible, falling from <1% and 3% respectively in 2019, to <1% and 2.2% in 2035. The beginning of the 2030's should see the emergence of so-called third-generation technologies, i.e. perovskite-based. These technologies are expected have a market share of around 5% by 2030 and 10% by 2035. A major part is foreseen to come from "tandem" cells with a layer of perovskites applied on monocrystalline silicon wafers. These trends can be mainly explained by the anticipated evolution of the average manufacturing cost and cell efficiency, the latter being presented in Section II.

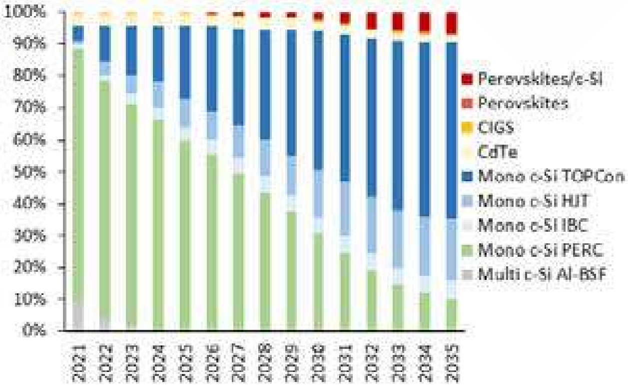


Figure 67- Evolution of the market shares of different PV technologies

(Sources: ITRPV, CPIA, Becquerel Institute Analysis)

The evolution of other technological trends, which can be rather seen as independent from cell technology, such as wafers' sizes, the type of material used for the back cover of the PV panel, framed or frameless modules, is also worth describing. Indeed, it impacts the demand for input materials and the need for production capacities to manufacture these components. As shown on the graph on the right and mentioned in the previous section, the size of wafers on the market is expected to change rapidly. Indeed, smaller wafers are expected to progressively exit the market, as G1 should have disappeared by the end of 2025, while M6 formats will represent less than a quarter of the market from 2025 on and larger wafer formats (M10 and G12) will dominate already in 2022, with approximately 55% of the market. Additional market assumptions on other parameters are presented on the various graphs below.

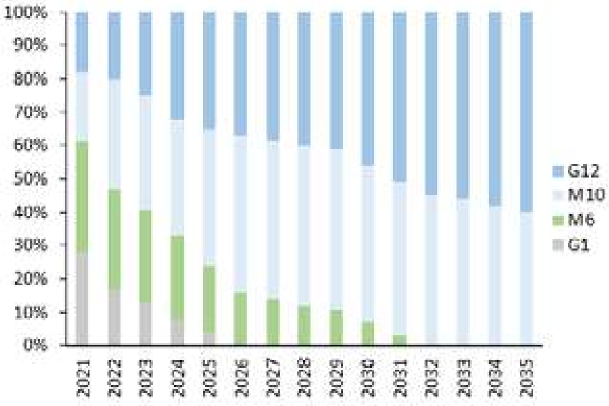


Figure 68- Evolution of different wafer sizes market shares

(Sources: ITRPV, PV Infolink, Becquerel Institute Analysis)

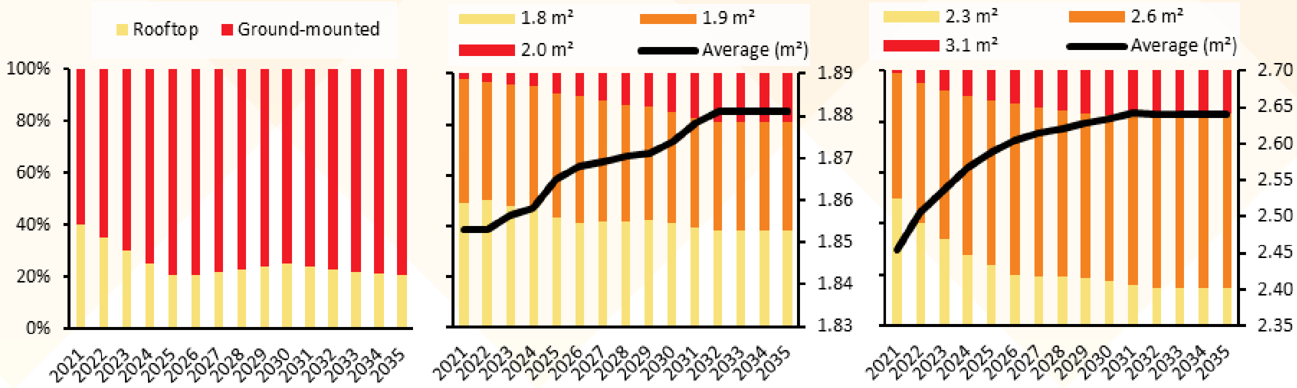


Figure 5- Distribution between rooftop and ground-mounted installations (left) and area distribution for rooftop (center) and ground-mounted (right) installations until 2035

(Sources: ITRPV, Infolink, CPIA, Becquerel Institute Analysis)

In order to estimate the future glass, encapsulant and backsheet demand, prospective assumptions have been made on the solar PV market segmentation. First, between rooftop and ground-mounted installations, as the average size of modules varies greatly across these segments. Then, the weighted average size of modules on these segments has been calculated. Overall, the size of module is expected to increase until 2030, and stagnate after that. It can be explained by the increased size of wafers and cells, as well as the savings in terms of balance of systems that a fewer number of modules can enable. One can also note that ground-mounted projects are expected to take a larger market share than rooftop projects. Indeed, the cost of ground-mounted projects is lower, which makes them more attractive, especially in developing countries. Moreover, the average capacity of ground-mounted projects is much higher than of rooftop projects, which also explains their dominance in terms of total capacity-based market share.

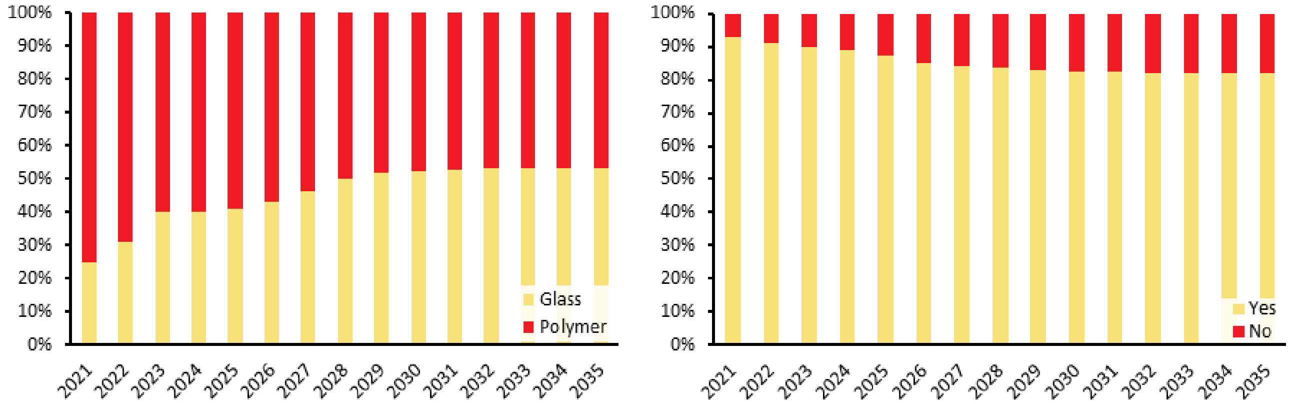


Figure 6- Distribution between glass and polymer backsheets (left) and part of Aluminum frames (right) until 2035

(Sources: ITRPV, Infolink, CPIA, Becquerel Institute Analysis)

Then, the market share of glass as back surface of modules must be assumed as well. As shown on Figure 72 the balance between glass and polymer backsheets is expected to be reached by 2029, as glass-glass modules will be increasingly adopted. On the other hand, focusing of frames, it can be seen on the right part of the above figure that the market should not change that much in the future and that by 2035, more than 80% of modules should still be assembled with an aluminum frame. To complete this scenario on the evolution of the market shares of existing and upcoming PV technologies, assumptions on material intensity for key consumables must be made, to estimate the demand for resources and the associated production capacities to be developed.

As shown on the graph on the left, silver consumption is expected to decrease significantly for all considered cell technologies. This is especially true for mono c-Si n-type technologies TOPCon and HJT. Looking at the weighted average, this decrease is less important, as the rate of reduction is much more limited for mono c-Si p-type, which should still make up for the bulk of the market until 2027.

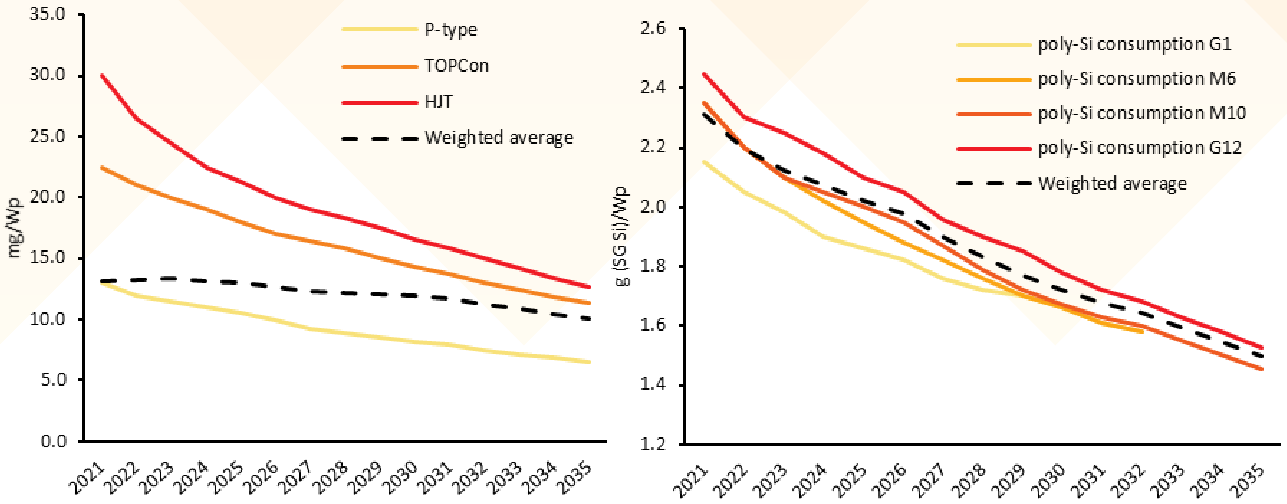


Figure 7- Silver (left) and polysilicon (right) consumptions until 2035
(Sources: Becquerel Institute Analysis)

Finally, in terms of average polysilicon consumption per Wp, this is expected to decrease at almost the same pace for all cell sizes until 2035. Note that the average quantity of solar-grade polysilicon consumed per Wp remains higher for larger cells as they are slightly thicker than smaller cells, to maintain their rigidity. Although, this should be solver in the future and by 2030, G1 M6 and M10 should be on par, while a gap should still exist with G12 cells, due to their very large scale.

What if these technology scenarios were different?

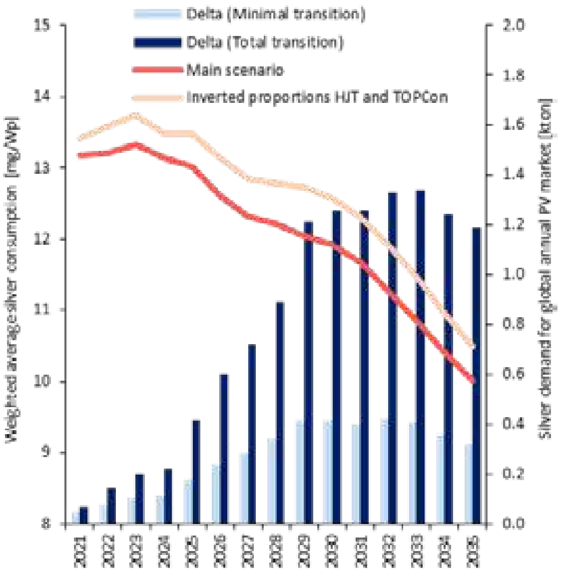


Figure 69- Impact of PV technology market share evolution on average silver consumption and silver demand
(Sources: ITRPV, CPIA, IEA, LUT, Becquerel Institute analysis)

As illustrated above, the PV market is expected to turn massively towards mono c-Si n-type TOPCOn and HJT, to a lesser extent. But as mentioned, although unlikely, the market could evolve differently. The shares of TOPCon and HJT could for instance be interchanged, which would significantly impact the figures presented in the next pages, especially the demand of silver. Indeed, if HJT were to dominate TOPCon, the weighted average silver consumption of all PV technologies would be slightly higher, leading to hundreds of tons of additional yearly demand for this material. A scenario that could have negative outcomes by creating supply/demand imbalance if the market was too slow to react, consequently pushing prices up and possibly jeopardizing solar PV deployment. Note that here only silver is studied, but the consumption of other materials could be impacted, such as indium, which is used in HJT as a transparent conducting oxide (indium tin oxide).

13. Future solar PV manufacturing

13.1. Future demand and manufacturing capacities from quartz to modules

The scenarios of future solar demand presented on the previous pages allowed us to estimate the future production capacities at various steps of the value chain. These figures have been estimated for each of the selected market scenario, using the average ratio between market demand and production capacity, as evaluated in 2021. The varying ratios at the different steps of the c-Si value chain explain the difference in terms of estimated required production capacities.

Table 3 Average ratio between market demand and production capacity, calculated using the data presented in section 2

Value chain step	Demand/Production Capacity ratio		Average production equipment's useful lifetime (years)
	2020	2021	
Polysilicon	60%	62%	10
Ingots & Wafers	59%	65%	10
Cells	57%	67%	7
Modules	84%	90%	5

Below are presented the global figures, while the possible geographical distribution across major regions of the world is discussed in the following sub-section

First of all, starting at the very beginning of the solar PV value chain, the required quantity of quartz to be extracted each year in order to cover the demand of the (c-Si) solar PV value chain has been estimated. As presented below on the left, it would have to significantly increase in order to keep up with the growing demand of the solar sector, at least until 2030, especially in the case of the "Total transition" scenario. As the global annual production of quartz (and quartzite) is estimated to amount to around 5,000 to 6,000 kilotons today, the competition for this resource will increase. On the other hand, it creates opportunities to develop mining sites in new locations or expand ones in order to cover this demand growth. Moreover, as prices of this commodity will probably be impacted upwards, sites that were previously non attractive from an economic point of view might become so. This might be the real bottleneck for the industry.

The next step in the solar PV value chain, metallurgical-grade polysilicon production, demonstrates the same evolution in the different scenarios, as shown on the graph presented on the right, which tells approximately the same story.

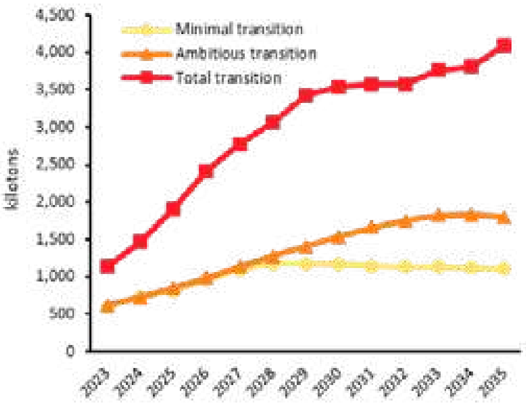


Figure 70- Required annual production of metallurgical-grade silicon for the three solar demand scenarios until 2035
(Sources: Becquerel Institute Research & Analysis)

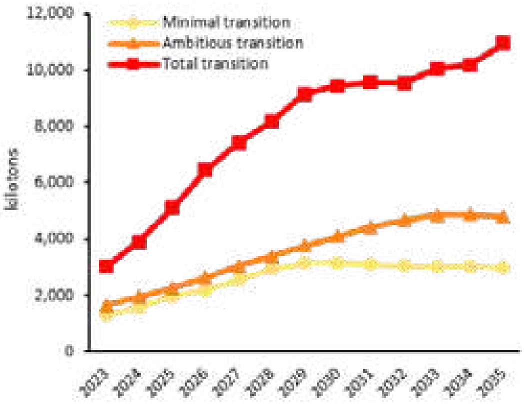
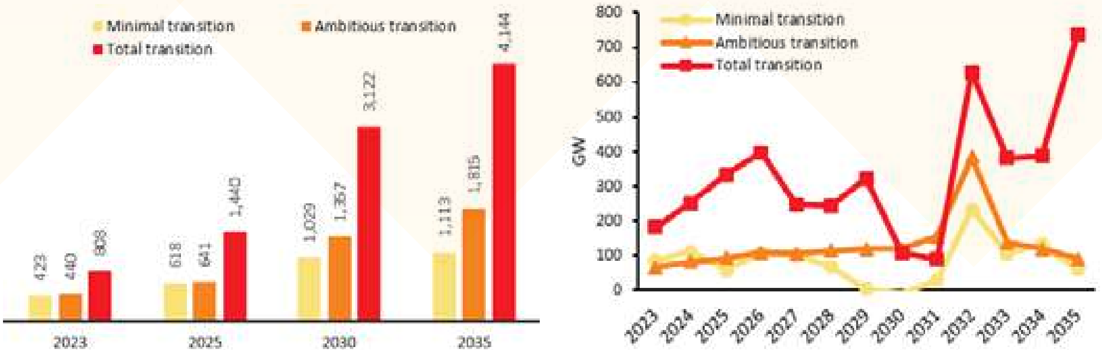
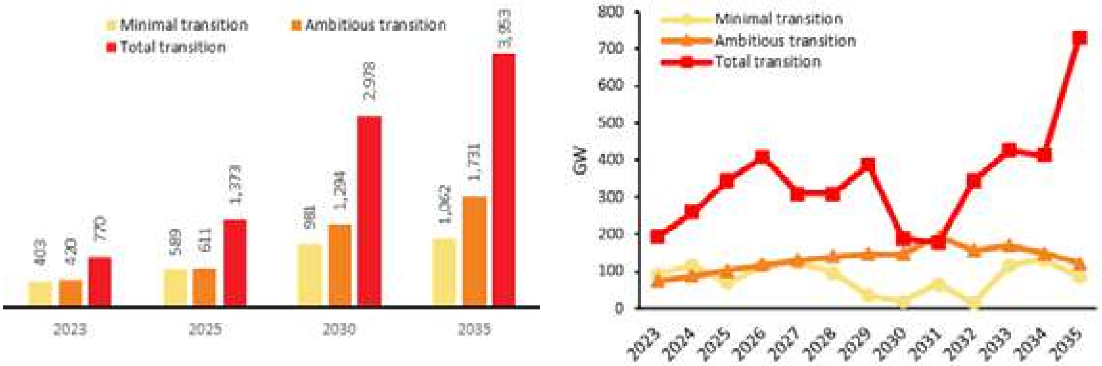


Figure 71- Required annual production of quartz for the three solar demand scenarios until 2035
(Sources: Becquerel Institute Research & Analysis)

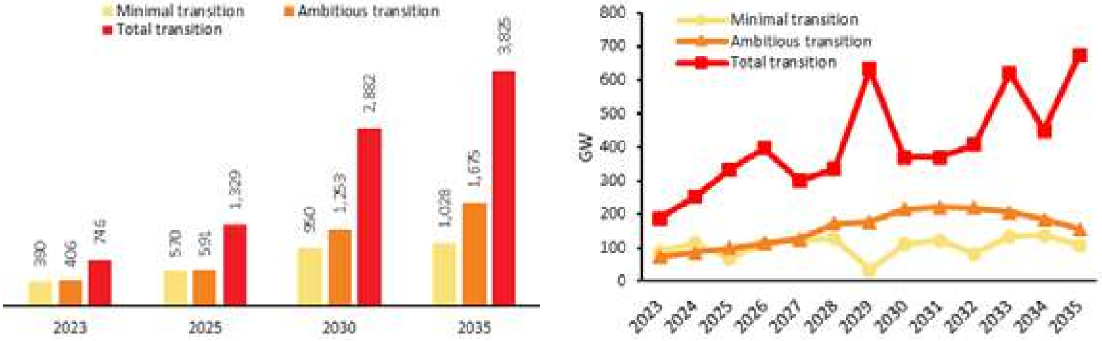
Polysilicon: total production capacity (left) & annual production capacity additions (right) [GW]



Ingots & wafers: total production capacity (left) & annual production capacity additions (right) [GW]



Cells: total production capacity (left) & annual production capacity additions (right) [GW]



Modules: total production capacity (left) & annual production capacity additions (right) [GW]

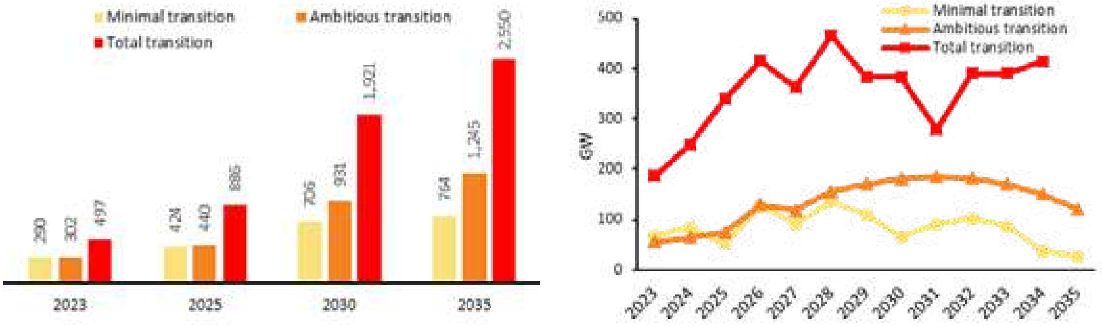


Figure 72- Required total production capacity (left) and annual production capacity additions (right) in GW for polysilicon, wafers, cells and modules for the three solar demand scenarios until 2035

(Sources: Becquerel Institute Research & Analysis)

The graphs presented on the previous page focus on the four main steps of the c-Si solar PV supply chain. The left graphs show the total production capacity, as estimated at various timesteps, required in the industry to cover the solar PV demand defined in the selected market scenarios. The right graphs show the annual production capacity's additions required to reach this total production capacity. For these evaluations, the average useful lifetime of manufacturing lines is taken into account.

The first striking element is that for (solar-grade) polysilicon, ingots and wafers, cells as well as modules, the existent and announced production capacities (black bars) would already be sufficient to cover the demand as defined in the "Minimal transition" and "Ambitious transition" scenarios for the upcoming years. Focusing on the estimated cumulative production capacities which would be required to cover the solar PV demand (left graphs), the "Minimal transition" scenario seems easy to achieve. Indeed, at all of the four major steps of the value chain, the required growth of manufacturing capacities between 2022 and 2035 is limited. Within this 13-year long timeframe, the cumulative production capacities would have to grow by a factor 2 to 3 at each of the four analyzed steps, which seems achievable considering the rapidity of the recent evolution of the solar PV industry. For the "Ambitious transition" scenario, this growth factor ranges between 4 and 5, which seems more challenging, although feasible. The last scenario, i.e. "Total transition", aiming at a 100% renewable energy-based society tells another story. With required growth factors of the total production capacity lying between 9 and 10, the challenge seems extremely difficult to overcome, if only possible.

Looking at the annual production capacities additions required to reach these total figures, the conclusions are similar. For the "Minimal transition" and "Ambitious transition" scenarios, the production capacity's expansions per year appear manageable. Although, one can highlight the case of modules, for which the production capacities to be added per year after 2026 is important and would only decrease starting from 2032. This is due to the useful lifetime of production lines which is assumed to only equal 5 years, instead of 7 or 10 years for upstream steps. This can be explained by the fact that technologies change rapidly, and investments are much lower compared to the upstream steps of the value chain, enabling a shorter payback time and a higher machinery turnover. Again, the "Total transition" scenario tells another story. The required annual production capacities' expansion would be colossal in regards of the usual annual additions witnessed in the industry, ranging from 400 GW to be deployed per year for cells or wafers, to approximately 700 GW for modules.

As depicted on the left graphs of cumulative production capacities, and to a certain extent by the right graphs of required annual expansions, most of the investment in production capacities would have to occur between today and 2030, in the three selected market scenarios. This is in line with the annual deployment of solar PV installations. Note also that the figures in GW are higher upstream than downstream, as historically the ratio between the global solar PV demand and the production capacity has been higher for cells and especially modules, while for polysilicon, ingots and wafers it is low.

Overall, these figures show that the solar PV industry already is on a path that could allow the sector to achieve defined scenarios, at least when focusing on the upstream part of the value chain. It also means that incumbent actors are well positioned and that the opportunities for new entrants would be much more limited in the "Minimal transition" scenario and, to a lesser extent, in the "Ambitious transition" scenario. Especially as most of the growth is expected to occur prior to 2030, which leaves limited time for new actors to prepare and act. On the other hand, the "Total transition" scenario, although extremely challenging, would create massive opportunities for new entrants, as the production capacities to develop are enormous.

13.2. Demand for input materials, components and consumables

Among the crucial materials to the c-Si solar PV industry is silver. It is indeed used in the form of a paste when wafers are transformed into cells, to create fingers that will collect and carry the electricity. Today, the solar industry is responsible of approximately 10% of global silver demand per year, which equals 3,000 kilotons [24]. Based on the selected market scenarios and taking into account technological evolutions, the demand would increase sharply until around 2030. Annual demand would be multiplied by a factor 3 to 4 at maximum in the case of “Minimal transition” and “Ambitious transition” scenarios, and by a factor 9 for the moist extreme scenario, i.e. “Total transition”.

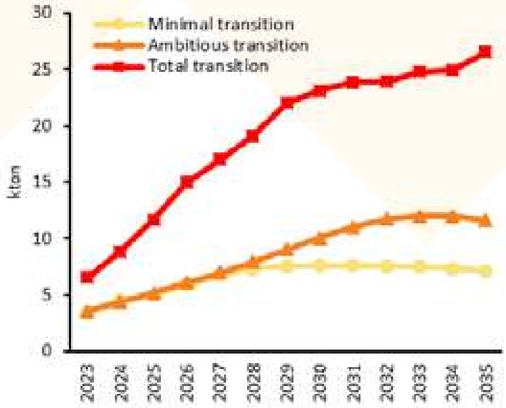


Figure 73- Annual silver demand for the three solar demand scenarios until 2035

(Sources: Becquerel Institute Research & Analysis)

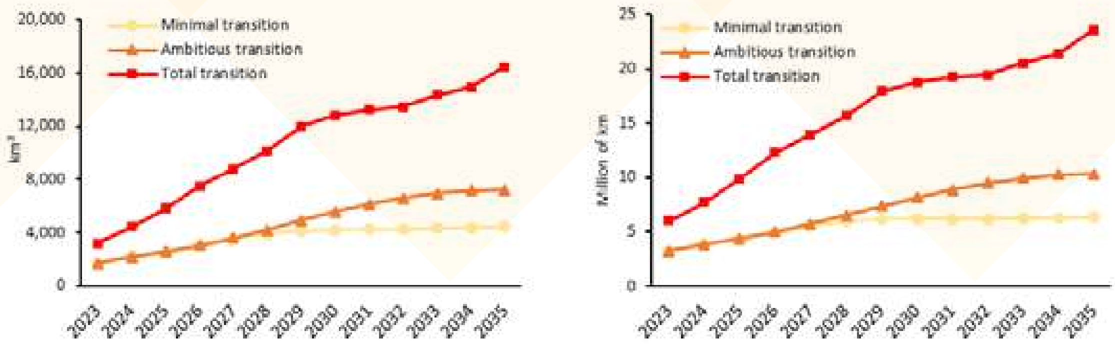
These findings are also valid for other input materials, components and consumables, as it can be seen on the graphs of the next page. For module’s bill of materials to balance of system’s components like cabling and inverters, the evolution of demand would follow a similar trend.

The estimations show that even in the least ambitious scenario, the demand for input materials, components and consumables would be multiplied by a factor 3 within less than 10 years. In more bullish scenarios, this factor could grow to 4 or even 9, depending on the considered component.

Thus, the industry, also in terms of supply of somewhat less crucial inputs, will have to adapt extremely fast. While there already have been evidences of shortages, for instance in terms of glass or encapsulant supply. This demonstrates that shortages and competition could arise, which could have negative impacts, both in terms of cost and market deployment. Even if efficient recycling largely develops in the future, it will fail at easing tensions, as decommissioned capacities are far from the levels of capacity to be installed in the coming years.

On a more positive note, this can be seen as an opportunity for new actors to enter the field of photovoltaics.

Bill of materials: solar glass demand (left) and aluminum frame demand (right)



Bill of materials: cell encapsulant demand (left) and backsheet demand (right)

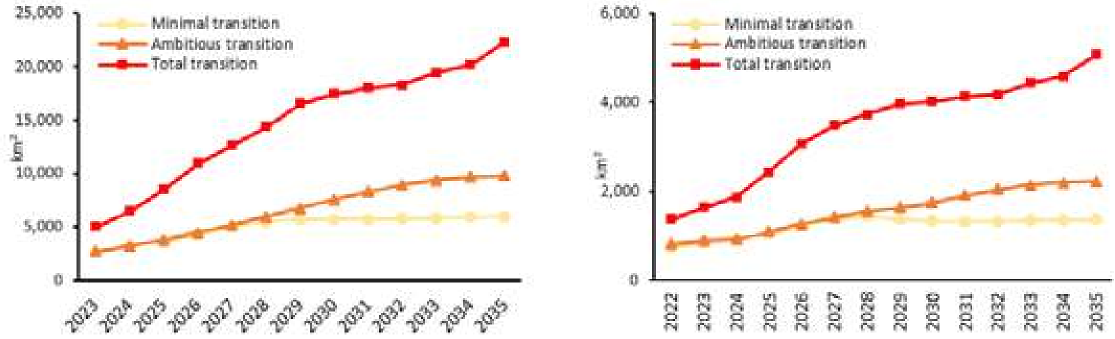


Figure 74- Demand for glasses, frames, encapsulants and back sheets for the three solar demand scenarios until 2035

(Sources: Becquerel Institute Analysis based on IEA, BNEF, LUT, ITRPV, CPIA, RTS Corporation)

Balance of system: cabling demand (left) and inverter demand (right)

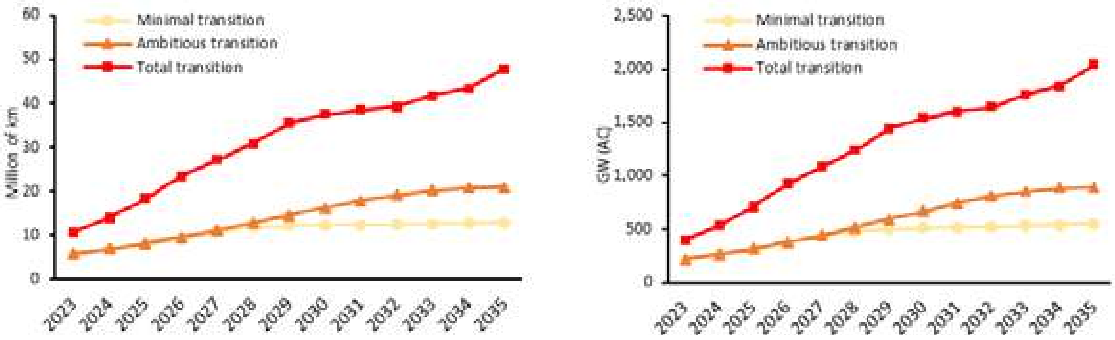


Figure 75- Likely required production capacity for cables and inverters for the three solar demand scenarios until 2035

(Sources: Becquerel Institute Analysis based on IEA, BNEF, LUT, ITRPV, CPIA, RTS Corporation)

13.3. Geographical distribution of production capacities

Aside of the evolution of required manufacturing capacities at different steps of the value chain, the question of geographical distribution is another crucial point.

As evoked in the section presenting the status of the solar PV value chain, most of the crucial steps of the value chain, from metallurgical-grade polysilicon to modules, are concentrated in China. This is also true for input materials, components and consumables such as glass, encapsulants or backsheets. Two scenarios have been developed, with different assumptions on the future geographical distribution of factories across major regions of the world.

The first scenario, called “business-as-usual” (BAU), assumes that in 2022 80% of production capacities are located in China, while the 20% left are distributed across other regions in function of the size of their domestic PV market. Moreover, it is assumed that this distribution will not dramatically change in the coming years, with China maintaining its dominance with 65% of global production capacities. The second scenario is called “Fully diversified” (FDi) and is fundamentally different. It assumes that production capacities are proportionally distributed across regions in function of their domestic PV market. In other words, this scenario assumes a fully “localized” solar PV manufacturing landscape.

Table 4 Assumptions for the scenarios of production capacities’ geographical distribution

Year	Share in global production capacities	Business-as-usual (BAU)	Fully diversified (FDi)
2022	China	80%	Proportional to market
	Rest of the world	20%	
2030	China	65%	
	Rest of the world	35%	

The graphs below illustrate these two scenarios, with BAU on the left and FDi on the right. They show that even in the “business-as-usual” case, for all three market scenarios, significant PV markets such as North America, Europe or India, production capacities by 2030 could stand between 50 and 100 GW for modules, partially contributing to their energy independence. On the other hand, in both the BAU and the FDi cases, small PV markets such as Africa, Central & South America or Middle East would only capture a negligible share of global production capacities. This demonstrates that in their case, exports would be necessary in order to develop a significant and sustainable local solar PV industry, as local solar PV markets lack scale. It may be worthwhile for more regions to enter the export market so as to increase resilience-ie. The risk of high trade concentration with a single market.

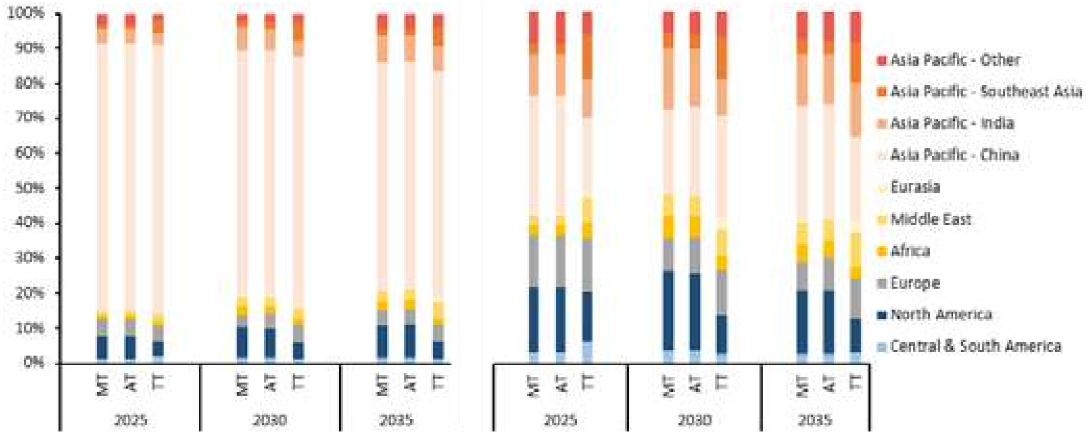


Figure 76- Geographical distribution of production capacities for the three solar demand scenarios until 2035 according to BAU (left) and FDi (right) transition scenarios

(Sources: Becquerel Institute Analysis based on IEA, BNEF, LUT, ITRPV, CPIA)

13.4. Assessment criteria to evaluate the suitability for solar PV manufacturing

To evaluate the potential to develop solar PV manufacturing in a specific region, it is crucial to understand the most influential factors. For this purpose, a list of essential requirements to consider when discussing the potential of establishing local PV manufacturing has been defined and is presented in Table 5. Note that their level of importance is of course highly dependent on the considered step of the value chain, which is expressed by the scoring from 1 to 3. This is discussed in further details after Table 5.

The essential requirements have been divided into four main categories:

- Baseline requirements
- Key requirements for CAPEX-intensive steps
- Key requirements for OPEX-intensive steps
- Key requirements for competence-intensive step

The first category, baseline requirements, encompasses six elements:

- The presence of an **existing industrial ecosystem** in the region or in the country testifies that other actors have succeeded in developing an activity at industrial level (even in another sector than photovoltaics or renewables at large) and have consequently paved the way for further industrial activities to develop.
- In the same vein, the presence of **existing upstream PV actors** is not only a proof that players from the same industry have managed to set up a local manufacturing activity but is also an opportunity to be positioned as a key supplier or off-taker of these existing stakeholders.
- The presence of well-developed **infrastructure** including electricity, gas and water networks characterised by wide coverage of the territory, reliability and adequacy in the frame of industrial activity development is essential as these are two critical commodities in solar PV industrial activities. A transport network featuring a good geographical coverage as well as proximity or connection to key logistics hubs such as ports will ensure both that input raw materials can be delivered under good conditions and that manufactured products can be shipped to nearby as well as distant customers.
- In addition to the access to key commodities such as water, gas and electricity, the **availability of raw materials** in the same region or country as the planned manufacturing activity can be key if the manufacturing process largely relies on one raw material or if the needed raw materials can be difficult to transport. This can be beneficial both in terms of cost and security of supply.
- The presence of a dynamic and relatively large **domestic solar demand** allows to secure more easily off-takers and to supply them at reduced transport and logistics costs.
- The **ease of doing business** is a broad indicator defined by the World Bank, which includes a series of elements such as the ease of starting a business, ease of receiving a building permit, status of juridical protection, existence of trade agreements, the level of taxation as well as the stability of the currency or of the political environment. These are general business-related issues that are nonetheless crucial for the success of manufacturing activities.

Then, key requirements for CAPEX-intensive steps include two elements:

- **Access to capital** refers to an applicant's ability to receive funding based on elements proper to the applicant's project (security of revenues, level of risk, …) but also on elements that are independent on the applicant and are rather attributable to the availability and conditions of financial institutions in a given region or country.
- Once the access to capital is granted, **interest rates** are an important element as they are a key influential factor for the final competitiveness that can be achieved. They are mostly based on the same factors as those impacting the access to capital (level of risk, local or national economic and political environment,).

Key requirements for OPEX-intensive steps gather three elements:

- For the considered industrial activities, electricity is a crucial commodity and the access to cheap **electricity** (and secured supply, see the baseline requirement related to infrastructure) is primordial to lower operational costs.
- Aside of the cost of electricity, its **carbon intensity** can also be relevant. For example, if a differentiation strategy based on the environmental footprint is put forward, or if new regulations are set up, access to electricity with low carbon footprint (typically generated from hydropower or from renewable energy sources in general) will be a key factor.
- Even though with increased automation the labor needs are on a decreasing trend, the labor-intensity of some PV manufacturing steps make **labor cost** a relevant indicator to consider. Specifically, the cost of low-to-medium skilled workers in a given country or region can be an important requirement.

Finally, key requirements for competence-intensive steps refer to three elements:

- While some PV manufacturing steps will be more dependent on low-to-medium skilled labor cost, other steps will on the contrary be more tied to the cost and more importantly the **availability of qualified labor**. While the implementation of training centres can be an efficient and rapid solution to train low-to-medium skilled workforce for specific manufacturing steps, it is hardly replicable for workforces with higher competence and qualification requirements.
- The presence of **R&D centers** is key to follow state-of-the-art and best practices when starting a manufacturing activity. It is also important to maintain such R&D centers once the manufacturing activity has started to be able to adapt to new technological trends. Indeed, as exposed in previous section, some technological changes can happen fairly rapidly (e.g., wafer sizes). Moreover, R&D centers can support companies in kickstarting their activity by providing advises on technologies, supporting the selection process of equipment and helping in fine tuning the different manufacturing steps in order to reach targeted efficiencies.
- **IP availability** refers to the possibility to have access to IP-protected technology or process. This IP does not have to be owned and can be acquired through licensing for example. Also, if locally available, it is a plus, although not mandatory to thrive.

Table 5 Overview of the importance of requirements for different step of the solar PV value chain (Source: IEA, NREL, U.S. Department of Energy, Becquerel Institute Analysis) [1] [2]

	Quartz mining	MG Silicon	SG Silicon	Ingot & Wafer	Cells	Module	Glass	Inverters	Plastic foils
Baseline requirements									
Existing industrial ecosystem	1	3	3	3	2	1	3	2	2
Domestic solar demand	1	2	2	1	3	3	1	2	2
Status of existing upstream PV actors	1	3	3	3	2	1	1	1	1
Infrastructure*	3	3	3	3	3	3	3	3	3
Raw material availability	3	2	1	1	1	1	3	1	1
Ease of doing business**	1	3	3	3	3	2	2	2	2
Key requirements for CAPEX-intensive steps									
Access to capital	3	3	3	2	2	1	2	1	1
Interest rate	3	3	3	2	2	1	2	1	1
Key requirements for OPEX-intensive steps									
Electricity cost	1	3	3	3	2	1	3	1	2
Electricity carbon intensity***	1	3	3	3	2	1	3	1	2
Labor cost	2	1	1	1	2	3	2	2	2
Key requirements for competence-intensive steps									
Qualified labor	2	3	3	3	3	1	2	2	2
R&D centers	1	2	2	2	3	2	1	1	1
IP availability	1	2	2	2	3	2	1	1	1

** Electricity, water, transport, …*

*** See World Bank indicator: Ease of starting a business, ease of receiving building permit, juridical protection, taxes, currency, political stability, existence of trade agreements…*

**** Typically related to the presence of hydropower*

1: listed requirement is of **limited** importance for considered PV value chain step

2: listed requirement is of **medium** importance for considered PV value chain step

3: listed requirement is of **high** importance for considered PV value chain step

Legend:

13.5 Strategic questions for the development of the solar PV industry

1. The rapid increase in production will create a strong demand for trained workforce

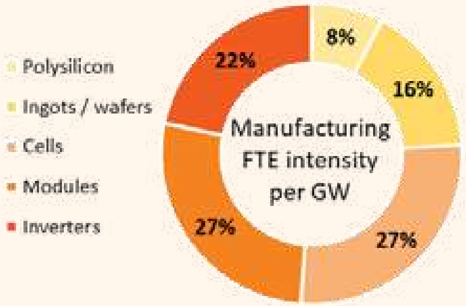


Figure 77- Global employment intensity share by value chain segments

(Sources: Becquerel Institute Analysis based on IEA)

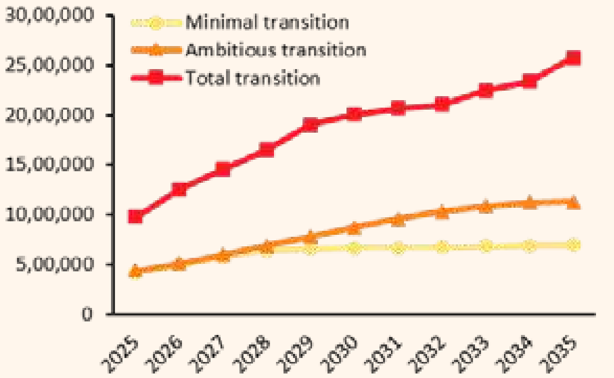


Figure 78- Cumulative global direct manufacturing employment forecasts (in FTE) to 2035 for the three solar PV demand scenarios

(Sources: Becquerel Institute Analysis based on IEA, BNEF, LUT, IRENA, SolarPower Europe)

The significant increase in production capacities at the main steps of the value chain (polysilicon, ingots/wafers, cells, modules and inverters) will create a strong need for (direct) manufacturing jobs. Under the minimal and ambitious transition scenarios, cumulative direct jobs on the five analysed manufacturing stages are expected to increase by a factor of 2 to 3 by 2030 compared to today [1]. Thus, solar PV manufacturing can be a significant source of job creation, with around **75,000 direct jobs created globally per year on average between 2025 and 2030** according to the Minimal Transition and Ambitious Transition scenarios. On the other hand, the workforce demand in the total transition LUT scenario would be such that it might be a bottleneck for the growth of the production capacities required by 2035 with two to three times the workforce required, which would represent up to 200,000 jobs created by 2030.

Among these jobs created, **30 to 40% are estimated to require training and a specific diploma (e.g., for engineers and technicians), which would represent 150,000 to 250,000 to be trained people by 2030**. The gap between the supply and demand of workforce could be especially problematic for these jobs. Indeed, for now few universities or schools have programs that train students to be directly employable in PV factories. Especially as the new factories breaking ground are of unprecedented sizes. Thus, even experimented researchers or people from the industry do not always have the right skillset/experience outside of existing manufacturing hubs, i.e. outside of China.

In the USA, Europe and India, difficulties in finding trained and specialised photovoltaic workers are already reported, for technical staff at every stage of the value chain, which results in slowing down the speed of development of some manufacturing projects. To mitigate the issue, a progressive ramp-up of manufacturing activities is generally the key to avoid creating a bottleneck in terms of workforce and reducing the quality of the products manufactured.

Another complementary solution is the creation of specific university programs or certification courses and awareness campaigns to contribute to increasing the workforce. An often-discussed option is also the deployment of “Training centers” or “Schools/academies”, in collaboration with various PV stakeholders, including researchers and (future) manufacturers, as well as technology and equipment providers. This is even necessary for operators, which need to be trained for a few weeks/months. Although part of the training can and should be provided by equipment and technology providers, this is often insufficient.

2. Production equipment: the cornerstone of solar PV manufacturing

The production lines used at each step of the solar PV chain, and the machines they are made of, are **strategic assets and the real source of value creation for manufacturers**. Indeed, this equipment allows to achieve, at industrial scale, the performances reached by researchers at a smaller scale, while maintaining costs (CAPEX and OPEX) at levels that permit to be competitive.

This crucial position can be illustrated with the strategic decision made by Meyer Burger in 2020 to pivot, from equipment manufacturer and supplier to manufacturer of PV cells and modules. This created difficulties for multiple of their former customers, who had few options to turn to in order to keep ramping up their production capacities.

Historically, as for the rest of the key roles in the solar PV sector, Western actors have dominated this part of the solar PV value chain. But as the industry shifted to Asia and China in particular, the expertise was lost by some and gained by others. **Today, while many providers of equipment for cells and modules manufacturing steps exist in Europe or the USA, as well as in Asia, the equipment required to pull, cut ingots and slice wafers can hardly be sourced outside of China**. Indeed, companies exist in Europe, but they struggle to keep up with the performances and scale reached by Chinese equipment. Most investors are thereby favoring Chinese equipment when investing at these steps of the c-Si solar PV value chain.

This position has been well understood by the Chinese authorities. In a tense geopolitical context between China and other countries, including the United States of America but also European ones, the **Chinese Ministry of Industry has launched a public consultation to assess the possibility of banning exports of some key ingot and wafer manufacturing equipment abroad**. Results of the consultation and a decision are expected for 2024.

While such protective measure would be a way for China to safeguard a unique expertise it has been building for a few years and reinforce its position in a strategic sector, **it could slow down or even endanger the development of manufacturing activities outside of China**.

Overall, this highlights **the need to redevelop local expertise and rebalance the distribution of the solar PV value chain across the global as rapidly as possible,** to allow for more resiliency and fair distribution of the benefits of solar PV development.

3. Why develop solar PV manufacturing locally?

Developing local PV manufacturing is an important step to **progress towards energy independency, while providing access to a strategic, low-cost and low-carbon electricity**. In addition, the economic advantages are important. For instance, as evoked previously, this industry has the potential to create many jobs, at different level of skills [26] [25] [16].

Nevertheless, the development of local solar PV manufacturing capabilities can have drawbacks. First, in terms of required CAPEX, all countries are not equal. Differences in terms of average building cost, cost of infrastructures or facilities' construction can lead to significant gaps between countries. This is illustrated below on the left chart where it is shown that **starting manufacturing activities in China and more generally in Southeast Asia is two times less capital intensive than in Europe or the United States**. Figure 80- Investment intensity by supply chain segments and by regions [1]

This can be explained by the **experience gained by the Chinese, as well as advantageous local conditions, as the authorities created a very favourable environment.** Effective support measures have been implemented in China, such as direct financial support such as subsidies, access to low interest loans, but also the provision of industrial infrastructure.

These differences in CAPEX, coupled with support measures and OPEX factors such as the cost energy or labour cost have substantial impacts of the production cost of solar PV components. In addition, additional OPEX savings are achieved in China thanks to the economies of scale allowed by their much bigger average factory sizes, including high-volume purchasing and optimized maintenance. As illustrated below on the chart on the right, today modules produced in China and Southeast Asia are 25 to 37% more competitive than those made in the United States or Europe. Nonetheless, **this gap can be compensated by factoring in the cost of transportation, and the fact that in some countries or segments, end customers are willing to pay a premium** for locally produced modules or modules with a lower environmental footprint.

Thus, new entrants in the PV manufacturing landscape will struggle to compete with Chinese products on a pure cost basis. But this gap will decrease in the long run as local manufacturing will develop and scale up. Plus, it brings additional benefits such as the ability to regain (partial) control of a strategic resource.

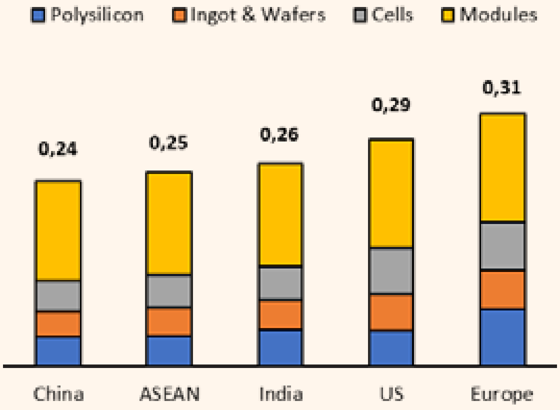


Figure 79- Production costs for mono PERC c-Si (in 2022, with a polysilicon price of USD 14/kg) by supply chain segments [1]

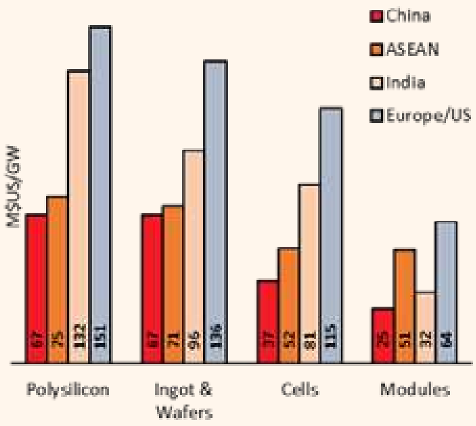


Figure 80- Investment intensity by supply chain segments and by regions [1]

4. Alternative and emerging PV technologies

While the majority of the solar PV sector relies on crystalline silicon (c-Si) technologies, many alternatives exist, in theory at least, as all are not suited (yet) for manufacturing at industrial scale.

First, it is worth noting that c-Si PV is a complex field, encompassing a broad range of variants. These are distinguished by doping (p- or n-type), by whether they are cast in multi-crystalline or quasi-mono form or drawn as a mono-crystalline ingot, as well as by the type of contacting used to extract current. Mainstream c-Si cell technologies cover (1) p-type aluminum back surface field (Al-BSF) cells (mono- or multi-crystalline), which are now exiting the market, and (2) p-type passivated emitter rear contacts (PERC) cells (mono- or multi-crystalline), that are by far the most common on today's market.

Then, advanced c-Si cell technologies are all n-types, aiming at overcoming efficiency limits of conventional p-type. Efficiencies are promising and production capacities are rapidly ramping up. Indeed, both in Asia and in Europe, n-type c-Si is the clear choice for new entrants and existing actors expanding their facilities. These are mainly focusing on TOPCon, but HJT is not that far behind in terms of announced manufacturing projects. On the other hand, investments in IBC technologies are much more limited.

The alternatives to c-Si are mainly thin film technologies, which are numerous. Among conventional ones, amorphous silicon (a-Si) and micro silicon (µ-Si) have almost disappeared of the market, while CdTe is the most mature of all, thanks to First Solar's industrialisation. CIGS has long been existing on the market, but no industrial actor has so far been able to ramp up production capacities, due to cost and efficiency issues. Thereby, CIGS cannot be considered as a bankable technology to invest in. The difficulty to sustain a CIGS-centered manufacturing business is real, as illustrated by the closure of SolarFrontier's plant of 900 MW (Japan), historical leader in CI(G)S, unable to follow the industry's race, as well as other manufacturers such as NICE Solar Energy and Solibro (Europe), or the difficulties of Hanergy (China).

In fact, except for First Solar, all manufacturers who bet on thin film have disappeared or pivoted to c-Si based technologies. Among others, this can be explained by limited efficiencies in mass production, technical complexity and high equipment cost, even if the number of manufacturing steps is in theory reduced compared to competing c-Si-based technologies.

Among emerging technologies, the most promising is perovskites, especially if used in combination with other conventional technologies as "tandem" cells. Other emerging thin film technologies such as organic PV, DSSC or CZTS are negligible and unlikely to disrupt the market of conventional PV applications. Technologies such as GaAs or multi-junction cell technologies are very efficient but too expensive to be viable as mainstream products. They are mainly used for space or other special applications.

In theory, perovskites have two main advantages compared to c-Si based PV, or even conventional thin-film technologies. Firstly, their production cost should be smaller (except if we are talking about tandem cells with conventional PV, which is a cost adder). Indeed, perovskites could in theory be produced using simpler, shorter manufacturing processes than conventional PV, in particular c-Si, where the number of steps from the raw material (silicon metal) to the final product (module) is high and fragmented. This process simplification would lower the costs in terms of energy consumption, consumables' consumption and equipment investment. For project developers, the benefits would mainly be on the balance of system (BoS). Indeed, as new technologies such as perovskites are expected to enter the market through tandem cell technologies, the cost of modules is expected to remain constant or to barely decrease at best, as the efficiency gain should be compensated by the cost of this extra perovskites layer. But higher cell efficiencies will lead to higher nominal module power. Thus, a lower number of modules will be required, for a comparable total plant capacity, which will lead to cost reduction, among others in terms of installation time, preparatory works or electrical components.

Nonetheless, many uncertainties exist regarding perovskites, and these possible benefits rely on preliminary assessments. The potential of perovskites will only be achieved under the condition that lab efficiencies are reached for commercial products, and that degradation rates are limited enough to guarantee a sufficient lifetime. Perovskites' current stage of development is not expected to allow a significant entry into the market before the end of the decade. Thus, in the short- to medium-term it should not be regarded as a rational choice for investors in new manufacturing capacities.

5. Financing needs

As shown on Figure 78, the minimum investments in local PV manufacturing must be large enough to allow for economies of scale and remain cost relevant compared with Chinese market leaders. These large investments can a priori be a significant barrier for new entrants but can be overcome with the support of authorities through the right measures, as presented in the Study cases in section III. This chart also shows that if access to financing is a limiting factor, cell or module manufacturing are the easiest entry points in the industry. It worth noting that having access to enough financing is not only critical to cover the required CAPEX to set up the factory, but also concerns the OPEX, which represents the bulk of costs, on a per unit basis

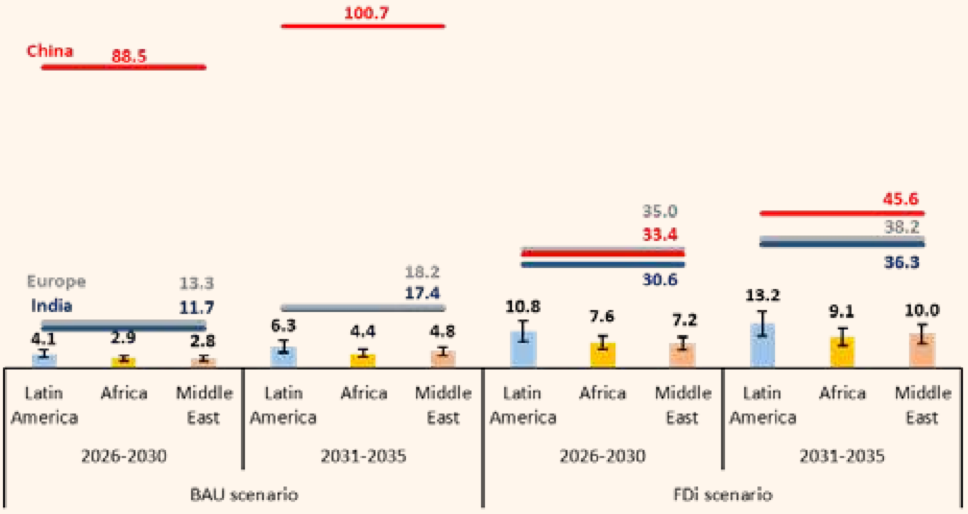


Figure 81- Investments in billion USD required in production lines by region until 2035 according to BAU (left) and FDi (right), Ambitious Transition scenario

(Sources: Becquerel Institute Analysis based on IEA, BNEF, LUT, ITRPV, CPIA)

To cover these financing needs, private equity investors, banks and financing institutions as well as authorities have a role to play.

Authorities can indeed largely contribute to reduce the level of risk for banks and private investors, by providing loan guarantee or through grants. Their involvement is crucial to ensure success, as demonstrated by the Chinese case.

Looking at the investment need associated with the future production capacities presented in sub-section 3.1, the figures do not appear as high as one could have expected. Even in the "FDi scenario", in which the future manufacturing capacities would be more developed locally, the CAPEX needs per region seem manageable, with regards to the amounts invested in other sectors, such as fossils. On a 5-year long period, total CAPEX needs would not exceed 15 billion US$ in the three studied emerging PV regions (Latin America, Africa and the Middle East). In already existing or developing manufacturing hubs (China, Europe, India), the amounts required would be 3 to 5 times higher but seems manageable as well.

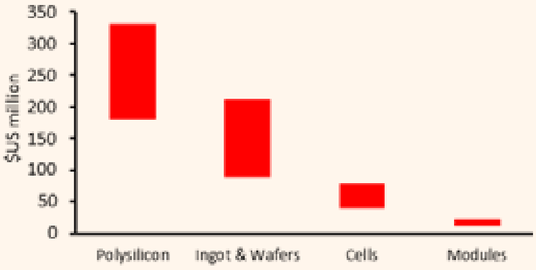


Figure 82- Average minimum investment required per value chain stepchain step

(Source: Becquerel Institute analysis based on IEA)

Looking at the listed requirements' importance assessment for the different considered PV value chain steps, several general comments can be made. Firstly, with the exception of the fully integrated module manufacturing, which gathers all the constraints of the manufacturing steps it encompasses, it appears that only a handful of requirements are really critical for each individual steps of the value chain. Secondly, the essential requirements largely belong to the same requirements' category. This indicates that a country or region may develop a manufacturing strategy building on its core strengths notwithstanding some weakness on other requirements.

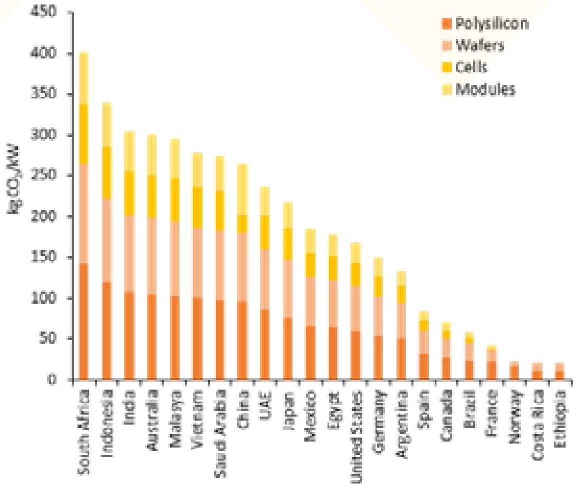


Figure 83- Average CO_2-intensity per country and per value chain step

(Source: IEA) [1]

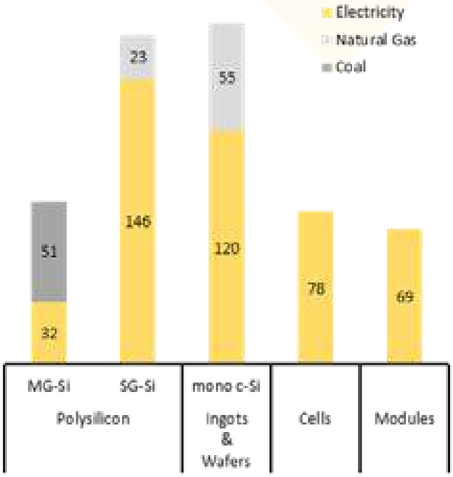


Figure 84- Average energy-intensity [kWh/kW] per energy vector and per value chain step

(Source: IEA) [1]

Quartz mining, module assembling, inverter assembling, and plastic foils' manufacturing gather the lowest constraints in terms of requirements. Module and inverter manufacturing rely on the assembly of elements that have been manufactured in more complex processes upstream in the value chain. They require low labor costs, reliable and developed infrastructure and, in the case of quartz mining, raw material availability. On the contrary, electricity costs (and consequently electricity mix carbon-intensity), qualified workforce are lower in terms of requirement ranking. Note that assembling is also significantly less capital-intensive and can thus be started with a lower initial investment.

Then, as far as cell manufacturing is concerned, electricity- and carbon-intensity are in the same order of magnitude as for module assembling. Minimum investments required to set-up manufacturing capacity, although higher than for module, also remain on the lower range compared to other value chain steps. The key complexity increase for the cell manufacturing step lies in the high competence-intensity making skilled workforce and the presence of R&D centers important requirements, in particular if innovative technologies are targeted, such as technologies based on n-type mono c-Si.

Manufacturing steps such as metallurgical-grade silicon, solar-grade silicon as well as ingot and wafer manufacturing show a large number of constraints with highly important requirements in all or most categories. They are the most capital-intensive and competence-intensive steps, while electricity is an important cost component for these value chain steps. Access to cheap and low carbon electricity (e.g. in countries with large penetration of renewables and typically hydropower) is of outmost importance to reach profitability and achieve enhanced environmental performance of the final product, as these steps represent around two thirds of the final CO2 intensity of a PV module.

The manufacturing of key inputs for module assembly, such as glass or plastic foils (encapsulants and backsheets), rely on different requirements. Glass manufacturing is a relatively energy-intensive sector thus it is relevant to develop such activity where cheap electricity is available. Infrastructure and raw materials availability are also ranked among the most importance requirements. Plastic foil manufacturing is also dependent on electricity prices although to a lesser extent. Overall, the different requirements' importance is low. Although these two value chain steps call for different requirement types and importance, they share the necessity to reach very competitive prices as they are almost considered as a commodity by module assemblers, and there are few differentiations factors.

What about scale?

In most cases, a large-scale domestic (i.e., in the same country or in a neighbouring country) solar demand is not a mandatory condition. South-East Asian countries (e.g., Malaysia) are a good demonstration of this as local manufacturing developed even with demand located thousands of kilometres away, namely in North America and Europe. Although not necessary, the solar domestic demand is still an important element to consider. Firstly, it can represent a non-negligible competitive advantage, allowing to benefit from lower transport and logistics costs between production and consumption points. Secondly, it can help reduce the risk of investing in a factory by contributing to secure future sales. An important domestic solar demand can also amplify the positive effects of local content requirements' regulations.

As far as the scale of the manufacturing activities is concerned, it is a decisive element as in most cases, especially capital-intensive manufacturing steps, economies of scale are a key driver of competitiveness. While this is certainly true for the upstream stages such as polysilicon manufacturing or for ingot and wafers production, or for commodity-like steps, there are exceptions when it comes to cells or module manufacturing. Indeed, for glass or plastic foil manufacturing, competitiveness is the sole driver with limited to non-existent possibility to value differentiating factors at a higher price. Consequently, economies of scale are critical. On the other hand, for module manufacturing, alternative drivers such as betting on differentiation for conventional market segments (based on efficiency, aesthetics, carbon footprint, …) or targeting niche markets (special sizes modules for off-grid application, BIPV, …) can justify the establishment of manufacturing facilities of reduced scale, i.e. around 500 MW and less.

Apart from these specific modules, it is rather recommended to invest in plants producing at least 1GW of conventional modules to achieve competitiveness. And this minimum scale is even greater up the value chain, i.e. the recommended minimum scale for cell manufacturing is around 3 to 5 GW, while for ingots and wafers, 5 to 10 GW.

14. Possible strategies & recommendations for countries to develop solar PV manufacturing

The strategy to apply in order to enter the solar PV manufacturing field and the associated recommendations vary in function of the characteristics of the concerned region or country as well as the pursued objectives. To provide an overview of this diversity, typical "profiles" have been defined and are presented below. They have been ordered according to their degree of complexity, from the lowest to the highest.

1. BOOTSTRAPPER

Profile

- Inexistent industrial ecosystem
- Available but low qualified workforce
- No natural resources (raw materials)
- Limited to no local solar PV market

Main objectives

- Create direct jobs
- Deploy rapidly
- Minimize the investment costs

Strategic points

- In the short term, focus on the production of simple components (cabling, frames, mounting structures)
- Starting activities such as module or inverter assembling is possible in the medium term
- Contact foreign players (established manufacturers, banks) to set up the factory is a possibility

Policy recommendations

- Avoid measures on local content, which would be ineffective in the absence of a local market
- Develop industrial zones close to ports with advantageous tax regimes and ready-to-go infrastructure
- Sign trade agreements to facilitate export

2. NICHE PLAYER

Profile

- Limited industrial ecosystem
- Available low-to-medium qualified workforce
- Local or neighbouring solar PV market with specific needs

Main objectives

- Create direct and indirect jobs
- Differentiate from foreign players
- Stimulate the local industrial ecosystem
- Support specific segments of local PV market

Strategic points

- Understanding market needs is crucial, including the sensibility of customers to cost
- The assembly of specific solar kits can be aimed to meet the local energy demand (solar lamps, solar pumps, solar heaters, ...)

Policy recommendations

- Local content requirements are useful if well designed, i.e. leveraging the specificities of local products and only in addition to (rather than instead of) existing solar tenders, mandates, etc. so as to avoid delaying the energy transition.

3. FOLLOWER

Profile

- Limited industrial ecosystem
- Available low-to-medium qualified workforce
- Limited local solar PV market

Main objectives

- Create direct and indirect jobs
- Develop local solar PV expertise
- Stimulate the local industrial ecosystem
- Support the local PV market

Strategic points

- Focus on assembling activities such as the manufacturing of modules or inverters, using mainstream technologies, including at cell level. Scale can be limited at the beginning, if other factors are favorable (land and building cost, labor cost, energy cost).
- Starting activities such as cell manufacturing is possible in the medium term, if expertise has been developed in parallel
- Partnering with foreign actors (manufacturers, or R&D centers in case of cells manufacturing) is advised

Policy recommendations

- Local content requirements could be useful if the local PV market is not too immature
- Develop industrial zones close to ports with advantageous tax regimes and ready-to-go infrastructure
- Sign trade agreements to facilitate exportation
- Develop local training programs to provide the necessary workforce and develop expertise

4. MINER

Profile

- Presence of natural resources (raw material)
- Limited to no local solar PV market

Main objectives

- Create direct jobs
- Generate tax revenues

Strategic points

- If the natural resource is easily accessible and of attractive purity, this is an opportunity to be leveraged
- Downstream integration to transform the raw material is possible but not mandatory, because of the complexity of such step and the additional requirements to fulfill (e.g., low energy cost)
- If no local expertise, develop a joint venture of local actors and authorities with foreign mining companies

Policy recommendations

- Facilitate permitting but not at the expense of environment/inhabitants' protection, which could backfire
- Map and document the resource-full areas and develop the infrastructure to access the mining sites

5. PIONEER

Profile

- Advanced industrial ecosystem
- Available highly qualified workforce
- Local R&D centers or universities

Main objectives

- Create direct and indirect jobs
- Differentiate from foreign players
- Stimulate the local research and industry
- Become a market leader in the long-term

Strategic points

- The upstream part of the value chain, in particular the cell level, should be targeted
- Game changers come from efficiency and/or cost, also looking at LCOE rather than manufacturing cost
- Partnerships between research centers and industrial actors is crucial, as well as support from authorities
- Understanding market needs is key, and niche market segments should be targeted at first, as they are less sensitive to cost

Policy recommendations

- Support to R&D is crucial to develop local expertise and stimulate the potential to differentiation
- Support to kickstart small- to medium-scale industrial activities is a plus (upstream direct measures)
- Downstream measures specific to the targeted solar PV market segments can help the industry, including technology or environment specific rules

6. MARKET LEADER

Profile

- Large and advanced industrial ecosystem
- Available highly qualified workforce
- Available capital
- Developed local solar PV market

Main objectives

- Create direct and indirect jobs
- Be independent from imports
- Long-term economic benefits

Strategic points

- Vertical integration should be prioritized, as part of a medium- to long-term strategy, beginning downstream, from modules' assembling, progressively integrating up to raw materials
- Leveraging mainstream technologies is possible at first, with cost as the main initial asset
- In the medium-term, becoming a technology innovator will be crucial to maintain the leading position
- Massive investments will be needed, thus the private sector and banks will have to be on board from the beginning

Policy recommendations

- Develop a holistic and integrated (upstream and downstream) long-term strategy, including all stakeholders of the sector
- Support to R&D is crucial to develop local expertise and stimulate the potential to differentiation, as well as to maintain the position of leader
- Direct upstream measures are crucial to create a favorable industrial environment
- Downstream measures to stimulate the local market (e.g., feed-in tariffs), thus securing market opportunities is key. Also, local content requirements or specific rules on technology or environmental conditions are efficient

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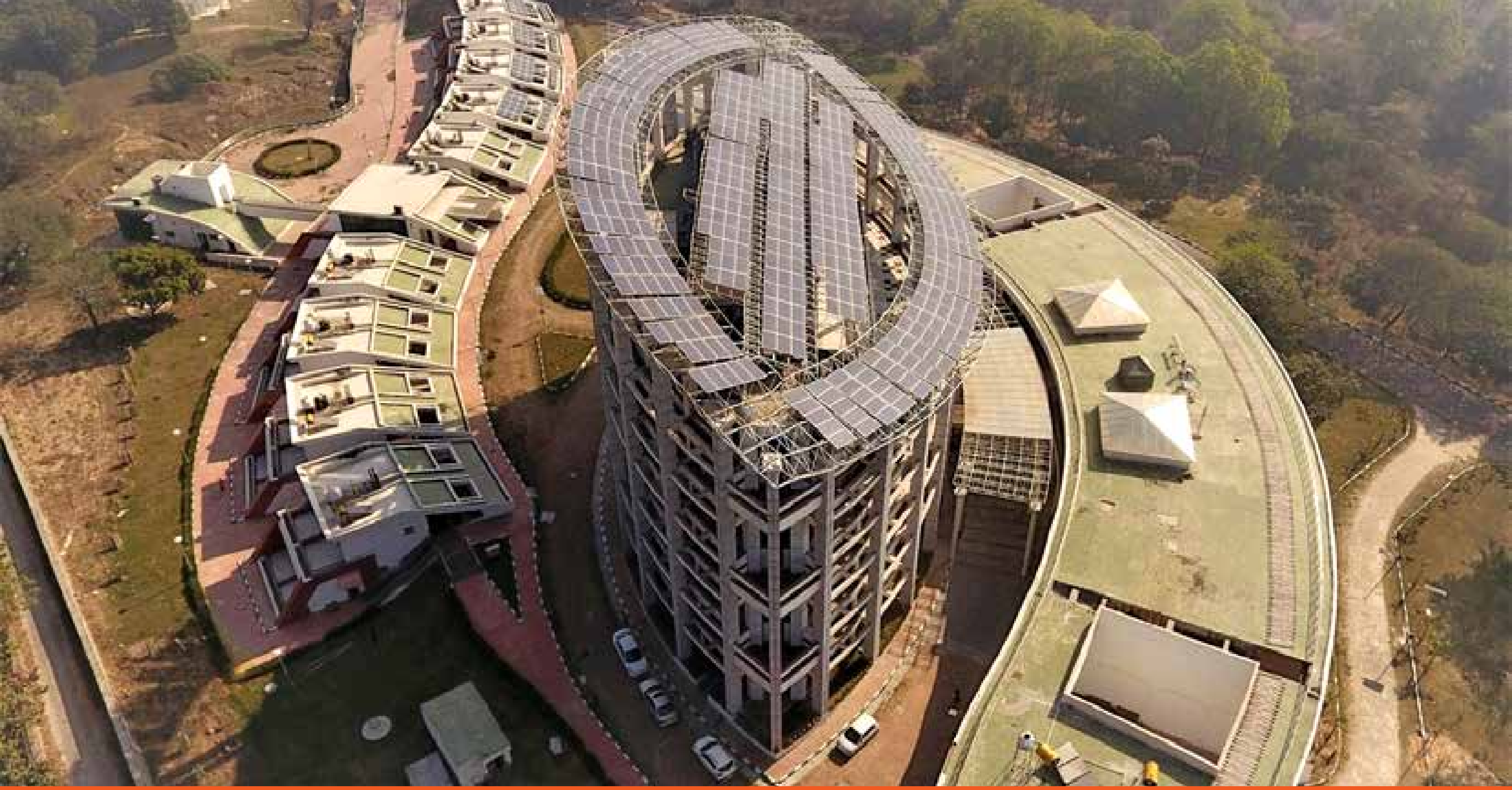

The International Solar Alliance (ISA) is an action-oriented, member-driven, collaborative platform for increased deployment of solar energy technologies as a means for bringing energy access, ensuring energy security, and driving energy transition in its member countries.

The ISA was conceived as a joint effort by India and France to mobilise efforts against climate change through the deployment of solar energy solutions. It was conceptualised on the sidelines of the 21st Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) held in Paris in 2015.

The ISA strives to develop and deploy cost-effective and transformational energy solutions powered by the sun to help member countries develop low-carbon growth trajectories, with particular focus on delivering impact in countries categorized as Least Developed Countries (LDCs) and the Small Island Developing States (SIDS). Being a global platform, ISA's partnerships with multilateral development banks (MDBs), development financial institutions (DFIs), private and public sector organisations, civil society, and other international institutions is key to delivering the change it seeks to see in the world going ahead.

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