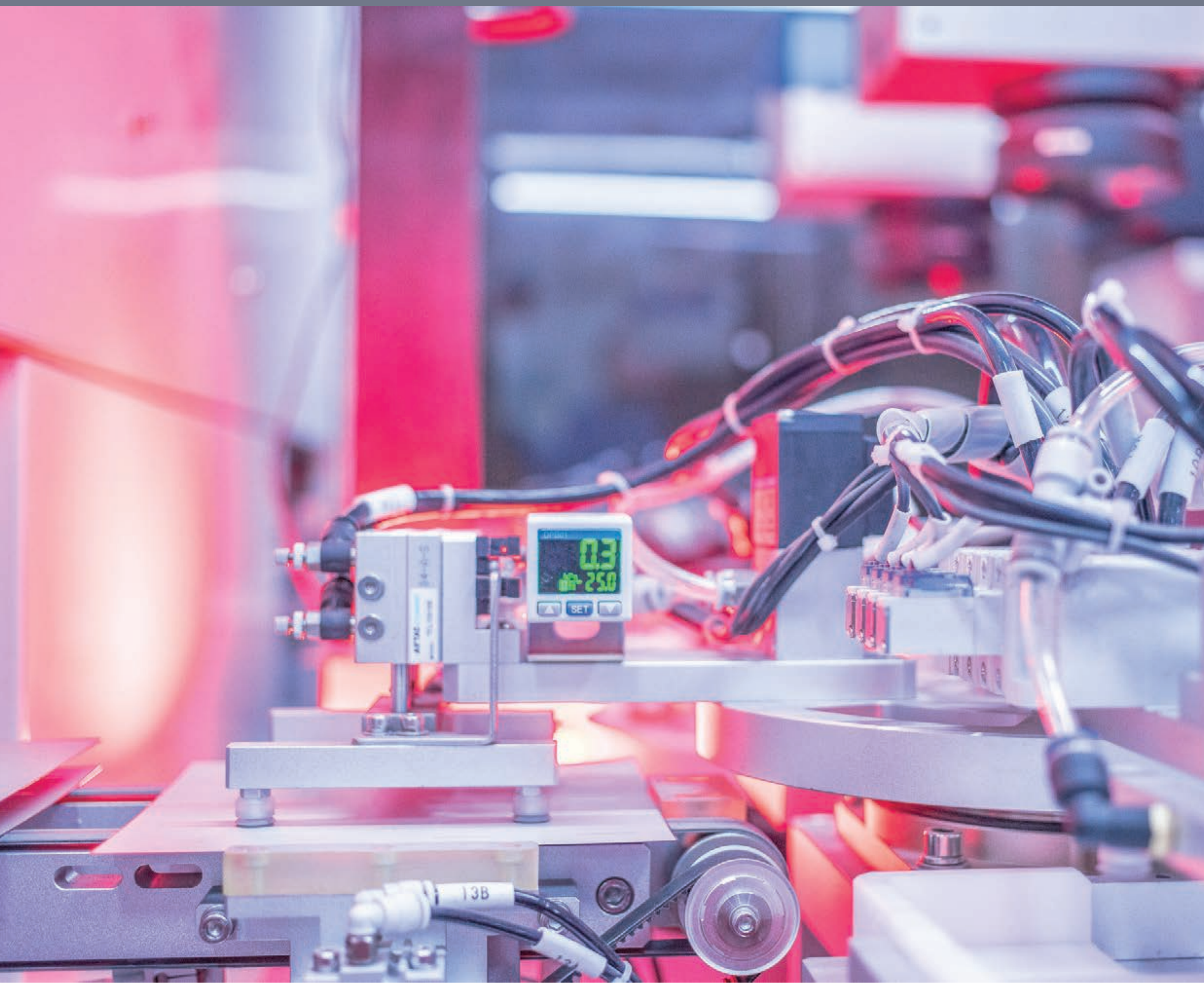
Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS



Edition 48

TOPCon maturity
N-type solar's accelerated trajectory

The future of bifacial
Entering the bifacial nPV era

Vertical integration
How fully-integrated PV manufacturing can accelerate the energy transition

Tabbing and stringing
CEA-INES explores recent advances in ECA-based tabbing and stringing

Tandem cell advances
CSEM details recent processing advances for full-wafer two-terminal tandem cells

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T: +44 (0) 7827 885311
E info@pv-tech.org
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Technical Publishing Director: Mark Osborne
Commissioning Editor: Adam Morrison
Sub-Editor: Steve D. Brierley
Design: Tina Davidian
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Foreword

Welcome to Photovoltaics International 48. Entering 2022, the solar industry would have been hoping for a year of stability or solace after what had been a phenomenally challenging and turbulent period. Be it material costs, logistics constraints, soaring market demand or the lingering impact of the COVID-19 pandemic, the global solar industry has certainly had its work cut out for it since the turn of the decade. With lockdowns persisting in large parts of China still, our thoughts remain with those impacted.

But in the face of such adversity solar has persisted, almost belligerently, with a sense of purpose and resolve. As we send this volume of Photovoltaics International to press, we're still reflecting on an Intersolar Europe exhibition which was a celebration of that resolve and an indication of the solar industry's direction of travel, which you can also see in the pages of this journal.

The continued introduction of TOPCon modules to the market was one of the overarching themes witnessed at Intersolar Europe and we have Fraunhofer ISE writing in the journal on how the industry is continuing to transition this "evolutionary upgrade" from the laboratory to industrial manufacturing. Furthermore, we have JinkoSolar providing a detailed look and investigation into its own experience and successes with TOPCon, having recorded numerous TOPCon cell efficiency records over the last two years, including what, specifically, was accounting for a majority of electrical losses.

The constraints and travails of the solar industry's supply chain have placed greater importance on vertical integration. Manufacturers need much greater control and transparency of their material and component supply in order to mitigate risk, prompting many leading solar manufacturers to incorporate such approaches into their own capacity expansion strategies moving forward. Our Fab & Facilities section of Photovoltaics International 48 includes a specific look at vertical integration from European manufacturer Kalyon PV and details the strengths such a strategy can provide, supported by evidence from Kalyon's own model.

Elsewhere we've papers from ISC Konstanz on the industry's ushering in of a bifacial nPV era and from CSEM on recent processing advances towards full-wafer two-terminal perovskite/silicon tandem solar cells, indicating how the industry is not merely settling on advancing TOPCon, but embracing the technological change that is set to occur throughout this decade.

That turbulence of the previous two years would appear to have set the industry in good stead for a decade of change, with solar thriving as a result.

Thank you for reading, and we hope you enjoy the journal.

Liam Stoker
Editor in chief
Solar Media Ltd.

Editorial Advisory Board

Photovoltaics International's primary focus is on assessing existing and new technologies for "real-world" supply chain solutions. The aim is to help engineers, managers and investors to understand the potential of equipment, materials, processes and services that can help the PV industry achieve grid parity. The Photovoltaics International advisory board has been selected to help guide the editorial direction of the technical journal so that it remains relevant to manufacturers and utility-grade installers of photovoltaic technology. The advisory board is made up of leading personnel currently working first-hand in the PV industry.

Our editorial advisory board is made up of senior engineers from PV manufacturers worldwide. Meet some of our board members below:

Prof Armin Aberle, CEO, Solar Energy Research Institute of Singapore (SERIS), National University of Singapore (NUS)

Prof Aberle's research focus is on photovoltaic materials, devices and modules. In the 1990s he established the Silicon Photovoltaics Department at the Institute for Solar Energy Research (ISFH) in Hamelin, Germany. He then worked for 10 years in Sydney, Australia as a professor of photovoltaics at the University of New South Wales (UNSW). In 2008 he joined NUS to establish SERIS (as Deputy CEO), with particular responsibility for the creation of a Silicon PV Department.

Dr. Markus Fischer, Director R&D Processes, Hanwha Q Cells

Dr. Fischer has more than 15 years' experience in the semiconductor and crystalline silicon photovoltaic industry. He joined Q Cells in 2007 after working in different engineering and management positions with Siemens, Infineon, Philips, and NXP. As Director R&D Processes he is responsible for the process and production equipment development of current and future c-Si solar cell concepts. Dr. Fischer received his Ph.D. in Electrical Engineering in 1997 from the University of Stuttgart. Since 2010 he has been a co-chairman of the SEMI International Technology Roadmap for Photovoltaic.

Dr. Thorsten Dullweber, Head of PV Department at the Institute for Solar Energy Research Hamelin (ISFH)

Dr. Thorsten Dullweber is leading the PV Department and the R&D Group Industrial Solar Cells at ISFH. His research work focuses on high efficiency industrial-type PERC and bifacial PERC+ silicon solar cells, where he co-authored more than 100 Journal and Conference publications. Before joining ISFH in 2009, Thorsten worked as project leader for DRAM memory chips at Infineon Technologies AG. He received his Ph. D. degree in 2002 for research on Cu(In,Ga)Se2 thin film solar cells. Thorsten is member of the Scientific Committees of the EU-PVSEC and SNEC conferences.

Dr. Wei Shan, Chief Scientist, JA Solar

Dr. Wei Shan has been with JA Solar since 2008 and is currently the Chief Scientist and head of R&D. With more than 30 years' experience in R&D in a wider variety of semiconductor material systems and devices, he has published over 150 peer-reviewed journal articles and prestigious conference papers, as well as six book chapters.

Florian Clement, Head of Group, MWT solar cells/printing technology, Fraunhofer ISE

Dr. Clement received his Ph.D in 2009 from the University of Freiburg. He studied physics at the Ludwigs-Maximilian-University of Munich and the University of Freiburg and obtained his diploma degree in 2005. His research is focused on the development, analysis and characterization of highly efficient, industrially feasible MWT solar cells with rear side passivation, so called HIP-MWT devices, and on new printing technologies for silicon solar cell processing.

Dr. Jochen Rentsch, Head of department "Production technology – Surfaces and Interfaces", Fraunhofer Institute for Solar Energy Systems (ISE), Germany

Dr. Rentsch received his Ph.D degree in physics in 2005 from the Albert-Ludwigs University of Freiburg, Germany. He studied physics at the Technical University of Braunschweig and the University of Sussey (Brighton, UK) and obtained his diploma degree in 2002.

His current work focusses on the acquisition and management of public and industrial funded projects, the publication and licensing of R&D results, the transfer of processes and cell structures in the PV industry as well as consultancy on and auditing of PV manufacturing facilities worldwide.

Finlay Colville, Head of Market Intelligence, Solar Media

Finlay Colville joined Solar Media in June 2015 as head of its new Solar Intelligence activities. Until October 2014, he was vice president and head of solar at NPD Solarbuzz. Widely recognised as a leading authority on the solar PV industry, he has presented at almost every solar conference and event worldwide, and has authored hundreds of technical blogs and articles in the past few years. He holds a BSc in Physics and a PhD in nonlinear photonics.

Photovoltaics International remains the solar PV industry's only independent technical journal, carrying papers written by recognised industry experts and leaders in their field, highlighting technological innovation and manufacturing excellence to drive the sector forward. The PVI advisory board therefore plays a critical role in ensuring that the themes and topics covered in each volume of the journal are truly representative. Members of PVI publisher Solar Media's publishing team liaise with the advisory board on a regular basis and ahead of each volume of the journal to establish industry trends, qualify the journal's selection of papers and guarantee technical relevance. For more information on the Photovoltaics International advisory board, contact info@pv-tech.org.

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News

Canadian Solar unveils PV manufacturing strategy shift
Canadian Solar has unveiled a new PV manufacturing strategy, bringing more upstream capacity inhouse to reduce its exposure to pricing volatility. Canadian Solar's manufacturing arm CSI Solar revealed that it intends to develop tens of gigawatts of solar ingot, wafer and cell capacity in the second half of 2022 at a total capex cost of around US$850 million. CSI Solar now expects to finish the year with 20.4GW of ingot capacity, 20GW of wafer capacity, 19.8GW of cell manufacturing output and, unchanged from its initial expectations, 32GW of module assembly capacity.

CAPACITY EXPANSIONS

LONGi to develop 20GW solar module project in Anhui
LONGi Solar is planning to develop a 20GW module assembly facility in Wuhu City, Anhui Province after signing a cooperation agreement with local authorities. The facility, set to be located in Shenxiang Town, Wuhu City of China's Anhui Province, is to be constructed in two phases of 10GW each. Production at the facility's first phase is slated to start in Q2 2023, while the second phase – construction at which is to begin in Q1 2023 – will be ramped from Q2 2024. LONGi signed a strategic cooperation agreement with the management committee of the Wuhu Economic Development Zone covering the facility in May 2022.

Risen rolls out HJT production line in China
Chinese solar manufacturer Risen Energy has started production at its 120μm heterojunction (HJT) solar cell production line in Changzhou City, China. The company upgraded its HJT pilot line between February and May 2022, with cells produced to now be used within its Hyper-ion modules which uses G12 120μm half-cut cells. Boasting a mass production cell efficiency of 25.5%, the cell structure uses a microcrystalline doping layer and has lower silver content paste than comparative PERC cells, Risen said. The power output of the modules for this cell can reach up to 700Wp+ with a module efficiency of 22.53%.

Hanwha to invest US$320 million in new solar cell, module manufacturing capacity expansions
Hanwha Solutions is to invest US$320 million in cell and module manufacturing capacity expansions in the US and Korea. A total of US$170 million is to be spent on the construction of a 1.4GW module production facility in the US, strengthening the company's position in the US module market. Hanwha unit Qcells already operates a 1.7GW module factory in Georgia and the capacity addition, slated to come online in H1 2023, will mean Qcells is responsible for around one-third of the US' total solar module production capacity. Meanwhile cell production capacity at Hanwha's existing cell production facility in Korea will be expanded by a further 900MW through an investment of US$150 million.

Meyer Burger optimising production expansion to 1.4GW in Germany to cater for European demand
Heterojunction cell and module manufacturer Meyer Burger has started development of a new module facility with an additional 400MW in Germany to cater for European demand. The equipment provider-turned-module manufacturer expects the Freiburg site to produce 1.4GW of module capacity from 2023 and has, for the short term, started using solar cell capacities at its Thalheim site in Germany instead of its US facility to help optimise its expansion plans and reduce transportation times. For this purpose, the company secured a long-term lease on a building near its current premises in Thalheim that will be dedicated to increasing production of solar cells.

TZS unveils US$323m polysilicon, R&D expansion plan
Zhonghuan Semiconductor (TZS) is to invest RMB2.06 billion (US$323 million) in a new 120,000MT-capacity polysilicon project and additional polysilicon R&D facilities in Inner Mongolia. TZS signed an agreement with both the Inner Mongolia Autonomous Region People's Government and Hohhot City People's Government that will see the manufacturer construct a high-purity polysilicon plant, a national silicon material R&D centre and other supportive projects in Hohhot. The terms of the deal will also see TZS receive grid connection agreements for solar PV projects in the area and favourable power price terms. TZS said it had selected Inner Mongolia as the location for this new expansion in accordance with its existing footprint in the region, having operated manufacturing facilities in Inner Mongolia for more than a decade. Zhonghuan claims its existing facility in Hohhot, dubbed the Zhonghuan Industry Park, is the largest mono-silicon production site in the world, with these new facilities adding to its capacity, turning the site into a "Chinese Silicon Valley", the company said.

Tongwei investing US$1.9bn in 32GW of new solar cell capacity

Major polysilicon and merchant cell producer Tongwei Group is to invest in an additional 32GW of solar cell capacity through a RMB12 billion (US$1.9 billion) investment in partnership with the government of Meishan City, in Sichuan Province, China. The capacity expansion will be conducted in two 16GW phases, Tongwei said, with the company aiming to bring the first phase of the project online by the end of 2023, after which work on the second phase will begin. Tongwei said in a stock statement that the new facility will be built on Qinglong Street, Tianfu New District, Meishan in cooperation with the local government.

Enel signs grant agreement with EU for 3GW bifacial PV module facility in Italy

Enel Green Power (EGP) has signed a grant agreement with the European Commission for a 3GW PV module plant in Catania, Italy, with an R&D commitment to pursue tandem cell production in the coming years. Under the European Union's first Innovation Fund for large-scale projects, it will contribute to the development of TANGO (iTaliAN pv Giga factOry) with a total investment of around €600 million (US$662 million). Additional funding from the EU of €118 million will help increase by 15-fold its current 200MW capacity. and will include the manufacture of bifacial heterojunction PV cells. The 3Sun plant is expected to be fully commissioned by July 2024, with a first line with a capacity of 400MW set to begin production in September 2023. Enel said 3Sun's lines will also produce heterojunction bifacial panels and further teased the development of modules featuring tandem cell structures in the future, but provided no specific timeline for this.

POLICY & LEGAL

EU solar plan tackles 'scarcity' of European solar manufacturing

The European Union's new solar strategy, published in May 2022, has outlined a list of measures designed to address what it has described as a "scarcity" of domestic solar manufacturing in the continent. The strategy commits to a continuation, through the Horizon Europe programme, of support for research and innovation into solar technologies, specifically referencing heterojunction cells, perovskites and tandem cells. In terms of commercial manufacturing, much of the strategy's focus is on supply chain resilience, speaking of the need for more prevalent and sources of materials such as silicon metal and polysilicon, as well as components including ingots, wafers and cells. The strategy describes the European Union as a "small actor in several critical manufacturing and assembly steps" in the solar value chain. It will also see the creation of an EU Solar PV Industry Alliance, launched on the back of the European Solar Initiative and its objective of establishing 20GW of solar PV manufacturing in Europe by 2025. A framework for coordinating on areas such as innovation and technology, supply chain, finance, regulation and skills will be developed, with the alliance intending to map the availability of financial support for the industry. The strategy does however point to existing mechanisms, such as InvestEU, the EU Innovation Fund and financing through the bloc's recovery and resilience and cohesion policy funds which can support manufacturing investment in Europe. Guidance for permitting procedures relevant to manufacturing facilities will also be produced by the EC.

ESMC launches EU-wide project for solar manufacturing

The European Solar Manufacturing Council (ESMC) has launched an Important Project of Common European Interest (IPCEI) for PV aimed at mobilising EU member states' support for breakthrough solar manufacturing technologies and aiding their commercialisation. The ESMC said it supported "the other initiatives presented in the EU Solar Energy Strategy," which has been well received by Europe's solar sector, "including the establishment of the EU Solar PV Industry Alliance, which will map the availability of financial support, attract private investment and facilitate dialogue and matchmaking between producers and offtakers". It also said the IPCEI-PV framework was designed to "ensure the long-term competitiveness of the European PV manufacturing industry by mobilising EU member states support for the innovative and breakthrough PV technologies".

Maxeon, Canadian Solar settle patent infringement suit in Japan

Solar module suppliers Maxeon Solar Technologies and Canadian Solar have settled an agreement on a patent infringement lawsuit in Japan. The terms of the agreement will see Canadian Solar withdraw any challenges to Maxeon's patent on shingled solar cell modules (Japan Patent No. JP6642841B2) and cease to sell shingled solar cell modules in Japan until the second quarter of 2025. It will, however, complete pending orders in 2022. Maxeon filed a patent lawsuit action against Canadian Solar back in 2020 for a patent it had retained after its spinoff from SunPower, but still retained the use of SunPower's brand, who had acquired Cogenra Solar in 2015; the company which developed the panels' architecture and manufacturing processes and was later sold under the 'SunPower Performance' brand.

Solaria, Canadian Solar settle shingled PV patent dispute

US solar manufacturer Solaria has settled patent infringement claims against Canadian Solar after winning a US International Trade Commission (ITC) ruling. Under the terms of the agreement, Canadian Solar has agreed to stop importing shingled solar modules to the US while Solaria will terminate its litigations against the module manufacturer after the ITC ruled in favour of Solaria in October 2021. The suit started after Canadian Solar "ignored" and violated Solaria's core intellectual property for two patents, said Tony Alvarez, CEO at Solaria. Canadian Solar will stop importing shingled PV modules into the US for seven years.

EFFICIENCY AND PERFORMANCE

LONGi claims new p-type heterojunction cell efficiency record of 25.47%

Solar manufacturer LONGi has laid claim to a new cell efficiency record for a gallium-doped p-type heterojunction PV cell. The 'Solar Module Super League' (SMSL) member said it had recorded a cell conversion efficiency of 25.47% using an M6 (274.3cm2) full-size cell, produced using mass production processes and monocrystalline silicon wafers. The efficiency was validated in testing conducted by the Institute for Solar Energy Research in Hamelin (ISFH). LONGi said the company's R&D team developed the p-type wafer processing solution for heterojunction cells and combined it with an interface passivation technology to achieve an open circuit voltage (Voc) of 747.6 mV. Furthermore, LONGi said that it did not regard processing techniques applied in this record to have been fully optimised, suggesting that the conversion efficiency could be pushed further.

Fraunhofer ISE claims 47.6% solar cell efficiency record

Researchers at the Fraunhofer Institute for Solar Energy Systems (ISE) have laid claim to a new solar cell efficiency record of 47.6%. Researchers said the efficiency for a four-junction cell had been increased from 46.1% to 47.6% at a concentration of 665 suns, thanks to improvements in a four-layer antireflection coating applied to the tandem cell structure. This reduced resistance losses and the reflection on the front side of the cell. The layer structure of this solar cell was developed back in 2016 alongside French semiconductor manufacturer Soitec, with the upper tandem solar cell made of gallium indium phosphide (GaInP) and aluminium gallium arsenide (AlGaAs), attached to a lower tandem solar cell made of gallium indium arsenide phosphide (GaInAsP) and gallium indium arsenide (GaInAs). Conventional solar cells made of silicon can only absorb sunlight up to a wavelength of 1200 nanometres but Fraunhofer ISE's record-breaking solar cell managed to expand the broad range up to 1780 nanometres.

JinkoSolar lays claim to new n-type cell efficiency record of 25.7%

JinkoSolar has laid claim to a new conversion efficiency record for a monocrystalline TOPCon solar cell of 25.7%. The record, independently confirmed by the National Institute of Metrology in China, was achieved using a 182mm n-type monocrystalline cell fabricated using a high-quality Czochralski mono-SI substrate. The cell used a number of techniques in its manufacture, including high temperature gettering, advanced diffusion, semi-transparent metallisation and JinkoSolar's own HOT technologies. A series of other, undisclosed material upgrades were also integrated into the cell process. At 25.7%, the cell's conversion efficiency is 0.3 percentage points higher than the previous record of 25.4%, JinkoSolar said.

Maxwell, Cybrid use light conversion film to boost HJT module power output

Solar cell production equipment supplier Suzhou Maxwell Technologies has increased the power of a 60-cell heterojunction (HJT) module by more than 5W thanks to the addition of a light conversion film. Through a collaboration with PV backsheet manufacturer Cybrid Technologies, Maxwell has developed a new module featuring a film that converts ultraviolet light with a low photon response for HJT solar cells into blue or red light with a higher photon response, thereby increasing the power. According to Maxwell, the current of HJT cells is lower than that of ordinary ones because the transparent conducting oxide (TCO) film and the amorphous silicon film absorb ultraviolet rays. Its new innovation aims to make up for this shortcoming. The company said that for HJT technology, light conversion materials absorb ultraviolet light and convert it into visible light with nearly 100% responsivity, boosting the current of solar cells and enhancing the power of modules, while the converted photons have no negative impact on the interface passivation of HJT products.

COLLABORATION

SunPower, First Solar in late-stage discussions to develop 'world changing' residential solar module

US residential solar installer SunPower is in late-stage discussions with US thin film manufacturer First Solar to develop the "world's most advanced residential solar panel", its CEO Peter Faricy revealed during an analyst day presentation that also set out the company's new strategy. The module will employ a dual technology approach, with First Solar's thin film technology sitting atop a layer of crystalline silicon cells, Faricy said, adding that if completed as envisioned it would be "the most technically advanced residential solar panel in history". First Solar would manufacturer the module with SunPower becoming the exclusive provider. All going well, the product could become available within two years. Faricy said the module had the potential to make a big difference in terms of efficiency, durability and value for consumers, who previously were unable to access First Solar's products as they were exclusive to the commercial and industrial (C&I) market. "We anticipate that it will significantly raise the bar for solar module efficiency and aesthetics," said SunPower's chief products officer Nate Coleman.

European solar manufacturing start-up Carbon enlists ISC Konstanz as technology partner

European solar manufacturing start-up Carbon has partnered with the International Solar Energy Research Center (ISC) Konstanz as it pursues a multi-gigawatt cell manufacturing facility in Europe. A technology agreement signed by the companies will see ISC Konstanz take responsibility for the technology choices taken by Carbon and design the initial steps of its manufacturing processes. It follows Carbon bringing on board French industrial group ACI as one of its founding shareholders in a deal that will see ACI act as an "industrial facilitator". Radovan Kopecek, co-founder and director at ISC Konstanz, said that the need for a competitive solar manufacturing scene in Europe has "never been more important than now". "We believe that TOPCon Technology is the first step towards European industry renaissance, and we work hard already on the next evolutions," Kopecek added.

Saule Technologies signs perovskite partnership with Google Cloud

Perovskite-based PV manufacturer Saule Technologies is partnering with Google Cloud and renewables company Columbus Energy to advance its technology. Google Cloud will become a strategic partner of both Polish companies, providing cloud computing services and technologies, as they plan to cooperate on Internet of Things (IoT) products and the development of distributed energy solutions. Saule Technologies has created lightweight and thin perovskite solar cells that it said perform well in artificial light, making them suitable for a range of IoT devices "in virtually all conditions, regardless of power grid availability". The company recently achieved a 25.5% cell efficiency for IoT applications.

INVESTMENT

Tandem PV raises US$6m to build Californian manufacturing facility

US perovskite company Tandem PV has closed on the first half of a US$12 million Series A raise after raising US$6 million for building a pilot manufacturing facility in its headquarters of San Jose, California. US-focused Tandem PV will use this investment to manufacture its first commercial grade tandem solar panels intended to equip customers with more efficient and affordable solar energy. The company specialises in 'ultra-high-efficiency' tandem metal-halide perovskite solar panels. It changes silicon solar panels into high-efficiency tandems by leveraging perovskite-coated front glass via a drop-in manufacturing replacement. Tandem PV was co-founded by materials science PhD Colin Bailie, who developed the design during his time at Stanford University, and solar industry stalwart and former CTO of Hanwha Solar Chris Eberspacher.

NexWafe working on technology development after closing Series C funding round

Solar wafer producer NexWafe has completed its Series C investment round, with proceeds earmarked for product and technology development on prototype lines in Germany. Having secured the backing of Indian conglomerate Reliance Industries in the first phase of the funding round in 2021, NexWafe bagged an additional €7 million (US$7.5 million) in the second phase, taking the total raised in the round to €39 million. The second close was led by an unidentified German family office and included participation from investment group Ecosummit. Germany-based NexWafe is developing monocrystalline silicon wafers grown directly from a feedstock gas through its EpiWafer process, which avoids intermediate steps such as polysilicon production and ingot pulling.

NGK Insulators invests in Kyoto University solar perovskite spin-off

Battery storage manufacturer NGK Insulators has invested in EneCoat Technologies, a spin-out of Kyoto University involved in the development of of perovskite solar cells. EneCoat is developing perovskites with a greater power generation efficiency and durability while at the same time establishing manufacturing process for larger scale projects. NGK's investment will also seek to establish production technologies that could help improve the quality of perovskite solar cells, with the company keen to explore ways of integrating the cells with its own battery energy storage products.

Product reviews

Fab & Facilities: **Kontron AIS**

PV manufacturers can secure quality, optimise processes and save costs using FabEagle MES solution by Kontron AIS

Product outline: Kontron AIS is supporting PV manufacturers with a standardised Manufacturing Execution System (MES) for production control, material track and trace and equipment performance tracking, covering all processes from crystal growing over wafer and solar cell production to module assembly. The MES has proven its ability to secure quality, optimise manufacturing processes and save costs across the PV industry for over 15 years.

Problem: The challenge is to integrate an MES system which allows a PV manufacturer to closely control every step of the value chain. This requires a full vertically integration of manufacturing processes such as crystal growing, wafering, solar cell processing and solar module assembly.

Manufacturers install such MES to achieve traceability for all products from raw silicon through crystal, ingot, wafer, solar cell up to the finished solar module. The goal is to keep track of all transactions and operations to determine precisely what was done to the product, when was it processed, at which equipment and under which conditions.

Solution: Process and equipment data acquisition is conducted using various standard compliant equipment interfaces like SECS/GEM, PV2, XML, OPC-UA and S7. These interfaces are used to reliably communicate the equipment state, material movement, process parameter and equipment data.

Material and carrier interlock commands are used to prevent material mishandling and to enforce the orderly execution of the steps in work plans. Product yield is improved, and scrap reduced by enforcing the execution of the work plan and tightly controlling and monitoring manual and automatic material processing.

Material tracking and tracing data ensures besides correct inventory data and end-to-end backward and forward genealogy. Backward tracking starts from the finished solar module relating it back to solar cells, wafers, ingot, crystal, raw silicon, and related consumables to build a module. Forward tracking starts from raw silicon tracking it to all the finished solar modules that were produced using a certain silicon lot.

Real-time connection to the ERP system is used to continuously exchange master data, work orders, production progress and quality information to keep track of semi-finished and finished product inventory and the associated consumption of raw material and consumables.

The acquired equipment data is used to calculate KPIs like OEE. This allows closely monitoring and improving equipment performance.

Applications: Crystal growing (e.g. Czochralski process) including silicon commissioning with recipe handling, different raw silicon types, dopant, seeds, crucible, hot zone part tracking, re-charge scenarios, multiple crystal unloads, scrap handling, manual data collection, yield and inventory tracking, cropping, automatic and manual lifetime, resistivity measurement, tracking of cropped parts and scrap recycling of silicon including etching, sorting.

Wafering processes including inspection, mounting, squaring, chamfering, slicing, singulation, pre- and final cleaning, classification and sorting.

Solar cell processing, batch and single wafer processes including texturing, diffusion, CVD, PVD, PECVD, printing, classification and sorting, transport system tracking, virtual wafer tracking and consumable tracking.

Solar module assembly processes including glass washing, stringing, matrix layup, inspection and rework, lamination, framing, junction box mount, flashing and palletizing.

Platform: Integrates seamlessly in local IT infrastructure or public cloud environments.

Availability: Available worldwide now.

Fab & Facilities: **Pfeiffer Vacuum HiPace**

Pfeiffer Vacuum HiPace Turbopumps combines high performance with reliability

Product outline: The Pfeiffer Vacuum HiPace-I series turbo molecular vacuum pump has been developed specially for the ion implantation process with the goal of increasing the lifetime at the harshest of such ion implantation processes.

Problem: Nowadays, the ion implantation process is inevitable for modern micro device fabrication. This process requires high vacuum which can only be provided with high performance turbomolecular vacuum pumps. In the source chamber of the ion implantation tool, several process gases will be inserted which causes considerable byproduct accumulation inside the turbopump. Due to the byproduct accumulation, the lifetime of the turbopump is threatened.

Solution: The Pfeiffer Vacuum HiPace-I series combines performance with reliability due to a new coating nickel coating technology. The revolutionary rotor design also provides good compression ratio for light gases such as He and H2 without any use of a drag (Holweck) stage. The abandonment of the drag stage provides a bigger gap between the rotor and the housing and avoids pump failure due to the accumulation of byproducts.

The HiPace-I series can be also equipped with specially developed accessories for the implanter processes such as a heating jacket in combination of temperature monitoring system (TMS) and sealing gas monitoring system.

Applications: HiPace-I series can be used for the source and beamline chamber of the implantation tool. For the use at the source chamber, a heated pump version is recommended.

Platforms: HiPace-I series is available in several sizes for the pumping speed between 1200 and 2800 l/s l in ISO-F, ISO-K and ISO-CF flange types.

Pumping speed class	Implant Standard	Implant Heated
1200 l/s	HiPace 1200 I	HiPace 1200 IT
1500 l/s	HiPace 1500 I	HiPace 1500 IT
1800 l/s	HiPace 1800 I	HiPace 1800 IT
2300 l/s	HiPace 2300 I	HiPace 2300 IT
2800 l/s	HiPace 2800 I	HiPace 2800 IT

Availability: Available worldwide now.

Vertical integrated PV production for an independent and speedy energy transition

Fırat Es[1], Güven Korkmaz[1], Kübra Çelen[1], Özlem Coşkun[1], Joris Libal[2] & Radovan Kopecek[2]

[1]Kalyon PV Research and Development Center, Kalyon Gunes Teknolojileri Uretim A.S., Ankara, Turkey; [2]ISC Konstanz, Konstanz, Germany

Abstract

PV energy production is becoming more widespread in all societies as a result of the decreasing price of PV systems due to technological improvements in PV cell and module production. Kalyon PV, located in Ankara, Turkey, is a special type of PV producer because of its implementation, under one roof, of vertical integration manufacturing outside of China, from ingot processing to module fabrication. Furthermore, Kalyon PV is more accessible to European countries than Asian PV producers, which is essential these days with the high cost of transportation and the risk of shipment delays. A vertically integrated factory concept, consisting of ingot, wafer, cell and module production, allows changes to be made to production lines, as well as adaptations to innovations in solar cell structures, in order to keep up with market trends more easily. Not only that, production under one roof contributes significantly to reducing production cost by eliminating some sub-steps, such as transportation. In this paper, all the steps in Kalyon PV's vertical production are described, and a cost of ownership (COO) analysis is performed for passivated emitter rear contact (PERC) and advanced cell concepts.

Introduction

Nowadays, with a growing population and an increase in technological advancements, supplying enough energy to meet demand is vitally important to humankind. Up until now, fossil fuels, such as gas, oil and coal, have been the primary source of energy; in 2020, 65% of electricity production around the world depended on fossil fuels [1]. The problem here is that fossil fuels do not regenerate over a short time period, and even more of a worry is that the process of energy production using these sources is causing damage to nature, which in turn is leading to an increase in global warming effects. Additionally, the dependency on foreign sources of fossil fuels for energy production poses a strategic risk for the countries involved.

Renewable energy resources are gradually coming to the fore as an important solution to foreign dependency on energy, maintaining the balance between economic development, environment and sustainability, energy efficiency and especially energy supply security, and providing significant gains in all these issues. Renewable energy sources make a significant contribution to the economic development of a country by ensuring that the required energy is available continuously and at an affordable price.

Solar energy is a renewable energy source that has great potential for ensuring the demand for energy is met. It is clear that among renewable energy sources, solar energy is the most promising and trustworthy energy source for the great majority of countries. Solar systems have been used to produce heat and electricity generation for several decades now. PV systems which convert solar energy to electricity directly have been the focus of scientific studies for a long time, and PV systems have become commercially available and more and more feasible during the last two decades. In March 2022, the total installed power capacity of PV systems reached 1TW worldwide [2]. The rate at which PV system capacity is increasing is growing in line with technological developments. Related to these improvements, it is estimated that the newly added power capacity of PV systems per year will reach 1TW until the year 2030.

Today's PV module systems that are being used to generate electricity show differences depending on the cell technology, such as passivated emitter rear contact (PERC), interdigitated back contact (IBC) and passivated emitter rear totally diffused (PERT). PERC, which is based on p-type Si, is one of the most universal technologies among the PV solar cell types, because the production methods, which have been developed over many years, are cost effective. With prices of around €0.2/Wp for bifacial PERC modules, PV has been the 'king of energy' [3] since 2020; the lowest bid for a levelized cost of electricity (LCOE) below €0.01/kWh [4] was achieved in Saudi Arabia.

The market recently began to be dominated by limited supply rather than by demand, and it was not long before PV entered a poly-Si crisis, similar to the one in 2005, but at a completely different capacity level. In addition, the Covid 19 crisis, with some production interruptions, even shutdowns, and a tenfold increase in transportation costs from China, changed the PV market completely.

> "Renewable energy resources are gradually coming to the fore as an important solution to foreign dependency on energy."

Figure 1. Kalyon Karapınar – 1GW bifacial horizontal single-axis tracker (HSAT) solar power plant in Konya, Turkey.

"Kalyon PV produces PV modules at a vertically integrated factory, meaning that the production of monocrystalline silicon through to the fabrication of modules is all done under the same roof."

Already at the end of 2021, at Intersolar in Munich in October, the change in mentality of EU's energy performance certificates (EPCs) and distributers became very apparent. The hike in module prices from China of well over €0.20/Wp at that time, as well as the lack of availability of these modules for import, prompted PV system companies to show increased interest in locally produced modules.

The huge ambitions of various EU member states, such as Germany, to install 200GW of PV systems through to 2030 [5] increased the hunger for modules and the desire for security of a stable supply. Since China has a target to set up 80GW of PV systems in 2022, the US 70GW and the EU 70GW as well, a severe shortage of modules and other components is expected in the coming years.

The last straw that broke the camel's back was the start of the war in Ukraine on February 22, 2022. At a historical meeting of the German Bundestag on Sunday, February 27, 2022, it was declared that renewable energies are 'freedom energies' [6] and their deployment needs to be even more accelerated. Finally, as a consequence, since the EU wants to gain independence from gas imports from Russia, as well as from other energy imports, on March 31, 2022, Kadri Simson, the EU Commissioner for Energy, announced that the EU will do "whatever it takes" to bring back PV production to the EU [7]. By that is understood 'vertical production', starting from ingot through to module, including the supply chain of poly-Si, glass and other necessary components. At the moment, the EU Commission and member states, such as Germany and France, are in discussion with PV networks, such as ESMC, SPE, ETIP and EUREC, to understand what will be needed to set PV production up with the necessary 'critical mass' for

Figure 2. Kalyon PV vertically integrated c-Si PV factory in Ankara, Turkey

it to become cost effective and sustainable. ESMC has prepared a list for this very purpose [8], and in May 2022, the EU Commission and several member states will announce the outcome. The future for large 50–70GW vertical PV production facilities in the EU looks bright.

Those countries that are aware of the promising future of PV systems have begun studies to encourage the set-up of renewable energy production systems. The Turkish government, an advocate of the widespread use of renewable energy sources for electricity generation, launched a new project to support the PV sector, which is becoming increasingly important among renewable energy sources. Within the scope of this project, a tender process was initiated for the installation of a solar PV power plant in Karapınar in Konya, Turkey, which is a desert-type region not suitable for agriculture. The solar power plant is expected to extend over an area of approximately 19.2km^2 at final completion of the installation (Fig. 1).

Kalyon started its vertical integration activities when the Turkish Government initiated its study regarding renewable energy resources, and put in the winning bid for the tender; permission was obtained by a partner to sell the electricity produced from the power plant. After finalizing the necessary tenders and contracts, Kalyon PV started production of PV modules for the Karapınar solar power plant.

Kalyon PV, established in Ankara, Turkey, which is located between Asia and Europe, produces PV modules at a vertically integrated factory (Fig. 2), meaning that the production of monocrystalline silicon through to the fabrication of modules is all done under the same roof. At the Kalyon site, there are four factories, consisting of ingot, wafer, cell and module production lines, supported by an R&D centre located within the integrated plant. The company, which began producing modules for Karapınar in August 2020, increased its G1 production (from ingot to module) to 500MW per year in a very short time. Since the beginning of 2022, it has increased its M10 cell and module production capacity to 500MW and is expected to reach a total annual production capacity of 1GW.

The manufacturing process begins with monocrystalline silicon ingot production from polycrystalline silicon in the first factory containing the ingot production line, and ends with module production in the last factory. Thanks to on-site production, the total manufacturing flow duration is shorter, while the transfer process between intermediate steps is eliminated. On top of these benefits, the integrated factory concept adopted by Kalyon PV also makes it possible and easier to keep up with new technological advances in the solar cell field. Kalyon PV's R&D centre activities carried out on the ingot, wafer, cell and module lines are based around production optimization and improvement, cost reduction and high-efficiency production studies.

First factory: ingot production line

For the production of monocrystalline ingots from 9N pure polycrystalline silicon, 72 Czochralski (CZ) furnaces are used (Figs. 3 and 4).

The fact that ingots used in wafer production have been produced directly in the factory on site brings the flexibility of producing wafers of various sizes and types. By optimizing the production parameters – pulling rate, temperature, rotating rates, etc. – the furnaces used in ingot production are also suitable for pulling ingots of different diameters. Controlling the doping process in ingot

Figure 3. Ingot factory at the Kalyon PV integrated facility.

Figure 4. Poly-Si to ingot growth using the CZ technique.

> "The fact that ingots used in wafer production have been produced directly in the factory on site brings the flexibility of producing wafers of various sizes and types."

production also enables the production of solar cells of different technologies.

Detailed investigations of creating ingots with Ga dopants for preventing light-induced degradation (LID) effects in PV modules, and n-type ingot production studies for future technologies, such as IBC solar cells, are ongoing in parallel with mass production. Since ingot production is carried out in the integrated factory, the facility can easily adapt to changing trends in cell size and type, depending on the extendable capacity of the ingot production line, with 24 free areas for furnace assembly.

Kalyon PV can supply ingots of size G1 and M10 in mass production. At the beginning of ingot production, B-doped p-type G1-sized ingots were produced, but today M10-sized ingot production is ramping up. As part of the R&D studies, Ga-, P-, and B-doped ingots of various types are produced on a large scale. Additionally, the diameters of the produced ingots can be modified from G1 to M6 sizes by changing the furnace variables. The created ingots are analysed to ensure they are of sufficient high quality for wafer production. According to the quality test results, ingot cutting steps are scheduled in order to eliminate the low-quality parts of the ingots.

Second factory: wafer production line

The wafer-slicing process includes two sub-steps, namely cutting ingots into bricks and slicing bricks into wafers. First, ingots that have passed the quality control tests are transferred to the wafer production line for cutting into bricks of equal length, which are then cropped to obtain a square section based on desired cell dimension. Second, the bricks are sliced into wafers, with their thickness being controlled by adjusting the distance between the diamond-coated cutting wires.

The ingot and R&D departments are working on increasing the wafer production yield and structural quality of the wafers, and decreasing the kerf loss during the wafer-slicing process. The produced wafers are classified depending on wafer quality tests, such as lifetime measurement, thickness control and total thickness variation (TTV). After these classifications, the wafers which demonstrate the best qualities are dispatched to the cell production line.

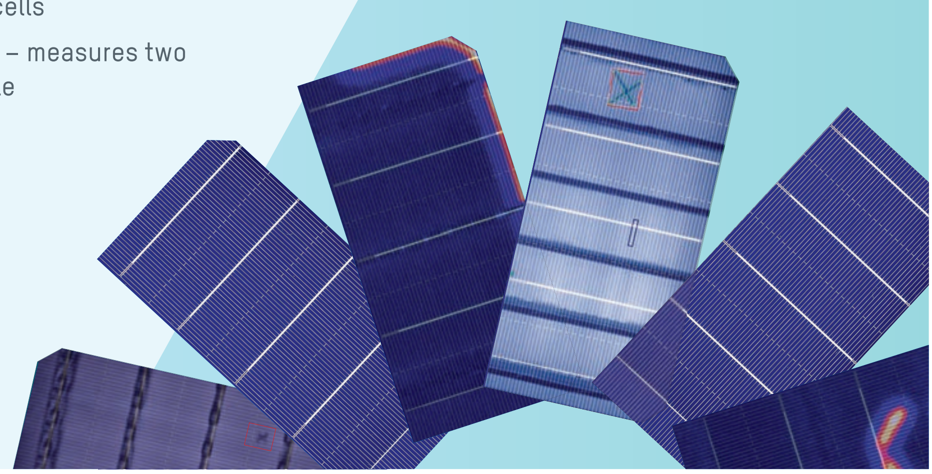

Figure 5. Clean room for bifacial mono-perc production (G1 line).

Third factory: cell production line

High-quality wafers from the second factory arrive at the cell production line for transformation into solar cells. Kalyon PV's cell factory consists of two mass-production lines, one for G1-sized bifacial PERC solar cells and the other for M10 versions. G1 solar cells with a minimum 22% efficiency and 70% bifaciality are being mass produced on the production line, with a daily throughput of more than 300,000 cells (Fig. 5).

The cell production line and the R&D departments have been studying ways to improve the efficiency, bifaciality, stability and lifetime of PERC solar cells. In addition to the performance

"A supervisory control and data acquisition (SCADA) centre, designed to cover all four factories, is currently at the installation stage."

Figure 6. Quality inspection after the stringing process in the module factory.

Figure 7. COO of PERC, TOPCon and low-cost IBC cells (a) and corresponding modules (b).

enhancement projects, cell production cost-reduction studies, such as decreasing the amount of Ag paste used, are managed. The R&D department has also been collaborating with national and international companies and institutes to keep up to date with new market trends in the solar cell field.

Fourth factory: module production line

Cells are subjected to a very rigorous quality control process after production and are divided into more than a hundred bins, depending on many factors, such as electrical parameters and colour. Cells displaying the same characteristics are transferred to the module section in one batch, thus ensuring that each module consists of matching cells. Kalyon PV modules are fabricated from 144 half-cells using half-cut solar cell technology (Fig. 6).

Glass–glass and glass–transparent backsheet modules, with and without aluminium frames, are constructed from G1 and M10 cells. Up until the lamination stage, the modules go through very meticulous electroluminescence (EL), *I–V* and visual checks, because there is no turning back after lamination. After the lamination phase is completed, the modules that pass a detailed characterization are packaged and sent to solar panel plants.

The R&D department, along with the module production department, is undertaking projects to investigate ways to increase the lifetime and power of the modules while also improving their stability. Besides these studies, the R&D department also manages sub-projects that include trials of new materials, such as backsheet, glass, frame and encapsulant, ordered from other companies, in order to develop the range of products. The R&D team is also conducting preliminary studies on flexible module structures that can be assembled on surfaces having different slopes.

The Kalyon PV integrated factory is endeavouring to invest in the industry 4.0 concept through different strategies. All the production parameters and measurement results at every stage, from ingot processing to module fabrication, are recorded by manufacturing execution system (MES) databases, whereby instant monitoring of the production can be carried out. Moreover, several research projects using big data analysis are under way; the data related to the production is continuously analysed using statistical methods, and production, quality and yield estimations are conducted. Additionally, a supervisory control and data acquisition (SCADA) centre, designed to cover all four factories, is currently at the installation stage, and will allow remote control of the production chain. The operating status, efficiency and product features of the systems will be controlled from the centre, and interventions can be made if necessary.

The value chain of Kalyon PV starts with ingot poly-Si and ends with module production. The PV module cost depends on lots of parameters, and the integrated factory concept also incurs many expenses. Depending on the reduced production cost, there is no doubt that, because of its rapid adaptation to new technologies, as well as the easy transportation due to its geographical location, Kalyon PV is showing itself to be a promising supplier for the EU solar market.

COO of PV production outside of China

The cost of PV production today is heavily dependent on the poly-Si price, which is still going up during the poly-Si crisis but that should abate by the end of 2022. The transportation costs from China are still at €0.03–0.04/Wp (container price of €15k), and experts believe that they will remain at least €0.02/Wp. Even though PERC solar cells are approaching their limit with regard to efficiency, the technology's cost of ownership (COO) can still be reduced through economy of scale and enhanced productivity (faster throughput and increased yield). It is believed that the M10 format will be the winner in terms of size for several reasons, mostly because of the optimum packing properties of modules consisting of M10-sized cells in containers.

Fig. 7 summarizes the COO for three different technologies for a 5GW production in the EU and a future silicon poly-Si price of €14/kg and a silver paste price of €650/kg (PERC: 170mg/cell; TOPCon: 260mg/cell; IBC: 265mg/cell).

The COO for all cells still depends mainly on the wafer and metal paste cost, but, even for the EU, the module costs can reach values of €0.22–0.26/Wp for all three of the most prominent standard high-temperature technologies. PERC will continue to dominate in the next five years; however, in the future, n-type technologies will start to gain a significant market share, as their efficiency potential has not yet been reached and because n-type has also several advantages in terms of lower degradation and lower temperature coefficient. With its ability to control the entire production chain, Kalyon PV is also considering upgrading the G1 cell and module lines to a high-efficiency n-type facility to meet the needs of the European and US residential rooftop markets. Studies are ongoing for the feasibility of such an upgrade at the beginning of 2023.

As the largest bifacial PV manufacturer in Europe, Kalyon PV invites readers to the bifiPV 2022 workshop to be held at Kalyon at the end of 2022 and share in the latest developments in bifacial PV technology, and to visit its vertical integrated factory for bifacial PERC technology.

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5th (2022) International Hydrogen and Fuel Cell Technology, Equipment and Application Conference & Exhibition

According to the anti-epidemic measures in Shanghai, SNEC PV POWER EXPO, originally scheduled on 24-26 May 2022, is now postponed to December 27-29, 2022.

SNEC
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December 27-29, 2022
Shanghai New Int'l Expo Center
(2345 Longyang Road, Pudong District, Shanghai, China)

http://www.snec.org.cn

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About the Authors

Dr. Fırat Es is an R&D manager and currently the head of the R&D Center at the Kalyon PV integrated production factory. After completing his undergraduate and graduate education in the physics department at METU, he went on to receive his Ph.D. in the micro and nanotechnology department. He has 13 years of experience in the field of crystalline silicon semiconductors and PV, and played leading roles in the installation stages of METU GÜNAM PV's clean room and PV pilot production line (GPVL), and Kalyon PV's integrated factory.

Dr. Güven Korkmaz joined Kalyon PV in June 2020 as an R&D researcher, and is currently an ingot, wafer and cell production supervisor at the R&D Center. He received his B.S. in 2006, and his master's in 2010 in physics from Anadolu University. He completed his Ph.D. studies on the growth of GaAs/AlGaAs quantum well structures via the MBE system and the optoelectronic characterizations of these structures, which were used for THz detection in 2017 at Anadolu University.

Kübra Çelen graduated from Bursa Technical University in metallurgical and materials engineering. She received her master's from Hacettepe University in nanotechnology and nanomedicine. During her master's studies, she was a member of the Superconductivity and Nanotechnology Research Laboratory at Hacettepe University and worked on alternative absorber layer materials for thin-film solar cells via vacuum systems. She has been an R&D engineer at Kalyon PV since February 2022.

Özlem Coşkun received her bachelor's degree in metallurgical and materials engineering from Gazi University and her master's in micro- and nanotechnology from TOBB University of Economics and Technology. For her master's, she studied improvements to electron- and hole-transport layers for tandem perovskite photo-electrochemical solar cells. She was also a group member of the Laboratory of Energy Research and worked on thin-film solar cells. She joined Kalyon PV as an R&D Engineer in February 2022.

Dr. Radovan Kopecek obtained his Diploma in physics at the University of Stuttgart in 1998. He also studied at Portland State University (Oregon, USA), where he obtained a master's in 1995. In 2002 he finalized his Ph.D. dissertation at the University of Konstanz and was a group leader there until the end of 2006. One of the founders of ISC Konstanz, he has been working at the institute as a full-time manager and researcher since 2007 and is currently the head of the Advanced Solar Cells department.

Dr. Joris Libal received his Diploma in physics from the University of Tübingen, and his Ph.D. on the topic of n-type crystalline silicon solar cells from the University of Konstanz. He has been involved in R&D along the entire value chain of crystalline silicon PV in the past, and joined the ISC in 2012. He is currently an R&D project manager, working on technology transfer and cost calculations in the areas of high-efficiency n-type solar cells and innovative module technology, as well as on ISC's activities in energy yield simulations.

Enquiries

Fırat Es
Research and Development Center
Kalyon Gunes Teknolojileri Uretim A.S.
06909 Ankara, Turkey

Tel: +90 444 6 559 (444 6 KLY)
Email: fes@kalyonpv.com
Website: www.kalyonpv.com

TOPCon – On the way to industrial maturity

Jochen Rentsch, Tobias Fellmeth, Sebastian Mack, Bishal Kafle, Sebastian Nold, Baljeet Goraya, Andreas Wolf, Sven Kluska & Ralf Preu, Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany

Abstract

The tunneling oxide passivating contact (TOPCon) solar cell concept is one of the most promising ways to realize carrier-selective contacts, as it offers an evolutionary upgrade to today's mainstream PERC. Currently, the PV industry is looking into different technologically feasible options for transferring this cell concept from laboratory research to industrial manufacturing. This paper gives an overview of the technological maturity of various TOPCon approaches with the goal of achieving the most cost-effective, resource-conserving and mass-production-capable implementation.

Introduction

The time required for new processes or process chains to transition from a successful laboratory demonstration to industrial mass production has been steadily reduced in the last 30 years.

"An accelerated transition of many production lines based on PERC technology to TOPCon can be expected in the coming years."

While it took considerably more than 10 years for a successful transfer of the passivated emitter and rear cell (PERC) concept to industrial production, solar cell concepts with passivating contacts, such as tunnel oxide passivating contact (TOPCon), have required less than five years between the demonstration of the principal potential in the laboratory to mass production capability (see Fig. 1).

As a result of this rapid development and the enormous expansion of (PERC-based) production capacities in recent years to currently more than 200GWp worldwide, an accelerated transition of many production lines based on PERC technology to TOPCon can be expected in the coming years. For this changeover to happen, various process routes are currently still being evaluated with regard to their suitability for the most cost-efficient, resource-conserving and mass-production-capable implementation possible. This

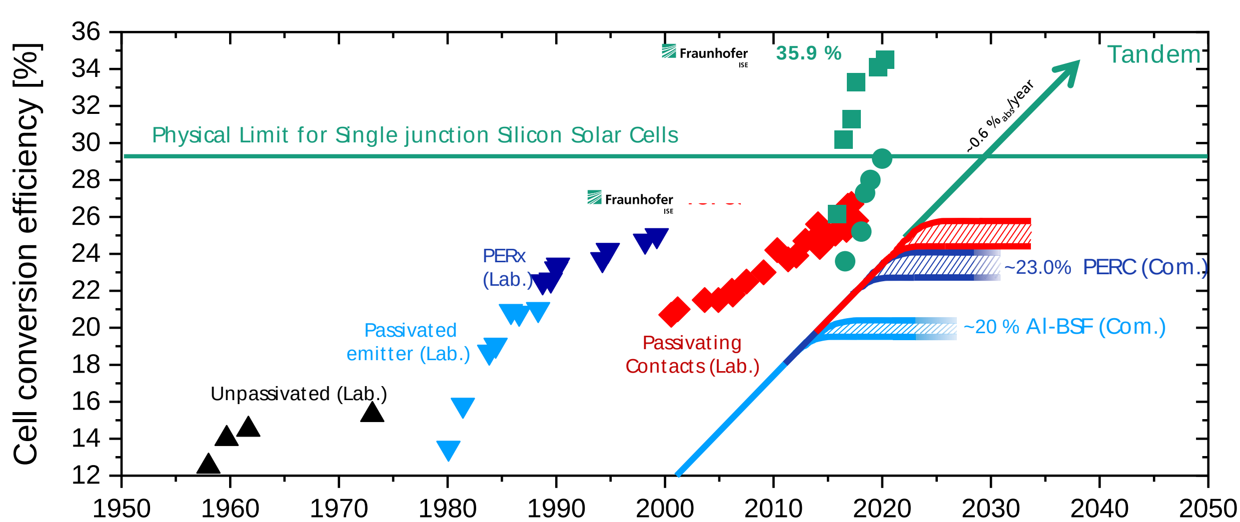

Figure 1. Evolution of laboratory and commercial solar cell conversion efficiencies. From PERC laboratory record cells to volume mass production, it took about ten years, while for TOPCon this time frame has already shortened to less than five years. (Graph adapted and extended from M. Hermle, ETIP PV Conference, Brussels (2017).)

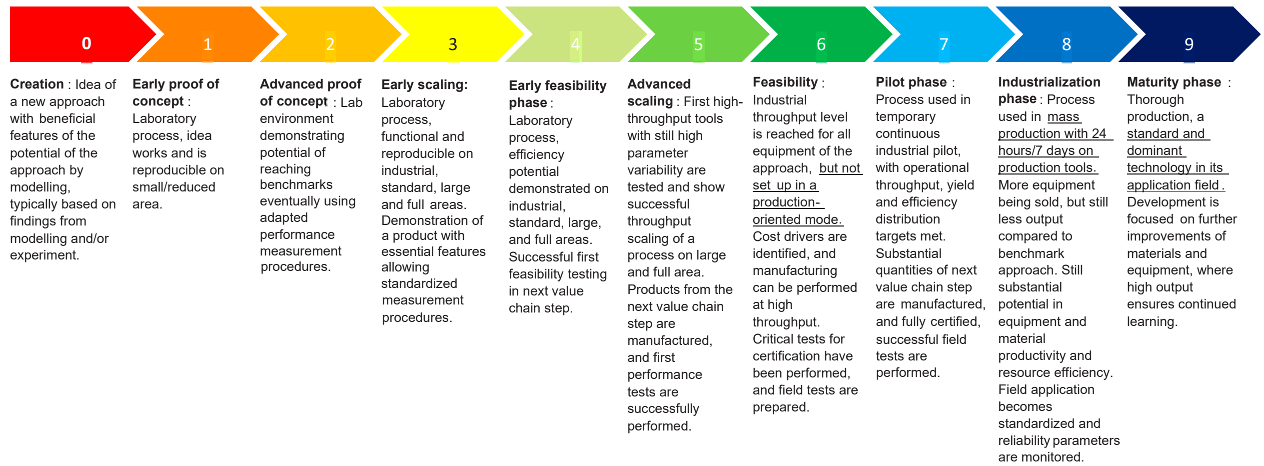

Figure 2. Technology readiness level (TRL) definition (adapted and extended from Baliozian et al. [1]) for assessing technological maturity.

paper presents the different process options and solar cell concepts and evaluates them with respect to their technological maturity.

Approach for assessing technological maturity

For the purpose of assessing the maturity of different PV technologies, Fraunhofer ISE has introduced a technology readiness scale for internal use that consists of ten different levels (gates) [1]. In comparison to earlier definitions by NASA [2] or the European Commission [3], Fraunhofer's scale is more quantitative and uses important selected parameters, namely area and conversion efficiency of the device as well as throughput (i.e. number of devices produced per unit time of production). Further, the definitions of these levels can be integrated into road-mapping in order to obtain better future projections. Fig. 2 shows the different technology readiness levels (TRL), or gates, used for the analysis in this work.

Principal process flow and upgradability from existing PERC production lines

Currently, the industrial version of the front-junction TOPCon cells on n-type c-Si, referred to as the *industrial TOPCon* (i-TOPCon) cell [4,5], is widely seen as the potential evolutionary upgrade to the incumbent p-PERC cells. The i-TOPCon cell design envisions a process route that benefits from processing similar to that for a PERC cell, thus requiring integration of only few additional process steps in the cell process chain. The cell architecture is reported to yield high efficiencies of greater than 24.0% in volume production [6] by leading cell manufacturers, with record efficiency claims of up to 25.5% on industrial wafers of sizes up to 210 × 210mm [7–9].

Fig. 3 summarizes the typical process steps used in creating an i-TOPCon cell. Note that the process flow is non-exhaustive and various process routes and a wide range of technology options for the TOPCon concept are currently under consideration by the PV industry in terms of both their technological and their economic viability. The process flow is largely dictated by the choice of the tunnel oxide (TO) formation and the amorphous (a-Si) or poly-silicon (poly-Si) layer deposition technology, and depends on whether the a-Si or poly-Si layers are doped in situ or require a subsequent external doping process. If technologically feasible, two or more process steps are combined within a single tool to ensure a lean process flow.

As a rule, boron doping is performed using a tube diffusion process to form the p^+ emitter on a textured n-type c-Si substrate. This is followed by an inline wet-chemical process for single-sided removal of the rear-side emitter. During emitter removal, the borosilicate glass (BSG) layer is usually kept intact at the front to act as a barrier against wet or dry chemicals, which are used later during wrap-around removal of the parasitic a-Si or poly-Si layer at the front side. Typically, a wet-chemical, UV light, plasma or thermal process then forms a thin TO layer at the rear surface, followed by deposition of the Si layer [10]. In some cases, the TO formation and Si layer deposition might be performed in situ in one process using a single tool.

The deposited Si layer itself might be intrinsic (nominally undoped) or phosphorus doped in situ. *Intrinsic layers* require a successive doping process ex situ, conventionally performed in a $POCl_3$-based tube furnace process that simultaneously also crystallizes the Si layer to form a fully crystalline poly-Si layer. For *phosphorus-doped in situ layers*, crystallization is achieved by a thermal annealing step. If single-sided poly-Si deposition is not warranted, a wrap-around removal process is required to remove unwanted poly-Si residuals on the textured front side. The wrap-around removal is normally performed using a wet-chemical process [10], although a dry alternative was reported recently [11]. In both cases, the remaining BSG layer on the front side serves as an etch barrier and is subsequently removed, typically in a wet-chemical process.

The next steps are dielectric surface passivation and anti-reflective coating (ARC) of the front and rear sides and a hydrogenation stage, which aims to improve the passivation property of the TOPCon structure. In an industrial scenario, the latter is generally performed by depositing hydrogen-rich dielectrics, for example an amorphous silicon nitride layer (a-SiN_x:H) by plasma-enhanced chemical vapour deposition (PECVD), which act as an efficient hydrogen source during the contact-firing step. Front and rear metallization is typically achieved by using screen-printed Ag-based pastes, followed by a fast-firing process to form the external contacts. This process yields a bifacial cell structure, as shown in Fig. 3(e).

Solar cell concepts based on TOPCon device features

Besides the 'standard' configuration of an industrial TOPCon solar cell featuring a diffused front junction (FJ) [12], with a TRL classification of 9 in Fig. 4, there are other options for implementing passivating contacts in a device structure: as the rear emitter in a back-junction (BJ) configuration [13,14] or as both contacts of an interdigitated back-contact (IBC) solar cell [15]. Currently, the highest conversion efficiencies achieved on a laboratory scale using these architectures are 25.8% (TOPCon FJ) [13], 26.0% (TOPCon BJ) [13] and 26.1% (IBC) [15].

Among the above-mentioned cell architectures, the IBC concept offers the highest potential in terms of monofacial conversion efficiency, as both contact polarities are located at the rear of the cell.

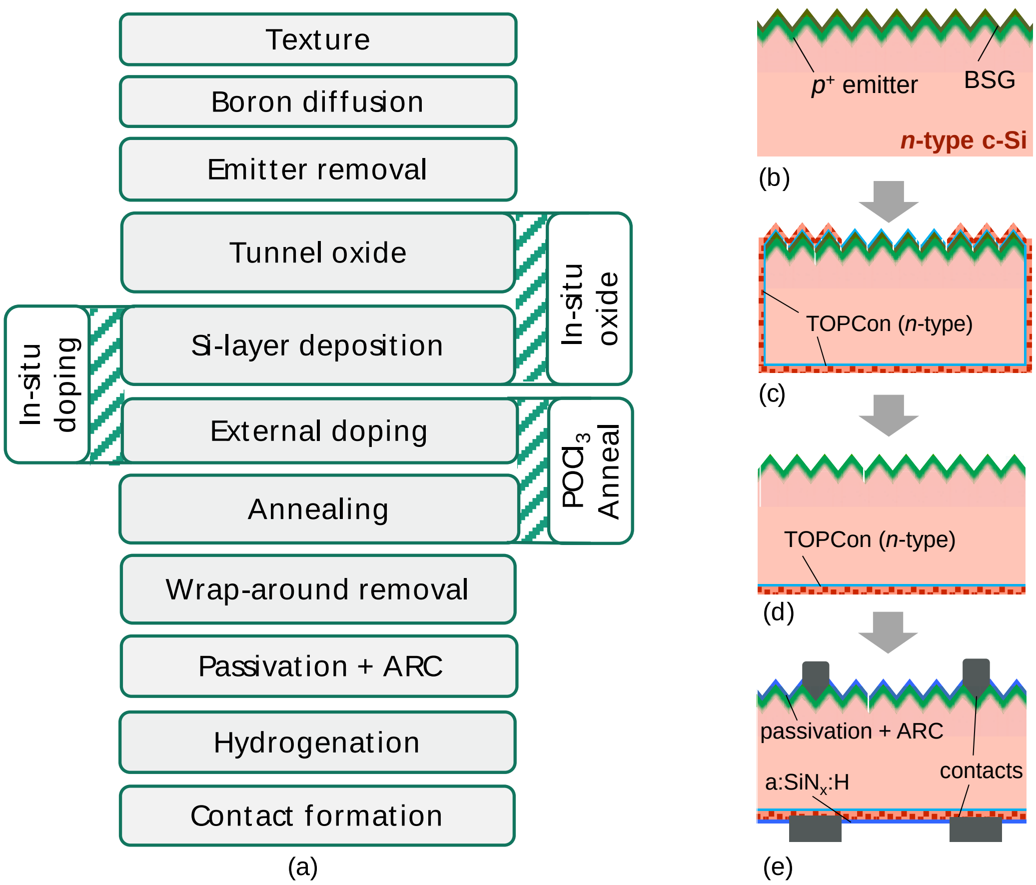

Figure 3. (a) Typical process flow for an i-TOPCon cell with the potential combination of two processes in a single process step. Schematic cross sections of cell precursors after some crucial process steps in typical TOPCon processing: (b) after texturing, boron emitter diffusion and single-sided emitter removal; (c) after TOPCon deposition, doping and annealing; (d) after wrap-around removal of poly-Si(n) at the front and the edges; (e) after dielectric layer deposition and contact formation.

However, it is also the most complex architecture for transfer to mass production, because several structuring steps are required during fabrication. Up to now, only the company SunPower/Maxeon has mastered the transition of such an IBC cell structure to industrial mass production, also demonstrating the highest efficiencies available in the market [16]. Known realizations of IBC with passivating contacts, such as the POLO IBC cell from ISFH [15], have been demonstrated on large-area industrial wafers in a laboratory environment, therefore having a designated TRL of 4 (Fig. 4).

Both-side contacted cells, on the other hand, have an additional advantage of high bifacial power gain, which is especially relevant for large-scale power plants. For the BJ cell concept (TOPCoRE), the n-TOPCon stack acts as a rear emitter on a p-type Si substrate. The main advantage of this configuration is that the whole c-Si substrate contributes to the charge-carrier transport towards the local front-side contacts, which makes a full-area highly conductive layer at the front surface obsolete, such as the full-area B diffusion in the case of the n-TOPCon cell. Consequently, the front-surface recombination can be significantly reduced. However, a localized p^{++} region is placed under the contact to limit the recombination and allow the formation of a low-ohmic contact. Since the minority carriers (here electrons) are collected at the rear junction, a high diffusion length (i.e. a high-quality base material with a diffusion length much greater than the cell thickness) is a primary requirement for the BJ concept. Additionally, the

“The IBC concept offers the highest potential in terms of monofacial conversion efficiency.

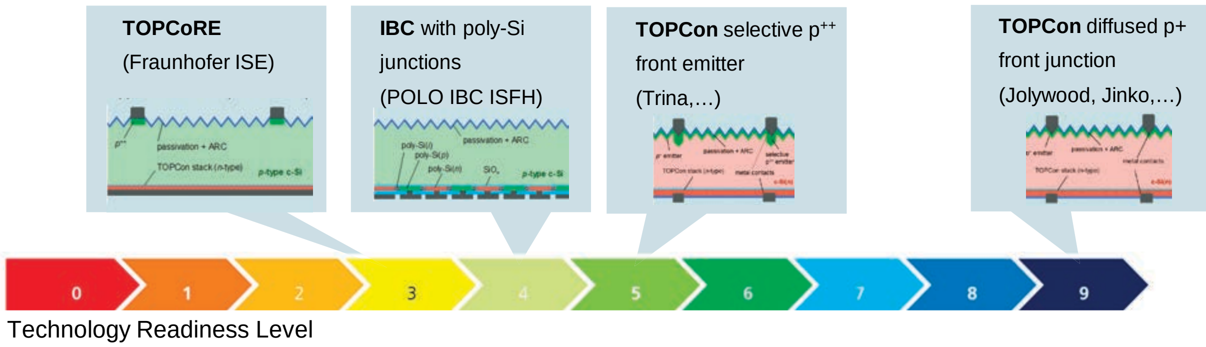

Figure 4. Different cell architectures featuring passivating contacts and their classification within the TRL scheme.

omission of a conductive front surface (p^+ front-surface field) has been found to not limit the majority transport to the front contacts unless very high resistive wafers are being used [13].

The cell architecture yielded conversion efficiencies of up to 26% in small-area devices with evaporated contacts on a laboratory scale, with a clear advantage in fill factor *FF* (more than $1\%_{abs}$) and open-circuit voltage V_{oc} (8mV) achieved by the n-type front-junction TOPCon cell. The transfer of this process to mass production is expected to encounter challenges in solving light and elevated temperature-induced degradation (LeTID), which is more critical for industrial standard p-type Cz Si than for n-type Cz Si; therefore, the overall TRL readiness of the TOPCoRE cell concept is not higher than 3 (Fig. 4).

Silicon layer deposition as the main differentiator – technical maturity of the different approaches

Typically, amorphous or partly crystalline silicon layers are first deposited and then subjected to a high-temperature step to form a poly-Si layer. Depending upon the deposition technology, the doping of poly-Si is performed either during the deposition process (in situ doping) or in a subsequent process, such as gas phase diffusion or ion implantation (ex situ). Importantly, the choice of the Si deposition technology dictates almost all the other important cell processing steps before metallization, especially based on whether the technology allows an in situ TO formation, in situ doping and a true single-sided deposition. Although several deposition methods are under investigation, most notable are chemical vapour deposition (CVD) and physical vapour deposition (PVD). CVD is performed either at low pressure (LPCVD), by means of PECVD, or at atmospheric pressure (APCVD), all using silane (SiH_4) as a silicon precursor and optionally phosphine (PH_3) or diborane (B_2H_6) as dopant gases.

LPCVD

Currently, industrial screen-printed TOPCon solar cells on n-type substrates are almost all based on LPCVD a-Si/poly-Si deposition technology, to which a TRL of 9 is assigned (see Fig. 5). LPCVD has been used as one of the important established processes in semiconductor facilities to deposit highly conformal layers of a-Si/poly-Si layers in low-pressure conditions [17]. The main advantages of this technology are:

1. Possibility of in situ TO formation by thermal oxidation.
2. Excellent thickness uniformity along the wafer and the boat in the case of intrinsic layers.
3. Pin-hole-free layers with good step coverage.
4. Large number of wafers per batch.
5. Option of in situ doping with a constant doping profile [18].

The last of the above advantages, however, still comes at the expense of reduced layer uniformity and deposition rates, and therefore lower throughput.

Some of the most promising technologies that are close to production readiness apart from LPCVD are briefly discussed below.

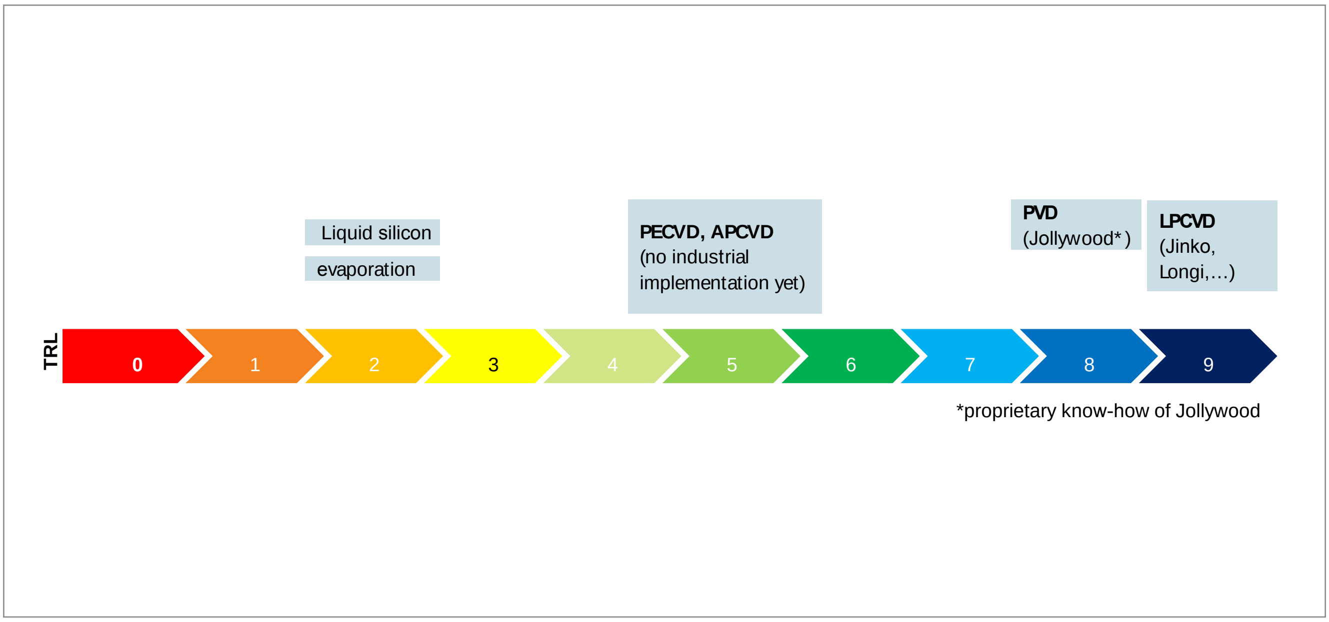

Figure 5. Technology readiness level (TRL) of different approaches for the formation of the poly-Si layer.

PECVD

PECVD is a well-proven technology in the PV industry for depositing dielectric passivation layers, and one of the most promising candidates for a-Si deposition. In fact, the International Roadmap for Photovoltaics (ITRPV) predicts a rapid adoption of this technology for a-Si deposition rather than LPCVD in the near future [19].

PECVD deposition of a-Si layers offers higher deposition rates than with LPCVD technology, thus promising greater cost effectiveness. Another advantage of using PECVD is the possibility of doping a-Si layers in situ; however, it should be pointed out that layer homogeneity and deposition rates in that case are also impacted. One of the challenges is to avoid blistering in thick layers (d > 100nm), which are currently still required for industrial TOPCon architecture because of the potential penetration of the poly-Si layer by the metallization.

Although PECVD is loosely considered a single-sided deposition process, avoiding the wrap-around of a-Si layers in an industrially feasible manner remains a major technological challenge for equipment manufacturers. Industrial tools allowing depositions in either batches [20] or an inline mode [21] are available, and cell integration results have also been published in the literature [20]. An advantage of the PECVD approach might be the option to implement a plasma oxidation step for in situ TO formation before the deposition of the a-Si layer, enabling a lean combined process for TO formation and Si layer deposition, similar to the LPCVD approach. To the authors' knowledge, a PECVD deposition process for TOPCon structures has not yet been implemented in any cell production, which is why a TRL of 4 to 6 is assigned to this technology (Fig. 5).

> "Currently, industrial screen-printed TOPCon solar cells on n-type substrates are almost all based on LPCVD a-Si/poly-Si deposition technology, to which a TRL of 9 is assigned."

APCVD

Atmospheric pressure chemical vapour deposition (APCVD) is another potential technology for depositing intrinsic and doped amorphous or partly crystalline layers in an inline mode at high deposition rates [22]. The process utilizes thermal dissociation of silane (SiH_4), which is inserted in a heated chamber using injector heads. Since the chemical reactions occur directly at the heated substrate, APCVD is also expected to provide good single-sidedness with a small wrap-around similar to that for the PECVD process.

Furthermore, in situ doping is reportedly easily achieved by directly inserting doping precursors in the SiH_4 flow, and cell integration results have been demonstrated [23]. Here, the TO layer needs to be formed before the APCVD process, for example in a wet-chemical process subsequent to the rear emitter removal. APCVD of silicon layers appears to have not yet been implemented in cell production, indicating a similar TRL as PECVD.

PVD

PVD as another industrial applicable production method and is capable of depositing high-quality a-Si layers using a silicon target, with the major benefit of providing true single-sidedness [24]. Both the silicon and an appropriate dopant element can be deposited using solid, non-toxic targets. Since

PVD is a vacuum-based inline process, a plasma oxidation for TO formation might be implemented in a separate chamber before the deposition.

The company Jolywood, a pioneer in industrial TOPCon cell manufacturing, is presumably also using PVD in their most recent production lines as their primary deposition technique (based on a technology called *POPAID* (plasma oxidation and plasma-assisted in situ doping deposition) introduced by the equipment manufacturer Jiangsu Jietai Optoelectronics Technology Co., Ltd. – JTech) [25]. PVD is therefore already in use industrially, but not yet as a mainstream technology, which is reflected in its TRL level of 8 (Fig. 5).

Metallization – decisive for cost and silver usage reduction

A key challenge in industrially upscaling the TOPCon solar cell concept lies in the metal contacting of the solar cells. The metallization on the TOPCon side especially has revealed itself to be challenging, as the tunnel oxide should not be damaged in order to guarantee its full functionality as a carrier-selective contact. As a state-of-the-art metallization technique for i-TOPCon solar cells, screen printing of Ag–Al and Ag is used on the front and rear sides, respectively.

The dominant loss mechanism of an i-TOPCon solar cell is associated with recombination induced by the metal electrodes on the emitter side and, to a reduced degree, on the TOPCon side [26]. The contact formation process, which typically takes place at peak temperatures in excess of 700°C, is industrially performed using a fast-firing oven (FFO). At those temperatures, the dielectric capping layers, mostly amorphous SiN_x, covered by the screen-printed electrode, are etched by glass frit components within the paste. Then, oxygen ions on both sides react with the crystalline or poly-Si, creating etching pits that facilitate the creation of an ohmic contact [27]. On the front, the metallization significantly increases carrier recombination, while on the rear, the etching pits consume the poly-Si, potentially reaching the thin oxide layer and consequently de-passivating the contact. The contact formation process on both sides is fuelled by elevated firing temperatures. On the one hand, the higher temperature leads to low-ohmic contacts and thus a high fill factor *FF*; however, on the downside, this comes with increased metal-induced recombination, mainly decreasing V_{oc} and ultimately limiting the conversion efficiency potential.

LECO

At Fraunhofer ISE, laser-enhanced contact optimization (LECO) [28] as a post-firing treatment is applied to reduce the contact firing temperature, which enables higher V_{oc} and simultaneously higher *FF* values on i-TOPCon solar cells. The LECO process locally applies a very intense laser pulse to the solar cell, which is held at a constant reverse voltage of 10V or higher. The resulting local current flow of several amperes is responsible for significantly reducing the contact resistivity between the semiconductor and the metal electrode [29].

By using a lower firing temperature in combination with LECO post treatment, an efficiency gain of up to +0.6%$_{abs}$ can be demonstrated, compared with the optimum for a firing temperature variation [30]. This gain originates from decoupling the dependence on temperature of V_{oc} and short-circuit current density J_{sc} on the one hand and *FF* on the other during the contact firing procedure. The LECO process enables one to benefit from high V_{oc} and J_{sc} values using low firing temperatures, while simultaneously achieving high *FF* values as if the firing had taken place at higher temperatures. As a result, a reduction in the optimal peak firing temperature of 20–40°C is observed. Moreover, metal-induced recombination is lowered because of the reduced firing temperatures of up to 40°C, mainly on the boron emitter side, leading to the observed gains in V_{oc} [30]. On both sides of the solar cell, the lower temperatures allow thinner and lighter-doped layers, and potentially the use of additional or thicker dielectric layers, which are more resilient to penetration by metal pastes, reduced metal area fraction and extended co-firing conditions.

Finally, LECO-treated i-TOPCon solar cells do not show any signs of LeTID using accelerated testing conditions. Furthermore, the LECO improved state does not degrade under these conditions, giving significant confidence in enduring, high module performance for these kinds of solar cell.

Ni/Cu/Ag contacts

Recent publications point out that the limited supply of silver and the increasing cost of raw materials will be critical factors for an increasing PV market heading towards terawatt scale within the next decade [31,32]. Conventional technology evolution (as expected according to the ITRPV [19]) is not sufficient to overcome these limitations, especially in the case of solar cell designs with silver contacts on both sides.

Electroplating of Ni/Cu/Ag contacts has been found to be a suitable candidate for metallizing bifacial TOPCon solar cells [33,34]. Plating is a lead-free metallization technique which allows narrow contact geometries (<25μm) and low contact resistivities (ρ_c < 1mΩcm^2) [35]. Furthermore, with the use of mainly Cu as the main conductive

> “The limited supply of silver and the increasing cost of raw materials will be critical factors for an increasing PV market heading towards terawatt scale within the next decade.”

Figure 6. Structure and process sequence for the manufacture of a bifacial TOPCon solar cell, based on laser structuring and Ni/Cu/Ag plating.

Cell area 267.85cm^2 (full area)	η [%]	J_{sc} [mA/cm^2]	V_{oc} [mV/cm^2]	FF [%]
Screen printing	23.5	40.7	705	81.9
Plating	24.0	41.0	715	82.0

CalLab PV Cells

Table 1. Certified record efficiencies for full-area (M2), nine-busbar, industrial TOPCon solar cells (the poly-Si layers were fabricated by LPCVD) [37].

component, a significant cost reduction is realizable, resulting in a cost of ownership (COO) advantage of around 45%, compared with screen printing [35].

The electroplating process developed at Fraunhofer ISE is illustrated in Fig. 6. Laser contact ablation of the ARC on the front and rear defines the grid pattern. After the necessary TOPCon activation via a short high-temperature firing step, single-side plating processes are applied to deposit a stack of a thin nickel seed layer (<0.5µm), copper bulk finger (1–10µm) and a thin surface-finish layer (<0.5µm) of either silver or tin. On industrial precursors, this plating approach yielded record efficiencies of up to 24.0%, compared with 23.5% using the suppliers R&D screen-printing metallization approach shown in Table 1.

A further advantage of the process, demonstrated in Kluska et al. [36], is the low contact recombination of the local contact opening (LCO) patterning, even for poly-Si thicknesses of down to 60nm on the TOPCon rear side. This would enable a reduction in the poly-Si thickness, and consequently an increase in process throughput, in the TOPCon deposition process.

Fig. 7 takes a closer look at the COO for the metallization backend for TOPCon solar cells. The main cost driver for screen-printed contacts is the cost of silver paste and its dependency on the volatile raw material price of silver. However, the more advanced stage in the learning curve for screen-printing-tool manufacturing means that equipment costs are fairly low. Since plating technology is at the beginning of its learning curve in PV, the equipment costs are significantly higher than for screen printing, but the costs of consumables are much lower.

Conclusion

The paper has summarized the current status of TOPCon implementation in industrial mass manufacturing and is intended to offer guidelines for the technology readiness levels of various process technologies along the process chain. While technology progress is visible in all steps of the process chain options, to date LPCVD still represents the only viable and industrially fully adopted process solution for the Si layer deposition, which represents the core process of any new TOPCon greenfield installation or upgrade from existing PERC. For future growth, technology development drivers are not only production-cost

"While technology progress is visible in all steps of the process chain options, to date LPCVD still represents the only viable and industrially fully adopted process solution for the Si layer deposition."

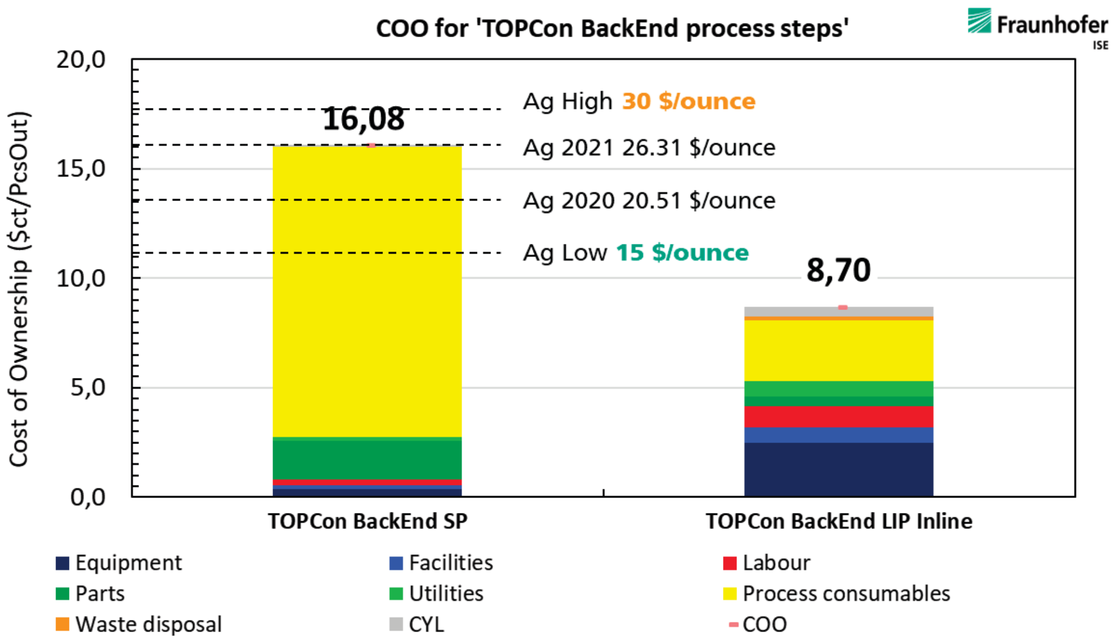

Figure 7. Cost of ownership (COO) comparison of a screen-printed-based metallization (120mg total Ag consumption) and the proposed Ni/Cu/Ag plating approach. Different Ag source material prices (indicated by the horizontal dashed lines) highlight the significant impact on metallization cost.

related but also arise from resource-criticality aspects. In metallization, therefore, alternative approaches for the current mainstream silver usage in screen printing will be one of the major topics for development in the near future.

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About the Authors

Jochen Rentsch is head of the Production Technologies – Surfaces and Interfaces department at Fraunhofer ISE. He studied physics at the Technical University of Braunschweig, obtaining his diploma degree in 2002. He then received his Ph.D. in physics in 2005 from the Albert Ludwig University of Freiburg, Germany. His research at Fraunhofer ISE focuses on the development of rear-passivated solar cells, new wet- and dry-chemical processing technologies, and the coordination of cell technology transfer projects.

Tobias Fellmeth studied physics at the University of Konstanz, and received his diploma degree in 2009 for his work at Fraunhofer ISE on the development and characterization of MWT

concentrator solar cells. He received his Ph.D. from the University of Tübingen in 2014 for his research on silicon-based, low-concentrator solar cells. He is currently a scientist and project manager at Fraunhofer ISE, where he focuses on the development of bifacial PERC and TOPCon solar cells.

Sebastian Mack studied physics at the University of Jena, Germany. In 2008 he joined Fraunhofer ISE, where he carried out research for his doctoral degree on thermal oxidation processes for industrial silicon solar cells. Since then, he has been working as a scientist in the Thermal Processes group. Over the last few years, he has been responsible for the development of process sequences for industrial p- and n-type TOPCon solar cell fabrication.

Bishal Kafle works as a scientist at Fraunhofer ISE. He received his M.Sc. and Ph.D. degrees in microsystems engineering from the University of Freiburg, Germany, in 2011 and 2017 respectively. His current research focuses on the integration of industrial relevant processes into novel cell architectures, such as passivated contact solar cells, and techno-economic assessment of various cell architectures in terms of cell/module/system costs and levelized cost of electricity (LCOE).

Sebastian Nold is head of the Techno-economic and Ecological Analyses team at Fraunhofer ISE. He studied industrial engineering at the Karlsruhe Institute of Technology (KIT), Germany, and at the University of Dunedin, New Zealand, earning his diploma in industrial engineering at the KIT in 2009. In 2018 he completed his doctoral thesis at the Albert Ludwig University of Freiburg (Germany). Since 2008 he has been working at Fraunhofer ISE in the areas of cost modelling, technology assessment and techno-economic and ecological evaluation of new concepts for the production of silicon solar wafers, cells and modules as well as emerging PV technologies.

Baljeet Goraya is a project manager within the Techno-economic and Ecological Analyses team at Fraunhofer ISE. He completed his B.Eng. in mechanical engineering at MSRIT, India, in 2011, and studied renewable energy engineering and management at the Albert Ludwig University of Freiburg, receiving his M.Sc. in 2016. Since joining Fraunhofer ISE in 2019, his work has focused on the techno-economic evaluation of established and emerging, next-generation solar PV technologies as well as evaluating production processes for PEM fuel cells.

Andreas Wolf studied physics at the Technical University of Darmstadt, Germany, and at the Royal Institute of Technology, Stockholm, Sweden. In 2007 he received his Ph.D. from the Leibniz University of Hannover, Germany, for his work on sintered porous silicon and layer transfer silicon solar cells, which he carried out at the Institute for Solar Energy Research Hamelin, Germany. Since 2008 he has been with Fraunhofer ISE, where he currently heads the Thermal Processes group in the Photovoltaics division.

Sven Kluska studied physics at the Albert Ludwig University of Freiburg and received his Diploma in 2010. He joined Fraunhofer ISE to pursue a Ph.D. in the field of laser chemical processing for silicon solar cells, and received his Ph.D. from the Albert Ludwig University of Freiburg in 2011. His research interests include electrochemical processing for solar cell applications, with a focus on plating metallization. He is currently co-head of the Electrochemical Processes group.

Ralf Preu joined Fraunhofer ISE in 1993 and is director of the Photovoltaics division, with a focus on production technology. He studied physics at the Universities of Freiburg and Toronto, and economics at the University of Hagen, and received his Ph.D. in electrical engineering and electronics from the University of Hagen in 2000. He has been teaching photovoltaics at the University of Freiburg since 2008, and has published more than 300 papers in scientific journals and at international conferences.

Enquiries

Dr. Jochen Rentsch
Fraunhofer Institute for Solar Energy Systems (ISE)
Heidenhofstrasse 2
79110 Freiburg, Germany

Email: jochen.rentsch@ise.fraunhofer.de
Tel: +49 (0)761 4588-5199

TOPCon efficiency breakthrough from cell to PV module

Johanna Bonilla, Roman Giehl, Calors Magistris & Roberto Murgioni, JinkoSolar GmbH, Munich, Germany

Abstract

Doped polysilicon-based structures with passivating contacts are expected to rapidly increase their market share, and, along with this, early hopes are starting to materialize for the tunnel oxide passivated contact (TOPCon) cell to be a natural successor to the passivated emitter and rear cell (PERC). Out of other passivated contact technologies, TOPCon is the only one in a similar position to PERC a few years ago when it replaced aluminium back-surface structures (AL-BSF), offering greater efficiency and performance advantages with few additional steps required in production. This paper reviews the steps to making a breakthrough in TOPCon efficiency, from cell to PV module, by using industrially viable manufacturing processes. A detailed characterization and investigation of the primary losses of JinkoSolar's TOPCon record cell of July 2020, with an efficiency of 24.8%, is presented. The results confirmed the high selectivity of the tunnelling oxide and the suppression of the rear-surface recombination by applying a subsequent n^+ poly-Si layer, but also identified that the front-boron-diffused region and resistive losses of the cell accounted for 63% of the electrical losses. These findings allowed further development, and a new record cell efficiency of 25.41% on a 163.75mm × 163.75mm solar cell is reported here, as independently measured in October 2021 by ISFH CalTeC. The transfer of the performance advantages to the module level are also discussed on the basis of laboratory measurements, simulations and complementary real-world field-test results.

Introduction

The market deployment of PV technologies requires a combination of factors be considered in order to achieve success: from a manufacturing perspective, the pressure to achieve higher efficiencies and reliability at competitive costs, while from an investor and developer standpoint, the pursuit for lower levelized cost of electricity (LCOE) to win power purchase agreements (PPAs). This dynamic has prompted extensive research into technological advances. In recent years, p-type passivated emitter and rear contact (PERC) cells have strengthened their market share, reaching 80% at the end of 2021 [1]. As a result of multi-busbar metallization, improvements in wafer quality, selective emitters and other aspects, PERC cells have achieved efficiencies above 24% [2,3]. The transfer of those developments into mass production has assured absolute annual efficiency increases of 0.5–0.6% [4] for PERC cells. Nevertheless, as the efficiency of PERC is reaching its limit, n-type substrates are emerging as the next technological development, moving the solar industry into a new era.

"TOPCon is considered a natural successor to passivated emitter and rear contact (PERC), since it offers technical advantages while only few additional processes are needed."

The expected percentages for the market share of n-type technology differ according to various sources, from 40% in 2031 [1] to an almost complete transition by 2028 [5]. Even for different scenarios, what is clear is that the so-called *n-type passivated contact* cell technologies, which include tunnel oxide passivated contact (TOPCon), interdigitated back contact (IBC) and heterojunction (HJT), have found the right momentum within the solar industry to begin their deployment on a large scale. From a manufacturing perspective, each of these cell architectures follows significantly different process flows. However, of the existing alternatives, TOPCon is considered a natural successor to passivated emitter and rear contact (PERC), since it offers technical advantages (see section 'Performance technical advantages: from cells to modules, from laboratory to real world') while only few additional processes are needed (see section 'Manufacturing process').

Key to the TOPCon cell is the *tunnelling oxide layer*, a structure adopted on the rear side of the n-type wafer. This ultrathin silicon oxide (SiO_x) layer has high selectivity, allowing the majority-charge carriers to *tunnel* through to the subsequent doped polycrystalline silicon layer; the electrons flow at a very low junction resistance, and thus there are negligible losses. At the same time, the tunnelling layer also provides chemical passivation, restraining the minority-carrier recombination.

JinkoSolar's TOPCon development

In terms of efficiency improvement, for PERC cells there is less room. Although the theoretical maximum efficiency is 24.5% [6], factors such as recombination losses, metallization contact regions and carrier transportation performance limit the overall efficiency level that this structure can achieve in a mass production scenario.

Other new alternative contact technologies, such as HJT or IBC, face major challenges with regard to becoming mainstream. HJT makes use of passivated contacts based on a layer stack of intrinsic and doped amorphous silicon, which implies a parasitic absorption in the front layer stack and consequently a reduction in short-circuit current. Its manufacture involves higher production tool costs, since processes above 200°C cannot be used after the amorphous silicon deposition. Moreover, there is a growing need to reduce the amount of silver, or replace it with copper, as well as cut down the use of indium in the transparent conductive oxide (TCO) layer [6]. IBC, on the other hand, needs to meet the challenge of becoming cost-competitive, because of the production complexity for obtaining perfectly fine and aligned layers, since it has doping and contacts of both polarities on one side.

On the production side, TOPCon offers a natural extension of PERC lines – with a few steps added – while providing improved efficiency and plenty of room for further improvement. With the highest theoretical efficiency of 28.75%, TOPCon is already close to the maximum theoretical conversion efficiency achievable by monocrystalline silicon cells [7,8].

The maximum cell efficiency increases linearly with the selectivity S_{10}, until the radiative recombination starts to limit further growth. This behaviour justifies the logarithmically scaled selectivity, defined as $S_{10} = \log_{10}[V_{th}/(J_0{*}\rho_c)]$, as shown in Fig. 1(b). It therefore depends on the thermal voltage V_{th}, the recombination current density J_0 and the contact resistance ρ_c.

JinkoSolar's TOPCon high selectivity relies on applying to the rear side of the n-type wafer a stack of silicon oxide and doped polysilicon films, providing a highly asymmetric equilibrium carrier concentration of majority and minority carriers in the contact, as detailed in Fig. 1(c).

Manufacturing process

JinkoSolar TOPCon wafers are prepared from Czochralski-grown (Cz) phosphorus-doped n-type monocrystalline silicon, with resistivity in the range 0.3–2.1Ω·cm and of size 182mm × 182mm, cut from a diameter of 253mm. Fig. 2, outlines the cell fabrication process.

Texturing

The process starts with texturing of the n type silicon wafers. The wafers are placed in a commercial alkaline solution (KOH) containing organic additives to form pyramid structures. This step serves to reduce reflection.

Boron diffusion

The wafers are then placed into a boron diffusion tube furnace (BCl_3 as a source) to form a homogeneous p^+-doped emitter layer.

Etching

The rear p^+-doped region is removed using an industrial alkaline single-side etching process to form the optimized rear-surface morphology.

Tunnelling oxide and poly-Si

Low-pressure chemical vapour deposition (LPCVD) at 500–600°C allows the in situ thermal oxidation of the crystalline silicon (c-Si) surface to form an ultrathin tunnelling oxide (SiO_x) before the poly-Si growth. The n^+ doping of the intrinsic poly-Si is carried out in a $POCl_3$ diffusion furnace and the

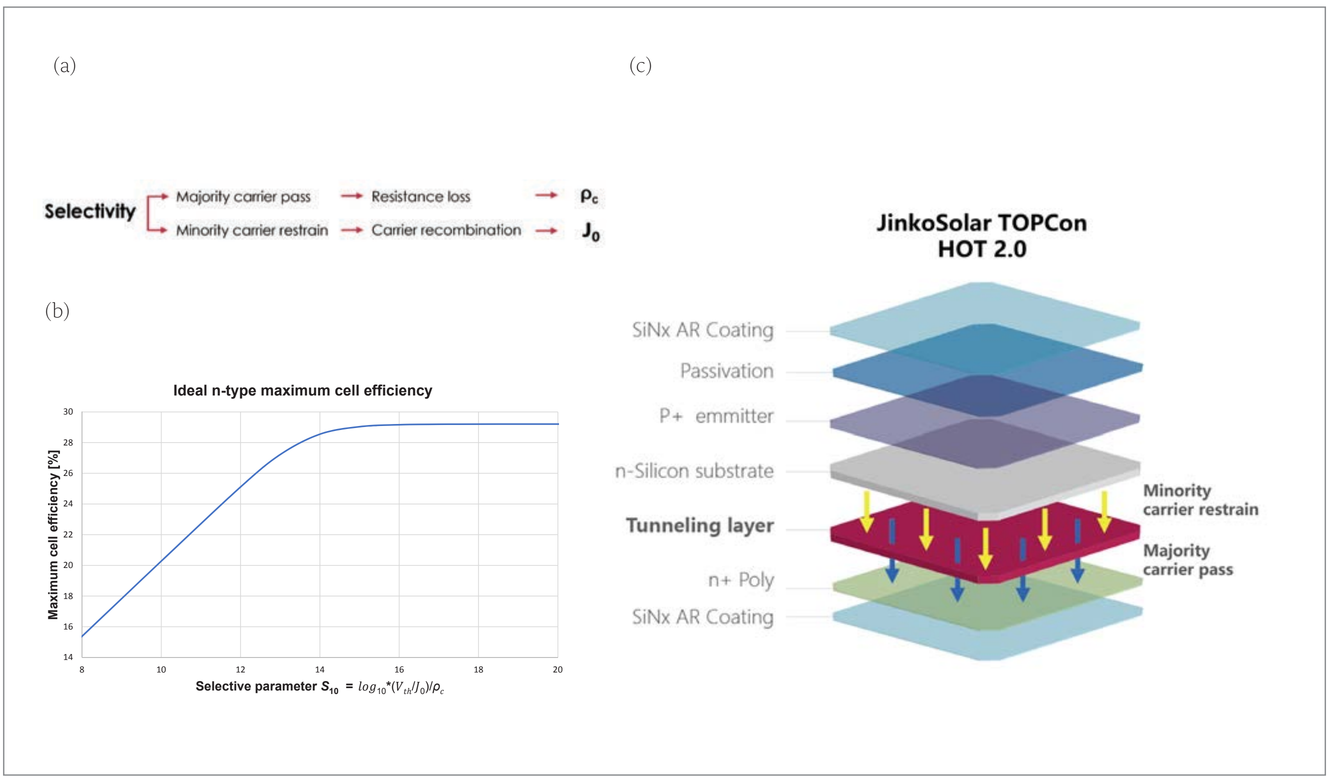

Figure 1. (a) Influence of passivation on majority and minority carriers. (b) Theoretical maximum efficiency as a function of the S_{10} selectivity of an n-type cell from a 2Ω·cm wafer of thickness W = 110µm, with Lambertian light trapping (J_{sc} =43.6mA/cm²) and with a single contact of selectivity S_{10}. The other contact is ideal, as described in Brendel et al. [7]. (c) JinkoSolar TOPCon structure, showing in red the tunnelling oxide layer.

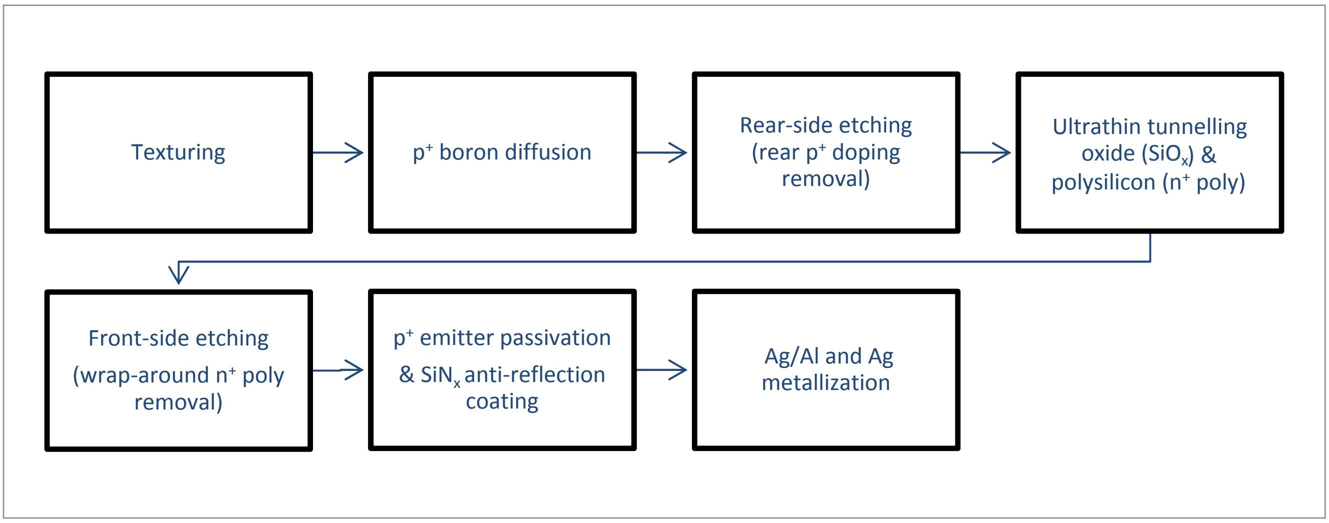

Figure 2. TOPCon cell manufacturing process.

n^+ poly-Si is formed. The n^+ poly-Si layer is less than 150nm in thickness, with a uniform doping profile within the poly-Si layer of about $3 \times 10^{20} cm^{-3}$, as measured using electrochemical capacitance–voltage (ECV).

It is important to mention that other methods can be used for the deposition of passivated contact cells, such as plasma-enhanced chemical vapour deposition (PECVD) and atmospheric pressure chemical vapour deposition (APCVD). However, LPCVD is a mature process, as it has been extensively used in the semiconductor industry for the deposition of poly-Si. In LPCVD, thin films are deposited from gas-phase precursors in a vacuum. In the course of this thermal process, the reduced pressure helps to prevent undesirable gas-phase reactions and to improve the field uniformity on the wafer. During the poly-Si deposition, silane gas is used as the reaction source, which is injected into the LPCVD tube and pyrolyses around the quartz wafer carriers. Suitable optimization of the process can provide a consistent reaction environment in terms of wafer temperature and nearby reactive gas flow; this results in excellent uniformity of the thin-film thickness and quality across the whole tube, as seen in Fig. 3.

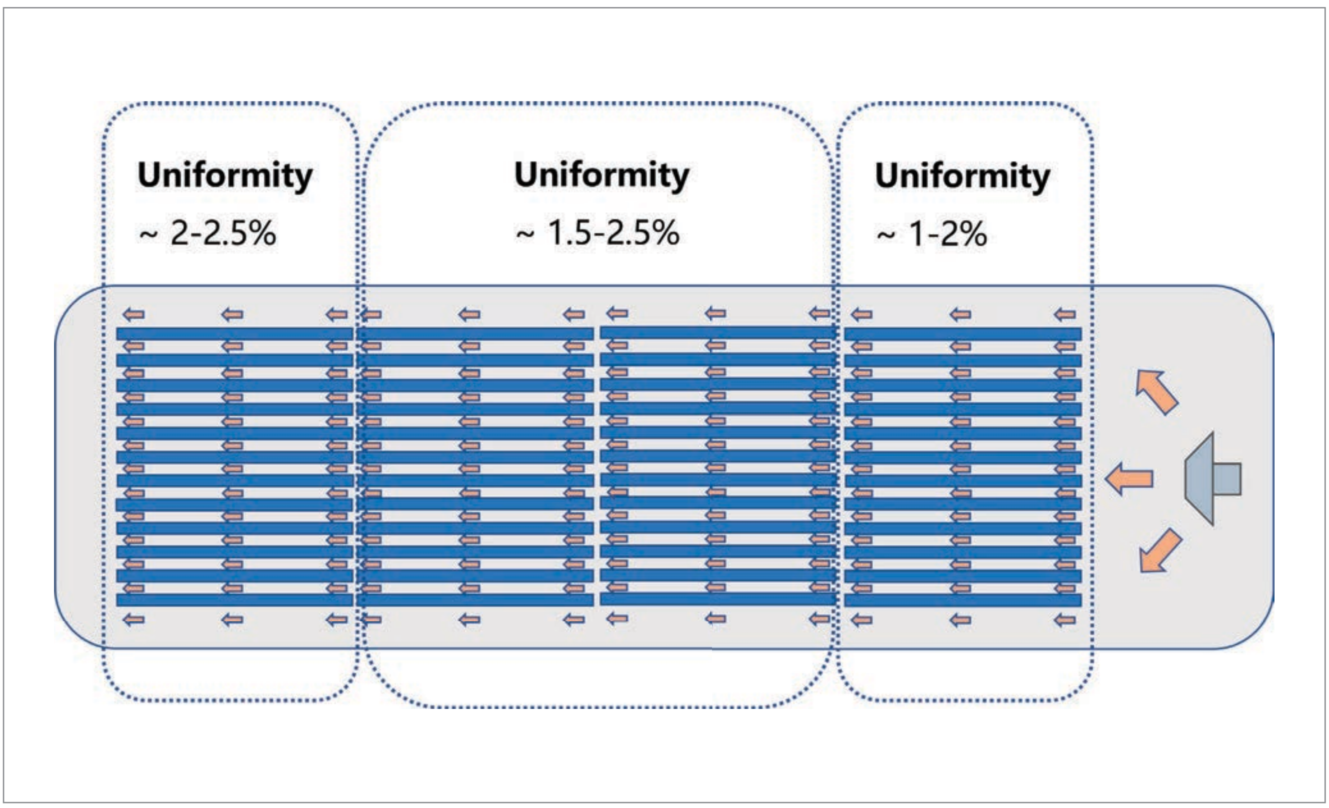

Figure 3. Uniformity of thin-film thickness and quality across the low-pressure chemical vapour deposition LPCVD tube. During the poly-Si deposition process, silane gas is used as the reaction source, which is injected into the LPCVD tube and pyrolyses around the quartz wafer carriers.

The challenges of LPCVD lie in being able to control the undesirable deposition of the poly-Si layer on the front, known as *wrap-around*. JinkoSolar's experience in the production of n-type technology, however, has enabled significant improvements to be made to the LPCVD configuration, resulting in a tweaked horizontal-loading LPCVD; moreover, an active wrap-around removal process (next process step) has been implemented, which assures the wrap-around is kept within acceptable limits, reducing the negative impact on the yield.

Removal (front-side etching)

Since the poly-Si is inherently deposited on both sides of the wafer, a wrap-around etching process is performed using a feasible mass-production chemical wet bench. With appropriate process control, the front-side p^+ emitter can be well protected, as shown in Fig. 4. The front-side borosilicate glass (BSG) and the rear-side phosphosilicate glass (PSG) layers are removed in diluted HF solution, followed by a cleaning stage.

p^+ emitter passivation and SiN_x anti-reflection coating

This step involves the passivation of the p^+ emitter side and the SiN_x anti-reflection (AR) coating, and the AR coating of the n^+ poly side.

Ag and Al metallization

Ag/Al and Ag pastes are screen printed and then co-fired in a belt furnace to form the front and rear contact grids, respectively.

Investigation of primary losses and pathways for further TOPCon efficiency improvement

Many players in the solar industry are competing in a perpetual race to achieve high efficiencies. To this end, JinkoSolar has been undertaking a long path of research and development of n-type cell structures since 2017, establishing various world records at the cell and module levels, as detailed in Fig. 5. In support of that work, the goal was the definition and implementation of viable industrial manufacturing processes for performance improvements.

In July 2020 JinkoSolar's record cell, with an efficiency η of 24.79% on a 163.75mm × 163.75mm solar cell, was reported and independently measured by ISFH CalTeC. This cell was characterized in detail and further simulations were performed in order to investigate the primary power and energy losses [9]. The results showed that rear-surface recombination is effectively suppressed by applying n^+ poly-Si, but 63% of the electrical losses can be attributed to the front-boron-diffused region and resistive losses of the cell.

Record cell recombination parameter results

The recombination current (J_o) values of the passivated and metallized fractions of the front layer of the rear surface were determined by using high-resistivity 10Ω·cm n-type wafers. Double-

"An active wrap-around removal process has been implemented, which assures the wrap-around is kept within acceptable limits, reducing the negative impact on the yield."

(a)

(b)

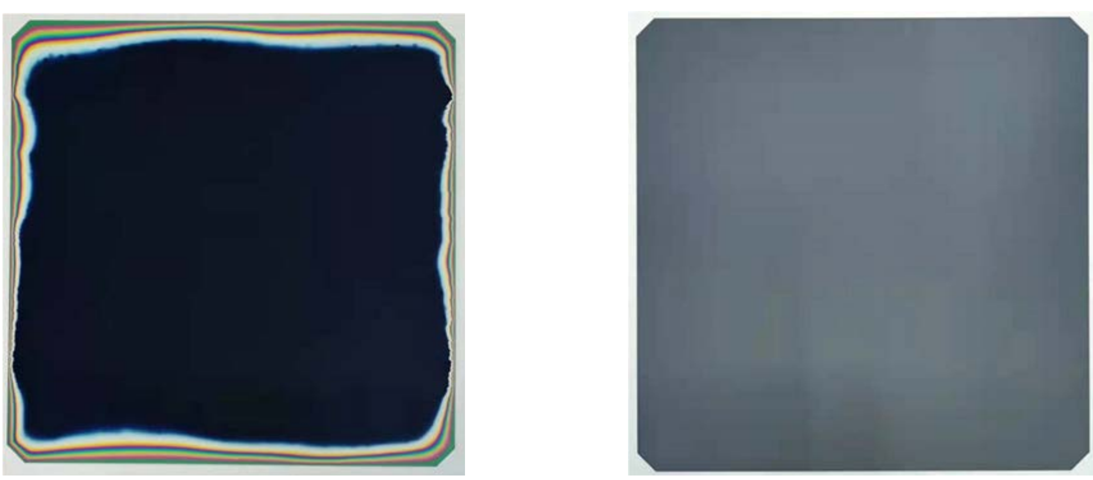

Figure 4. (a) Wafer before the wrap-around removal. (b) Wafer after wrap-around poly-Si layer removal using JinkoSolar etching technology.

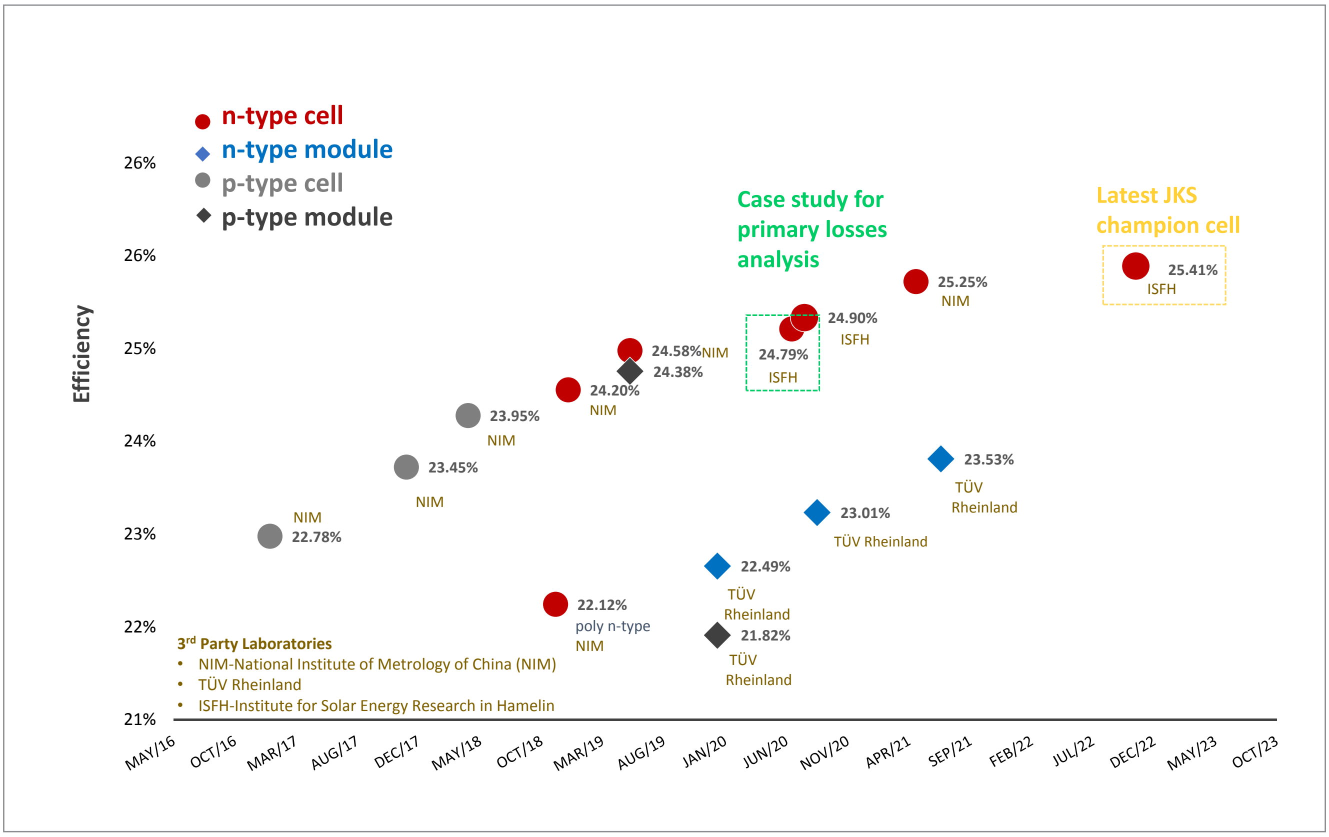

Figure 5. JinkoSolar world efficiency records: marked in green is the cell used for the primary loss case study, and in yellow, the latest champion cell. Both efficiency measurements were performed independently by ISFH CalTeC under standard test conditions.

side boron-diffused textured wafers were used for the front-side J_o measurement. To analyse the effect of additional thermal budget on the boron doping and associated changes in recombination, the wafers were masked and subjected to $POCl_3$ diffusion. Multiple thin-film stacks (Al_2O_3/SiN_x) were used for passivation, followed by firing of the samples in the same belt furnace as the cells. The excellent quality of the front-side passivation was demonstrated by the value obtained for $J_{o,front}$ of 6.2fA/cm^2 [9].

For the rear n$^+$ poly-Si structure, wafers were etched in the same industrial HF/HNO_3 solution as the cells, and subsequently passivated with PECVD SiN_x and fired along with the cells; the resulting value of $J_{o,rear}$ was 3.2fA/cm^2. The study also assessed the J_o of the front Ag/Al-contacted area, by using double-side boron-diffused textured wafers and applying different metallization fractions (0% to 37%) to the rear side; the value of J_o was found to be 720fA/cm^2.

Although the J_o between the Ag paste and the n$^+$ poly-Si region for the rear side was not accurately determined, the upper limit was established to be 50fA/cm^2 in the study [9].

Record cell series resistance

The resistance of the Ag/Al paste was 2.2mΩ·cm^2 for the front side and 1.0mΩ·cm^2 for the rear. The latter was an estimation of the contact resistivity between the Ag and the poly-Si, since no removal of the poly-Si was performed. Therefore, the series resistance R_s was determined by comparing the Suns-V_{oc} method with the light I–V measurement at the maximum power point. The resulting pseudo-fill factor (pFF) of the record cell was 84.96%, and the effective R_s of the cell was determined to be 0.2Ω·cm^2.

Record cell simulation

Additional simulations were carried out to identify avenues to explore for further improvement of the state-of the-art manufacturing processes. A three-dimensional simulation based on the reported measured recombination and resistance values was used to analyse optical losses.

Optical losses

The external quantum efficiency (EQE) of the TOPCon record cell showed a superior blue response (wavelength range 300–500nm) as a result of the optimization of both the boron-diffused region and the anti-reflection coating (ARC). Front-grid shading (1.2mA/cm^2), escape reflection (1.4mA/cm^2) and bulk and rear parasitic infrared absorption (1.8mA/cm^2) contributed to the major optical losses, as illustrated in Fig. 6(a).

On the basis of these results, it is possible to identify lines of approach for achieving optical improvements. Front-grid shading losses, for example, can be limited by reducing the finger width and contact resistivity. Developments in

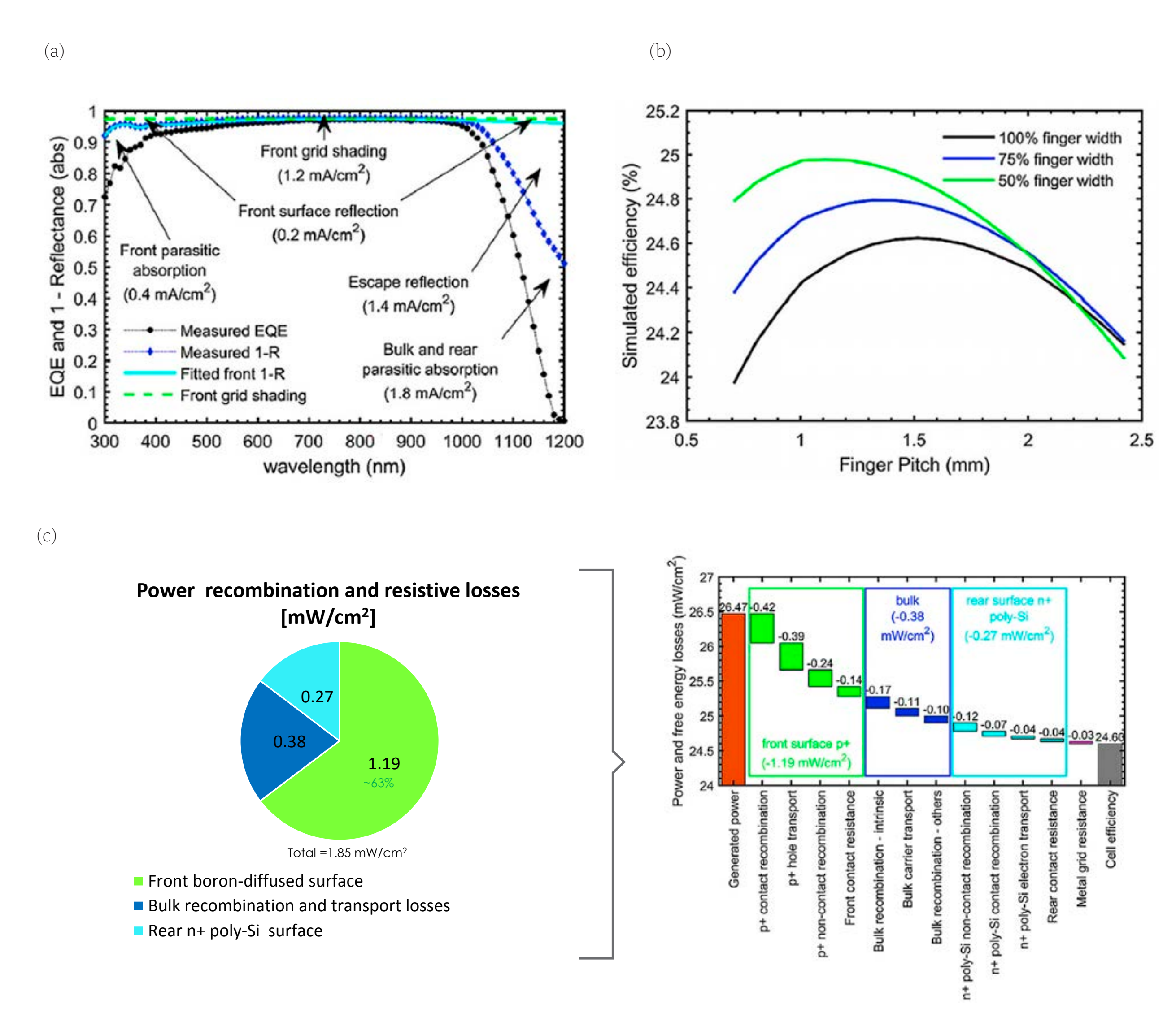

Figure 6. Analysis of the losses of the record cell with η = 24.8% [9]. (a) Optical analysis losses, showing the measured EQE (performed independently by ISFH CalTeC). (b) Results of cell efficiency simulations as a function of the front-finger pitch for 100%, 75% and 50% finger widths. (c) FELA results, based on simulations. The total recombination and resistive losses are 1.85mW/cm^2.

gridding are ongoing and expectations are high; according to ITRPV [1], finger widths from 36 to 20µm are expected by 2031. In addition, narrower fingers also allow smaller pitch, improving the performance of the boron emitter of the front side. The simulations results, as shown in Fig. 6(b), demonstrated that a reduction of 25% in the finger width improved the efficiency by 0.2%$_{abs}$, and a further reduction of 50% resulted in an additional 0.2%$_{abs}$ efficiency improvement [9].

Electrical losses

The free energy loss analysis method (FELA), as described in Brendel et al. [7], was used for the electrical analysis. Fig. 6(c) shows the breakdown of the power losses, which amounted to 1.85mW/cm^2 overall. The boron-diffused region on the front surface accounted for losses of 1.19mW/cm^2, representing 63% of the total losses. Out of this, the single largest contributor was the p$^+$ contact recombination, with 0.42mW/cm^2. Reported bulk recombination and transport losses were 0.38mW/cm^2, while the rear-side n$^+$ poly-Si accounted for total minor losses of 0.27mW/cm^2 [9]. In the same way, pathways for further improvement for the optimization of the boron-diffused front surface were revealed, in agreement with Chen et al. [10].

Implementation of findings: boosting large-area efficiency to 25.41%

The findings of the detailed analysis in 2021 were used to advantage to enable further cell developments, allowing JinkoSolar to establish a new cell efficiency record of 25.41% on a large-area TOPCon cell by the end of that year. The main current–voltage (*I*–*V*) parameters are detailed in Table 1, and the independent measurement by ISFH CalTeC is shown in Fig. 7.

Cell *I–V* parameter	Measured result
V_{oc} [mV]	719.1
J_{sc} [mA/cm^2]	42.24
FF [%]	83.66
η [%]	25.41

Table 1. Measured current–voltage (*I–V*) parameters of JinkoSolar's latest large-area n-type TOPCon record cell.

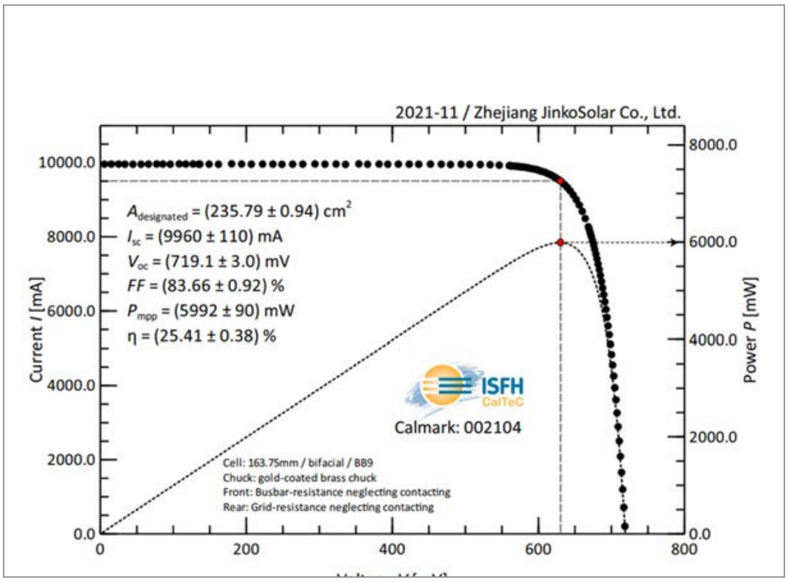

Figure 7. Illuminated current–voltage and power–voltage characteristics of JinkoSolar's latest large-area n-type TOPCon record cell, with 25.41%. The measurement was independently performed by ISFH CalTeC under standard test conditions.

"The TOPCon cell has a natural immunity to boron–oxygen-related LID, and well as resistance to LeTID."

Specific key factors for improving cell efficiency were:

1. The morphology of the rear-side surface was optimized and the poly-Si layer thickness was reduced, to enhance the spectral response of the cell in the infrared range, resulting in increased short-circuit current.

2. Surface passivation quality was enhanced on both front and rear cell surfaces, as a result of systematic process optimization of the passivation layer, as well as the tunnelling oxide/poly-Si stack.

3. The cell structure at the front was optimized, resulting in improved passivation quality and spectral response in both UV and visible light ranges. Thus, impressive values of V_{oc} and J_{sc} were achieved.

Performance technical advantages: from cells to modules, from laboratory to real world

TOPCon's response to LID/LeTID

Because of its structural make-up, the TOPCon cell has a natural immunity to boron–oxygen-related light-induced degradation (LID), as well as resistance to light- and elevated-temperature-induced degradation (LeTID). The higher tolerance to impurities means that these advantages can be seen not only in the laboratory but also in mass production. Although the nature of the LeTID effect has been extensively investigated, the hypotheses proposed for its constitution are diverse. Several studies attribute the degradation effect to metallic impurities [11–14]; however, more current evidence points to the participation of hydrogen in this phenomenon [15,16].

It has been found that the hydrogenated silicon nitride (SiN_x:H) film is able to release hydrogen into the silicon bulk during fast firing [17–19]. Jensen et al. [20], however, demonstrated the presence of LeTID with plasma hydrogenation as well, linking the phenomenon to hydrogen and not to the technique.

With the discussion still open regarding the cause, what has become clear from these studies is that n-type modules are less sensitive to this phenomenon, which implies a reduction in losses. Jinko has also verified this by independent laboratory tests, and it is an attractive factor for long-term investments.

Power–temperature coefficient (γ)

The temperature-dependent rate of change of each *I–V* parameter – namely the maximum output power (P_{max}), the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) – can be described through the so-called *temperature coefficients*. To determine these coefficients, a sweep of *I–V* curves is performed under different temperatures and a constant illumination of 1,000W/m^2. The slope of the least-squares-fit straight line of the plotted *I–V* parameter as a function of temperature determines its respective coefficient [21].

The factor that most decisively characterizes energy efficiency losses due to temperature during operation is the P_{max} temperature coefficient, designated by γ. It is inversely proportional to the temperature change (–%/K); therefore, to obtain high yields, the value of γ should be as low as possible. Power–temperature coefficients depend more on cell technology than on manufacturing processes or PV module design. Here, JinkoSolar TOPCon structures, with –0.30%/°C, offer a natural advantage over PERC, with 0.35%/°C, and even over other n-type cell technologies, such as passivated emitter, rear totally diffused (PERT), with 0.32%/°C (see Fig. 8).

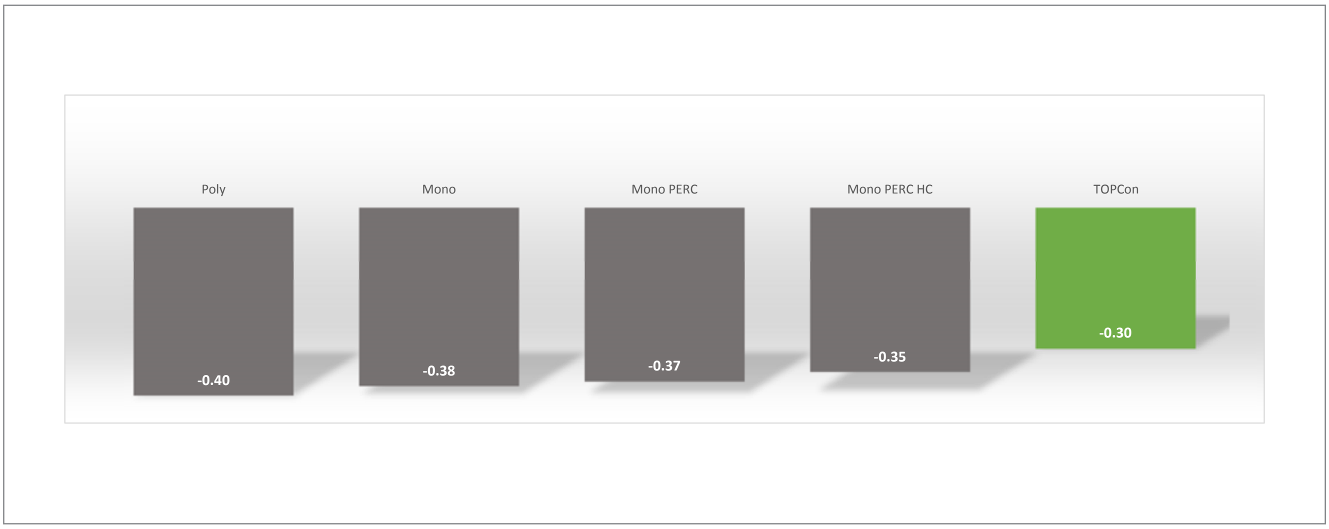

Figure 8. Power–temperature coefficient (*γ*) for different cell technologies. Values have improved with every generation of PV technology, but the switch from PERC to TOPCon will further improve it by +15%.

Bifaciality

Bifaciality is the efficiency ratio between the rear side and the front side under standard conditions, specified as an irradiance of 1,000W/m^2, a temperature of 25°C and an air mass of 1.5 [22]. An advantage of TOPCon structures over PERC technologies is their higher bifaciality, which is ~85% at the cell level. Fig. 9 shows the bifaciality results for a 182mm production cell.

A higher bifaciality means a higher utilization of the irradiance on the rear side of the module, which in turn means an increase in energy. At the module level, the bifaciality of n-type modules is ~80%, compared with ~70% for most p-type modules. The increase in production, in turn, results in a reduction in the LCOE. The degree of importance of this factor will be determined by the specific project, and depends on the reflectivity (albedo) and installation conditions. However, when all these factors are kept constant, and only the bifaciality is varied, an overall advantage is seen.

Table 2 shows the simulation results for a 3MW PV power plant in Syców, Poland. The same module was used to obtain the system production when just the bifaciality factor was varied, with the rest of the installation and environmental conditions kept constant. The results show an energy contribution of up to 1.5% by changing the bifaciality factor, in addition to a bifacial gain of 7.4%.

From a manufacturing point of view, improving bifaciality is a complex trade-off task. On the one hand, enhancing the front side of the cells, while representing an overall improvement, also implies a negative impact of the bifaciality; on the other hand, only improving the bifaciality does not fully contribute to an upgrade. Therefore, resources are allocated, as a first step, to an improvement of the front side as a priority, and, in a second step, to the improvement of the bifaciality. Improving the latter feature of the structure can be done either by changing the wafer thickness, which will directly reduce the light absorption in the doped polysilicon layer, or by improving other aspects, such as the wafer passivation and quality, the metallization through reducing rear-side shading, and the rear-side structure through texturing or polishing.

"To obtain high yields, the value of the P_{max} temperature coefficient γ should be as low as possible."

Low irradiance performance

Fig. 10 shows a comparison of the low-irradiance behaviour for n-type and p-type modules. The *I–V* performance at different irradiances was measured with a pulsed solar simulator, varying

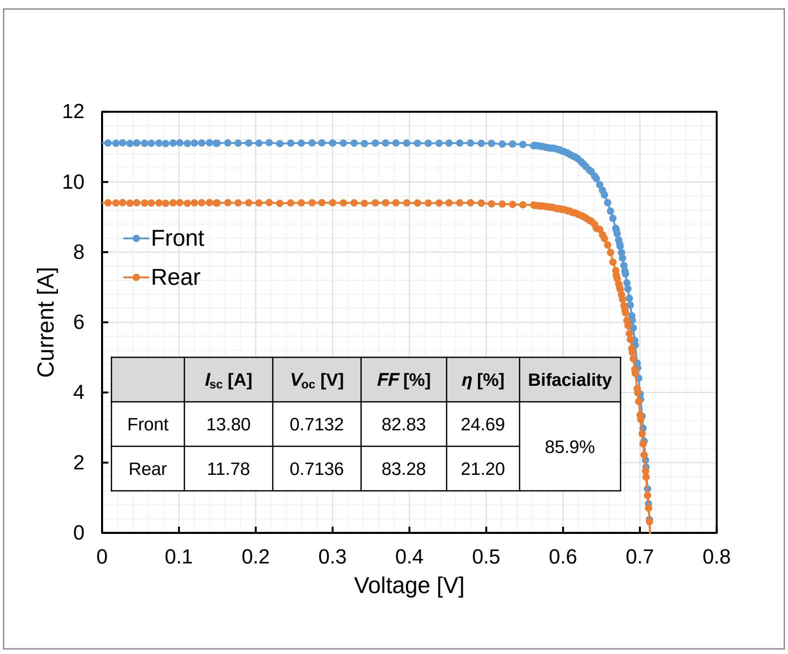

Figure 9. *I–V* characteristics of the front and rear sides for a 182mm production cell.

Location	Syców, Poland (51.31°N, 17.72°E)			
Capacity	3MW (front only)			
Albedo	25–30%			
Height	1.5			
Tilt	30°			
Module	Bifaciality factor	System production [MWh/a]	Bifacial gain [%]	ΔGain [%]
Monofacial n-type 550W	0	3340	Monofacial	Benchmark
Bifacial n-type 550W	0.70	3587	7.40	7.40
Bifacial n-type 550W	0.75	3605	7.90	0.50
Bifacial n-type 550W	0.80	3622	8.37	0.98
Bifacial n-type 550W	0.85	3640	8.87	1.48

**Module Tiger Neo Bifacial JKM550N-72HL4-BDV*

Table 2. PVSyst simulation results for a 3MW PV plant in Poland, with variations of only the bifaciality factor, with all other module, ambient and installation conditions remaining the same.

the irradiance from G = 100W/m² up to G = 1,000W/m², in accordance with the IEC 61853-1 standard [23]. The homogeneity of the irradiance was tracked in order to satisfy the requirements of IEC 60904-9 [24]. The relative efficiency was calculated to be:

$$\eta_{rel} = \frac{P_{max,meas} \cdot 1{,}000\text{W/m}^2}{G_{meas} \cdot P_{max,STC}} \quad (1)$$

The performance at low irradiance depends more on the manufacturing processes and PV module design than on the cell technology itself [25,26]. At the module level, n-type technologies achieve high parallel resistance to reduce losses at low illumination, while low series resistance reduces the losses at high currents.

Performance of n-type PV modules under real-world conditions

TOPCon's higher efficiencies at the cell level are

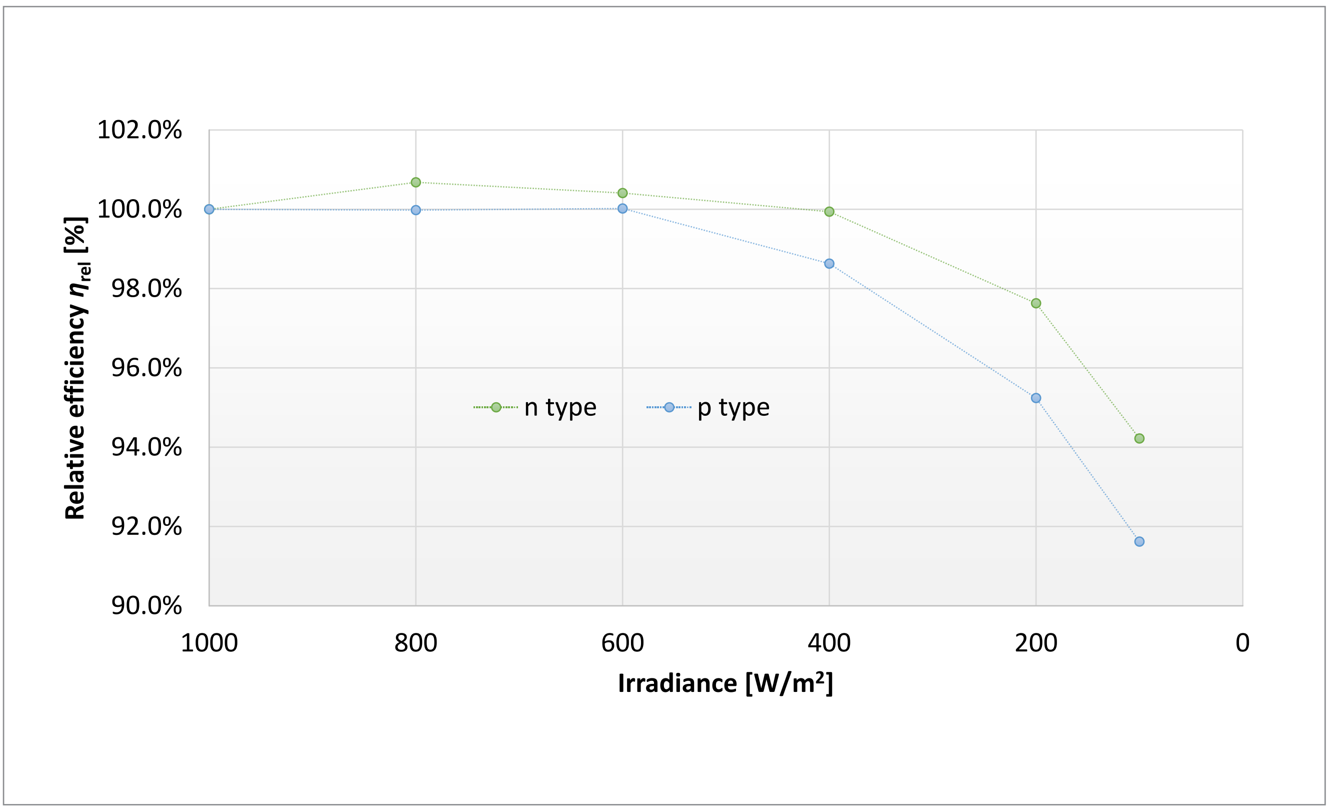

Figure 10. Low-irradiance performance of n-type and p-type modules. *I–V* measurements were taken in a pulsed solar simulator at irradiances G ranging from 100W/m² to 1,000W/m², in accordance with IEC 61853-1.

reflected in enhanced performance at the module level and have already been verified by outdoor test results. JinkoSolar has compiled a series of field results since 2019 for 163mm wafer modules in different locations around the world.

At the NWS location, in Australia, the performance of bifacial modules was monitored from December 2019 until May 2020, in order to contrast with their monofacial equivalents. Three types of module were deployed: one monofacial (p-type), along with one bifacial n-type and one bifacial p-type, both with a transparent backsheet. The bifacial gain for the n-type module averaged 10.86% and for the p-type, 7.80%, which represents an increase of 3.06% due to cell technology alone, as shown in Fig. 11(a).

At the Ningxia location, in China, two strings incorporating bifacial n-type and p-type tilling ribbon (TR) technology, both with a transparent backsheet, were compared. The results revealed an increase in energy generation of 2.7% for n-type over p-type, as shown in Fig. 11(b).

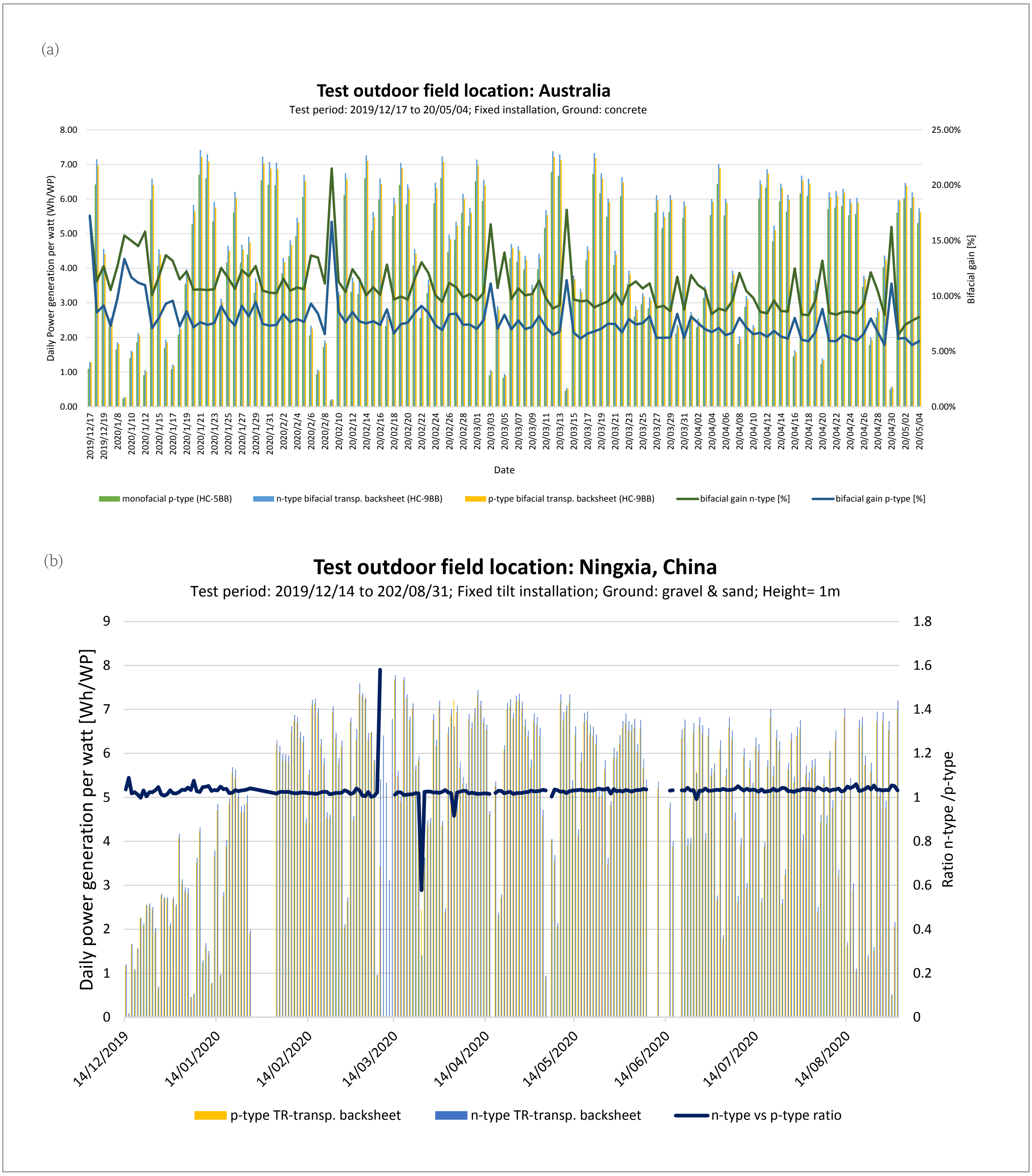

Figure 11. Results of outdoor tests for different locations: (a) Australia, with daily resolution. (b) Ningxia, China, with daily resolution.

"Further efforts will focus on achieving TOPCon's theoretical limit, based on large wafer sizes, with economically feasible procedures for mass production."

These results have been reproduced at different locations, where the energy production advantages of n-type modules have ranged from 1.5 to 3% compared with p-type modules.

Summary and conclusions

Several factors are responsible for establishing n-type TOPCon cell technologies in a key leading position for the next PV technology transition:

- Technological and economic limits are being reached with regard to efficiency improvements of PERC structures (currently about 24%), with little room remaining for further viable production improvements.
- Project developers are demanding better efficiencies at increasingly competitive costs.
- TOPCon's similarities in production to its PERC equivalent offer advantages over other doped polysilicon-based passivating-contact structures, not only in manufacturability but also in performance, with the highest theoretical maximum efficiency within these structures.

This paper has presented JinkoSolar's efforts in researching this particular cell structure, which has led to the launch of large-scale production of TOPCon modules. As an example, the power loss analysis of the 2020 best-performing cell with a record 24.8% was presented, and on the basis of these results, the implemented improvements that led to a new record of 25.4% by the end of 2021 were discussed. Both efficiencies were independently measured by ISFH CalTeC on a 163.75mm × 163.75mm solar cell.

Given that the advantages of the TOPCon cell are also reflected at the module level, and have been verified at JinkoSolar's outdoor test centres, further efforts will focus on achieving TOPCon's theoretical limit, based on large wafer sizes, with economically feasible procedures for mass production.

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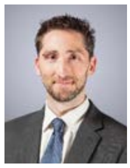
About the Authors

Johanna Bonilla holds a B.Sc. in electrical engineering, with a two-year specialization in power systems. In early 2016 she received her master's in renewable energy from the University of Applied Sciences in Cologne, Germany, and then became a member of the solar team at TÜV Rheinland Energy. She joined JinkoSolar in 2020 as a technical service manager. Her expertise includes PV module characterization, PV modules and systems performance analysis, field failures and bifacial technologies.

Roman Giehl is responsible for technical business development in the DACH region and the Netherlands. Since 2003 he has been working for several leading PV manufacturers and distributors in the PV industry and joined JinkoSolar in 2016. Coming from a chemical engineering background, he has an in-depth knowledge of PV technology and module development, and expertise in polymers, metals, silicon and industry, which have enabled him to successfully support technical business development in Europe.



Calors Magistris has 17 years of work experience in the PV sector. Prior to joining JinkoSolar, he worked as an independent technical advisor and consultant, where he carried out various field-test services. He has also collaborated in the creation of the new IEC TS 62941 standard. Throughout his career, he has worked with developers, IPPs, EPCs, financial institutions and manufacturers in mitigating product and system risk in various markets. He is a member of the international PV committee IEC-TC82.

Roberto Murgioni holds a B.Sc. in electrical engineering and a master's in renewables and nuclear energy engineering. He joined JinkoSolar in 2017 and currently leads the Technical Service and Product Management team in the EU. He began working in PV in 2006 and has held a variety of similar positions at other Tier 1 module manufacturers. He has also worked as an expert project engineer for various EPC companies, managing large PV power plant projects in Europe, Latin America and Africa, including design, construction and commissioning.

Enquiries

Johanna Bonilla
JinkoSolar GmbH
Freisinger Str. 9
85716 Unterschleißheim bei München
Germany

Email: Johanna.bonilla@jinkosolar.com
Website: www.jinkosolar.eu

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The role of silver in terawatt PV production – Perspectives and options

Jonas Bartsch[1], Sven Kluska[1], Markus Glatthaar[1], Estelle Gervais[1], Andreas Lorenz[1], Angela de Rose[1], Brett Hallam[2], Yuchao Zhang[2] & Loic Tous[3]

[1]Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany; [2]Photovoltaic and Renewable Energy Engineering, UNSW, Sydney, Australia; [3]PV Cells and Modules, imec, Leuven, Belgium

Abstract

As the PV industry rapidly advances towards annual PV production and installations on a terawatt scale, many aspects that are currently not critical will need to be considered. Among these, material availability is probably one of the most pressing ones. Established production routines will need to be changed, which may pose significant time constraints in the light of the fast-growing market. The focus of this paper will be on the use of silver for solar cell metallization. Past developments are discussed and an overview is given of the fast-growing number of relevant publications from the scientific community that deal with the problems associated with silver. There is increasing recognition that silver will become a concern in a terawatt-scale PV landscape. The authors present their own thoughts on how this issue will be addressed, taking into account the various cell and metallization technologies. It seems highly likely that, at least in some cell technologies, copper-based cell metallization will become a reality in the next 5–10 years.

Introduction

Multi-terawatt-scale PV production will be necessary in order to realize the worldwide energy transformation and to achieve the Paris climate goals. While even conservative players such as IEA [1] and BP [2] predict PV production to rise to 0.3–0.7TWp/a by 2030, depending on the scenario, many scientists and organizations predict multi-terawatt per annum PV production to become a reality between 2030 and 2035 [3,4]. PV production will be increased by roughly one order of magnitude compared with the present-day situation. This will impose all sorts of challenges, ranging from building lots of factories and manufacturing tools and ensuring the availability of different materials, to bringing in the (qualified) labourers needed both in the factories and especially for the installation of the PV power plants.

With regard to materials, the availability of aluminium [5], flat glass [5] and other critical raw materials [4,6–8] needed for solar cell fabrication are currently a topic of interest. Of the cell materials, silicon seems the least critical from a geological perspective, as it is the second-most-abundant material in the earth's crust. Obtaining enough wafer material is a question of installing enough refining, ingot pulling and sawing capacity (which will still be difficult). Materials such as bismuth, indium and silver, which are commonly used in cell and module electrodes, are far less available and are therefore widely discussed in detail in the PV community. A few examples are:

- General considerations on a terawatt-scale PV were reported by Haegel et al. [9] in 2019, including the statement: "For current manufacturing, silver consumption is 20 metric tons (±5 tons) per GW of production. At these levels, terawatt-scale production could exceed total worldwide silver production by 2030. Targeted R&D is needed to reduce Ag use, perhaps via replacement by Cu, coupled with recycling efforts."

- Verlinden [7], in 2020, offered the estimation: "On a 156mm wafer, typically 120mg–130mg of paste is used, corresponding to 96–104mg of Ag or about 20mg/W. The PV industry currently uses about 20 tons of silver per GW of production (2,400 tons of silver in 2019) or a bit more than 10% of the global production of silver. If nothing changes in the consumption of Ag in PV production, at the 1TW level of production (around 2028), the PV industry will use 100% of the global production of silver." Note, however, that this was conjectured on the basis of standard passivated emitter rear cell (PERC) technology, which uses less silver than more advanced approaches.

- More detailed aspects for silver specifically were considered by Zhang et al. [6] in 2021, who also looked into material use for different cell technologies. A silver usage of less than 2mg/Wp was suggested for sustainable growth to a terawatt production level, which far exceeds the targets aspired to in the ITRPV roadmap.

- Goldschmidt et al. [4] examined the effect of a terawatt PV market on different materials, including silver. They found: "If the silver consumption per cell remained constant such that only device efficiency increases reduce the per Wp silver consumption, the demand of the PV industry will exceed today's global

"Many scientists and organizations predict multi-terawatt per annum PV production to become a reality between 2030 and 2035."

silver production as early as in the year 2027…", considering an aggressive growth scenario.

- In 2022 Ballif et al. [10] considered terawatt-scale PV production options and concluded: "Substitution materials can be used for critical elements (for example, silver has been replaced with copper and indium with zinc and/or tin in SHJ cells)."

This paper aims to give an overview of the current state of knowledge regarding the use of silver in PV production, its limitations and possible alternatives.

Looking back – learning rates and price fluctuations

In the early stages of PV development, evaporated and plated contacts were mostly used for solar cell metallization. In the 1980s, printed silver contacts were introduced and became state of the art in production, with a few exceptions [11]. Initially, printed contacts had poor conductivity and contact resistivity [12], large feature size and high material consumption. As the general state of development was not very advanced for silicon solar cells, these contacts still fulfilled the requirements of the solar cells that existed at the time.

More importantly, the introduction of screen-print technology into solar cell production represented a major cost reduction in comparison to the use of vacuum evaporation (see Table 1), which typically had poor material utilization and was both time consuming and labour intensive [13]. Although the metallization cost of screen-printed silver contacts was considerably higher than that in today's solar cells, it only accounted for less than 0.2% of total module costs back then, providing little incentive to reduce silver paste usage for cost benefits.

With the rapid uptake of screen-printed contacts in the 1980s, the use of plated contacts also declined until BP Solar revived this approach in their 'SATURN' cells, which were manufactured from the 1990s to 2008 using an electroless copper (Cu)-plating sequence [14]. The main driving force of using Cu-plated contacts was to overcome a series of limitations of screen-printed silver contacts in the 1990s, such as poor metal conductivity, large finger width, poor aspect ratio and mandatory requirements imposed on heavily diffused emitters [15]. In 2009 Suntech introduced the 'PLUTO' cell, which featured simpler processes for forming the Cu-plated contacts using a combination of high-throughput laser doping and electrolytic plating equipment.

Even though BP Solar and Suntech both discontinued the production of Cu-plated cells, significant progress has nevertheless been made in the last two decades in addressing the challenges linked to Cu-plated metallization,

	Front-side metallization cost in 2020 [US$/W]	Module cost in 2020 [US$/W]	%
1975 evaporated titanium-palladium-silver [13]	45	110.3	40.8%
1975 SP Ag [13]	0.203	110.3	0.18%
2020 SP Ag [3]	0.0128	0.2	6.42%

Table 1. Metallization costs for evaporated contacts in 1975, and for screen-printed contacts in 1975 and 2020.

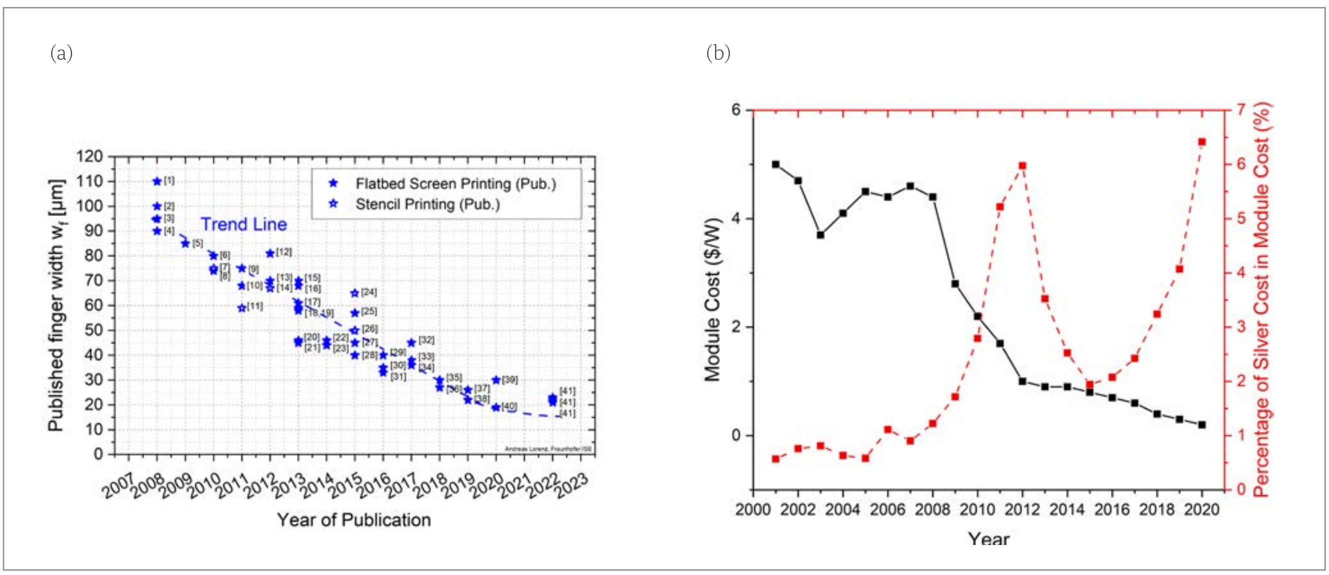


Figure 1. (a) Learning curve of the mean front-side finger width using screen and stencil printing, based on published results from 2008 to 2021 (modified and updated version based on Lorenz et al. [19]). (b) Historical metallization cost from silver paste usage and share of metallization costs in total module costs.

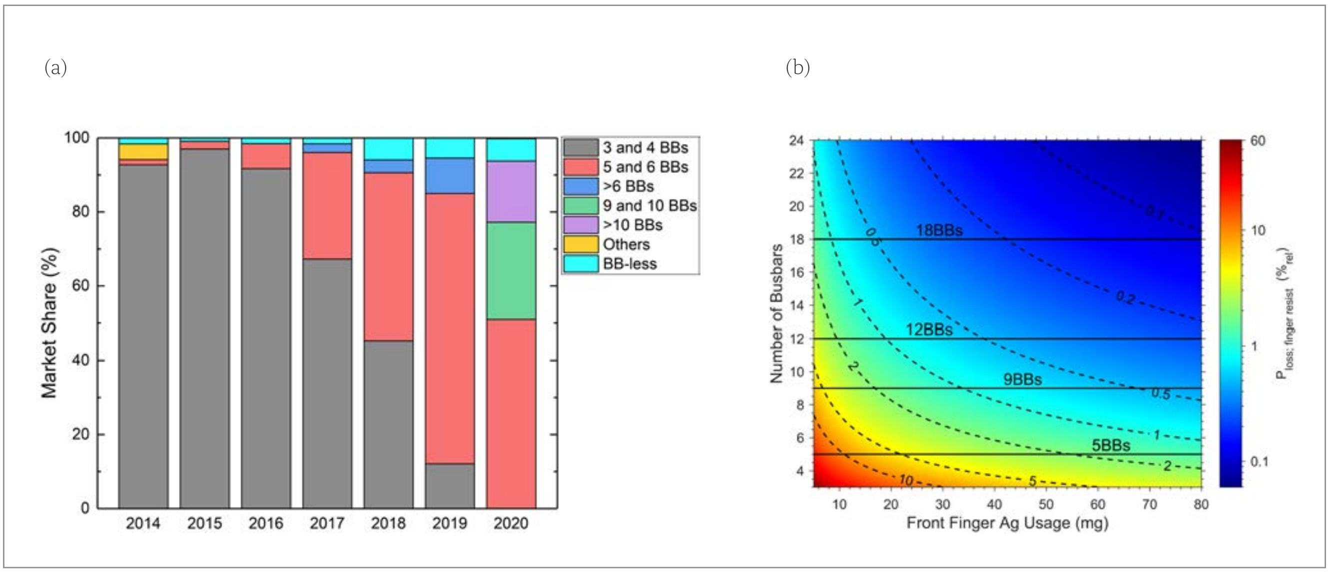


Figure 2. (a) Historical market share of interconnection technologies with different numbers of busbars. (b) Relative finger resistive losses in typical industrial PERC solar cells as a function of the number of busbars/interconnection wires and front-side silver usage in the fingers.

as reviewed by Lennon et al. [11]. SunPower has been commercializing high-efficiency Cu-plated interdigitated back contact (IBC) cells and modules since 2008, with excellent performance and reliability. In addition, several institutes and companies are now demonstrating excellent efficiencies, reliability and manufacturability using Cu-plated contacts in TOPCon [16] and HJT [17] cells. For this reason, approaches based on Cu-plated contacts are still expected to play an important role in the future, as will be discussed further in a later section.

Continued development of printing technology, and especially of paste materials, has enabled silver screen printing, as a dominant metallization technology, to remain suited to meeting the challenges encountered in subsequent cell development. For instance, the transition towards lightly doped emitters has led to the requirement for smaller finger spacings and finger widths in order to reduce losses due to emitter lateral resistance and optical shading from the fingers, as well as prompting the development of silver pastes designed to form low-resistivity metal-semiconductor contacts with such emitters [18]. Meanwhile, increases in wafer dimensions and reduced optical reflection have significantly augmented the current output of solar cells, which imposed much stricter requirements on the conductivity of silver pastes. A major boost of innovation was triggered around 2010/2011 when silver costs skyrocketed to above US$1,500/kg, primarily because of speculation, and the share of silver paste cost reached an all-time-high level of ~6%, compared with just 1% of total module cost in 2000, as shown in Fig. 1(b). This made the goal of reducing silver usage in screen-printed contacts one of the top priorities in the PV industry to bring down module manufacturing costs.

Since 2011, cell interconnection technologies have been rapidly evolving towards interconnection concepts with more numerous and narrower busbars, as shown in Fig. 2(a) (data from ITRPV 2015–2021 [3]). This evolution effectively triggered the development of fine-line screen-printing processes and materials, as the usage of such interconnection concepts substantially decreased the requirements regarding the lateral resistance of the front-side contacts, as shown in Fig. 2(b) [6]. Concurrent with this evolution, rapid progress was made regarding paste formulation and development of new screen architectures for fine-line printing. This impressive progress, primarily within the last 15 years, is clearly visible in the steep 'learning curve' of the mean finger width of typical c-Si solar cells, based on published results, as shown in Fig. 1(a). As a result, the silver usage (mg/W) has been significantly reduced by a factor of four during the past 20 years, leading to a sevenfold reduction in the metallization cost associated with the use of silver pastes.

Notably, the cost ($/W) of silver pastes has remained within a tight range (1.28–1.55¢/W) during the last five years because of the relatively stable silver price and significantly slower rate of reduction in silver usage, as shown in Fig. 1(b). The silver usage per cell has only reduced by ~ 30mg/pcs during the last five years, compared with almost 200mg/pcs from 2010 to 2015. This shows that, after aggressive silver reductions with a remarkable evolution of screen-print technology, further reductions in silver usage are becoming more and more challenging. Meanwhile, the total module cost has fallen dramatically by ~75% during the last five years, making the slow decrease in cost of silver pastes an increasing concern to the PV industry.

In 2020 the production of ~180GW of PV modules consumed approximately 12.7% of the global annual silver supply [20]. As the PV industry heads towards a terawatt manufacturing capacity, despite ongoing efforts in reducing the silver usage in industrial silicon solar cells, the silver demand by the PV industry will most likely rise significantly. Therefore, besides costs, the issues surrounding supply and availability of silver are setting the alarm bells ringing in the PV industry. Goldschmidt et al. [4] show that the demand from the PV industry could exceed today's global silver supply as early as 2027 if the silver usage per cell remains unchanged. With a historical learning rate of 15–20% in silver usage, by 2050 the PV industry will have an annual silver demand of 10–18kt, corresponding to 40–75% of today's global silver supply. To allow sustainability with regard to material consumption in terawatt-level PV production, silver usage needs to be swiftly reduced for all cell technologies to less than 5mg/W, or even 2mg/W [6,7] – a level that will not be met in the next decade according to the current trajectory from ITRPV. This highlights the need for urgent technological advancements in existing screen-printing technologies to allow more aggressive reductions in silver usage, or a transition towards alternative metallization techniques.

"To allow sustainability with regard to material consumption in terawatt-level PV production, silver usage needs to be swiftly reduced for all cell technologies."

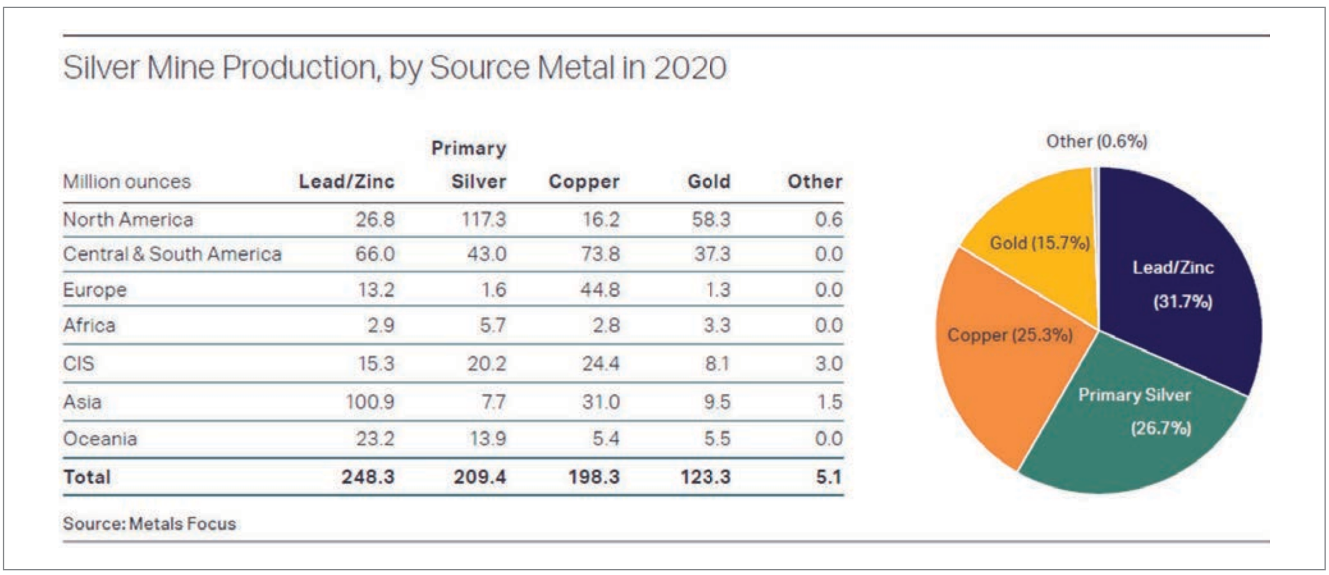
Looking forward – predictions and considerations

Silver availability – abundance, supply and price fluctuations

While silver is geologically far less abundant than copper [23], the main supply risks related to

	Ag	Cu
Supply		
Mine production	24kt	20,677kt
Actual price range from 1990 to 2021	US$195.5–1,569.3*1,000/t	US$2.0–11.7*1,000/t
Main mining countries	Mexico (23%), Peru (14%), China (14%), Chile (6%), Russia (5%), Poland (5%)	Chile (28%), Peru (12%), China (8%), Congo (7%), USA (6%)
Mining market concentration *Ranges from 0 (low) to 1 (monopoly)*	Low – 0.11	Low – 0.12
Political stability of mining countries *Ranges from 0 (low) to 100 (high)*	Medium – 37	Medium – 55
By-product dependency	Primary Ag (27%), Pb/Zn (32%), Cu (25%), Au (16%)	Primary Cu (91%), Ni (5%), Au (2%), Pb/Zn (2%)
Demand		
End-use market shares	Industrial (54%), investment (22%), jewellery (17%), silverware (4%), photography (3%)	Equipment (32%), building construction (28%), infrastructure (16%), transport (12%), industrial (12%)

Table 2. Comparison of silver and copper supply and demand [21–26].


Silver Mine Production, by Source Metal in 2020

Million ounces	Lead/Zinc	Primary Silver	Copper	Gold	Other
North America	26.8	117.3	16.2	58.3	0.6
Central & South America	66.0	43.0	73.8	37.3	0.0
Europe	13.2	1.6	44.8	1.3	0.0
Africa	2.9	5.7	2.8	3.3	0.0
CIS	15.3	20.2	24.4	8.1	3.0
Asia	100.9	7.7	31.0	9.5	1.5
Oceania	23.2	13.9	5.4	5.5	0.0
Total	**248.3**	**209.4**	**198.3**	**123.3**	**5.1**

Source: Metals Focus

Figure 3. Companionality of silver mining, i.e. the percentage of silver stemming from mining activities dedicated to mining silver/other metals.

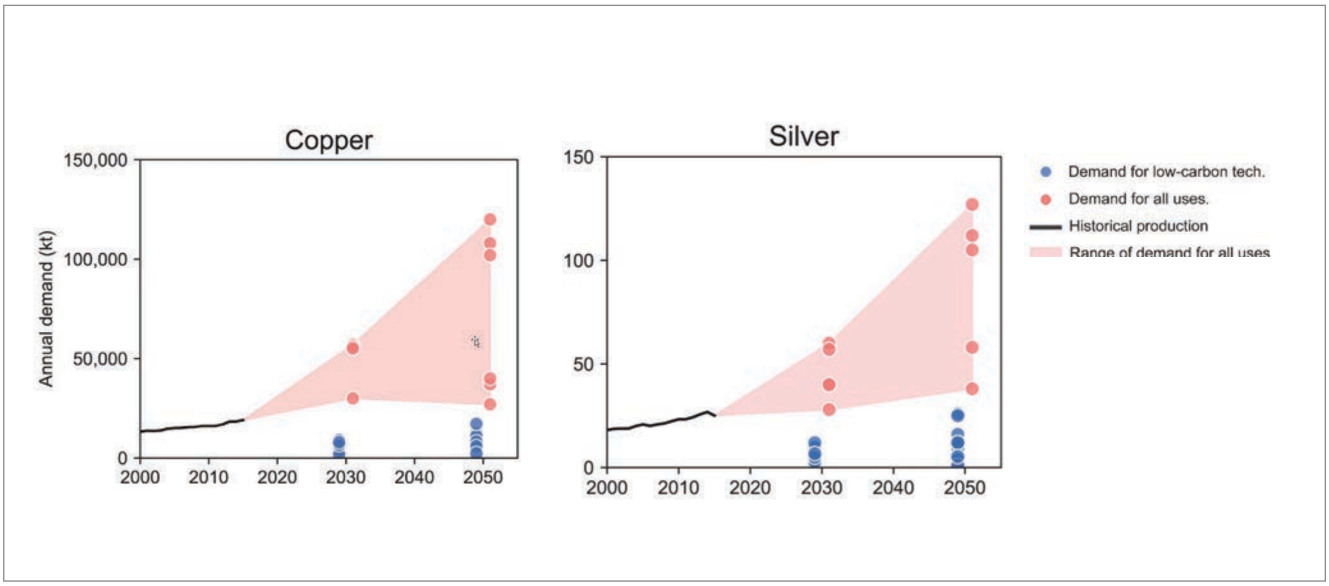


Figure 4. Literature review of demand outlook for copper and silver for all end-uses and low-carbon technologies (reproduced with permission from Watari et al. [28]).

silver for PV in the short term originate from its price volatility, by-product dependency and an anticipated mismatch between demand and current mining production (see Table 2). Over 70% of silver mining is derived from by-product sources [21]. This companionality means that silver supply is mostly dependent on the market for the host metals lead/zinc, copper and gold, and less reactive to changes in silver demand (see Fig. 3). (*Companionality* is the degree to which a metal is obtained largely or entirely as a by-product of one or more host metals from geologic ores.)

Silver mining activities are geographically relatively well scattered but partially located in countries with a relative risk of politically-motivated violence – and therefore of supply constraints – such as Mexico, Peru, China and Russia [25]. An overall huge increase in demand for metals is additionally expected in the next few years in the context of the global energy transition [27]. Besides PV, electromobility will be one the main drivers for silver demand. The consumption of copper, as a key material in all energy technologies and grid infrastructures, is projected to increase as well [28] (see Fig. 4).

While from these factors it is not straightforward to formulate a prognosis on silver cost, the mere fact remains that silver is intrinsically more expensive than copper by a factor of 50–100, and that an annual PV production on a terawatt scale will consume substantial shares of silver, irrespective of how much the consumption per Wp can be reduced.

In the case of copper, even considering a fairly high consumption of 30mg/Wp, a 3TW annual PV production would only consume 0.5% of the current annual mining volume, or 1% of the current annual recycling volume.

Silver usage in PV

If PV production capacity increases to a terawatt level, at least 30% of the annual silver production will be consumed, even if learning rates for silver reduction were to be considered more aggressive than predicted in the ITRPV roadmap (Fig. 5). At a regular rate of innovation progress, this amount will instead be 50–100%, which will result in severe consequences regarding cost. The deepest insights are given in Zhang [6] and Goldschmidt [4].

Apart from cost, silver has a disadvantage in terms of sustainability, as its CO_2 and water

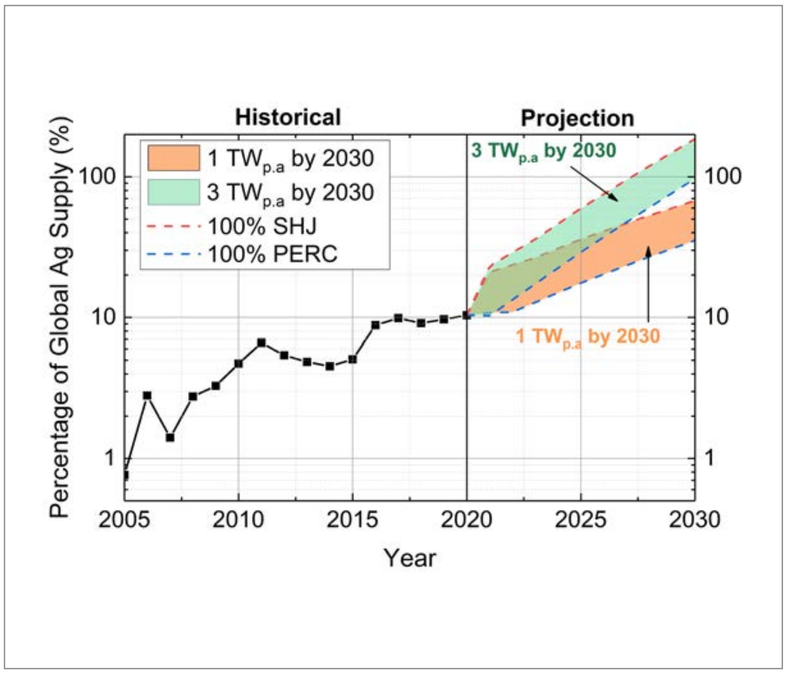


Figure 5. Calculation of the silver usage in PV as a percentage of global Ag supply, depending on PV production growth. The areas of uncertainty represent the variation in the progress made in silver reduction.

"If PV production capacity increases to a terawatt level, at least 30% of the annual silver production will be consumed."

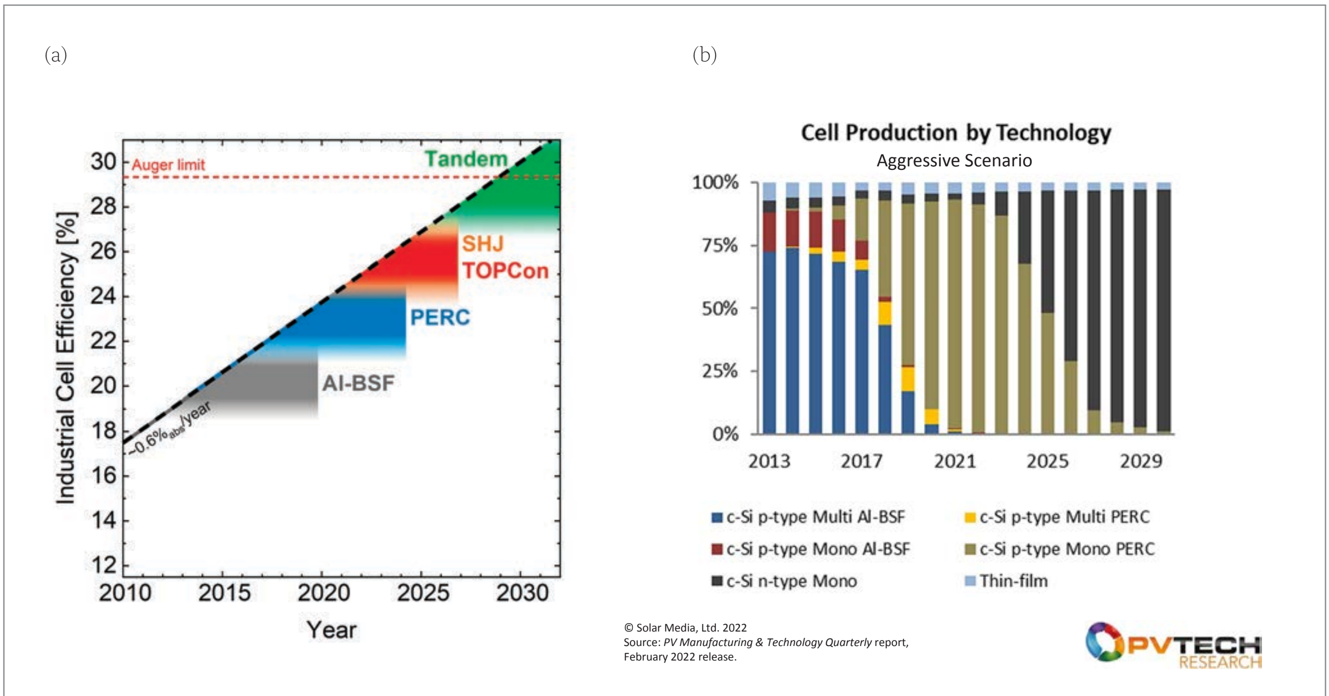


Figure 6. Expected evolution of production efficiencies with corresponding cell type to enable and efficiency progression of ~0.5–0.6%$_{abs}$/year [31]. (b) Expected decline in PERC production through to 2030 [32].

footprints are larger than those for copper. This may be important in markets that have established incentives for sustainable PV (such as France).

The rate of increase of PV production is hard to predict. Ambitious growth trajectories are desirable, considering climate goals and an increased amount of green energy in PV production itself and other sectors. This, however, would advocate an even faster transition to copper metallization, both from a carbon footprint and a silver usage point of view.

Metallization of future solar cell concepts

Solar cell producers are expected to rapidly transition from currently dominant standard bifacial p-type PERC to future solar cell concepts such as n-type tunnel oxide passivated contact (TOPCon), silicon heterojunction (SHJ) and IBC (significant market shares until 2025), and eventually silicon–perovskite tandem technologies, in order to maintain an efficiency improvement rate of ~0.5–0.6%$_{abs}$/year (Fig. 6).

Unlike the current bifacial PERC technology, which makes use of aluminium pastes for the rear-side metallization, industrial TOPCon and SHJ cells require silver grids on both sides, and so a major issue is that silver consumption is significantly higher. Recent publications indicate that the silver usage for TOPCon cells manufactured in 2020 was about 25.6mg/W (66% more than for PERC), while for SHJ cells it was 33.9mg/W, which is too high to sustain terawatt-scale production of SHJ cells, given the global annual supply of Ag [6].

Silver usage per cell in TOPCon and SHJ cells is expected to rapidly decrease in the coming decade because of the constant progress made in screen-printing technology, the rapid introduction of pastes with lower silver content by weight (e.g. low-temperature Cu pastes for SHJ cells), and the adoption of advanced metallization concepts enabling lower Ag usage, such as laser transfer printing, dispensing, rotary printing and plating [29,30].

In the long run, the transition to tandem solar cell concepts, such as silicon–perovskite or perovskite–perovskite, seems very likely. While the current is lower for these types of cell, it is more difficult to achieve highly conductive metal lines because of temperature restrictions and incompatibilities with wet-chemical processes. As a consequence, modifications to existing solutions for screen printing, physical vapour deposition (PVD) or plating approaches will be necessary.

Messmer et al. [33] discuss the requirements for the minimum line conductivity of the front-side metallization of a Si–perovskite tandem solar cell as a function of the transparent conductive oxide (TCO) thickness, finger pitch and interconnection design (e.g. number of wires), highlighting the challenges for all existing metallization approaches. State-of-the-art low-temperature pastes for screen printing are applicable for contacting tandem solar cells [34] but face the challenge of either high silver content or low line conductivity for these low-temperature ranges.

Alternative metallization approaches, such as plating, provide low line resistance and low process temperatures but run the risk of exposing the perovskite to aqueous solutions and acidic or alkaline electrolytes. A proof of concept for plated contacts for perovskite solar cells was demonstrated by Hatt et al. [35] using PVD layers to protect the perovskite from exposure to the chemical environment. The ideal metallization for perovskites has yet to be found, but economizing silver is advisable in any case, even though less metal might suffice for loss-free current extraction.

As regards silver availability, the market share of perovskite-containing solar cells in 2030 is expected to be only a few per cent. While these types of cell may relieve the pressure in relation to silver usage in the long term, their small market share in the near future will not lead to significant savings in silver.

Interconnection technologies

Besides the progress made with regard to the metallization technology itself, the development of new interconnection approaches has played an important role in the past two decades and has to be considered to be closely connected to the evolution of the metallization process (see above). Depending on the choice of interconnection technology, the metallization can be greatly influenced, which affects the Ag consumption.

The conventional approach by soldering does not involve any Ag regarding interconnection. A few years ago, Sn62Pb36Ag2 was the established solder alloy, but has now been replaced by near-eutectic Sn60Pb40, totally eliminating Ag within the solder joint. New concepts using multiple round wires instead of flat ribbons allow further material consumption economies, as well as savings in the solar cell metallization (i.e. small contact pads instead of continuous busbars).

Commercial approaches have been launched by Meyer Burger GmbH with its SmartWire Connection Technology (SWCT) [36], or by Schmid with a multi-busbar interconnection. Both of these allow considerable reductions in Ag paste consumption for the electrodes: for example, 20–25mg is required for modern busbarless solar cell designs for the front side, whereas 60–80mg is needed per side for current 9 BB to 12 BB H-pattern grids for PERC or TOPCon [37]. In addition, a lean and reasonable pad design in combination with wave-shaped wires offers the possibility of realizing stress-reduced interconnection of high-efficiency solar cells [38]. Another approach is to omit the rear-side Ag pads of monofacial solar cells and directly solder onto the Al rear-side electrode [39,40]; however, new challenges arise with respect to critical resources such as indium and bismuth, which are needed for the solder coating during low-temperature interconnection [6].

An alternative to the conventional soldering process is the low-temperature and lead-free interconnection with electrically conductive adhesives (ECAs). Beside the polymeric matrix, ECAs contain electrically conductive particles, typically Ag with a filler content between 25 and 30 vol%. Additionally, the ribbons used in combination with ECAs feature a thin Ag coating to protect the Cu core from oxidation. In the past few years, efforts have been made to decrease the amount of ECA for ribbon interconnection in order to reduce material consumption and save costs [41].

> "To pave the way for terawatt PV production, advanced module interconnection can play a large part, but that alone will not fix the material issue."

Another important trend is the so-called *shingled cell interconnection*, based on a concept developed in the late 1950s [42]. Multiple cell stripes are cut out from a metallized and fired host cell with a special, screen-printed metallization layout on the front and rear sides. The cell stripes are interconnected into a shingled string by overlapping and connecting the rear busbar of one stripe to the front busbar of the next stripe [43]. Because of the edge interconnection nature of a shingle cell, fingers with a higher lateral conductivity as well as a busbar for interconnection are needed, which increases the total silver usage. In addition, Ag-containing ECAs are used for interconnection. However, the demand for alternative and flexible interconnection technologies is very high. PV modules with high requirements in terms of aesthetic appearance are needed in the growing market of integrated PV. The so-called *shingle matrix technology* offers high energy densities in the module as a result of the increased active area, which in turn lowers the costs per Wp [44].

In short, wire interconnection offers the greatest promise for reducing silver consumption (unless other materials are used to print busbars), but still faces important technological- and material-related challenges. Busbar-based interconnection will remain very important in the coming years. To pave the way for terawatt PV production, advanced module interconnection can play a large part, but that alone will not fix the material issue.

Technologies for silver reduction and replacement

Improvements in 'standard' printing

Steady progress in silver paste printing technology is expected as a result of the continuous optimization of screens, pastes and printing processes. Further progress in the field of flatbed screen printing towards even finer front-side contacts can be anticipated. Recently devised models [45] for the advanced simulation of screens and pastes will enable a focused development of these materials. The use of high-performance fine-mesh screens and so-called *knotless screens* with a mesh angle of 0°, as well as the continual optimization of silver pastes, already enable reliable printing of contacts down to a width of approximately 20μm with high aspect ratio and good lateral conductivity for high-efficiency PERC solar cells [37]. Additional breakthroughs can be expected which will enable reliable screen-printing processes for contacts down to a width of 10–15μm in the near future.

In parallel, further promising printing technologies which have been extensively evaluated and developed in recent years are approaching the industrial application stage and might challenge flatbed screen printing as the dominant technology for solar cell metallization. Rotary screen printing, multi-nozzle dispensing, high-resolution stencil printing and pattern transfer printing [46] have recently produced impressive results regarding fine-line metallization and substantial silver reduction. Nevertheless, the economic and technical benefits of these innovative approaches have yet to be proved, and it is unclear whether one of these technologies will achieve a ranking among the applied metallization methods in industry.

It is important to recognize that the amount of silver used cannot be reduced indefinitely. Ever narrower and lower printed lines may give rise to reliability issues or introduce complications regarding contact formation and interconnection.

On the basis of the historic learning rates of silver printing technology, a silver consumption of approximately 10mg/Wp can still be expected in a terawatt production environment, which would clearly be too much considering the data presented earlier in this discussion.

Plating technology

Copper plating has been under development for several years as an alternative metallization approach for c-Si solar cells. The abundance of copper provides the opportunity to realize significant savings with a material cost of up to 100 times lower than that of silver, yet with similar conductivity. Typically, the combination of a stack of a thin nickel seed layer (plating height < 0.5μm), a bulk copper layer (<5–10μm) and a thin silver or tin surface finish (<0.5μm) is a suitable replacement for screen-printed silver fingers for PERC [47] or TOPCon [16] solar cells. For SHJ solar cells, the nickel seed layer is typically replaced by PVD metal seed layers. The silver consumption per solar cell can be reduced by 90% compared with screen printing through the application of plating, and even silver-free metallization can be achieved when a tin surface finish is used.

Plated contacts have been successfully demonstrated in PERC, TOPCon and SHJ solar cells, leading to record efficiencies of 22.2% [48], 24.0% [49] and 26.07% [17] respectively. The development status and learning curve of screen-printed contacts for c-Si solar cells is about 15 years ahead of the development of plated contacts. The main research topics for plated contacts address improvements in process throughput, tool footprint, capital expenditure (CAPEX) cost reductions and optimizations in the process sequence to further improve solar cell efficiency. Major factors in the comparison of cost of ownership calculations for silver screen-printed metallization and plated metallization are printed silver mass and silver price for screen printing and CAPEX costs of the plating cluster. In particular, solar cell designs with increased silver consumption, such as TOPCon and SHJ, are the most likely scenarios for implementing plated contacts. Since plating tool development is at the beginning of its learning curve, it is estimated that scaling effects will lead to a decrease in CAPEX costs and an increase in process throughput.

Overall, plating seems to be a possible technology replacement for tackling the upcoming silver dependence in a multi-terawatt market. However, this will require a market penetration over the next few years that exceeds that of the early adoption phase.

“Overall, plating seems to be a possible technology replacement for tackling the upcoming silver dependence in a multi-terawatt market.”

Printed copper metallization

Replacing silver pastes with similarly conductive copper pastes has the big advantage of being a drop-in replacement in current production environments, as the same production equipment can be used. Yet, copper metallization also poses great challenges with respect to paste manufacturing, handling in the metallization process (oxidation of Cu particles) and possible negative effects on the solar cell because of diffusion of copper into the cell [50,51].

The use of copper paste for the metallization of c-Si solar cells is easier to realize for cell concepts like SHJ using low-temperature silver paste, since particularly sophisticated problems such as copper in-diffusion during the fast-firing process can be avoided, as the TCO layer acts as an effective diffusion barrier for copper [52]. Furthermore, the considerably lower temperature of the curing process is less critical with regard to oxidation [52]. The use of copper pastes for SHJ solar cells gained particular interest in the early years after 2010 because of the high silver price at that time. Early investigation with newly developed low-temperature copper pastes showed promising results with respect to printability, finger geometry, lateral resistance, contact resistance and adhesion on Si material with a TCO layer on the front side [53,54]. Furthermore, oxidation during the printing process and subsequent curing was not considered a major problem.

Another promising approach is the application of a dual printing process using non-contacting copper paste for the busbars and silver paste for the fingers [55,56]. This method can result in considerable savings in silver without the additional problems related to copper-printed fine-line fingers. Yet another approach is the use of pastes based on silver-coated copper particles, which effectively eliminates the problems related to oxidation [57]. While good results on SHJ solar cells could be obtained using this type of paste, the economic benefits were not entirely convincing, as the fabrication of Cu-coated Ag particles is an elaborate and rather costly process.

Applying a printed metallization with Cu paste in high-temperature sintering cell concepts, such as PERC and TOPCon, is far more complicated, as additional problems become relevant: for example, fast oxidation during fast firing, diffusion of copper into the silicon bulk material at elevated temperatures, and degradation due to Cu precipitates which penetrate the p-n junction. Usually, an effective diffusion barrier below the copper metallization is needed in order to prevent the copper from migrating into the bulk material; this can be realized, for example, by a printed seed layer diffusion barrier using silver or nickel pastes [51]. The results of a few studies indicate realistic prospects for implementing this approach on solar cell concepts using high-temperature pastes, such as PERC [58,59]. However, certain important aspects, for example the contact behaviour between the contact grid and the emitter, oxidation of Cu particles and long-term stability in the module, have not yet been fully resolved.

Conclusion

On the basis of the knowledge collected above and on the authors' experience, the following conclusions are drawn.

Status and 'standard' printing perspectives:

- Silver cost and availability will become a growing issue in PV production. Innovation will be needed in order to lower the silver consumption or to replace silver.
- Flatbed screen printing continues to make rapid progress in reducing finger width and silver lay-down for all cell concepts.
- Several innovative technologies, e.g. rotary printing, dispensing, high-resolution stencil printing and pattern transfer printing, compete with screen printing with regard to throughput, fine-line metallization and reduced silver lay-down. The technological path which will provide the most benefits for industrial mass production in the future is not absolutely clear at present.
- The evolution of silver printing will continue, but physical limitations for the minimum amount of silver per cell are expected without sacrificing too much efficiency. The precise amount depends on cell type and interconnection strategy and should be the subject of research efforts.
- From historical data (for various cell types), an average ~10mg/Wp silver for TWp production capacity may be realistic.

"The authors believe that some copper-based cell metallization will probably be realized for at least some, if not all, cell concepts, which will take some pressure off the silver supply situation."

- Advanced module interconnection can make a contribution to reducing silver consumption, but in itself will not fix the material issue.

Disruptive approaches:

- Printing of copper pastes is a strong point technologically, as any solution based on printing can be a drop-in replacement and has low process complexity and CAPEX, ***but***
  - printing of copper pastes faces technological challenges (conductivity, oxidation, printability, etc.), with it being currently unclear if these can be overcome
  - pastes based on silver-coated copper particles can fix the oxidation issue, but face higher costs and still significant silver usage
- Copper plating, which has been demonstrated to a very high level, has technological benefits over printing technologies. Silver consumption can be reduced to negligible levels, or even to zero, ***but***
  - plating has a lower technology readiness level (TRL), higher process complexity, higher CAPEX and higher maintenance cost
  - the cost learning curve for plating is still in its early stages

Future cell concepts:

- Perovskite–silicon tandem technology will increase cell efficiency, and the lower current/higher voltage will enable reduced metal consumption.
- It is highly likely that production capacity for standard silicon PV will be increased to critical levels before perovskite–silicon tandem cells reach market maturity, and so metallization innovations are still needed.

Overall, it is clear that innovations in metallization and interconnection technologies are much needed, and are likely to pay off in the near, or at least in the not-too-distant, future. Of course, the exact technology that will make it to production cannot yet be identified without uncertainty. The authors believe that some copper-based cell metallization will probably be realized for at least some, if not all, cell concepts, which will take some pressure off the silver supply situation.

On the one hand, this will mean a disruption to the current mainstream, but on the other, copper-based metallization approaches have been used successfully in the past in silicon PV.

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About the Authors

Jonas Bartsch studied chemical engineering at the University of Karlsruhe and received his diploma in 2007. He joined Fraunhofer ISE to pursue a Ph.D. in the field of advanced front contacts for silicon solar cells with plating technology. After receiving his Ph.D. from the Albert Ludwig University of Freiburg in 2011, he continued to work on plating and other chemical/electrochemical techniques for PV fabrication at ISE. He is currently co-head of the Electrochemical Processes group.

Sven Kluska studied physics at the Albert Ludwig University of Freiburg, receiving his diploma in 2010. He joined Fraunhofer ISE to pursue a Ph.D. in the area of laser chemical processing for silicon solar cells, and was awarded his Ph.D. by the Albert Ludwig University of Freiburg in 2014. His research interests include electrochemical processing for solar cell applications with a focus on plating metallization. He is currently co-head of the Electrochemical Processes group.

Markus Glatthaar studied physics at Eberhard Karls University in Tübingen, Germany. In 2007 he received his Ph.D. in physics from the Albert Ludwig University of Freiburg, studying organic bulk heterojunction solar cells. From 2008 to 2010 he held a postdoc position at Fraunhofer ISE, and joined RENA GmbH in 2011 as a senior solar cell technologist. From 2012 to 2021 he was in charge of various departments at Fraunhofer ISE, and since 2022 has been head of the PV2plus spin-off team.

Estelle Gervais is a research scientist at Fraunhofer ISE in the fields of raw material criticality, sustainability strategies and circularity in PV. She holds an M.Sc. in energy technology from the Technical University of Kaiserslautern and the National Institute of Applied Sciences of Rouen. She has worked as a project engineer for the development of climate plans in the public sector in France, and joined Fraunhofer ISE in 2019, where she is pursuing her Ph.D. on sustainable material supply chains for PV.

Andreas Lorenz studied printing and media technology at Stuttgart University of Applied Sciences. After receiving his diploma degree in 2006, he worked for six years as a process engineer and junior product manager for a global printing machine manufacturer. In 2012 he joined Fraunhofer ISE and worked from 2014 to 2017 as a Ph.D. student on the development of rotary printing processes for solar cells. Since 2020 he has been head of the Printing Technology group.

Angela De Rose studied physics at RWTH Aachen and the University of Valencia, and received her master's in 2015 from RWTH Aachen. In 2016 she joined Fraunhofer ISE as a Ph.D. student in the field of solder interconnection technology for silicon PV modules. Her studies focus on the interconnection of SHJ solar cells and soldering on aluminum surfaces. Since 2020 she has been head of the Soldering team in the Module Technology department.

Brett Hallam is an associate professor in the School of Photovoltaic and Renewable Energy Engineering at UNSW Sydney. In the past he has worked on advanced hydrogenation for the treatment of LID in silicon solar cells, as well as contributing to the understanding of the role of atomic hydrogen in passivating silicon solar cells. He has now shifted his research focus to sustainability issues surrounding the materials and technologies used in silicon solar PV systems, and addressing critical sustainability challenges for terawatt-scale PV deployment.

Yuchao Zhang received his bachelor's in photovoltaics and solar energy from the University of New South Wales (UNSW), and has been working towards a Ph.D. at UNSW since 2019. His current research interests include laser processing for high-efficiency crystalline silicon solar cells, material sustainability of PV manufacturing, and novel screen-printing technologies for industrial silicon solar cells.

Loic Tous received his Ph.D. in 2014 from the KU Leuven, Belgium, and has led PV cell and module activities at imec since 2020. He is currently the coordinator of the HighLite project, which aims to significantly improve the competitiveness of the EU PV manufacturing industry, as well as the research lead of the imec.icon SUNDRIVE project, which deals with integration in the 3D curved roofs of electric vehicles. Since 2016 he has been co-organizer of the Workshop on Metallization & Interconnection for Crystalline Silicon Solar Cells.

Enquiries

Dr.-Ing. Jonas Bartsch
Head of Electrochemical Processes Group
Photovoltaics Division
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstr. 2
79110 Freiburg, Germany

Tel: +49 (0) 7 61/45 88-5737
Email: jonas.bartsch@ise.fraunhofer.de
Website: http://www.ise.fraunhofer.de

bifiPV2022 status and future: Entering the bifacial nPV era

Radovan Kopecek & Joris Libal, ISC Konstanz, Germany

Abstract

After several years of technological developments, measurement and quality standard specifications, and bifaciality implementations in energy yield simulation programs, bifacial PV has become reliable and will shortly become accepted as a valuable commodity. Since 2020, bifacial passivated emitter and rear cell (PERC) technology has been king of the energy markets, and, in combination with simple tracking systems (e.g. horizontal single-axis tracking – HSAT), the lowest electricity costs have been achieved. Because PERC is reaching its limit in terms of efficiency, and n-type technology is gaining momentum, in the future n-type PV (nPV) will replace PERC technology as the workhorse of the PV electricity market. This paper describes why, and most likely when, this will happen and which n-type technologies will be leading the pack in the race to bring electricity costs well below €0.01/kWh.

Introduction

We did it! Mid-March 2022 saw the installation of a cumulated capacity of 1TWp of PV system power worldwide [1]. In 2021 the total installations added up to about 180GWp, even though PV was currently in a poly-Si supply shortage crisis and, in consequence, the market was driven by availability and no longer by demand. In 2022, total installations of about 230GWp [2] are expected, and in the coming years, unlike what the International Energy Agency (IEA) or BENEF are predicting, an exponential increase will be necessary in order to reach the ambitious goals regarding CO_2 reduction. In the authors' opinion, such an exponential growth is not only necessary but also realistically possible, as the global world comes to understand the technological and economic potential of PV.

Fig. 1 depicts IEA's forecast of GW added per year compared with the actual figures. For more than 15 years, the predictions have been wrong, and the yearly installed PV technology power has always been underestimated. The increased growth follows a simple rule, identified by Pierre Verlinden some years ago: every third year, production doubles, which has been the case during the last 15 years. The authors are sure that the same trend will be true in future years as well, before saturation is reached at several TW. This means that from 2028 onwards, PV capacity

"From 2028 onwards, PV capacity is likely to reach 1TWp/year."

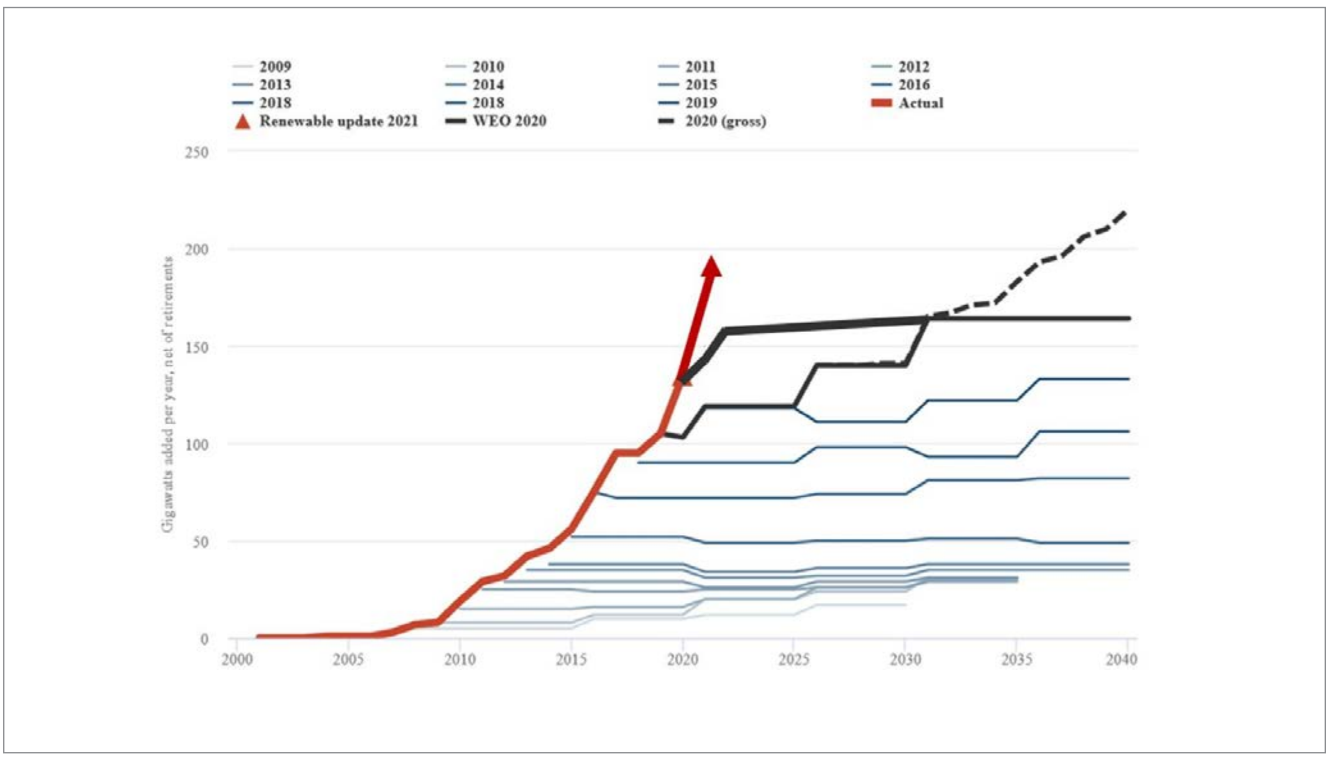


Figure 1. IEA's forecast of GW added per year versus reality (adapted from "IEA forecasts" [3]).

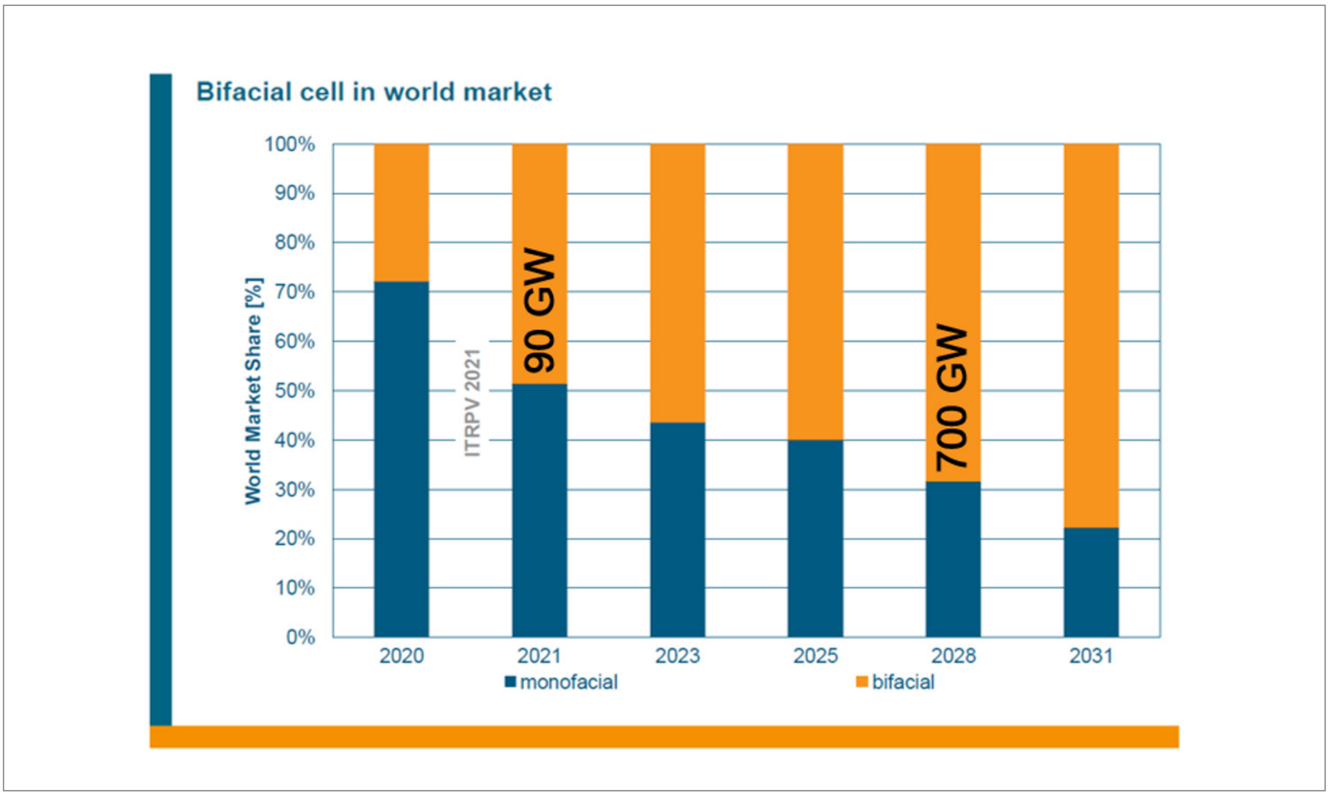


Figure 2. ITRPV 2021's forecast of the market share of bifacial cell technology.

is likely to reach 1TWp/year, with the major share being picked up by bifacial technology. Fig. 2 shows the forecast of the International Technology Roadmap for PV (ITRPV) of the market share of bifacial technology. Already 90GW bifacial cells had been produced in 2021, whereas 700GW are expected in 2028.

By 2030 there will be hardly any monofacial cell technology remaining on the market, almost entirely thereafter being replaced by its bifacial rivals. The technologies that will dominate at that time are the topic of discussion in the following section.

Status of bifacial technology

Bifacial PV's beginnings can be traced back to the first bifacial PV system at the MWp level incorporating n-type nPERT technology in a fixed-tilt configuration, such as the one located in Japan in 2013 using EarthON nPERT technology [4] (see Fig. 3). Bifacial nPERT was much more expensive at that time, mainly because the cost of n-type wafers was more than 30% higher than the cost of p-type wafers.

MegaCell, in 2015, started BiSoN (**bi**facial **so**lar cell on **n**-type) cell and module production. Using BiSoN modules, MegaCell set up a 2.5MWp [5] fixed tilt system, and ENEL a 1.75MWp [6] HSAT system, both in Chile in 2016. The year 2016 was, however, also the time when bifacial passivated emitter and rear cell (PERC) technology entered the market and offered a more cost-effective alternative for bifacial modules. While this slowed down the growth of n-type cell technologies, it helped a lot in pushing bifacial PV at that time. Since 2018, large HSAT bifacial PERC systems have begun to enter the market very quickly, and are monopolizing the bifacial PV market today. One of the largest of these is the planned 1.3GW HSAT bifacial PERC system in Karapinar (Turkey), which will be finalized in 2022 [7].

How did bifacial PV become standard? When the bifiPV workshops began in 2012 in Konstanz, there were still many challenges to overcome, as the benefits of bifaciality were not commonly recognized by the PV community. The developments considered to be the most important to make bifaciality bankable and sustainable were:

1. Implementation of bankable energy simulation programs.
2. Development of bifacial PERC technology.
3. Use of white reflectors between cells.
4. Combination of HSAT with bifacial modules.

Standards are important as well, but are not being used by many for measuring modules, and bifaciality is more of a priority. The authors believe that this will change when bifacial modules achieve the higher bifaciality of PERC modules, with bifacial factors between 0.6 and 0.7. Fig. 4(a) illustrates the white ceramic reflector on the rear side of the bifacial PERC module, which increases the front-side power of the module (and slightly reduces the bifacial factor). The final production stage of frameless double-glass modules is shown in Fig. 4(b).

On the one hand, PERC cell technology is now approaching its efficiency limit, while on the other, cell technologies based on n-type Si material offer the potential for not only higher efficiencies and

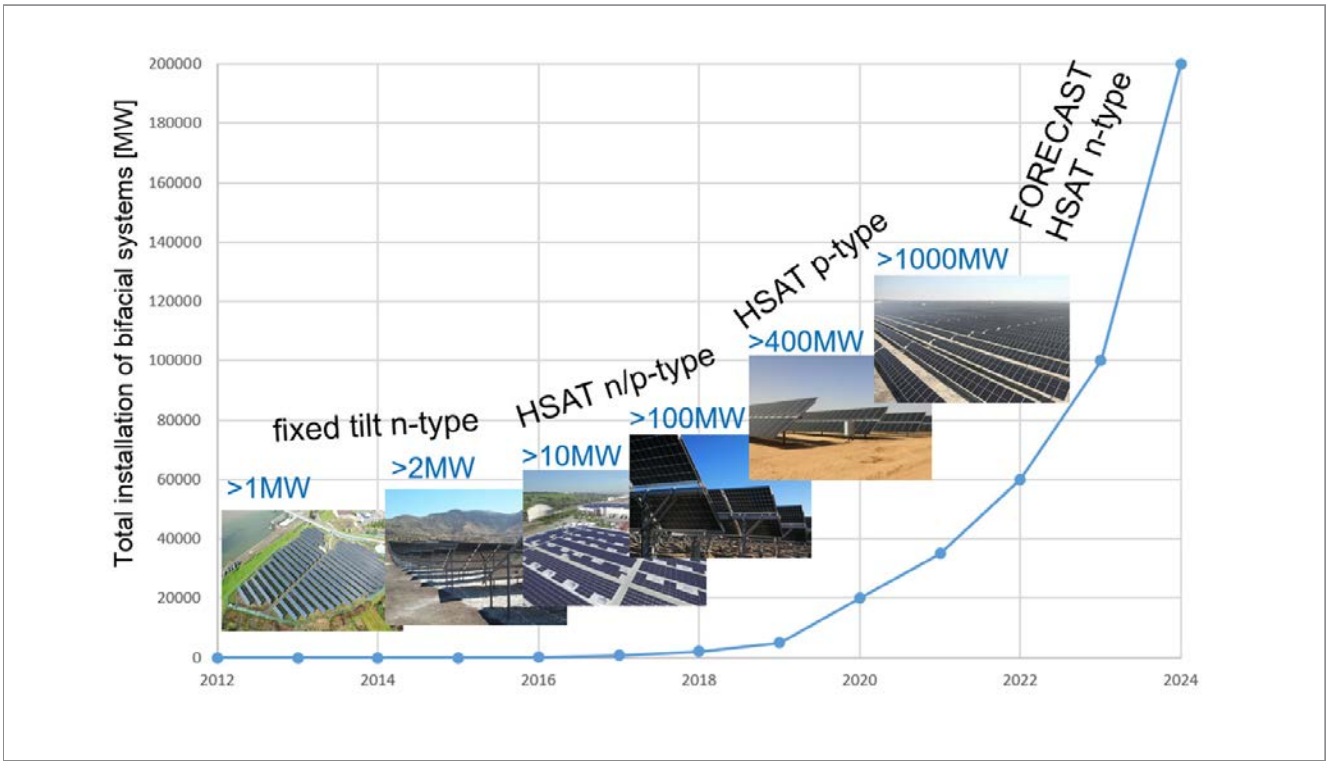


Figure 3. Cumulated bifacial PV system power over the years and the most prominent technologies in use at the time.

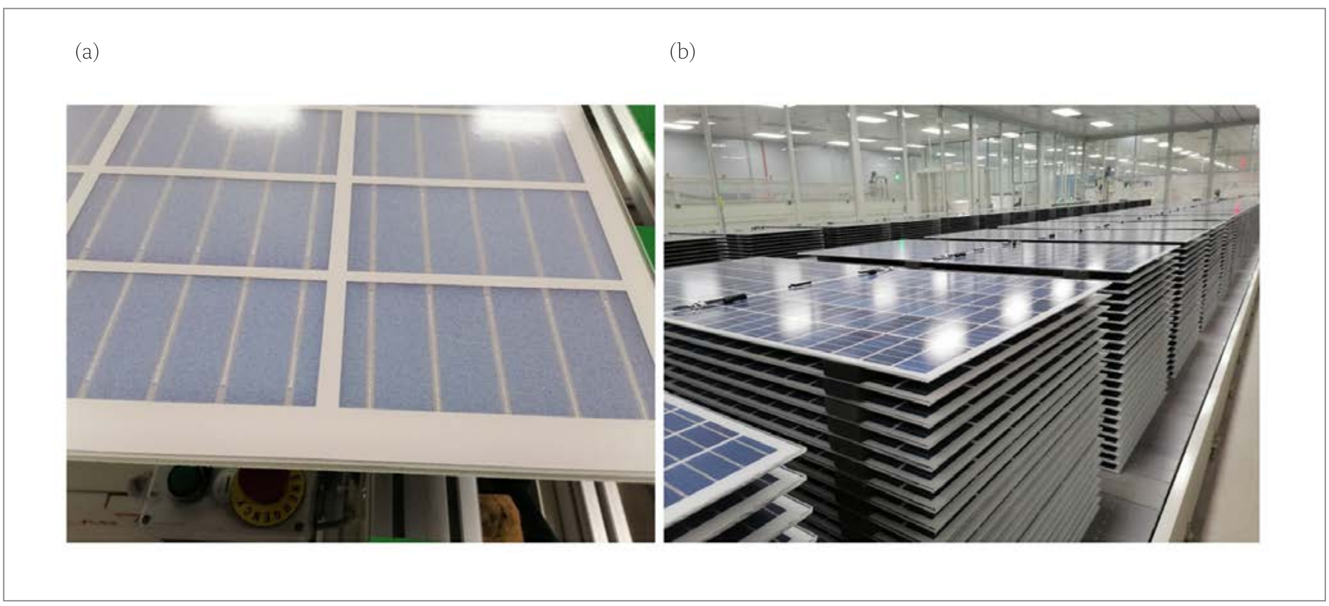
lower temperature coefficients, but also lower yearly degradation rates and higher bifaciality. For these reasons, the authors are convinced that the beginning of a bifacial n-type PV (nPV) era is imminent.

Upcoming solar cell technologies

The high-efficiency potential of all the important solar cell technologies on the market has already been reported in the previous edition of *Photovoltaics International* [8]. PERC will end up with efficiencies of between 23% and 24% in production, whereas n-type technologies will soon exceed 24%, and even 25% in the future.

Table 1 summarizes the available modules on the market, where among the top ten, nine are n-type modules consisting of interdigitated back contact (IBC), heterojunction technology (HJT) and tunnel oxide passivated contact (TOPCon) solar cells. Whereas PERC technology modules deliver efficiencies between 21 and 22%, most n-type technologies are starting to exceed 22%. They also have a lower temperature coefficient as well as a higher bifacial factor. Furthermore, if processed correctly, n-type technologies show lower degradation as well.

In the following discussion, not only will the efficiency and other device advantages and



Credit: Kalyon.

Figure 4. (a) Rear side of a bifacial PERC module before lamination. (b) Curing of glued junction boxes of frameless modules.

CLEAN ENERGY REVIEWS — **Most Efficient Solar Panels 2022 *** — V3.2 - Mar 2022

Manufacturer	Model	Max power (W)	Cell Type	Efficiency
SUNPOWER	Maxeon 6	440W	N-type **IBC**	22.8 %
CanadianSolar	CS6R-MS	440W	N-type **HJT** Half-cut	22.5 %
LG	Neon R	405W	N-type **IBC**	22.3 %
Panasonic	EverVolt H	410W	N-type **HJT** Half-cut	22.2 %
Jinko Solar	Tiger NEO	480W	N-Type TOPcon Half-cut	22.2 %
SPIC	Andromeda 2.0	435W	N-type **IBC** Half-cut	22.1 %
REC Solar	Alpha Pure	405W	N-type **HJT** Half-cut	21.9 %
Trinasolar	Vertex S +	425W	N-Type Mono Half-cut	21.9 %
MEYER BURGER	White	400W	N-type **HJT** Half-cut	21.7%
JA SOLAR	Deep Blue 3.0 light	420W	P-Type Mono Half-cut	21.5 %

Table 1. Highest-efficiency solar panels available on the market in March 2022 [9].

"Whereas PERC technology modules deliver efficiencies between 21 and 22%, most n-type technologies are starting to exceed 22%."

drawbacks be examined, but also the maturity of each technology and its production costs (cost of ownership – COO). The COO of n-type technologies is edging closer to that of PERC, but is not yet overtaking it for several reasons.

PERC is the current industry standard but is getting close to its efficiency limits at the module level, demonstrating between 21% and 22% (Fig. 5). *TOPCon* is considered to be the 'next big thing', as it is a natural upgrade of PERC technology using n-type wafers, passivating contacts (poly(n^+)-Si) on the rear, and B diffusion on the front. Since it is an evolutionary upgrade of PERC, it can benefit from the existing process equipment and material supply chain. In addition, the module technology does not have to be adapted.

The next step would then be to include passivating contacts using poly-(p^+)Si as well, and adapt it in a back-contact technology. *IBC* technology offers the highest efficiency combined with perfect aesthetics and is a very simple and effective module technology. A negative gap with overlapping IBC cells is extremely easy to realize when both contacts of each polarity are on the rear.

HJT is a revolutionary successor with a simple low-temperature cell process. However, it incurs high production costs, as it is extremely sensitive towards wafer quality and impurities within the production process, as well as demanding a relatively high consumption of costly low-temperature Ag pastes. In addition, the module technology is not standard, because the solar cells cannot be exposed to high temperatures during soldering and lamination. A further hurdle caused by HJT requiring scarce materials (such as Indium and Bismuth) will become evident when PV enters the 1TWp/year era soon.

A rudimentary assessment of all technologies is presented in Fig. 6(a), in which several categories have been identified. The highest score (largest area of the polygon) is attributed to PERC and TOPCon; however, in the near future IBC – which so far has already been realized by a few Tier 1 manufacturers – will too see more benefits.

The major advantages of HJT are the low temperature coefficient and the high bifaciality. In other categories, however, HJT has huge drawbacks, and that is why it is commonly believed that this

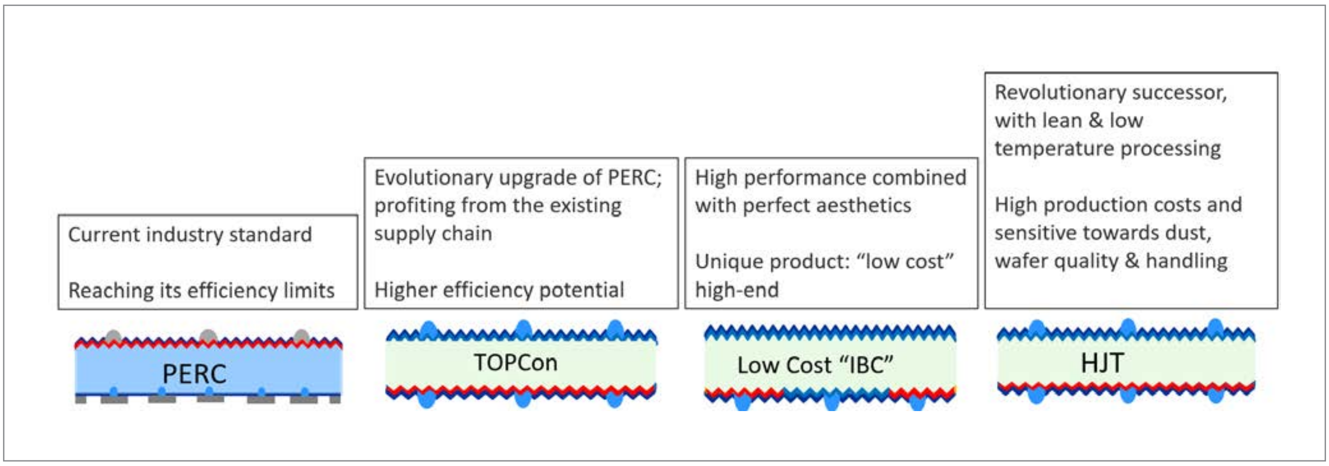


Figure 5. Dominating c-Si cell technologies at the present time and those of the future.

technology will not play a major role in the future. TOPCon has the brightest future, as forecasted by PVInfolink in Fig. 6(b), and will be PV's next workhorse. Nevertheless, it is thought that, after 2025, IBC technologies will also enter the PV market, and prior to 2030 will play a major role, as they have the highest efficiency potential and will be the next upgrade step from TOPCon. Indeed, they are already being introduced, e.g. by LONGi and AIKO, who are currently setting up GW-scale production facilities for IBC technology. Moreover, a French Consortium in collaboration with ISC Konstanz will set up a 5GW production capacity in France built on TOPCon and IBC technology [11].

COO and LCOE

The COO has been very dynamic in recent months, as the cost of poly-Si – and therefore also of the wafer – have increased dramatically. One year ago, the COO for a PERC solar cell was of the order of

"It is thought that, after 2025, IBC technologies will also enter the PV market, and prior to 2030 will play a major role, as they have the highest efficiency potential and will be the next upgrade step from TOPCon."

US$0.1/Wp, whereas it has increased to around US$0.17/Wp at the moment. These calculations are based on prices of US$0.96 for a p-type M10 Cz-Si wafer and US$1.05 for an n-type M10 Cz-Si wafer.

Fig. 7(a) shows the cell costs and how dominant the wafer costs are. In the following, since wafer costs are very dynamic, in order to compare different technologies, it makes more sense to look at the relative differences between costs. It can be seen at the module level (Fig. 7(b)) that the difference between PERC and TOPCon is only US$0.026/Wp (only 10% higher), which is very low, as TOPCon

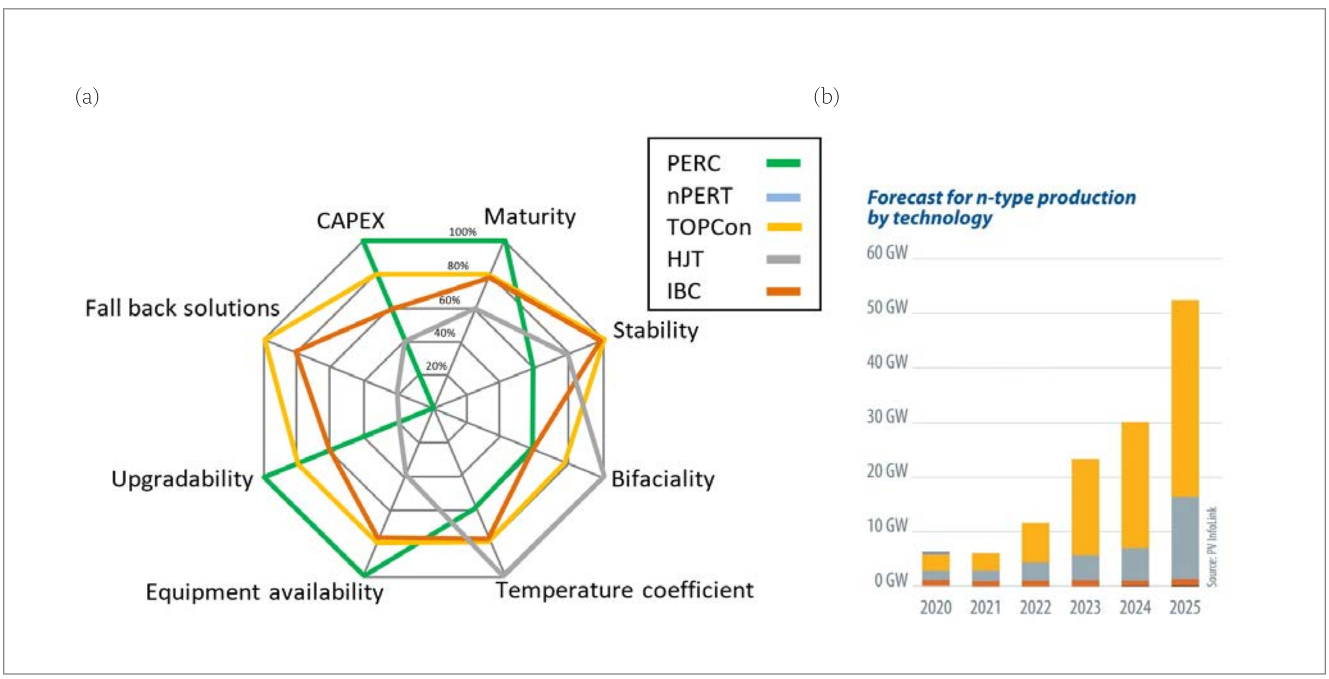


Figure 6. Technology evaluation matrix (a) and forecast for n-type technologies (b) [10].

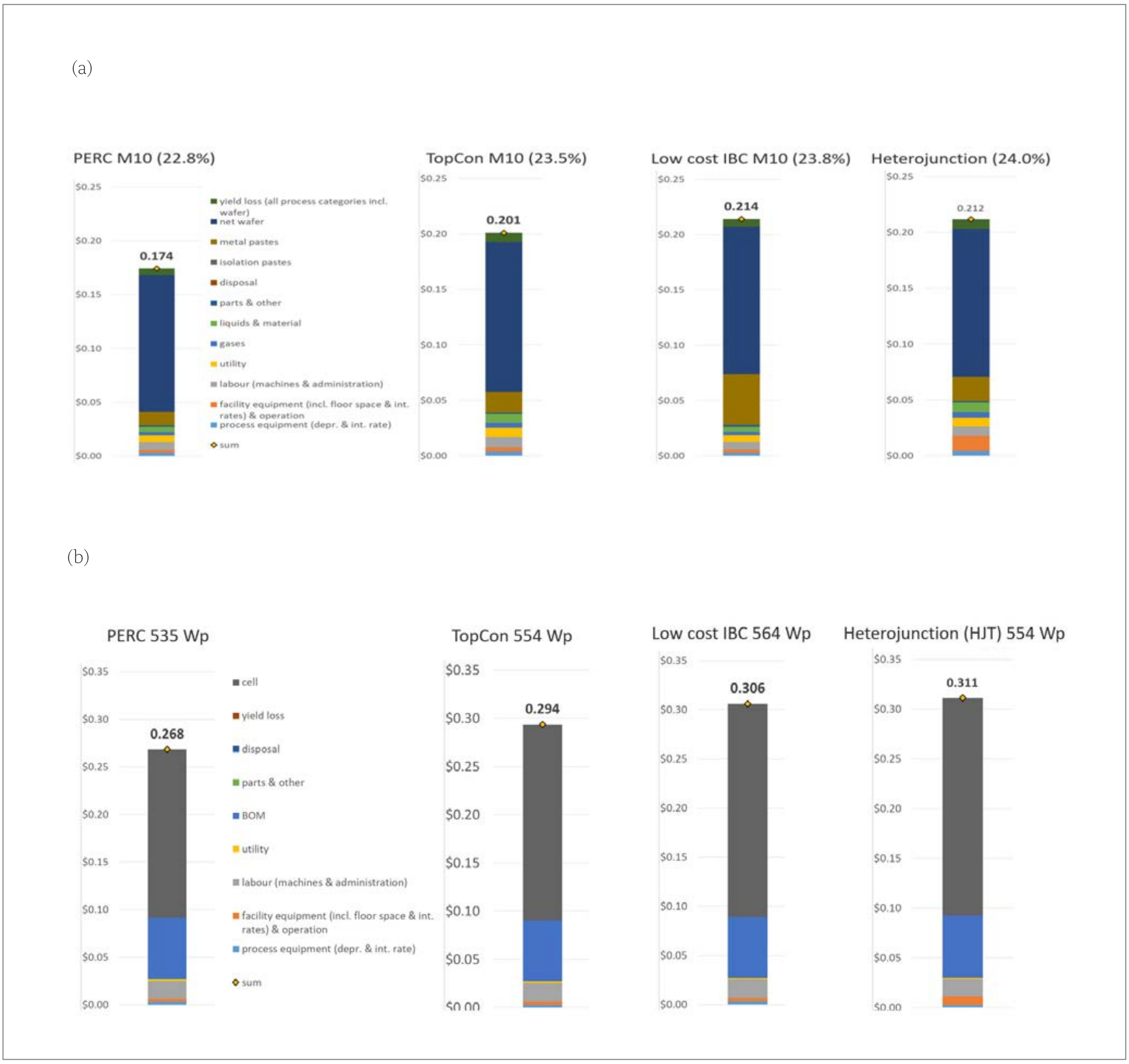


Figure 7. Result of COO calculations for (a) cells and (b) modules for different technologies in the case of a 5GWp/year cell and module factory in a low-cost Asian location (calculations based on current polysilicon and wafer costs).

modules offer many advantages in terms of the levelized cost of electricity (LCOE).

The cost factor between PERC and TOPCon at the module level is only 1.1, and this will eventually decrease even more as a result of the higher efficiency of TOPCon and less silver consumption. It is therefore beyond doubt that the future belongs to bifacial n-type technology, and that the bifacial nPV era is on the horizon. This can be already be seen now on a LCOE level in some cases. Take, for example, a region with a high radiation of 1,830kWh/m^2 (e.g. Malaga in Spain), a high average temperature of 23°C and a high albedo of 30%. Again, it is more interesting to look at differences rather than absolute numbers. It is immediately evident from Fig. 8 that using bifacial modules is beneficial in any scenario, with monofacial PERC showing a higher overall LCOE. The lowest LCOE is achieved by TOPCon technology, which will put even more distance between it and PERC in the future.

It is not surprising that in hot regions, on sites with high albedos, bifacial nPV is already starting to be used in large utility-scale systems, yielding a yearly bifacial energy gain of up to 30% [12]. Jolywood and Risen have set up the largest systems for TOPCon and HJT respectively (Fig. 9). Because of the higher bifacialities, lower temperature coefficients and lower degradations, these systems will most likely demonstrate superior performance – in other words, a higher specific energy yield (kWh/kWp), as it is known in PERC technology parlance. With the beginning of the nPV bifacial era, it is clear that IEC standards for the measurement of bifacial cells and modules will become more important as module producers try to push the power of the rear side as well ('bifi100' or 'bifi200' according to IEC TS 60904-1-2:2019) as a selling point.

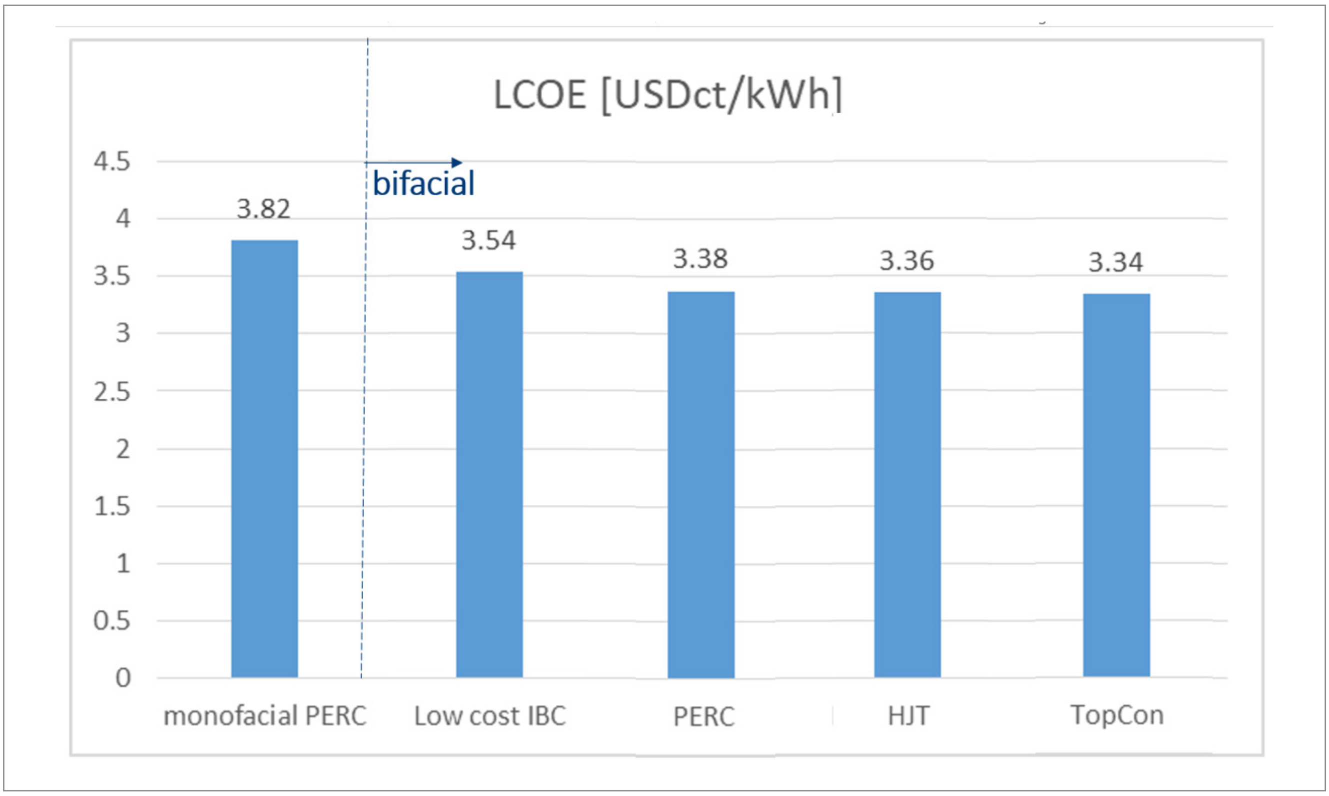


Figure 8. Result of a sample LCOE calculation for Malaga, Spain, for monofacial PERC in comparison to bifacial technologies, based on a discount rate of 5% and a system lifetime of 25 years.

Summary and outlook

With PERC as its mainstream technology, enabling electricity costs below €0.01/kWh, PV has been the king of the energy markets since 2020. To become emperor, however, the following conditions will have to be met:

- Market availability of effective and low-cost storage.
- Reduced PV balance of system costs.
- Increased solar cell and module efficiency.

Satisfying the third requirement above will result in a slight further decrease in costs/Wp, ultimately stabilizing at around €0.15/Wp (module cost).

With PERC getting ever closer to its efficiency limits – around 22% at the module level – n-type crystalline silicon technologies are currently on the upswing, yielding module efficiencies well above 22%. However, it is not only efficiency that matters, but also lower temperature coefficients, lower degradation rates and higher bifaciality. Although n-type technologies still involve higher costs/Wp, they are becoming more and more interesting, even for large utility-scale deployment in hot regions with high albedo, such as the 500MW Ibri II project in Oman; this

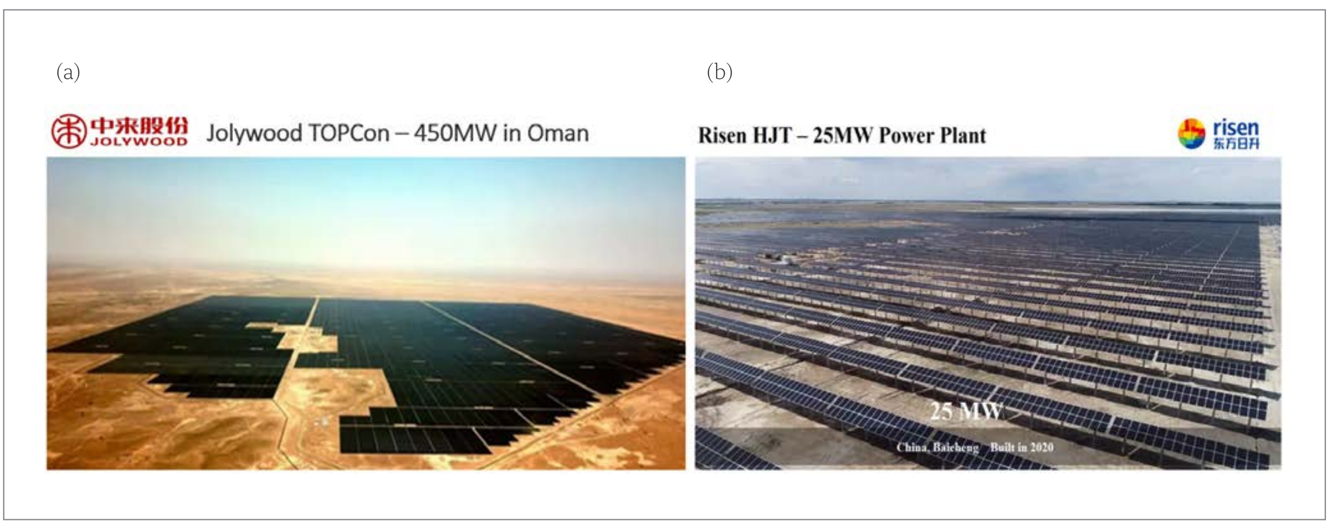


Figure 9. Use of TOPCon and HJT modules in bifacial HSAT utility-scale systems: (a) Jolywood in Oman; (b) Risen in China.

"Bifacial PV started with n-type, PERC made it standard, and soon n-type technology will take over again."

system, comprising bifacial TOPCon modules from Jolywood, demonstrates the beginning of the new 'bifacial nPV era'. Bifacial PV started with n-type, PERC made it standard, and soon n-type technology will take over again.

During the switch from Al-BSF to PERC, the most critical hurdle was the standardization of the process and equipment. At the beginning, there were still many open questions: for example, how to open the dielectrics on the rear side (wet chemically, by lasers, shadowing masks) or how to even fire through the Al paste with lasers (laser-fired contacts, LFC). The other critical process was to select the best passivation technology for the p-type Si rear surface of the cell. As soon as the most effective processes had been selected and the machines developed, the switch was accomplished very quickly.

In the case of TOPCon, the process sequence has already been selected – the only thing now that remains to be standardized is the deposition tool for poly-Si and its doping. Once this is done, then the switch from PERC to TOPCon could be completed within 3–5 years. After that, because of its even higher efficiency potential, a shift to IBC technology will be the next logical step; here, not only the n^+ contacts but also the p^+ contacts will be passivated after introducing an industrial cost-effective process for the deposition of B-doped poly-Si. If we could look into a crystal ball, in about 10 years from now IBC technology may well be seen to be gaining a market share of up to 50%.

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About the Authors

Dr. Radovan Kopecek obtained his Diploma in physics at the University of Stuttgart in 1998. He also studied at Portland State University (Oregon, USA), where he obtained a master's in 1995. In 2002 he finalized his Ph.D. dissertation at the University of Konstanz and was a group leader there until the end of 2006. One of the founders of ISC Konstanz, he has been working at the institute as a full-time manager and researcher since 2007 and is currently the head of the Advanced Solar Cells department.

Dr. Joris Libal received his Diploma in physics from the University of Tübingen, and his Ph.D. on the topic of n-type crystalline silicon solar cells from the University of Konstanz. He has been involved in R&D along the entire value chain of crystalline silicon PV in the past, and joined the ISC in 2012. He is currently an R&D project manager, working on technology transfer and cost calculations in the areas of high-efficiency n-type solar cells and innovative module technology, as well as on ISC's activities in energy yield simulations.

Enquiries

Radovan Kopecek
ISC Konstanz
Rudolf-Diesel Straße 15
78467 Konstanz, Germany

Email: radovan.kopecek@isc-konstanz.de
Website: www.isc-konstanz.de

Latest advances of ECA-based tabbing and stringing at CEA-INES

Remi Monna[1], Corentin Lucas[1], Vincent Barth[1], Xabier Hernandez[2], Romain Soulas[1], Jean-Philippe Aguerre[2] & Eszter Voroshazi[1]

[1]Université Grenoble Alpes, CEA, Liten, INES, Le Bourget du Lac, France; [2]Mondragon Assembly, Aretxabaleta, Spain

Abstract

Low-temperature interconnection processes for high-efficiency PV cells will be a key R&D topic in the coming years. In reality, to avoid significant deterioration of the surface passivation, the metallization and interconnection processes of silicon heterojunction (SHJ) cells are limited to temperatures below 200°C; tandem cells with a perovskite subcell demand an even greater reduction in process temperature, namely below 130°C. Moreover, to ensure the sustainability of PV production on a TW scale, the use of scarce materials, especially silver, needs to be reduced, as 10% of the world's supply was already dedicated to PV in 2020. This paper addresses the results obtained in terms of reducing the silver consumption in interconnection technology based on electrical conductive adhesive (ECA) and Pb-free ribbons. The first demonstration of stencil-printing-based ECA deposition with an improved accuracy using equipment from Mondragon Assembly is reported. This equipment allows a minimal amount of ECA deposition while maintaining highly reproducible results, as demonstrated through the fabrication of 400 glass–glass modules and the validation of process reliability. This paves the way towards creating Si/perovskite tandems that involve ECA curing at temperatures below 130°C with sufficient adhesion (> 0.8N/mm) of the ribbon to the cell, as well as offering a means to consistently reduce Ag usage. Furthermore, improvements to the Mondragon Assembly stringer to handle next-generation cells are outlined.

Introduction

The sustainable manufacturing imperative of the PV industry triggered by the exponential growth to a TW-scale annual production capacity in the context of energy transition and sovereignty is redefining technical roadmaps, industrial landscapes and market projections.

The recent European PV renaissance is heavily based on silicon heterojunction (SHJ) technology, with ENEL Green Power and its expansion announcement [1] and Meyer Burger as the major players, and more competitors in the starting blocks [2]. The advantages of SHJ as a passivated contact technology are numerous, such as high power conversion efficiency coupled with a low temperature coefficient and elevated bifaciality, enabling the highest energy yield among single-junction devices [3]. Moreover, the low-temperature process technology and compatibility with thin wafers also make SHJ a low environmental footprint technology [4]. Global SHJ production capacity is rising in line with the rapid proliferation of n-type wafers and is conservatively projected by ITRPV to take 40–50% of the market share by 2030.

> "To avoid severe deterioration of surface passivation, the SHJ cell metallization and interconnection processes are limited to temperatures below 200°C."

To avoid severe deterioration of surface passivation, the SHJ cell metallization and interconnection processes are limited to temperatures below 200°C. Therefore, SHJ modules integrate low-temperature interconnection technologies with either In- or Bi-based soldering of ribbons or wires like the proprietary SmartWire Connection Technology (SWCT) foils or ribbon tabbing with electrically conductive adhesives (ECAs). This latter technology has matured rapidly, with equipment being offered by several tool manufacturers and technology qualification by leading institutes, complemented by the latest generation of materials from an increasing number of suppliers. Although, historically, the PV industry has relied on soldering because of its reliability, the latest improvements in ECA formulation are reversing this trend, with carefully designed formulations offering superior performance and long-term reliability, as well as compliance with Pb-free regulations that are also emerging in the PV sector [5].

The sustainability of PV production on a TW scale requires a close examination of the availability of scarce materials, with the main concern being the use of Ag, since already 10% of the global supply was directed to PV in 2020 [6]. The current combined silver consumption for cell metallization and module interconnection of bifacial SHJ modules is 35mg/Wp. To reach sustainable levels, Verlinden [7] suggests the ambitious target of less than 5mg/Wp be met by 2030, requiring the co-design of cell and module metallization, the refinement of printing techniques and the (re) introduction of abundantly available copper. An additional strategic aid to meeting this goal is the increase in module performance offered by silicon-perovskite tandem devices as well as their potential to reduce Ag consumption owing to lower current density. The pressure to reduce the use of In and Bi in PV production on a TW scale is even greater, given their limited supply, discouraging the use of low-temperature solder alloys with their current formulation.

This paper presents an overview of ECA-based ribbon tabbing interconnection technology as a workhorse for current SHJ modules, as well as the latest advances and roadmaps in terms of performance, reliability, sustainability and compatibility with perovskite-based two-terminal tandems.

“The low processing temperature makes the ECA type of interconnection suitable for thin wafers and/or future silicon/perovskite tandem cells.”

ECAs – material properties and CEA-INES's approach to qualifying process development

ECAs are composite materials consisting of electrically conductive particles, primarily silver, in a polymer matrix, such as epoxy, acrylic or silicone [8]. They were first utilized in shingling applications, but have recently also been used in ribbon attachment [9] and became the main alternative to the soldering process for interconnecting solar cells. ECA-based interconnections have various advantages inherited from the family of adhesives, such as a low toxicity (no lead), a tolerance towards mechanical deformation, and a low processing temperature (between 120°C and 200°C compared with 250°C for typical lead-free solder). The low processing temperature is critical to reducing the thermomechanical stress placed on the wafer, and makes the ECA type of interconnection suitable for thin wafers and/or future silicon-perovskite tandem cells.

The conductive fillers confer excellent electrical properties to ECAs, typically a conductivity of around 1–5Ω·cm. However, to achieve such conductivity, the selection of the conductive material is key. Silver is unique in this regard because of the high conductivity of its oxide, even after exposure to heat and moisture. To address the issue of excessive consumption of silver in PV module manufacturing, silver alternatives are under development, for example a silver/copper combination or a new type of conductive particle [10].

The polymeric matrix accords excellent flexibility, giving an advantage of ECA over soldering, in that it can more easily absorb stress induced by thermomechanical processes and by differences in the thermal expansion coefficient of the various materials in the module [11].

To evaluate the PV performance of ECAs, a sequential qualification process has been developed at CEA-INES. First, the process window of the ECA is assessed using differential scanning calorimetry (DSC). *DSC* is a thermal analysis technique in which the heat flow into or out of a sample is measured as a function of temperature or time, while the sample is exposed to a controlled temperature programme. It is a very powerful technique for evaluating material properties, such as glass transition temperature, melting, crystallization, specific heat capacity, cure process, purity, oxidation behaviour and thermal stability. DSC also measures the rate of heat flow and compares differences between the heat flow rate of the test sample and known reference materials. This difference determines the variations in material composition, crystallinity and oxidation.

Based on the input outlined above, a process optimization for the interconnection is begun in order to determine the screen- or stencil-printing parameters for the ECA deposition and curing condition with direct heat or IR heating. The fast-feedback method of adhesion measurement of the ribbons on the cells assists the process optimization, aiming for a minimum value of between 0.5 and 1N/mm in a 180° peel-test configuration. Once the process conditions have been defined, strings of full or half-cut SHJ (or PERC) cells are fabricated in an automated manner, and mini-modules are manufactured with a previously qualified bill of materials (BOM) for initial performance and (highly) accelerated ageing in a thermal cycling chamber [12]. The electrical parameters are measured after 100, 200 and 400 cycles, with a particular focus on the fill factor (*FF*) of the module and the use of electroluminescence imaging to reveal possible series resistance increases and interconnection failures.

Further material analyses are performed to gain a deeper understanding of the mechanical behaviour. In particular, measurements taken on the cured ECA sample using dynamic mechanical analysis (DMA) give access to the thermomechanical properties (E', E", time–temperature superposition); these can then be implemented in a computational simulation of the thermomechanical behaviour of the module (during lamination and thermal cycling), or later on in real application conditions. Silver content measurement complements the characterization for purposes of comparison of the different ECAs, in particular in a life cycle analysis, which is also integrated in CEA-INES's qualification protocol.

In the final stage of qualification, industrial-size modules with 144 half-cut cells and qualified BOM are fabricated with selected ECAs and submitted to a sequence of thermal cycling and mechanical stress testing in static or dynamic mechanical loading in accordance with IEC 61215, where electrical parameters are controlled at intermediate intervals. In the case of an interconnection/module failure, opto-electrical measurements are supplemented with an in-depth analysis using advanced material characterization tools (SEM-EDX, TEM, etc.), and thus providing suggestions for improvements.

The first round of lowering Ag consumption – ECA reduction through process and deposition optimization

The amount of silver consumed along the cell-interconnection processes is linked to the number of ribbons and the amount of ECA deposited on each cell busbar (BB). To achieve economic sustainability, it is imperative to find a method to decrease silver consumption. The first solution is to reduce the amount of ECA deposited on each BB. At the beginning of this optimization study, a straight solid line of ECA, 600μm wide, was deposited on each BB; for a half-size M2 cell, using a reference ECA, this represents about 5mg of ECA per BB. Considering the upcoming increases in wafer size and the use of multiple ribbons, a drastic reduction is necessary in order to cut down on Ag consumption and to keep manufacturing costs competitive. To achieve this result, the four main possibilities are:

1. Reduce the ECA line width.
2. Reduce the deposited ECA thickness.
3. Deposit ECA pads instead of a continuous ECA line.
4. Use ribbons without an Ag coating.

Ideally, a combination of all four of the above mitigating approaches would be the most appropriate and promising route to take.

The reduction of the ECA line width is strictly related to the stringer machine accuracy. Indeed, using a 0.6mm-wide ribbon and an ECA line width of 400μm, a relative positioning accuracy of 100μm per cell is required for both ECA deposition and ribbon/wire positioning. Moreover, decreasing the ECA line width will directly reduce the adhesion and the contact surface with the ribbons. The tuning of the ECA deposition thickness can also even be detrimental, interfering with the cell metallization and the mechanical stability of the ribbon. Consequently, the ECA thickness has to remain greater than that of the cell metallization for example.

A preliminary study (the CEA reference) was carried out on a semiautomatic screen-printing and stringer unit to cure the ECA. Ribbons were manually placed on the cells, which limited the risk of misalignment. Analyses of the ECA mass deposition amount and the adhesion strength of the ribbons on the cell, as well as a thermal cycling reliability test, were performed. The initial screening test revealed some already interesting results:

- Importantly, a too aggressive reduction of the ECA line thickness (ECA thickness should remain greater than that of the metallization, typically between 10 and 15μm) is not compatible with an industrial process because of the low ribbon/cell adhesion (<0.2N/mm). The handling of such strings would lead to a very high scrap rate in an automatic production line.

- With the Mondragon Assembly stringer (accuracy of 100μm), a line reduction down to 200μm with 0.6mm ribbons could be possible.

- The implementation of pads allows the highest amount of ECA reduction (40–65% ECA mass reduction). However, a minimum amount of ECA has to be deposited in order to guarantee reliability.

These preliminary results led to the following test plan, carried out using the ECA tabber–stringer from Mondragon Assembly. Width reduction and the use of pads were implemented, as well as a combination of both approaches.

A significant overall reduction in ECA was obtained (up to 65%). However, thermal cycling test results at 400 TC showed a slight decrease in reliability with the higher ECA reduction designs (Fig. 1), revealing an optimum trade-off for the ECA reduction with the reference paste combination ('Pads B', 'Width 1' in Fig. 1(a)). A loss of less than 1% was observed after 400 TC with a 45% (11mg/W) reduction in deposited weight.

> "To achieve economic sustainability, it is imperative to find a method to decrease silver consumption."

(a)

ECA reduction [%]	ECA design	
0	Full line	Width 1
40	Full line	Width 2
40	Pads A	Width 1
45	Pads B	Width 1
55	Pads A	Width 2
65	Pads B	Width 2

(b)

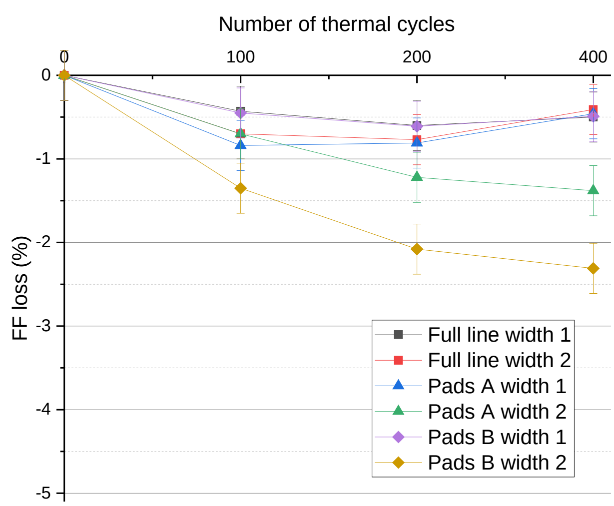

Figure 1. (a) Description of the different ECA designs, along with the silver reductions achieved. (b) Fill factor (*FF*) loss after 100, 200 and 400 thermal cycles (–40°C to +85°C).

Reduction of ECA deposited weight with stencil printing and the advantages over screen printing

Stencils have been widely used for the last 30 years in the surface mount technology (SMT)/printed circuit board (PCB) industry for printing solder paste onto boards. An SMT board, however, differs significantly from a thin, fragile silicon solar cell, and the nature of the solder pastes is entirely different from that of ECA adhesives, not to mention the speed of printing. Still, lessons can be learnt from the SMT stencil-printing application, but clearly their practice cannot be copied.

In the pursuit of printing finer lines with a higher aspect ratio, the effective open area in the screen mesh becomes smaller and the quality of the opening in the emulsion layer poorer. The open area and the interior finish are important aspects for ECA transfer into the screen mask area and for the release of the ECA onto the substrate [13]. A finer mesh, better emulsion material, and improved screen manufacturing will help, but ultimately these parameters will be limited in screen printing. In stencil printing, the open area is larger: for a typical front-side screen with 280 mesh, the open area is 53%, while for a laser-cut stainless steel stencil, the open area is 100% in this case (Fig. 2).

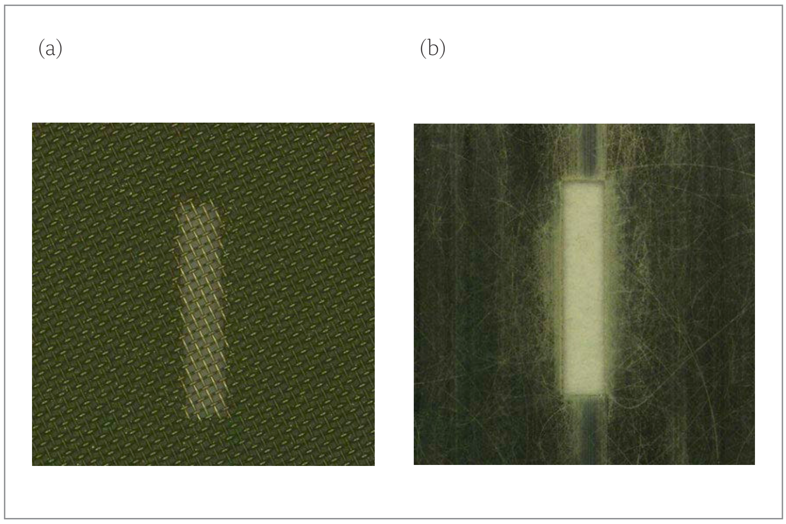

Figure 2. (a) Screen opening. (b) Stencil opening.

Stencil-printing technology uses a metal plate with openings as a mask. The process mode is 'back and forth', meaning that the ECA is scraped one way by the first metal blade and then the other way by a second metal blade. The thickness of the stencil mask determines the thickness of the deposited adhesive. In contrast, screen-printing technology uses a meshed screen and the printing is done in only one direction: a squeegee scrapes the ECA through the openings, and then a metal counter-squeegee spreads it over the entire surface of the mask, ready to be scraped again.

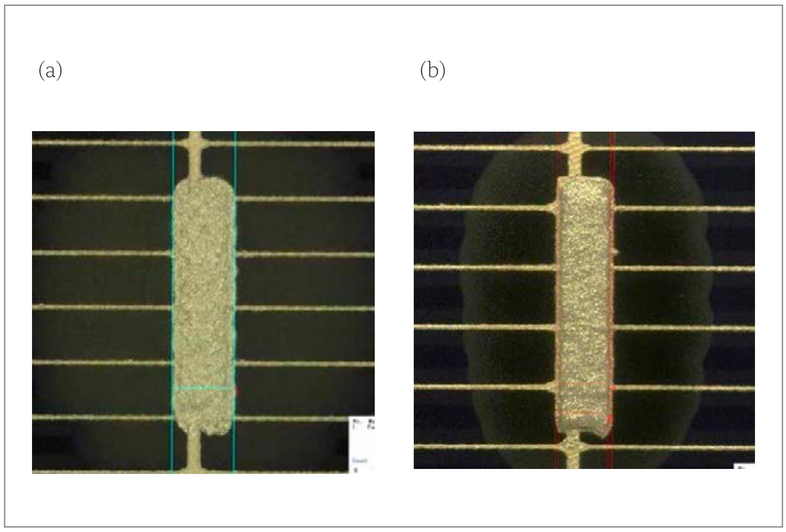

Figure 3. Print quality comparison: (a) with a screen, and (b) with a stencil.

Fig. 3 compares the conductive adhesive deposits obtained with the stencil and with the screen. It can be seen that the sharpness of the print is better with stencil technology; this is due to the absence of any gap between the stencil mask and the cell, and because the hole of the stencil is completely open, which allows better release of the ECA. It was also observed that on the stencil screen, in contrast to the mesh screen, there is no displacement of ECA by capillary action under the screen, which makes it possible to have a sharp edge and a width of deposit equal to the width of the opening of the screen.

Mondragon Assembly recently developed an industrial ECA tabber–stringer, the 'ECA-MTS', for the ECA interconnection of high-efficiency cells, after productive work within the European-funded GOPV project. The improved accuracy of the ECA-MTS leads to a very small quantity of deposited ECA to perform a reliable interconnection. This will have a direct effect on Ag consumption for a module, while permitting the use of a narrower ribbon or smaller wire, which results in a reduction in the shadowing effect. In addition, a more accurate positioning of the ribbon will also affect the metallization design – another way to limit Ag consumption at the cell level. The new equipment will therefore significantly affect the levelized cost of electricity (LCOE) in relation to module manufacturing, thus allowing the ECA interconnection process to compete with the soldering process for heterojunction technology (HJT) cells.

The ECA-MTS industrial machine will be an evolution of an initial pilot line developed within the framework of the GOPV project, where the stencil-printing method was selected for ECA deposition because of diverse beneficial factors, such as longer durability, higher dimensional reliability, lower mechanical loads to the cell, and reduced downtime of the tool. The aforementioned advantages have been widely explained throughout this paper.

One of the highlights of this new equipment is the high accuracy when depositing the ECA and positioning the wires on the cell. The deposition accuracy is achieved by the long-term dimensional stability of the stencil pattern, and by the auto-adjustment system of the printing mask, which continuously checks the ECA deposition and

"Stencil printing uses less ECA than screen printing, mostly on the front side, because of the smaller thickness of the front stencil mask."

automatically adjusts the printing station if necessary, eliminating the need for an operator. This ECA deposition is carried out at two independent printing stations, which has the advantage of optimization of the printing if the sunny side/back side of the cell have different requirements. Independent printing will simplify the printing process configuration, and hence reduce related machine downtime.

The positioning of the ribbon/wire on the cell is also more precise as a result of better controlled handling. A relative positioning precision of 100μm of the wire/ribbon with respect to the bus can be achieved, enabling easier process control and a more reliable connection.

For the first stencil-process qualification, a 50μm-thick stencil was chosen on the front, while a 70μm-thick stencil was chosen on the back; the thicker stencil is necessary on the back because of robustness and front-side textured ribbons, which demands thicker ECA to enhance the adhesion. Fig. 4 shows a comparison of screen and stencil deposition mass on the front and back sides of the half-size M2 cell, at the beginning and end of the daily string production (after 6,000 prints). Stencil printing uses less ECA than screen printing, mostly on the front side (4mg less), because of the smaller thickness of the front stencil mask. The authors believe that it will be possible to further reduce this deposit thickness by 50%. No difference is observed in the weight deposited at the beginning of the production and at the end.

Fig. 5 shows a comparison of peel forces for screen and stencil ECA deposition on the front and back, and at the beginning and end of the string production. It can be observed that the peel forces are still equivalent for both technologies, at around 0.8 to 1N/mm for the rear side and 1.2N/mm for the front side.

From the work carried out at CEA-INES, the following can be concluded:

- Solar cell stencil printing is not the same as SMT stencil printing: lessons can be learnt, but SMT cannot just be copied.
- For an optimal mechanical holding of the stencil, only separated pads can be printed, not continuous lines. Cell metallization design has to be compatible and optimized for correct mechanical adhesion and reduced electrical conductivity losses.
- For improved aspect ratio printing, beneficial specifications for stencils are demonstrated as compared to screens.
- Simpler printing (lower pressure), with better ECA transfer and release, was identified with stencil printing.
- Higher throughput is possible with stencil printing because of the 'back and forth' process.
- After more than 35,000 prints, no issues in terms of print quality were noticed with stencil printing.
- Stencil printing has high durability and robustness, as cell breakages did not cause stencil breakage.

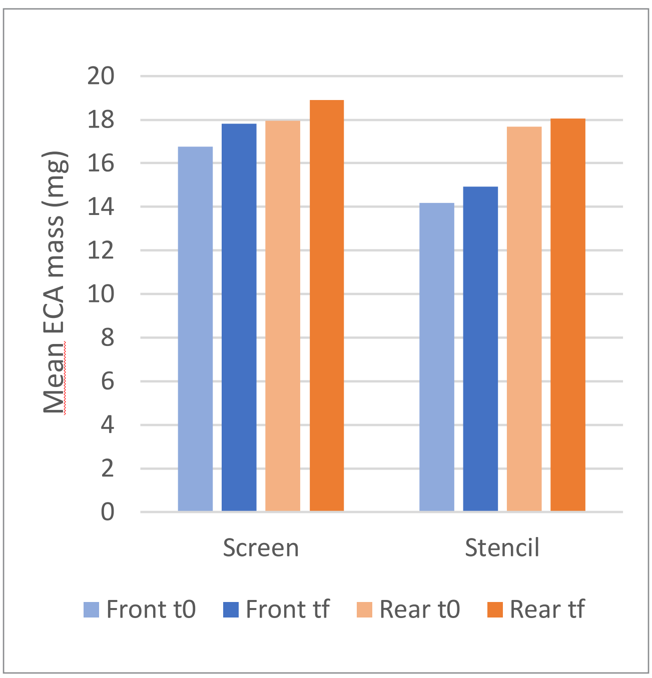

Figure 4. ECA mass analysis (half-size M2 cell).

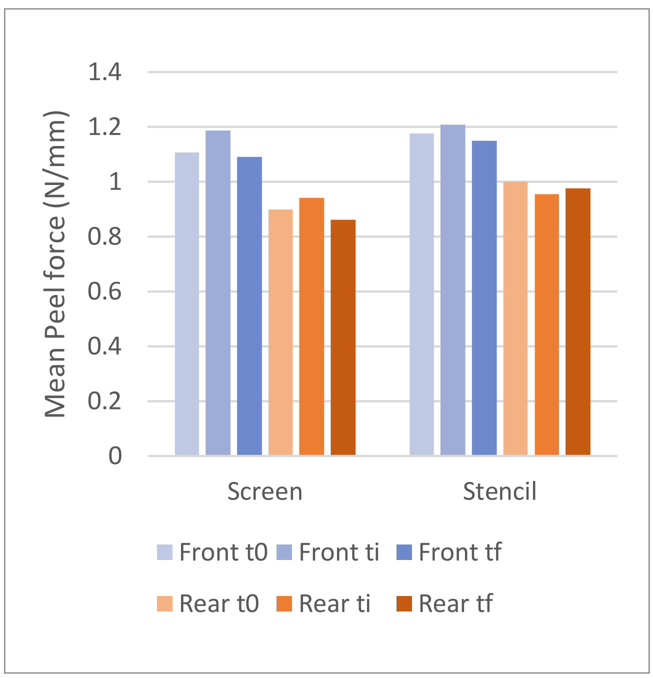

Figure 5. Peel force analysis.

(a)

ECA	Matrix filler	Ribbon coating
A	Acrylate	Ag
B		SnAgCu
C		Ag

(b)

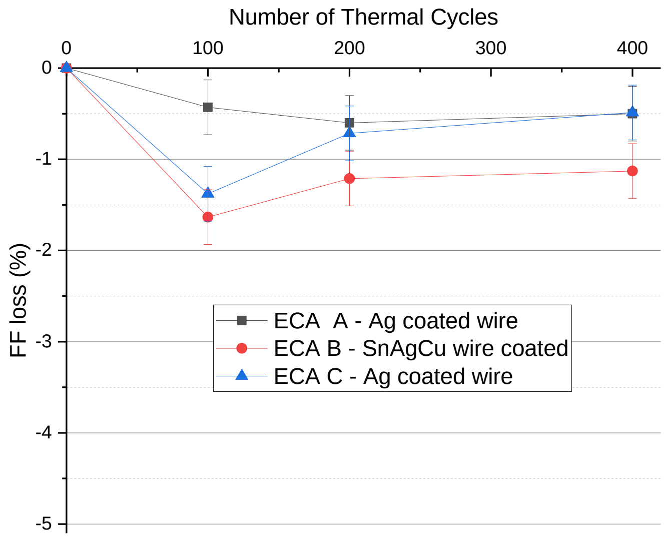

Figure 6. Fill factor (*FF*) loss after 100, 200 and 400 thermal cycles (–40°C to +85°C) for a variety of ECAs with different wire coatings (pads B design/ width 1/45% reduction in Ag consumption).

- Stencil printing allows a 10% reduction in the weight of the deposited ECA. This reduction can be further increased with the use of thinner metal plates.

Going further with Ag consumption reduction using new ECA formulations

As illustrated in Fig. 1, ECA reduction appears to be reaching a limit with just the optimization of the deposition parameters. With increases in wafer size, coupled with the consequent increase in the number of BBs, a reduction of the amount of ECA per BB will not be sufficient to achieve a silver target of less than 5mg/W.

Several approaches can be taken to further reduce the amount of silver. The first is a direct silver reduction inside the ECA mixture by the introduction of other conductive particles, such as copper, aluminium or something else, which seems the obvious thing to do. However, silver is quite difficult to replace if one wants to keep the same performance and reliability. Thus, engineering the ECA composition with additives to avoid oxidation and/or to enhance the conductivity of the material is necessary. Material research with a potentially significant impact on Ag reduction is ongoing, and the first formulations are in the qualification stage.

Another important way to reduce silver usage inside the module is to use ECA that is compatible with all types of ribbon coating. Indeed, ECA is usually compatible with silver-coated ribbons; yet, even considering low coating thicknesses (<2µm), it is an important silver consumption item (>30mg per half-cell). This line of approach is currently under investigation, and it is now possible to find a large variety of ECA designed for PV applications among each silver paste manufacturer. Fig. 6 shows a comparison of different ECAs with two types of ribbon coating. After 400 thermal cycles, a small loss in *FF* (about 1%) can be observed when combining a specific adhesive with SnAgCu coated wires. It can be concluded that different ECAs that are compliant with the IEC 61215 norm are now available on the market, whatever the ribbon coating used. The number of qualified ECAs should quickly increase, along with their availability on the market.

Module prototyping: results of the production of 400 HJT modules and 6,000 strings with stencil printing

Modules totalling 125kWh were produced for the final qualification of reduced ECA deposition, stencil printing and Mondragon ECA interconnection equipment within the H2020 European project GOPV [14]. These modules integrate the latest developments carried out during the entire project. Thus, material reduction – such as silver, silicon and encapsulant – or reduction of ribbon thickness was performed to lower the final LCOE. The latest architecture optimization also was selected in order to improve the electrical properties of the produced module.

To achieve the goal of realizing 125kWh, 400 modules were produced, which will be monitored in a large field using a fixed- and a one-axis tracker. String manufacturing was performed using the automated Mondragon ECA tabber–stringer. To reduce the ECA consumption, a pad design that cuts the amount of ECA by 45% in weight was selected. Screen- and stencil-printing technologies were used for string manufacturing without any impact on the final reliability. The fabricated strings showed good adhesion (>1N/mm) and very reproducible dimensional aspects, such as inter-cell distance, bending effect and total length. Adhesion remained very stable throughout the production. In all, 6,000 strings were manufactured for the module production.

	V_{oc} [V]	P_{max} [W]	V_{max} [V]	I_{max} [A]	I_{sc} [A]	*FF*
Min	52.09	360.15	42.95	8.30	8.75	0.77
Max	53.22	369.49	44.28	8.42	8.91	0.79
Standard deviation	0.16	1.92	0.22	0.02	0.02	0.00
Mean	52.69	364.96	43.66	8.36	8.86	0.78

Table 1. Electrical data for the 400 modules.

Modules were partially produced manually, as the quantity of modules was quite low, and so it was difficult to dedicate a production line just for this production. Following the qualification of the BOM, a glass–glass architecture with a polyolefin elastomer (POE) encapsulant (sourced from Europe) was chosen.

The lamination process was performed using a membrane laminator. An aluminium frame was used to reduce the pinching effects that are usually present at the module corners in such a glass–glass configuration. A lamination recipe optimization was carried out in order to achieve optimal glass to encapsulant adhesion and encapsulant cross-linking rate, with a particular focus on final reliability. A total of 400 modules were manufactured, with a very low rejection rate (<5%), considering the manual operations.

Table 1 shows the electrical data for the 400 SHJ modules of 363.5±1.9Wp with highly reproducible electrical module parameters. These results highlight the process quality and control, at both cell and module material levels.

Stringing development for tandem PK/Si cells

Tandem cells of various configurations are today on the agenda of many research teams all around the world. The technology is interesting and promising, as it seeks to overcome the theoretical limits for single-cell efficiency (~30%). Perovskite tandem hybrid cells have already proved to be quite efficient and low cost, owing to the inexpensive materials used.

A major issue with the perovskite subcell is that it suffers from severe degradation when exposed to temperatures above 130°C for long durations, limiting the possibility of using high-temperature soldering processes for the stringing. Because of its simplicity and cost effectiveness, screen printing of silver-containing low-temperature pastes will be used first for the metallization in industrial production. It has been shown that the weak adhesion for such pastes (busbars) on the wafer, combined with the fact that the lowest liquidus temperature is 139°C for the metal alloy ($Sn_{42}Bi_{57}Ag_1$), means that the stringing of such cells is not possible using a soldering process. Consequently, interconnection using ECA will be the most suitable technology for such very low temperature cells.

Following CEA-INES's development sequence, the thermal characteristics of the ECA were measured first by DSC. The initial study consisted of determining the maximum temperature of cross-linking of two different commercial ECAs. Fig. 7 indicates the heat flow into or out of two ECA samples as a function of temperature after several heating/cooling cycles. This cross-linking peak is exothermic and the phenomenon is irreversible; in other words, the material once cross-linked cannot change its state and remains hard and rigid. The study was carried out with a heating rate of 10°C/min.

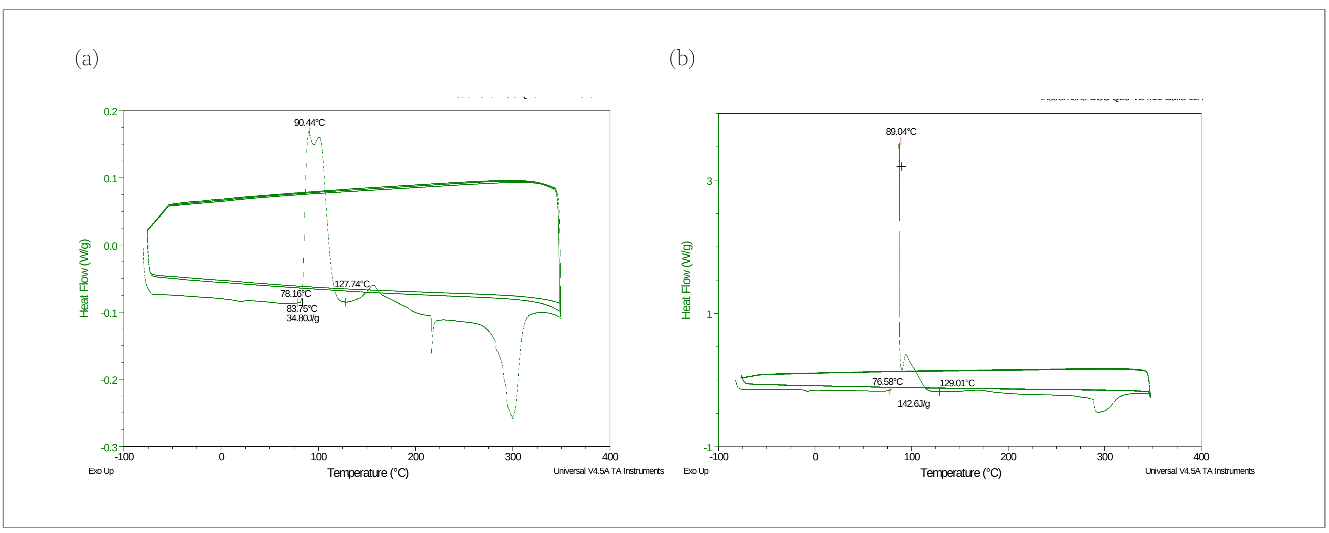

Figure 7. Comparison of heat flow vs. temperature for two different ECAs: (a) DSC analysis of ECA A; (b) DSC analysis of ECA B.

A comparison of the two ECA printing samples shows that the one where the temperature at the maximum of the cross-linking peak is lower will take less time to cross-link at a given temperature than the one where the temperature at the maximum of the cross-linking peak is higher. To reduce the curing time, it is therefore interesting to move towards ECAs whose temperature at the maximum of the cross-linking peak is fairly low. For each manufactured string, several adhesion tests were conducted using a peel force tester at a 180° angle on the bus of the cells. Table 2 presents the results of the peeling tests that were performed on the six busbars present on the front and on the back of the cells, at three different temperatures around 130°C. The result obtained represents the mean value of the measurements taken along the bus.

The peel force test results are not in agreement with the DSC results. According to DSC, it seems that ECA B is more adapted to low-temperature processes than ECA A. The cross-linking temperature differences are, however, relatively small, and the better peel force for ECA A can be attributed more to its higher Ag content.

It can be concluded that sufficient adhesion (>0.8N/mm) is obtained with both types of adhesive, cured at temperatures below 130°C. This realization highlights the capacity of the ECA tabber–stringer to interconnect different kinds of cell using very low temperature processes. Further reliability testing of these ECAs is currently under way.

	Front side [N/mm]		Back side [N/mm]	
Temperature	ECA A	ECA B	ECA A	ECA B
120	1.3	1.0	1.0	0.7
130	1.5	1.2	1.2	0.8
140	1.7	1.2	1.3	1.0

Table 2. Peel forces after the manufacture of the strings (before lamination).

"A major issue with the perovskite subcell is that it suffers from severe degradation when exposed to temperatures above 130°C for long durations, limiting the possibility of using high-temperature soldering processes for the stringing."

New equipment and processes for HJT and tandem perovskite/silicon cells

Mondragon Assembly has already launched its high-precision tabber–stringer machine with ECA technology for HJT high-efficiency cell technology, and is capable of producing up to 2,600 HJT cells per hour (Fig. 8). For this new development, which comes with independent printing of both sides of the cells, flexibility is a key aspect of this machine, since it can produce strings of up to 15 busbars with cell sizes of up to G12 (210mm × 210mm) in full-, half- or third-cell format. In addition, it is able to handle cells as thin as 110μm, and is also compatible with gapless and paving technologies. With regard to the interconnection elements that can be handled by the machine, ribbons as narrow as 0.2mm × 0.5mm and wires down to 0.25mm in diameter can be accommodated.

Thanks to the numerous visual controls that have been installed after each step of the process, this new machine guarantees a high precision and quality of the manufactured strings; this allows the efficiency of the machine to be increased and better manufacturing results to be obtained in less time. In order to increase the available uptime of the machine, the equipment includes a cleaning station to assure continuous printing, as well as straightforward filling because of the open lay-out of the printing stations.

However, the developments and commitment made by Mondragon Assembly go a step further: jointly with CEA-INES, the development of a multi-busbar wire-soldering solution for HJT is also in progress.

Conclusion

To avoid severe deterioration of the surface passivation of a SHJ cell due to the degradation of

Figure 8. The MTS-ECA (MTS1105-1) stringer.

its surface passivation properties, interconnection processes are limited to temperatures below 200°C. ECA-based interconnections have various advantages inherited from the family of adhesives, such as low toxicity (no lead), tolerance towards mechanical deformation, and low processing temperatures (between 120°C and 200°C, compared with 250°C for standard lead-free solder). The latter property is critical to reducing the thermomechanical stress within the wafer, and makes the ECA type of interconnection suitable for thin wafers and/or future silicon/perovskite tandem cells.

At CEA-INES, a sequential qualification process has been developed to evaluate the PV performance of ECA-based stringing processes. First, the process window of the ECA is assessed using DSC. Based on this input, a process optimization on the ECA-based stringer is begun in order to determine the screen- or stencil-printing parameters for the ECA deposition and curing conditions with direct heat or IR heating. The fast-feedback method of adhesion measurement of the ribbons on the cells assists the process optimization, aiming for a minimum value of between 0.5 and 1N/mm in a 180° peel-test configuration.

The sustainability of PV production on a TW scale requires examination of the availability of scarce materials, with the main concern being Ag usage, as already 10% of the global supply was directed to PV in 2020. It is essential that Ag consumption is drastically reduced in the future if PV is to be sustainable. Taking into account the upcoming increase in wafer size and the use of multiple ribbons, four main options for Ag reduction at the interconnection level were proposed and discussed.

Excellent reliability, with less than 1% loss in fill factor, over 400 thermal cycles was obtained when the deposited weight of ECA was reduced to 45% (11mg/W). The use of SnAgCu -coated ribbon associated with adapted ECA allowed further reductions in the amount of silver coating used, to 4mg/W. A decrease of less than 1.2% in fill factor was observed after 400 thermal cycles with this low-Ag process. The authors believe that the use of silver can be decreased still further by employing thinner stencil plates and ribbons without any silver coating at all.

Mondragon Assembly recently developed an industrial ECA tabber–stringer – the ECA-MTS – for the ECA interconnection of high-efficiency cells, as a result of productive work within the framework of the European-funded GOPV project. The improved accuracy of the ECA-MTS means that only a very small quantity of deposited ECA is necessary to create a reliable interconnection. Accuracy alignments of less than 100μm for ribbons of 0.6mm on ECA lines of less than 300μm in width have been demonstrated. Moreover, the use of a stencil instead of a mesh screen improves the alignment as a result of less screen deformation and better reproducibility of the deposit during the processing time. More accurate positioning of the ribbon will also affect the metallization design – another way to limit Ag usage at the cell level.

Tandem cells of various configurations are currently on the agenda of many research teams worldwide. Perovskite tandem hybrid cells have already proved to be quite efficient and low cost, mostly because of the inexpensive materials used. A major issue with the perovskite subcell, however, is that it degrades severely when exposed to temperatures above 130°C for long durations; this limits the possibility of using high-temperature soldering processes for the stringing. Because of its simplicity and cost effectiveness, screen printing of silver-containing low-temperature pastes will be used first for the metallization in industrial production. It has been shown that the weak adhesion associated with such pastes (busbars) on the wafer, combined with the fact that the lowest liquidus temperature is 139°C for the metal alloy ($Sn_{42}Bi_{57}Ag_1$), makes the stringing of such cells not possible using a soldering process. Consequently, interconnection with ECA will be the technology most suited to such very low temperature cells.

It was demonstrated that sufficient adhesion (>0.8N/mm) was obtained with two different types of ECA adhesive, cured at temperatures below 130°C. This outcome highlights the capacity of the ECA tabber–stringer to interconnect different kinds of cell with very low temperature processes.

“Excellent reliability, with less than 1% loss in fill factor, over 400 thermal cycles was obtained when the deposited weight of ECA was reduced to 45% (11mg/W).”

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About the Authors

Remi Monna received his Ph.D. from the University of Strasbourg in 1997 with a thesis topic on the development of thin-film polycrystalline solar cells. He joined the EDF-Photowatt Company in May 1998, where he developed and industrialized a new cell manufacturing process. In 2003 he joined the National Institute of Solar Energy to launch the 'industrial solar cells' activity through the start-up of a small pilot line. After 17 years of working in the field of silicon solar cells, he joined the PV module team and is currently in charge of cell-interconnection activities.

Corentin Lucas studied materials and physics engineering at INSA Rennes, France. In 2020 he joined the PV module laboratory at CEA-INES as an R&D engineer, to work on the improvement of interconnection technologies, mainly for HJT cell application. In addition to his various research activities, he is responsible for the Mondragon Assembly ECA stringer at INES.

Vincent Barth received his Ph.D. in 2014 from the Sorbonne University in the field of organic PV, working on the synthesis of small molecules as a donor material or as a hole transport layer (HTL) material, and their use in PV devices. He joined CEA-INES in 2017 to work on PV module technology. His work focuses on industrial manufacturing of HJT modules and on interconnection solutions.

Xabier Hernandez is a project engineer within the R&D department at Mondragon Assembly. He studied industrial engineering at the University of Navarra (TECNUN) of San Sebastian, and later received his Ph.D. from the University of the Basque Country (EHU) in Bilbao in 2017 in collaboration with Tecnalia. He currently works as a mechanical manager of research projects in the PV industry.

Romain Soulas received his Ph.D. in 2012 from the University of Grenoble in the field of metallurgy and corrosion of nuclear power plants. He joined CEA-Liten in 2012 within the nanocharacterization platform and worked on material characterization by electron microscopy. In 2019 he moved to CEA-INES to work on PV module technology, and in particular on the industrial manufacturing of HJT modules.

Jean-Philippe Aguerre is head of the R&D group at Mondragon Assembly. After finishing his studies at the University of Besançon, he worked as a project manager in the electronics domain. Since 2007 he has led the innovation team specializing in the areas of solar, robotics and automation.

Eszter Voroshazi received her Ph.D. in 2012 from KU Leuven in Belgium in the field of thin-film solar cells and modules and a study of their reliability. She previously worked at imec as an R&D manager of its PV modules and systems activities. She joined CEA-INES in 2021 as head of the PV Module Process Laboratory, focusing on novel materials, module interconnection and packaging technologies for conventional and integrated PV modules, from early concepts up to pilot-scale demonstration.

Enquiries

Remi Monna
Université Grenoble Alpes
CEA, Liten,
ITE INES.2S
73375 Le Bourget du Lac
France

Tel: +33 (0)4 79 79 29 31
Email: remi.monna@cea.fr

Assessing reliability risks using the FMEA production process

Bengt Jäckel[1], Matthias Pander[1], Ringo Koepge[1], Stephan Großer[1] & Karl-Anders Weiß[2]

[1]Fraunhofer Center for Silicon Photovoltaics CSP, Halle, Germany; [2]Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany

Abstract

PV manufacturing has progressed quite a bit in recent years, from handmade products entailing high human-effort-based assembly to fully automated cell and module factory production in just the last decade. Machine-based production offers high reproducibility; nonetheless, it can lack the ability to easily make required production process adjustments. Production windows can be maintained comfortably provided nothing changes; however, if materials change and require more process adjustments, those – no longer appropriate – processes can lead to variable production quality and can therefore cause long-term durability issues. This paper presents a way to evaluate production windows and related field issues using an adapted failure mode and effects analysis (FMEA) approach. Since PV modules are the most important component in terms of longevity and warranties, the focus of Fraunhofer's work has been on module manufacturing. The process, however, can also be applied to cell manufacturing and other steps in the value chain. By means of FMEA methodology, a group of equipment and module manufacturers, along with several interdisciplinary scientists, have analysed possible production issues and their impact on reliability and have determined the important factors for risk, detection and severity. The processes with the highest risk priority numbers (RPNs) are followed up with regard to process variations and a detailed indoor and outdoor test study. In view of the fact that data analytics is gaining importance for process optimization, an example is given to demonstrate how data can help to improve process stability, as well as increase efficiency, reliability and production yield.

Introduction to PV module production FMEA

Failure mode and effects analysis (FMEA) protocols have been used for several years in other industries to improve production yield, overall quality and reliability of the end product. This methodology is not limited to the product itself and its use, but can be applied to individual production processes as well. This paper describes the introduction of FMEA to certain steps of the PV value chain, while not being limited to them. Furthermore, there will be a brief discussion of how large data sets collected during manufacturing can be used to optimize production yield and efficiency, and therefore further reduce the CO_2 footprint associated with PV electricity.

"The aim of the FMEA methodology is to install enhanced and standardized procedures for future material and machinery changes within the manufacturing process."

The PV industry is always under pressure to enhance the efficiency of cells and modules [1] and optimize production processes in order to obtain higher yields, while at the same time further improve the longevity of the products and reduce costs. Most modules come with a performance warranty of at least 20 to 25 years, with some manufacturers even stating 30 or more [2]. The majority of known failures consist of mainly 'infant mortality' issues, typically occurring within the first 5 to 10 years of operation [3–11].

Wafers used in the solar sector have seen a significant increase in size in recent years, moving away from the classical 6-inch (156mm) wafer to the M12, with an edge length of 210mm. Logically, this has meant a need for considerable improvements in crystallization and wafering processes. There have also been significant changes in the development of solar cells and modules. Incremental, but still significant, technology improvement phases occur within a time frame of 6 to 12 months. Accelerated testing in climate chambers, however, should be as short as possible and durations range from a few weeks to a few months. Therefore, highly accelerated stress tests would be needed to really speed up degradation processes by a factor of around 100. In durability and reliability testing, reasonable ageing acceleration can mostly only be achieved with a factor of around 10 if a correlation to normal operation processes can still be ensured. Within these constraints, the best possible decisions must be made at each stage of PV product manufacture. The FMEA approach can help to narrow down certain risks and to add more R&D efforts to address the riskier issues that may lead to significant effects on return rates or safety concerns. Consequently, there must be a thorough understanding of which effects the test protocol should address, and what possible root cause is behind the degradation or failure mode.

The focus of the work reported in this paper is to look at all relevant production processes of a standard c-Si PV module with an adapted PV-specific FMEA protocol. The adapted FMEA procedure is set to focus on a more in-depth understanding of the severities of production process variations and material variations within given types of material. The aim of the FMEA methodology is to install enhanced and standardized procedures for future material and

Figure 1. Major production steps in the PV module value chain.

machinery changes within the manufacturing process. The protocol should therefore help to avoid production-caused defects, enhance overall quality and lower the risk of field returns, while improving field return estimation.

Ongoing optimizations and enhancements of production processes are essential for reliable and cost-competitive products in the future. The aim of the production process FMEA approach is to basically perform a design of experiment (DoE) to optimize permissible production windows in order to achieve reliable products and/or improve production yield (more products per hour and/or better utilization of materials and reduced waste). The designed experiments should help to better address the specific related degradation and failures.

The FMEA approach

The FMEA methodology was developed by an interdisciplinary team with contributions from PV module manufacturers, research institutes and equipment suppliers. It is an analytical method of reliability engineering and performed to provide a sort of qualitative statement. Possible product defects and failures are evaluated according to their significance for the customer or during their intended use, their probability of occurrence and their probability of detection.

Fundamentals of the FMEA approach

In general, the FMEA approach can be supplemented with a study to include the criticality, for instance regarding life hazards and claim rates leading to an FMECA protocol (C = criticality). However, it was decided to reduce the complexity and to cover those issues causing life hazard risks as safety hazards, and as such set severity S = 10.

The general principle of the FMEA methodology is to identify, prioritize and rate field defects, with the aim of achieving a deeper understanding in order to overcome in the long term such risks/defects. Following the methodology of the FMEA approach, the risk priority number (RPN) is the multiplication of the rating values for severity S, probability of occurrence O and probability of detection D (in the factory). The latter is important, as this number sets a focus on specific production processes, materials and product designs. Severity, occurrence and detection can take on values of 1 (no impact, very low probability of occurrence, 100% detection probability) to 10 (severe impact, very low probability of detection, safety hazard); this results in RPNs from 1 (best product, no problems) to 1,000 (very high risk of catastrophic failure, not detectable in the factory). An additional prioritization number – the priority number (PN) – is calculated by multiplying S and O, leading to priority numbers from 1 to 100 (high risk of catastrophic failure).

An all-inclusive FMEA approach for all PV plant components is not yet feasible. The current work described here therefore mainly focused on the production processes within the PV module value chain (see Fig. 1), and how such processes can influence long-term module reliability. Some aspects, such as specific PV module designs or failures due to specific climatic/weather events, are thus excluded.

Fig. 1 shows a brief overview of the PV value chain. A detailed insight into the PV module production steps (marked in green) is given below. However, as a prime example of additional data analytics, a section of this paper will focus on the ingot manufacturing part (marked in orange).

PV module production FMEA

For PV module manufacturing FMEA, the following steps, as indicated in Fig. 2, were investigated. The sequence begins with incoming goods inspection, which also includes source material verification, such as the quality of cells and the homogeneity of (for example) backsheets and encapsulation materials.

Some of the materials require certain storage conditions (e.g. EVA, ECA), which may impact

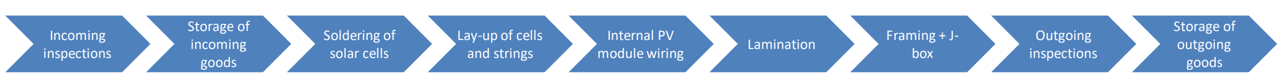

Figure 2. Main PV module production steps.

the long-term reliability of the product. Solar cell soldering (stringing), lay-up of cells and strings, contacting of cell to cross connectors, contact formation to junction box, lamination, framing (including trimming of the laminate and curing of the typically used silicone), outgoing goods inspection (important for the detection) and finally the packaging and storage of the PV modules prior to shipping were evaluated.

Before evaluating each production step, the points to allocate to a certain O, S and D (1–10) must be defined. Table 1 gives the details for the evaluation of the FMEA criteria used in this study. As can be seen in the severity definitions, the focus was on performance but also on critical issues, such as failures which can lead to serious injuries or, in the worst case, to fatality.

Depending on the type of manufacture, the emphasis/priority may lie on different topics and will be determined by process and machinery understanding. This paper focuses on the general aspects related to PV module manufacturing that can be used for any factory. Specific manufacturing for so-called *Sondermodule* (special module) [12–13] production, as used for vehicle (ViPV) or building-integrated PV (BiPV), will be discussed elsewhere.

The incoming goods inspection is intended to verify material specifications that were established on the basis of product design and proper material selection (type of material and manufacturer). This forms part of the design phase and will not be discussed here, as the focus will instead be on production. However, it is an essential procedure in order to produce reliable PV modules, since measurable material variations compared to specifications can become critical during later operation.

Depending on the supply chain and delivery lots, the storage of goods must be considered a part of the overall value chain. The impact will be minor if storage is properly carried out and according to the vendors storage specifications (time, temperature, humidity, light). The lay-up of cell strings, if done with care, and the framing process only have a minor impact on product reliability; therefore, these were not focused on in detail. It must be pointed out, however, that misaligned strings or spacings between cells and strings not as designed have an aesthetic drawback; moreover, they might cause serious 'defects' for 'Sondermodules' or may void spacing requirements stipulated by IEC 61730-1, therefore possibly leading to higher degradation rates, for example as a result of moisture ingress.

The main emphasis was placed on the electrical contact formation (e.g. soldering parameters) and lamination process. Soldering is a complex process of electrical contact formation, and the reliability highly depends on the materials (solder, solar cell, ribbon, coating) and the process parameters (temperature, time for heating and cooling). In typical PV modules there are three steps involved in electrical contact formation: 1) cell interconnection; 2) cross connection of cells; 3) cross connectors in the junction box. With modern half-cell module designs and the increased number of busbars, the cross-connection process becomes more and more important, especially in the centre of the module.

Lamination is typically a heat- and pressure-controlled process to achieve cross-linking of the materials (in the case of EVA, for example). There are several steps, including liquefaction of the encapsulant to achieve a homogeneous film of encapsulation material around all components, and a vacuum process to remove any air and moisture bubbles and cross-linked by-products. Depending

Probability of occurrence O	Impact/Severity S	Probability of detection D	Points
Unlikely	Hardly noticeable	High	1
		The error is detected in any case by common measures, so that a very prompt correction is possible.	
Very low	Fairly insignificant	Moderate	2 to 3
	Aesthetic, very little effect on performance, no impact on safety, does not fall under warranty.	Procedures are in place to enable early detection. However, measurement and test results can be misinterpreted, for example, or incorrect assessments can lead to the defect being overlooked/disregarded.	
Low	Moderately serious	Low	4 to 6
	Measurable and clear effect on performance, increased clarification effort with customers to be expected, no impact on safety. Compensation or repair is possible at reasonable expense.	Only detectable with accurate and comprehensive testing, which is rarely performed on small samples – detection likely to occur after module delivery.	
Moderate	Serious	Very low	7 to 8
	Measurable and clear effect on performance, impact on electrical safety or fire. High liability risk and high follow-up costs to be expected (e.g. module replacement).	Not detectable with common QA measures. Process monitoring does not provide any clues. Detectable using very elaborate tests, but these are not routinely performed. Detection certainly only after module delivery.	
High	Extremely serious	Unlikely	9 to 10
	Can lead to serious injuries or fatality.	There are practically no effective early detection methods. Defects only become evident in operation after delivery.	

Table 1. FMEA evaluation criteria.

on material quality (mixture of the encapsulant) and the lamination process, various things can go wrong and the defined specifications, such as transparency and degree of cross-linking, are not met. Besides the cross-linking, the process steps are also similar for other encapsulation materials, for example polyolefins (POs), and almost identical for EVA/PO-blends (POEs). Alternatives also exist, however, such as the use of silicone-based materials, where such multi-step lamination processes are not necessary. Other obstacles such as the correct and homogenous mixture of two component materials must be overcome.

Outgoing inspections play an important role in the possible detection of defects. Misaligned strings, large bubbles or impurities within the laminate, such as pieces of gloves or insects, can typically be easily identified by visual inspection. Significantly damaged cells or bad soldering will lead to low-output power modules and low fill-factors in *I–V* curve testing, and most likely will be evident in electroluminescence (EL) imaging. Such defects are deemed to not be severe in the long term, because the detection probability is very high (and hopefully will be sorted out). The more concerning issues are those that are not visible in the 100% routine testing that is typically carried out; examples are low gel content due to poor EVA material, improper working heating plates in the laminator, or bad soldering due to temperature, solder or cell variations that were not detected in the incoming goods sampling and process surveillance.

After the outgoing inspections the modules are stacked, packaged and sent to a warehouse. This is usually not an issue, but there may be transportation problems if packaging material is not carefully selected or is damaged. However, this aspect falls outside the scope of the presented study.

The results presented below focus on electrical contact formation and the influence of the encapsulation process.

Details and results of PV module FMEA

As described in detail in the previous section, the FMEA focused on the PV module production processes rather than the materials or the design itself. As indicated, the emphasis was placed on soldering (electrical contact formation) and encapsulation processes. Both are essential for the long-term reliability of the PV modules; therefore, uncontrolled and incorrect assessments of process variations can lead to significant reductions in long-term durability and so represent an increase in quality issues. A selected part of the FMEA, with the highest PN and RPN, is summarized in Table 2 and will be introduced and discussed separately below.

Predicated on the results of the FMEA, different parameters are selected that will serve as the basis for the specification of tests and for optimizing module production. Test results for specific process variations are presented in the experimental results section.

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Electrical contact formation

The electrical contacts (cell to cell, ribbons to cross connectors, and connections in the junction box) are essential elements in the electrical power output of PV modules. Each cell must be interconnected in series with an increased number of contacts (3 to 15+ busbars in multiwire technology) in order to achieve a reasonable voltage and a certain current so that the power inverters can work effectively. Typically, 20 to 24 cells are therefore interconnected in series. These undergo further serial and parallel interconnection to 60 (120 half cells) to 72 (144 half cells) in a PV module, where in a system, strings of 15 to 30 of such modules are connected in series. This results in a few thousand cells connected to an inverter input, which underlines the importance of excellent electrical interconnection of solar cells, even if there are some backup strategies, such as bypass diodes, built into the PV modules. Furthermore, it must be noted that with a further increase in solar cell size (M6 to M12), besides half-cut cells, third-cut cells are used. Additionally, other techniques, such as shingling with electrically conductive adhesives (ECAs) [15], will use even smaller fragments of cells (1/5, 1/6, ...), but contact formation by ECAs is not the focus in this paper and will be evaluated in future work.

Four selected results for cell solder interconnections are presented in Table 2 ('#1' to '#4'), which range from an RPN of 48 (acceptable) to 168 (can have significant impact). The severity of the selected processes is fairly similar (S = 7–8) and can be a significant concern. The occurrence for each is not very high (O = 3–5), but must still be considered. However, the largest difference lies within the detection probability (D = 2 or 8). With D = 2 ('#2' fluxing issue, '#4' heating issue) the process deviation is reasonably easy to detect, whereas with D = 8 ('#1' 'bad' material, '#3' ribbon crimping) it is more difficult and may require in-depth and costly analytics or detection equipment.

The first two items, 'Soldering #1' and 'Soldering #2', deal with the soldering flux application. Two cases were examined: the first discussed the problem of contaminated flux and the second with no flux application. Because for both cases the occurrence was very low and the more obvious case of no flux application can be detected very well (no soldering), no follow-up actions were considered as a result of the FMEA.

The third item ('Soldering #3') pertains to ribbon pre-treatment within the stringer machine and might not be applicable to all machinery used in PV for cell soldering. The quality of the ribbon crimp is relatively difficult to assess (D = 8). Since the

Process filter	Fault/Question	Severity S	Occurrence O	PN (S × O)	Detection D	RPN (S × P × D)
Soldering #1 – cell	• Flux is contaminated • Occurs infrequently, as typical flux nozzles will be clogged What is the impact on solder joints if impurities are integrated in the joint?	7	3	21	8	168
Soldering #2 – cell	• Flux is not applied • Occurs if flux nozzles are clogged because maintenance intervals are not properly chosen What happens to the contacts?	8	3	24	2	48
Soldering #3 – cell	• Ribbon crimp: material damage to the ribbon • Rare occurrence – typically only if broken tooling is used What is the impact of pre-damaged ribbons on long-term stability of the PV module?	7	2	14	8	112
Soldering #4 – cell	• Hot cell string: over-soldered cells due to machine stoppage • Occurs several times per day It is unclear what the long-term effects of hot cell strings are. Currently, such strings are segregated – but is that necessary?	7	5	35	2	70
Soldering #5 – cross	• Not soldered or badly soldered ribbon-to-cross connector joints • Misalignment What is the long-term impact of individually uncorrected ribbons at cross connections? Does extra bending or misalignment reduce reliability and lead to early connection fatigue? Section separated into 3–6 BB (top) and ≥9 BB (bottom).	7 5	5	35 25	4 7	140 175
Lamination #1	• Low or excessively high degree of cross-linking of EVA encapsulant • Occurs if process control for heating phase is faulty: heating phase is 20–30% too long or too short • Observation: modules look normal, with no drift of cells within the laminate How is module durability affected with over-cured EVA?	5	5	25	7	175
Lamination #2	• Low degree of cross-linking of EVA encapsulant • Occurs if fault in laminator, bad material, or lamination process performed too quickly What happens in the case of a gel content in the range 65–80% or lower?	5	5	25	7	175

Severity S: 1 (very low risk) to 10 (deadly)
Occurrence O: 1 (very low) to 10 (very high, certain)
Probability of Detection D: 1 (certain – fault will be caught on test) to 10 (fault is undetectable)

Table 2. Selected part (highest PN and RPN) of the FMEA process. (Adapted from Jaeckel [14].)

occurrence in the particular machinery used was regarded to be very low, no immediate follow-up was agreed on.

The last item ('Soldering #4') discussed here for solar cell soldering relates to process time and temperature profile during the soldering process. Such variations occur more frequently (e.g. as a result of production stoppages due to cell breakage) and therefore have a more important impact on overall production yield. As a very similar heating process is performed to cure ECA in both shingled and H-grid technologies, this FMEA step is important not only for soldering, but also for future ECA-based electrical interconnection. The focus for follow-up tests was set to that 'process-stop' observation, even when the RPN was not very high. However, in standard production, case '#4' occurs more frequently than the other discussed issues. Additionally, it allows one to gain a more in-depth understanding of the significance of permissible process windows. To investigate the effect on the long-term stability of the modules, special samples were built which incorporated the particular defect, and long-term test-to-failure experiments (including extended thermal cycling tests per IEC 61215-2 MQT 11) were commenced. The results will be given in the next section.

To conclude the soldering discussion, the impact of internal module string-to-string soldering is addressed ('Soldering #5'). Where in the past, for three to five busbar cells, 6 to 10 interconnections had to be done, for modern half-cell modules with 9 to 15+ busbars, 18 to more than 30 individual connections are necessary. For half-cell modules with the so-called *butterfly* design, this becomes even more complex in the centre of the module, because ribbons must be interconnected to one cross connector from two sides. Therefore, it becomes very likely that a connection is either not properly formed or not at all. The detection of such defective electrical connections might not be easy.

In *I–V* curve measurements, the impact of one missing ribbon for a higher number of busbars (>4) is fairly small and will most likely not be visible.

With the use of EL imaging, it is clearly visible in the case of three to five busbar cells, but becomes more difficult to see with an increased number of busbars, and almost impossible for 'bad' solder connections, where 'bad' can mean just a pressed contact without solder-joint formation. Other detection methods, such as magnetic field imaging (MFI), might be required [16]. A detailed study of this production step is planned in combination with novel detection and root cause analytic methods.

Encapsulation process

The encapsulation process is one of the key processes in PV module manufacturing, as it is intended to protect the solar cells from all environmental influences – such as moisture and mechanical hazards like snow, hail and wind – and ultimately to assure electrical safety in protecting against the hazard of electrical shock.

Most manufacturers use a lamination process to encapsulate the solar cells. Because lamination is primarily the bottleneck process, optimization is often done at this point, with a focus on reducing process time and thus increasing throughput. Lamination is a complex process requiring several parameters to be balanced out (heating, vacuum, pressure, time) and is moreover significantly dependent on material properties. It is also influenced by environmental parameters, such as ambient temperature of the manufacturing facility. Smaller variations in material properties and environmental parameters are summarized with regard to their impact on the degree of cross-linking; their impact is only slightly greater if the degree of cross-linking varies within ±10% ('Lamination #1' in Table 2). Typically, such modules show no obvious optical findings directly after manufacturing, and detection is quite challenging (D = 7).

Modules with a very low degree of cross-linking are made intentionally by significantly accelerated lamination processes, caused by a defect in the laminator, or result from very poor quality of the encapsulation material ('Lamination #2'). The latter should be detected earlier on in the incoming goods inspection. A defect on a heater plate in a laminator can occur and may not be detected immediately and depends on the type of laminator and the sensors in the laminator. In consequence, it can happen that several batches are processed prior to the problem being detected (D = 7). Depending on module tracking in the factory, such modules can be traced back, but this also depends on the sensors and tracking of modules throughout the module production process. From past experience, modules with a low degree of cross-linking demonstrate a higher probability of delamination.

An example of a six-year-old module is shown in Fig. 3(a). On the basis of the RPN and the importance for the production quality and yield, this process flaw was further evaluated, and samples were constructed to better assess the direct influence by comparing good and low degrees of cross-linking.

Experimental results

On the basis of the FMEA results, specially designed modules were constructed and tested against

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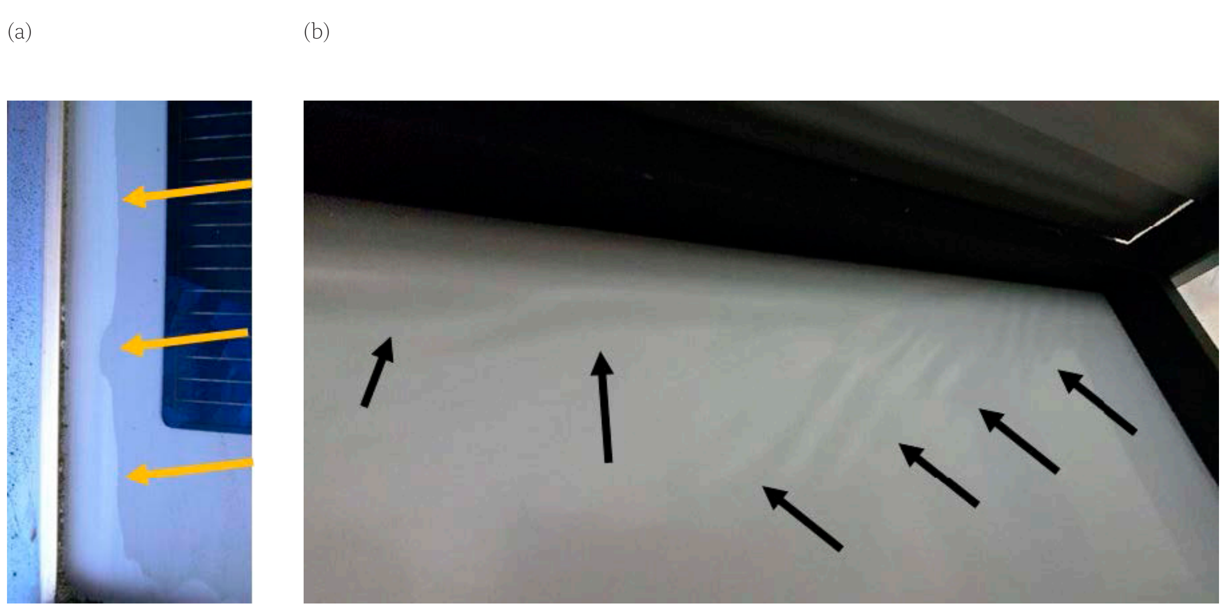

Figure 3. (a) Delamination and bubble formation of a field module from central Europe after approximately six years. (b) Large-area delamination and bubble formation of a specially prepared, low-gel-content PV module after damp-heat exposure (prior to damp heat, the backsheet was optically up to standard), similar in nature to other observations in the field (e.g. in Bosco et al. [17]).

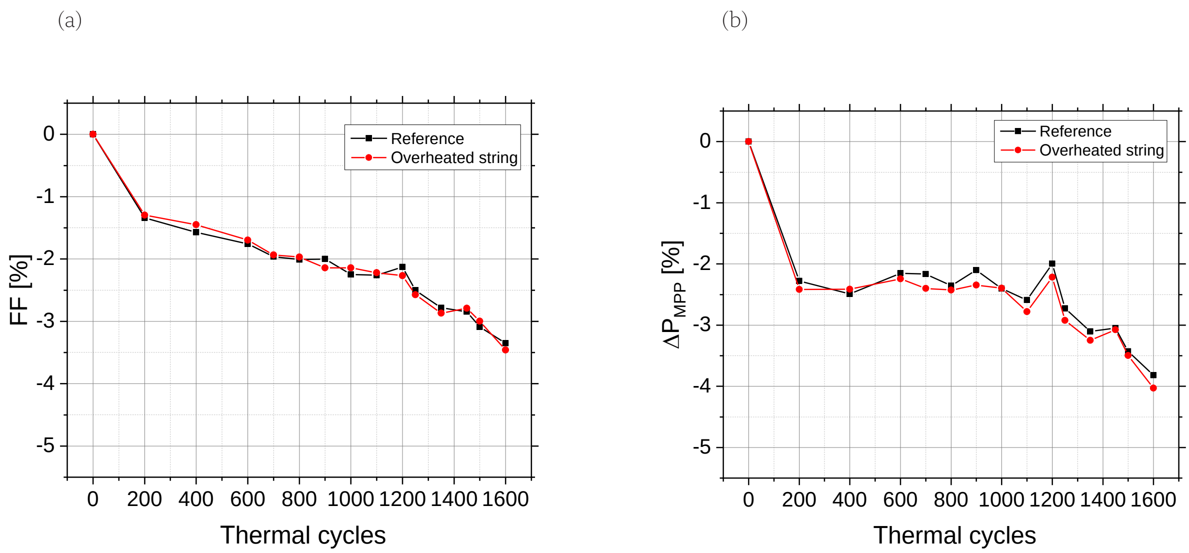

Figure 4. Results of extended TC testing of modules containing an overheated cell string: (a) trend in fill factor; (b) trend in power loss.

reference modules (in-spec, within process window) without variation of the process.

Electrical contact formation

The results for the solar cell soldering process evaluation of overheated strings are given in Fig. 4. A standard type-approval testing temperature cycling (TC) sequence in accordance with IEC 61215-2 contains 200 cycles, running from –40°C to +85°C. Even after extending the stress period by a factor of eight, to more than 1,600 cycles, no significant differences between reference and out-of-spec can be detected in *I–V* curve measurements. In the EL images, a darkening at the edges of the cells becomes visible (see Fig. 5); this is not correlated to the soldering process, however, since a similar darkening effect was observed on the in-spec module.

Encapsulation process

To evaluate the influence of a low degree of cross-linking (<50%), specially prepared modules were manufactured. The module output power results for extended damp-heat (DH) testing using the test parameters specified in IEC 61215, namely exposure at 85°C and relative humidity of 85% for 1,000h, are given in Fig. 6. The initial delamination effects were visible after ~1,000h of DH, as shown in Fig. 3(b). Standard modules with a high degree of cross-linking (~85%) do not show such delamination.

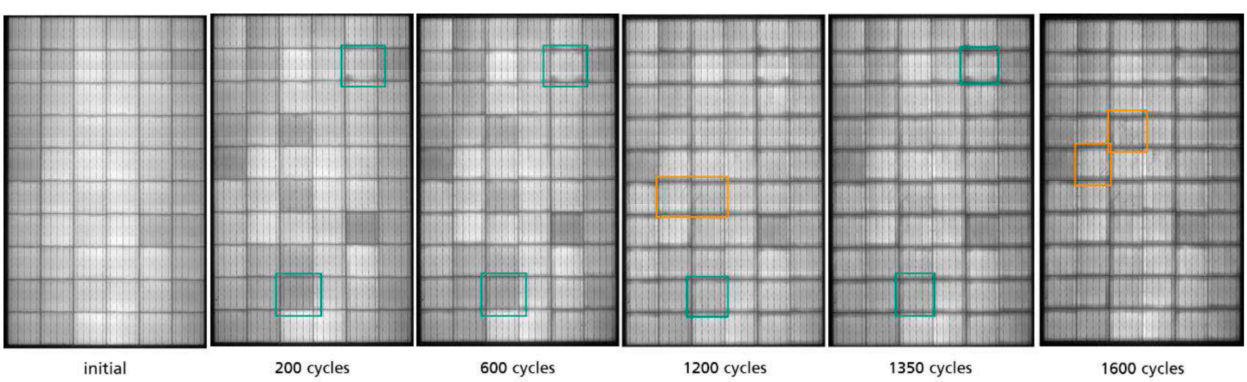

Figure 5. EL images of a module with an overheated string during extended TC tests. Cells with deteriorated edges and with homogeneity changes due to boron– oxygen (BO) degradation/regeneration leading to grey-scale variations are highlighted.

However, the power loss difference after 1,000h is not huge (2% vs 3%), but the trend of the sample with a low degree of cross-linking (red – 'low GC') is expected to be stronger than that of a normally processed module, where losses of around 3–5% are expected after 2,000h. The offset after 2,100h is related to a regeneration treatment and to the particular cells in use. The reference module would have shown a similar jump, which is a kind of dark-state non-current-injection effect.

Process data analytics

Manufacturing processes provide data over the entire PV process chain, the steps of which are shown in Fig. 1. On the one hand, simple protocols are manually established for each process step, but on the other, data are automatically mined, with a high number of values during the process time. Data management becomes necessary for all types of data, and smart analysis demonstrates the potential to reduce process issues and increase production yield [18,19]. In addition to FMEA, state-of-the-art machine-learning algorithms are able to perform process analyses. Multidimensional process data cannot be handled by humans; however, that can be analysed using computer systems by applying artificial intelligence and other approaches from machine learning. Applications for machine learning are available in every step of manufacturing.

For example, if a single process parameter exceeds the limits of the standard production window, the costs of the crystal-growth manufacturing process will increase noticeably. An exorbitant amount of energy is required and costs rise when the crystal needs to melt and is pulled again. Fig. 7(a) shows the melt temperature for approximately 60 crystallization runs, with this melt temperature being just one of 90 process parameters for each run. This means that a 90-dimensional parameter set-up describes a single process run. Successful and failed processes are indicated on the graph in green and red respectively: *failed* means structure loss and re-melting of the crystal. It is not possible to manually distinguish between pass or fail by plotting 90-dimensional process data; thus, machine-learning classifiers were applied and a complete cross validation was performed for each classifier. Support vector machine (linear), support vector machine (radial basis function), K-nearest-neighbour, logarithmic regression and random forest classifier methods were applied for comparison purposes, with the logarithmic regression yielding the best prediction accuracy of 72%.

The machine-learning classification provides a probability of success that can easily be compared to all process parameters by performing a correlation

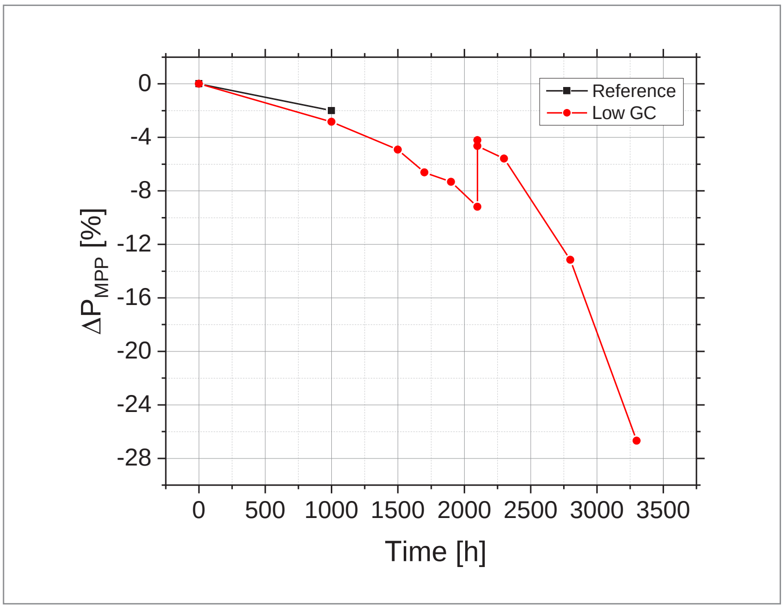

Figure 6. Latest results of extended DH testing of samples containing normally cured EVA modules (degree of cross-linking ~85%) and a module with a low degree of cross-linking of less than 50%. Cells, glass, backsheet and encapsulation material are the same in both cases. These tests are still ongoing.

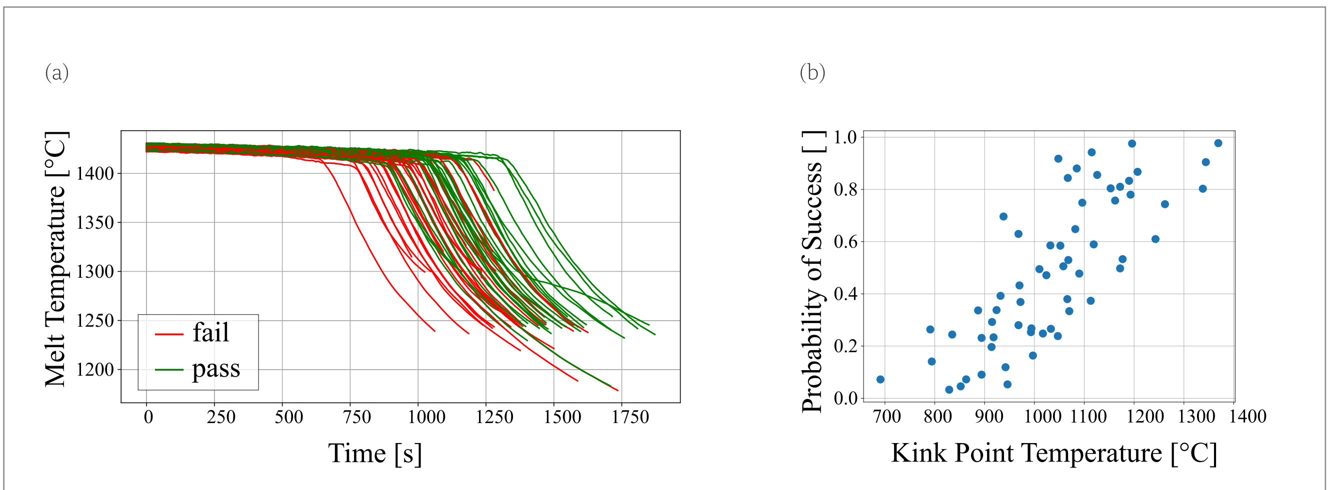

Figure 7. Application of a machine-learning algorithm to distinguish between process failure and process success. (a) One parameter (melt temperature) in 60 crystallization violates the process time limitation (process result is indicated by the colour of the curve). (b) A correlation between process parameter and process result was found by cross validation of different regression models.

analysis; the results are shown in Fig. 7(b). A linear correlation is clearly visible between the probability of success of the crystallization process and a relevant process parameter (time of drop in melt temperature). Without machine-learning support, this analysis would not be possible. By using this information, the success rate of the process can be improved as a result of visualization simplification. Thus, time consumed, costs and CO_2 emissions can be reduced, while increasing production yield and company profit.

If larger corresponding data sets are available, this kind of analysis can be applied to any process step in the PV industry and elsewhere along the chain. For instance, the given bill of materials (BOM) data together with the process data could be correlated to PV park performance data and site conditions in order to produce site-specific reliability reports.

Summary and conclusion

The interdisciplinary combination of a detailed FMEA by manufacturers, equipment suppliers and research institutes, together with modern data analytical methods, can support the future development of the entire PV value chain. On the basis of the module production and focused FMEA discussions, a long list of processes and a short list of important parameters to prioritize were developed. This insight can now be applied by the PV industry to assess new processes or materials. The FMEA approach supports the understanding of critical processes, the mitigation of unwelcome effects, and the avoidance of implementing materials and processes that will result in non-reliable products.

Similar long-term stress-testing results to those presented here have been reported in the literature [17,20–23], but the methodology for improving the understanding of the growing complexity of correlations is far more systematic, traceable and more reproducible if each step is well documented.

The results of this FMEA will be used for future applications to assess other encapsulation materials combined with different processes and module structures. Material-wise, the FMEA structure will help in figuring out critical processes, for example to adapt the current lamination process for PO or POE materials [24]. Furthermore, it can be utilized to investigate, for example, the impact of using either a polymer backsheet or a glass structure as the back-side cover.

Unfortunately, a comprehensive cross-value-chain FMEA and data collection scheme does not yet exist. The presented data analytics of just one step of the value chain has demonstrated the potential for improvements and it can enhance subsequent steps, such as the evaluation of cell efficiencies on the basis of certain wafer processes. More thought can be put into the module, including soldering and lamination, to finally link certain processes to field failures and differences in energy production.

This project has shown the feasibility of such a data-based analysis and its power to support the optimization of processes and the making of decisions. The results presented prove its potential, and motivate the use of the possibilities that also come along with digitalization and Industry 4.0 for PV reliability issues.

"The interdisciplinary combination of a detailed FMEA by manufacturers, equipment suppliers and research institutes, together with modern data analytical methods, can support the future development of the entire PV value chain."

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About the Authors

Bengt Jäckel received his Ph.D. in materials science from TU Darmstadt in 2005. Since 2007 he has been working in the PV industry, holding various positions covering the entire value chain. He joined Fraunhofer CSP in 2018 and currently heads the PV Modules, Components and Manufacturing group with a focus on multi-scale analytics to develop fundamental root-cause understanding for next-generation PV modules and components. He also leads the PV Module group at DKE and is the German representative in IEC TC 82.

Matthias Pander received his master's in mechanical engineering from Leipzig University of Applied Sciences in 2010. He has been working in the Reliability of Solar Modules and Systems group at Fraunhofer CSP since 2010. He specializes in the field of finite-element simulation of PV modules and material modelling, as well as lifetime evaluation.

Ringo Koepge received his Diploma degree in materials science from Martin Luther University Halle-Wittenberg in 2010. Since then he has been working as a research scientist with the Material and Process Analytic team at the Fraunhofer CSP. His research in the field of improvement of manufacturing processes for crystals, wafers, cells and modules focuses on data science, especially on the application of machine-learning algorithms for clustering, classification and regression of data.

Stephan Großer studied physics and received his Ph.D. in 2008, and worked in the PV industry as a process engineer and researcher. In 2011 he joined Fraunhofer CSP, where he leads a team that focuses on the microstructure diagnostics of materials and devices and the root-cause analysis of defects.

Dr. Karl-Anders Weiss studied physics and economics and holds a Ph.D. in physics. He has been at Fraunhofer ISE since 2005, working mainly on the reliability of materials for solar energy systems, with a particular focus on degradation and service-life modeling, non-destructive analytics, coatings and polymeric materials. He recently worked on sustainability topics, especially the influence of reliability and durability on sustainability or renewable energies.

Enquiries

Bengt Jaeckel
Fraunhofer Center for Silicon Photovoltaics CSP
Otto-Eissfeldt-Strasse 12
06120 Halle, Germany

Tel: +49-177-7503123
Email: Bengt.Jaeckel@csp.fraunhofer.de
Website: https://www.csp.fraunhofer.de/

Recent processing advances towards full-wafer two-terminal perovskite/silicon tandem solar cells

Brett A. Kamino, Soo-Jin Moon & Arnaud Walter, Swiss Center for Electronics and Microtechnology (CSEM) Sustainable Energy Center, Neuchâtel, Switzerland

Abstract

Two-terminal tandem solar cells based on perovskite/silicon (PK/Si) technology represent one of the most exciting pathways towards pushing solar cell efficiencies beyond the thermodynamic limit of single-junction crystalline silicon devices. While laboratory efficiencies of these tandem cells have risen to very impressive levels, many important innovations towards enabling their eventual manufacturability have also been made in this rapidly evolving field. In this paper, a number of these processing innovations are highlighted in order to give a more complete view as to the viability of scaling up the processing of these devices. Specifically, the focus is placed on how today's crystalline silicon process flows could be adapted in order to allow existing cell lines to produce PK/Si cells. Additionally, the adoption of new processes for deposition of the perovskite subcell is also examined. The discussion of these innovations aims to spotlight the significant advances in this field, but also to highlight many of the future manufacturing challenges that this technology will face.

Introduction

Over the last few decades, the cost of PV energy systems has plummeted, with massive reductions in overall system cost on a dollar per watt basis [1]. This reduction in cost has been partially driven by significant improvements in overall module power conversion efficiency. At the heart of this improvement has been the deployment and optimization of new crystalline silicon cell technologies, which have been successful in pushing module efficiency ever higher. Today, the industry is getting ready for the large-scale roll-out of silicon heterojunction (HJT) cells, as well as cells based on high-temperature passivating contact (HTPC) structures [2]. With these technologies, a number of companies have realized wafer-level efficiencies of over 25% [3,4]. Such values are gradually approaching the practical limits of single-junction silicon PV [5].

As these technologies are being scaled up in production, research interests have been shifting towards the next technology to push device efficiencies even further, and hopefully continue the gradual reduction in the levelized cost of PV electricity. For the moment, most of this hope rests on the development of a tandem solar cell based on metal-halide perovskite materials on top of a crystalline silicon wafer in a two-terminal configuration (PK/Si tandem structure). Laboratory-sized devices (~1cm^2) based on these structures have shown remarkable progress over the past seven or eight years, with the current world-record devices sitting at an impressive 29.8% efficiency [6].

While this efficiency is certainly a remarkable achievement, it is perhaps not the most interesting development in the technology. A survey of the literature reveals an astounding diversity in the variety of PK/Si device structures which can exceed the highest both-side-contacted single-junction crystalline silicon device (at an efficiency of 26.3% [7]). This diversity includes different cell polarities (NIP [8] vs. PIN), bottom cell technologies (both HJT and HTPC [9]), bottom cell surface texture (planar, pyramidal, microtextured) and perovskite deposition techniques (spin coating, meniscus coating [10], hybrid deposition [11], and co-evaporation [12]). Such diversity in efficient device structures is unprecedented among thin-film technologies and suggests a tremendous degree of freedom in designing high-efficiency tandem devices.

As a result of the rapid pace of development in the field, as well as the clear potential for extremely high-efficiency devices, the solar cell industry has begun to invest in research, and most major PV manufacturers are now placing PK/Si technology somewhere on their research roadmaps. Although there are certainly still many challenges to overcome for this technology, mostly around the question of device stability and defect control, the question of manufacturability is now relevant for solar cell producers looking to incorporate this technology into their own lines.

In this paper, some recent advances in the scale-up of two-terminal PK/Si tandem devices will be discussed and evaluated. Specifically, the focus will be on looking at the challenges of transferring current high-efficiency laboratory devices to full-wafer devices that could be compatible with current manufacturing processes. This paper will aim to give a perspective on the state of the field rather than a comprehensive review of all the progress that has been made in this area. In addition, the discussion will centre exclusively on two-terminal PK/Si structures rather than including four-terminal-type

"Most major PV manufacturers are now placing PK/Si technology somewhere on their research roadmaps."

devices. Four-terminal tandem technology does have various advantages over two-terminal structures. Nevertheless, a large majority of current crystalline silicon manufacturers are currently devoting their attention to the two-terminal configuration; the discussion in this paper will therefore be limited to this device configuration.

Integration of commercial bottom cells into tandem structures

The most common implementation strategy envisioned for PK/Si tandem manufacturing is that it could be deployed as an upgrade to current cell lines somewhat analogously to how passivated emitter and rear cell (PERC) technology was viewed as an upgrade to aluminium back-surface field (Al-BSF) technology [13]. A simplified version of this would be a modification to existing processing stations to adapt the bottom cells for tandem integration, the addition of several processing stations for deposition of the perovskite sub cell materials, and a subsequent modified back-end process including metallization, interconnection and module lamination.

Modification to silicon solar cells for bottom cell compatibility

When considering an upgrade of an existing crystalline silicon line to a tandem production line, it is worth discussing how a high-performance crystalline silicon solar cell needs to be modified in order to be compatible for tandem integration. Two active developments in this area are: 1) modification of wafer surface texture, and 2) exploration of different bottom cell technologies.

In the area of engineering wafer texture for PK/Si integration, there have been several important advances in the past few years which greatly widen the processing window for the production of these devices. Previously, practically all tandem solar cells were constructed on small float zone (FZ) wafers with a chemically-mechanically polished (CMP) front surface or with a standard pyramidal texture derived from this polished surface. Tandems built on CMP polished wafers benefited from good compatibility with current laboratory deposition methods (i.e. spin coating) for the perovskite absorber layer as well as the contact materials. This allowed a direct transfer of highly optimized deposition recipes from single-junction perovskite solar cell development to tandem solar cells. However, this approach is obviously held back by the unreasonable cost of the CMP process for silicon wafers and is not suitable for industrial production. The other approach, based on a standard pyramidal texture [11], does not have this disadvantage, because this type of texture is the industry standard for monocrystalline silicon solar cells. Be that as it may, this approach is constrained by the need for careful conformal deposition of the perovskite absorber and contact layers, and careful control of the pyramid size and distribution [14]. Despite these constraints, high-efficiency devices have been demonstrated using the pyramidal texture approach [11].

In recent years, two specific advances have been made in the field which greatly enlarge the parameter space for these types of device. First, several groups have demonstrated a technique for fabricating planar tandem solar cells starting from a commercial diamond-wire-cut Czochralski (CZ) wafer [15,16]. This approach relies on wet-chemical polishing of the front surface to remove most of the surface features generated during the wire-sawing process. While this type of chemistry is well known [17], it was unclear whether it could provide sufficient planarization of the wafer surface to be compatible with solution-based perovskite deposition methods. This strategy provides an interesting pathway to achieving planar tandem solar cells using commercial CZ wafers.

The second important advancement in this area has been the fabrication of tandem solar cells using a very small pyramidal texture (microtexture) [18,19]. This method differs significantly from the standard textured approach in that the perovskite layer is deposited so that it effectively planarizes the surface texture by filling in the valleys between the pyramids. Like the chemical planarization approach, this method can exploit well-known wet-chemical etching chemistries for silicon wafers and would, in principle, be compatible with current silicon wet-chemistry processes. The major disadvantage of this technique is the requirement for a fairly long diffusion length in the perovskite layer. Moreover, it remains to be seen how sensitive these kinds of cell are to variations and distributions both in pyramid size across the wafer or between wafer batches and in perovskite thickness. Intriguingly, this method has been shown to be also compatible with potentially scalable perovskite deposition methods based on meniscus coating [19,10].

While neither of these two advances in texture control has yet resulted in record-breaking efficiencies, they are nevertheless important to the field, since they greatly widen the processing window scope for these devices. Specifically, previous arguments about the merits of flat versus fully textured tandems are now less relevant, as it is starting to become clear that intermediate texture devices can now work.

Another important advancement in the modification of crystalline silicon solar cells for tandem applications has been the diversification of the types of bottom cell technology. In the academic literature, most reports on PK/Si tandem solar cells rely on HJT bottom cell technology. The reasons for this are several. First, the high open-circuit voltage and excellent near-infrared (NIR) response of these cells make them an efficient partner in a tandem configuration. On a more practical note, however, these kinds of cell can be prepared fairly quickly in a university/research environment, making them a

"The deposition of the perovskite absorber and its associated contact layers is perhaps the principal challenge in this field."

convenient starting point in tandem development.

On the other hand, the vast majority of commercial solar cells (and thus produced cells) are based on PERC solar cells fabricated on p-type wafers. Indeed, a meaningful economic argument can be made for PK/Si tandem solar cells exploiting this existing production capacity [20]. A recent report demonstrated such a tandem solar cell built on a PERC rear side and a poly-Si on oxide (POLO) front side [16]. Although efficiencies are still very low, it is likely that significantly higher efficiencies will be within reach for this tandem configuration.

Beyond HJT and PERC type cells, there have also been meaningful demonstrations of tandem solar cells based upon a HTPC approach [21,22]. Recently, the group at CSEM has pushed this concept further, with the demonstration of a 28.3% 4cm² tandem solar cell based on a p-type wafer with HTPCs on both sides [23]. In addition, a collaboration between Qcells and HZB demonstrated a device with 28.7% efficiency based upon Qcells' passivating contact bottom cell technology [9]. It can be seen, on taking a step back, that more and more bottom technologies appear to be adaptable for high-efficiency tandem devices. Again, this agrees with the overall theme of a large processing window for these devices.

Large-area deposition of perovskite layers and contact layers

The deposition of the perovskite absorber and its associated contact layers is perhaps the principal challenge in this field. While there have been many important advances in the upscaling of single-junction perovskite mini-modules [24] in recent years, the same cannot yet be said for PK/Si tandem devices: very few examples of devices beyond several centimetres squared in size have so far been demonstrated. This statement is rather surprising, as the technology for making larger-area bottom cells certainly exists, and an increasing number of researchers have been able to demonstrate impressive efficiencies with single-junction perovskite modules with device areas of several tens of centimetres squared [25–27].

In relation to the above, it is worth highlighting some of the differences in the process and material requirements for a tandem device in comparison to most single-junction devices, which may partially explain this dearth of large-area PK/Si tandems in the literature. These differences can be summarized and placed in three categories:

1) Requirements for thermal stability
2) Tandem-specific bandgap
3) Deposition over rough surfaces

Beginning with thermal stability, a tandem device with perovskite layers must undergo several processing steps that require a certain amount of thermal budget, specifically the buffer layer deposited by atomic layer deposition (ALD), the annealing of a screen-printed Ag paste for the front electrode contact, and the lamination and encapsulation of the module assembly. This thermal budget requirement is not always met by perovskite solar cells, as certain perovskite compositions can be more sensitive to thermal degradation. As a result, these devices must use perovskite compositions with the best thermal stability possible. Practically, what this means is that the simplest perovskite compositions based on the use of a methylammonium cation ($MAPbI_3$) must be replaced with either methylammonium-free or methylammonium-reduced formulations to survive some of these processes [12].

With regard to bandgap, the targeted electronic bandgaps for perovskite materials in a tandem configuration are typically higher than those used in the best single-junction perovskite modules. The need for a higher bandgap and greatly reduced methylammonium content in the perovskite places additional constraints on the perovskite stoichiometries used in tandem devices.

Finally, the deposition surface in a PK/Si tandem will always have some inherent roughness, whether this be a full-size pyramidal texture or a silicon surface after chemical polishing. Even in the case of a chemically polished wafer, this roughness is markedly higher than in single-junction perovskite modules, where the layers are usually deposited on very flat, drawn glass substrates.

In short, what these differences mean is that not all results on a large-area perovskite single-junction device are directly transferable to a PK/Si tandem device.

Even though examples of large-area PK/Si tandems are few and far between, several do exist. In most of these examples, however, the device area is simply increased while still relying on steps, such as spin coating and evaporation of the top metal contact [28,29], that cannot be scaled to a full-size 6" wafer. The group at CSEM has also followed this strategy while incorporating a screen-printed Ag top collection grid to achieve efficiencies of 24.3% on an active area of 57.4cm² [30].

Looking beyond such spin-coated devices, only two examples of a relatively large-area PK/Si tandem device which does not use any spin-coating processes were able to be identified. OxfordPV has presented a tandem solar cell with an efficiency of 26.67% over an area of 200cm², built on an M6 wafer [31]. Unfortunately, the processes and materials used to achieve this result have not been published. The group at CSEM has also presented details of such a device at the EU PVSEC 2021 conference [32] (Fig. 1). In this example, a PK/Si tandem solar cell was fabricated on a rear emitter HJT on a CZ

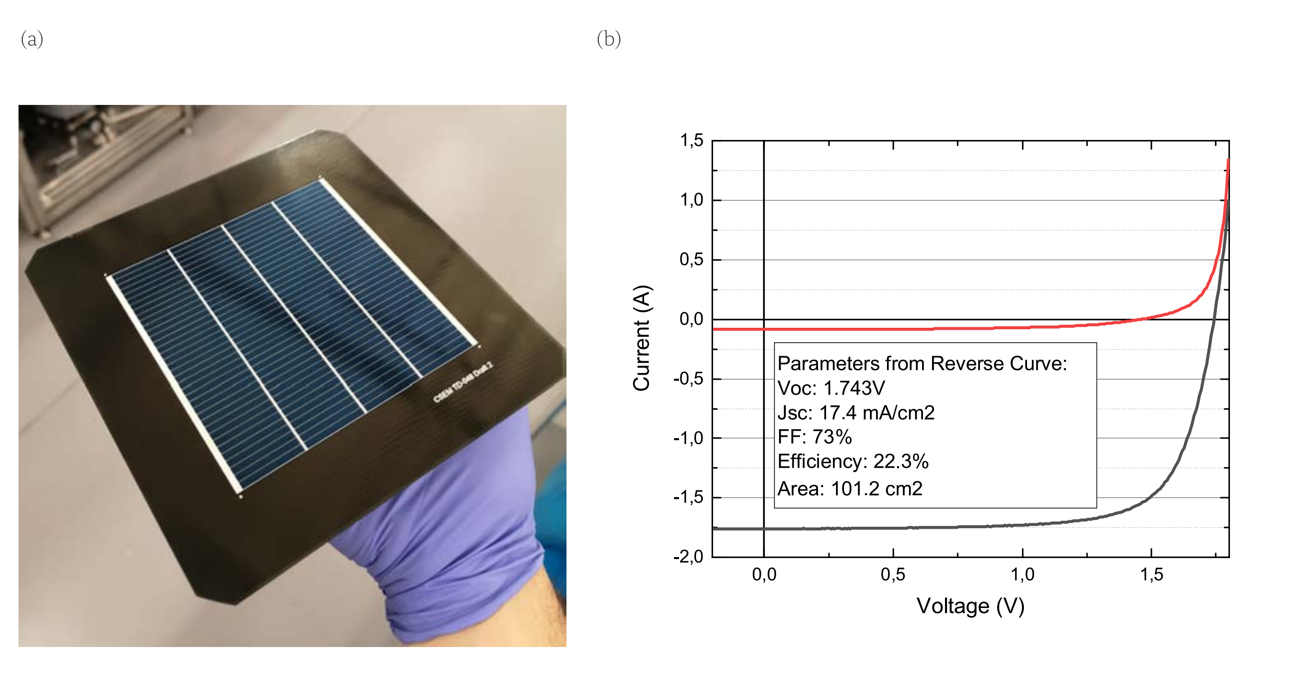

Figure 1. (a) A 101.2cm² PK/Si tandem solar cell built on an M2 HJT bottom cell. (b) *I–V* curve of the record cell with a stabilized efficiency exceeding 22%.

M2 wafer with an active area of 101.2cm². The front side of the wafer was chemically polished to be relatively flat, whereas the rear side was textured to improve the light-trapping efficiency. For the perovskite top cell stack, all the contact layers in that device were deposited by vacuum deposition processes (sputtering, thermal evaporation, ALD), while the perovskite layer itself was deposited using a solution-based blade-coating process and the front metallization was achieved by screen printing a low-temperature Ag paste. The record cell from this experiment yielded an efficiency of 22.3% over an active area of 101.2cm². Despite this efficiency not yet being competitive with a commercial crystalline silicon device, the authors believe that this result is significant for the PK/Si tandem field, as it demonstrates a device using commercial wafers, wet-chemical etching, potentially scalable deposition processes and printable front metallization. In effect, such devices were constructed using a process flow that could potentially be adapted by industry.

Although few examples of large-area PK/Si tandem solar cells have been demonstrated, there have been many groups working on processing technologies which may enable deposition of large-area PK/Si solar cells. Specifically, the past few years have seen several new advances in the scalable deposition of perovskite layers.

One of the fundamental challenges in the scale-up of PK/Si tandem devices is the question of how to deposit the perovskite layer with very high uniformity and high throughput across an entire wafer. One solution which stirred a lot of interest in the industry has been thermal co-evaporation of the perovskite layer directly on a wafer. While co-evaporation of perovskite layers has been known for a relatively long time [33], the successful processing of perovskite layers for PK/Si tandem integration had been lacking from the field until recently. Recent work from a group at HZB showed that this method could be used to create PK/Si tandem devices directly on standard textured bottom cell surfaces, resulting in efficiencies of over 24% [34]. Moreover, several other groups have demonstrated similar methods to produce tandem-appropriate perovskite layers, albeit in single-junction devices [35–37].

These advances are encouraging, but several practical challenges remain with this deposition approach [38]. Primarily, co-evaporation of the perovskite layer remains an extremely slow process, with typical deposition rates of the order of 1–3Å/s. Assuming a 400nm-thick layer, this would result in a processing time of the order of tens of minutes. While some process optimization could be expected, significant improvements to this deposition rate would need to be demonstrated with good repeatability. Related to this challenge is the question of deposition tool design. All examples of thermal co-evaporation in the literature rely on point sources, as is typical for research tools. A production tool would most likely take the form of an evaporator with linear sources. As in the case of evaporation of copper indium gallium selenide

"One of the fundamental challenges in the scale-up of PK/Si tandem devices is the question of how to deposit the perovskite layer with very high uniformity and high throughput across an entire wafer."

(CIGS) materials, perovskite compositions suitable for tandem integration would require multiple chemical species being co-deposited with high spatial and chemical uniformity along with high deposition rates. This is not a trivial task, and it remains to be seen how toolmakers and research groups will respond to this challenge.

The other major classes of demonstrated scalable perovskite deposition methods are those based on slot-die coating. *Slot-die coating* is a well-established large-scale coating technology for several products in the semiconductor sector, including LCD display panels and xerographic photoreceptors. Several groups have reported in the literature high-efficiency single-junction devices with tandem suitable chemistries using this technique [39]. Moreover, the theoretical deposition time of a perovskite layer on an M6 wafer using this method is of the order of tens of seconds rather than tens of minutes. Additionally, these methods have already been demonstrated to be useful on tandems with chemically prepared surfaces [19,32].

Despite the demonstrated potential of the slot-die coating approach, significant challenges also exist. First, most examples in the literature rely on high-toxicity solvents such as N,N-dimethylformamide (DMF) for the perovskite ink. Large-scale production of PK/Si tandem solar cells would utilize large quantities of this solvent. Adequate controls to limit worker exposure and scrub this solvent from the factory exhaust could pose a significant challenge and incur additional processing cost. Other solvent systems do exist and in fact such a DMF-free solvent system was used in the example of a large-area blade-coated tandem shown in Fig. 1.

Another major challenge with slot-die coating of perovskite layers for PK/Si tandems is related to the geometry of the wafer itself. Unlike other applications where slot-die coating is deployed, a solar cell wafer uses its entire surface area to generate power. In a tandem application, this means that the perovskite top cell must be deposited as close to the edge of the wafer as possible for maximum efficiency. Moreover, the edge of the coating area must be as homogeneous as the rest of the coating area so as not to produce local areas of low efficiency.

A further challenge is the precise control over the beginning and ending of the coating zone. Slot-die coating often requires a small area at the start of the coating zone for the meniscus to equilibrate. Likewise, the end of the coating area requires careful control so that excess solvent is not left on the substrate. Finally, solar wafers are not perfectly square, which means that the effective coating width will change at different points along the coating path. As in the case of the co-evaporation process, solutions to these challenges will require significant support from toolmakers in the form of innovative tool design, tight process control and significant process optimization.

Apart from the two deposition examples described above, there are a number of other potentially scalable methods for perovskite deposition that could be utilized for large-area PK/Si tandems [40]. Some of these approaches, including ink-jet printing or spray coating, can produce single-junction laboratory solar cells with efficiencies approaching 20%. On paper, these deposition methods are extremely interesting and may be able to overcome some of the disadvantages of the two principal techniques covered here. However, these other methods have not yet been demonstrated on PK/Si tandem solar cells on any scale.

Back-end processes – metallization, interconnection and module fabrication

Following the deposition of the perovskite absorber layer and its contact materials onto a wafer, a tandem solar cell still requires several processing steps before a completed module can be obtained. These steps include screen-printed metallization, sorting, interconnection and finally encapsulation into the final module assembly. Because of the unique thermal and chemical compatibility of the perovskite solar cell, modification of these steps will be necessary, since the typical processing conditions used in commercial devices are not compatible with most current tandem devices. Undeterred by the fact that no completed modules have yet been demonstrated by the research community, several key advances have been made in the last few years which provide an insight into how these back-end processes could successfully be optimized for a PK/Si tandem solar cell.

Screen-printed deposition of a silver front grid is a standard process for practically all crystalline silicon solar cells. Modern processes allow very efficient Ag utilization to produce high-aspect-ratio silver fingers with good contact resistance and bulk conductivities to minimize spreading losses across the front electrode and across the device. For PK/Si tandem solar cells, nearly all laboratory cells utilize evaporated metal contacts, which can provide adequate current collection for small-area devices. However, full-wafer devices will most likely require a screen-printed Ag front grid for integration into existing solar cell process flows. The key challenge in achieving this is the low thermal budget available for curing the Ag ink after deposition. The group at CSEM has previously shown that this is indeed possible; however, the available silver pastes at the time resulted in a rather high contact resistance between the silver paste and the top transparent conductive oxide (TCO) of the tandem cell [41].

Since that initial publication, the availability of very low temperature silver pastes compatible with perovskite solar cells has increased dramatically. Internal tests within the laboratory at CSEM confirm that some of the best pastes are now able to achieve contact resistances of less than $10m\Omega\cdot cm^2$ and bulk resistivities of less than $1\times10^{-5}\Omega\cdot cm$ while curing at

(a) (b)

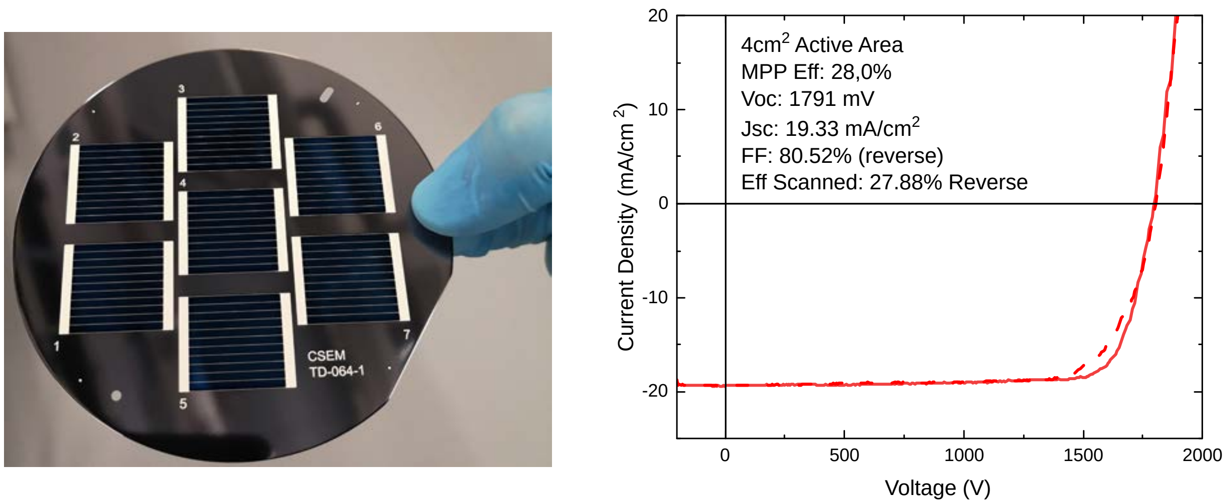

Figure 2. (a) A 4" FZ wafer with multiple PK/Si devices across its surface, including printed metallization. (b) LIV curve of a 4cm² PK/Si tandem with printed metallization, showing a fill factor of over 80% and a stabilized efficiency of 28.0%.

130°C. Such values now approach what is possible for silicon heterojunction solar cells.

These pastes are now being used routinely in the fabrication of the tandems in the group at CSEM (Fig. 2), where it has been possible to create cells with fill factors of more than 80% over a moderate area of 4cm² [23]. While the efficiencies of these devices are not currently on a par with those of the very best small-area cells, progress in this area shows that the front silver grid is not a barrier to achieving high-efficiency tandems over a large area. In addition, it would be remiss not to mention recent work demonstrating copper electroplating on perovskite devices [42]. This rather surprising work hints at the possibility of removing the Ag entirely from future tandem designs.

Similar to printed metallization, module assembly is another back-end process which requires careful consideration for use with PK/Si tandems. Because of the rather high sensitivity of perovskite devices to moisture ingress, PK/Si tandem modules would quite likely need to be assembled in a glass–glass configuration with a butyl edge seal. The actual encapsulation would take place during a lamination process, where pressure and temperature are applied to the stack to produce a hermetic seal. This process exposes the PK/Si tandem solar cell to potential thermal, mechanical and chemical degradation. A recent comprehensive review on the subject gives a far more detailed discussion of this [43].

Accounts can be found in the literature from a number of groups who have demonstrated processes to make encapsulated single-cell devices in order to test the stability of the cell to external stimuli [11,44]. However, in these previous examples the crucial encapsulant layer was omitted. Real-world cells require this encapsulant layer for improved mechanical strength of the module and for better optical coupling.

Very recently, several examples of glass–glass encapsulated PK/Si tandem solar cells with encapsulant layers were reported [45]. This idea was also demonstrated by the group at CSEM using somewhat larger cells with printed front metallization (Fig. 3). With careful optimization of encapsulant material and processing conditions, it was possible to achieve cell encapsulation with minimal degradation to the cell, except for a notable drop in the photocurrent of the cell due to the as yet unoptimized optics in the encapsulated stack. Otherwise, no obvious damage to the cell during the encapsulation processes was found. These preliminary results are very promising and show that a typical glass–glass encapsulation process can be successfully implemented in PK/Si tandem devices.

The glass–glass type of encapsulation scheme appears to provide sufficient isolation of the PK/Si cell from moisture ingress, as verified by damp-heat tests, where the best cells lost about 5% of their efficiency after 2,000h of stress testing. These initial results from the group at CSEM and

"Module assembly is another back-end process which requires careful consideration for use with PK/Si tandems."

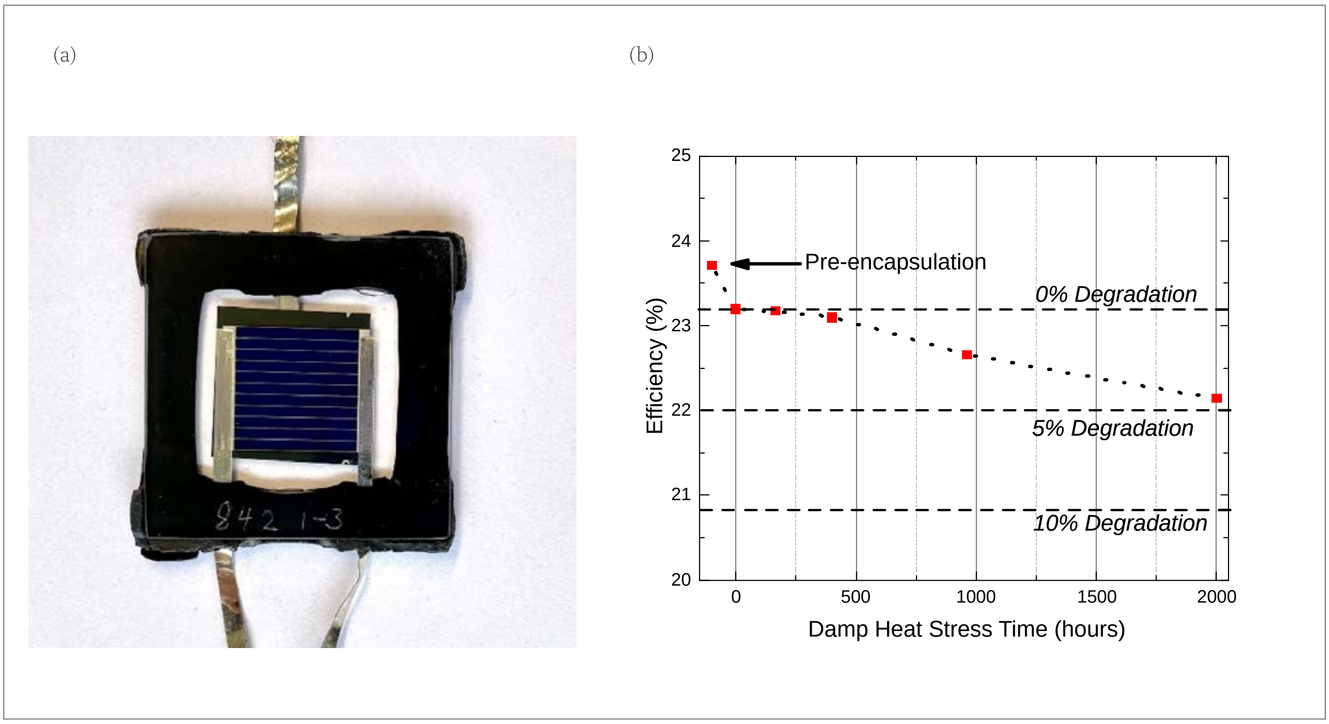

Figure 3. (a) Example of a 4cm^2 PK/Si tandem solar cell with printed metallization and glass–glass encapsulation with a butyl edge sealant. (b) Damp-heat stress testing of this cell, demonstrating approximately 5% degradation in efficiency after 2,000h at 85°C and 85% RH.

"The steady rise in record cell efficiency is seeing the emergence of a diverse collection of processing pathways towards building efficient tandem devices."

others strongly suggest that modifications to standard glass–glass encapsulation processes could be a suitable starting point for the integration of PK/Si tandems into a standard PV process flow. Of course, further work on multiple cell interconnection for larger devices is still needed in order to investigate the various challenges that may exist here. In particular, the poor mechanical adhesion of some of the perovskite subcell layers may pose significant challenges in achieving reliable module-level interconnection [46].

One final area of note, which has received very little attention so far, is the measurement and sorting of PK/Si tandem devices prior to their module integration. This process is typically done to bin solar cells together in order to produce the best overall module performance. As is true for all industrial-scale processes, this measurement and sorting must be done extremely quickly (of the order of several hundred milliseconds per cell). Unfortunately, because of pseudo-capacitive effects and ionic movement within the perovskite solar, the high speeds can greatly distort the cell performance measurements [47]. Future work to look into this issue will be another necessary step on the road to integrating PK/Si tandem solar cells into existing process flows.

Conclusions and outlook

In summary, the development of two-terminal PK/Si tandems continues to advance at a respectable rate. The steady rise in record cell efficiency is seeing the emergence of a diverse collection of processing pathways towards building efficient tandem devices. For the most part, these different processing pathways are the result of research groups identifying and finding unique solutions to the many challenges faced in terms of materials and processing. These advances have touched on every aspect of the solar cell process flow, from wafer texturing to module encapsulation. Indeed, it is encouraging that many researchers are actively focusing on meeting the challenges of scale-up rather than simply looking to improve device efficiency.

These excellent advances, however, have not yet translated to the engineering of large-area devices which incorporate many features of standard solar cell devices (such as commercial CZ wafers, large-scale PK deposition and printed metallization). This is hardly a criticism of the field, as such work can demand significant resources and access to certain toolsets. Recent investments in this area by a number of established PV manufacturers will probably change this state of affairs in the near future. Regardless, major challenges still exist in finding a deposition process for the perovskite layer that is both high throughput and forms a high-quality material. Additionally, many open research questions exist in respect of the module lay-up process of these types of solar cell and how their unique physical properties will affect module reliability and stability.

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About the Authors

Brett A. Kamino received his Ph.D. in chemical engineering from the University of Toronto, Canada. Since 2013 he has devoted his time to commercializing perovskite PV technology, working with various start-ups and research centres. He is the author of numerous papers in the field of thin-film PV, as well as the co-inventor on several key processing patents for perovskite tandem solar cells. He currently works as a senior R&D engineer at CSEM, where he focuses on the scale-up of PK/Si tandem devices.

Soo-Jin Moon is a senior R&D Engineer at CSEM. She received her Ph.D. from the Ecole Polytechnique Fédérale de Lausanne (EPFL). Before that, she worked as an R&D engineer at Samsung and LG in Korea. She is the author of over 40 peer-reviewed papers and her research interests lie in materials for energy generation, such as solar cells and batteries, and in the characterization of these devices and materials.

Arnaud Walter is a senior R&D Engineer at CSEM, where he works on diverse research projects involving perovskite materials for PV, LEDs and sensors. His main interests are in the integration of PK/Si tandem technology with industrial crystalline silicon solar cells.

Enquiries

Arnaud Walter
CSEM SA
Rue Jaquet-Droz 1
2002 Neuchâtel, Switzerland

Email: awr@csem.ch
Website: www.csem.ch/se-center

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