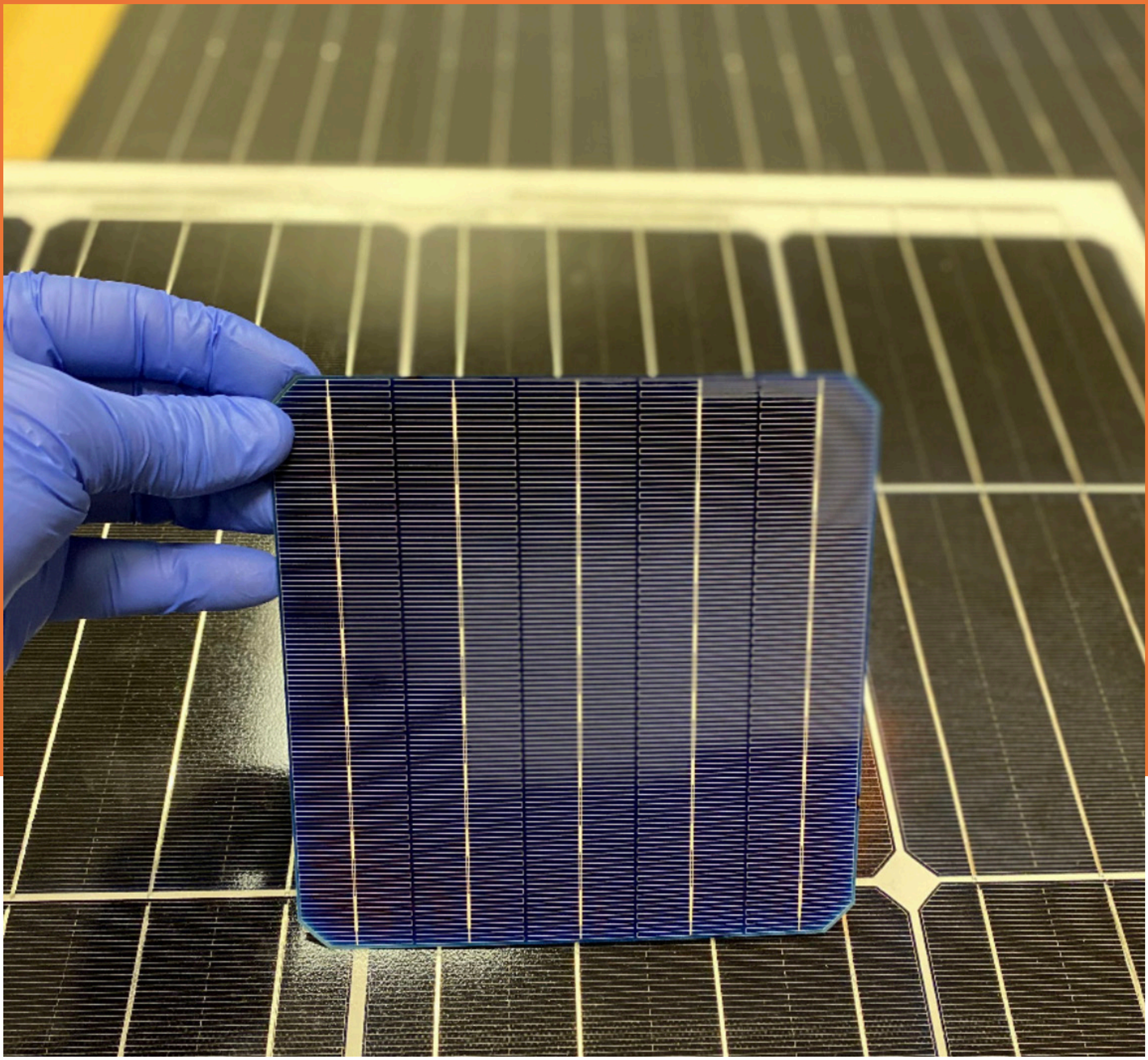

Resistively bounded subcells:

A breakthrough for enhancing the performance of silicon solar

By Dr. Benjamin M. Damiani
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SOLAR INVENTIONS

Introducing resistively bounded subcells: A breakthrough in silver reduction

Breakthrough new electrical cell architecture enables PV manufacturers to gain immediate cost savings of US$300,000 to US$500,000 per gigawatt with existing production equipment and processes. All with no risk.

We are excited to introduce a breakthrough in the science of silicon photovoltaics, called Resistively Bounded Subcells (RBS). This new approach to photovoltaics requires no additional factory equipment or materials and it has sweeping applications across the solar industry.

- Mainstream panels and cells — reduced silver, and potential for increased power.
- Large format wafers — cells greater than 6 inches will benefit from reduced current loss due to electrical heat dissipation for elevated current flows.

Invented by Solar Invention's Chief Scientist, Dr. Benjamin Damiani, RBS creates multiple electrically isolated subcells on a single silicon wafer, using equipment and processes that already exist in most of the world's solar manufacturers. RBS works with 95% of all silicon cell architectures including monocrystalline, polycrystalline, PERC, HJT, and bi-facial. While scientists have long understood the idea of subcells (also called "monolithic cells"), creating them required specialized processing and was prohibitively limited in efficiency. Now, any manufacturer can immediately improve their profits, fabrication losses, and warranty returns — all without risk to throughput or quality.

First commercially available product — the Configurable Current Cell (C3)

The first commercially available product based on the RBS innovation is the Configurable Current Cell (C3). C3 reduces silver costs by 4-10% on the sunny side of a PV cell and between 5 and 15% on the rear side of a PV cell. In late 2019, the US Department of Energy recognized the promise of C3 by awarding Solar Inventions nearly $1 million as the first-ever recipient of the American Made Solar Prize. On October 21, 2021, Solar Inventions was awarded US Patent 11,145,774 for the C3 technology, with the patent pending in China, India, Europe, Taiwan, and 12 other countries. For a 300-MW PERC cell and module manufacturer, C3 creates US$300,000 in value through this reduction in silver. Because C3 strengthens the electrical divide for current inside a cell, heat-related issues are lowered, which reduces warranty claims and fire risks. For cell manufacturers, C3 requires only small changes in metalization print patterns and selective doping. Manufacturers can implement C3 by working with Solar Inventions to modify their print screens and make a small set of additional easy and risk-free changes to their production lines. For modules, C3 configures the subcells in parallel to a cell's traditional busbars and therefore requires no changes to the tabbing and stringing of panels, making it quick and easy to introduce into an existing module manufacturer. C3 mimics some of the benefits of split-cells and half-cells without the costs associated with physically cleaving the cells. C3 improves split-cells by effectively creating a larger number of virtual splits. C3 will power even more exciting applications as the industry continues increasing the size of cells. By subdividing the current in larger cells, C3 can reduce the resistive losses that increase as cell sizes grow past six inches.

Product roadmap — the Configurable Voltage Cell (CVC)

By connecting subcells in series within a single cell, the cell's voltage is increased proportionately. For example, a traditional cell might produce 0.65 volts at 9 amps, whereas a CVC cell with two subcells will produce 1.3 volts at 4.5 amps. This can be readily scaled up to any number of subcells — CVC has been successfully fabricated and tested with up to 12 subcells at UNC Charlotte and the Georgia Institute of Technology, generating more than 5 volts from a single, unbroken cell.

The applications of CVC are exciting and broad:

- Solar shingles with greatly simplified wiring requirements, greatly reducing the cost of residential solar
- Higher-voltage panels that can be wired in parallel, which simplifies inverter designs and reduces external power electronics
- Lower-cost single cells that directly power electronics, like phone chargers and solar lanterns for low-income countries.

CVC is still in laboratory development. Commercial pilots are anticipated for late 2020 or early 2021. C3 and CVC are complementary and can be used together, laying the foundation for rapidly commercializing a range of brand-new functionality and price-points in the solar marketplace.

The science behind Resistively Bounded Subcells

The patented breakthrough behind C3 creates isolated changes in cell resistance. This is done through a combination of metalization laydown changes. Dr. Damiani's research has uncovered specific metalization patterns, both on the top and bottom of cells, that together create precise areas of higher cell resistance, which in turn are used as electrical boundaries around the hybrid subcells. These subcells exhibit characteristics that have previously only been possible with exotic wafer processing techniques or physical cleaving such as half-cells.

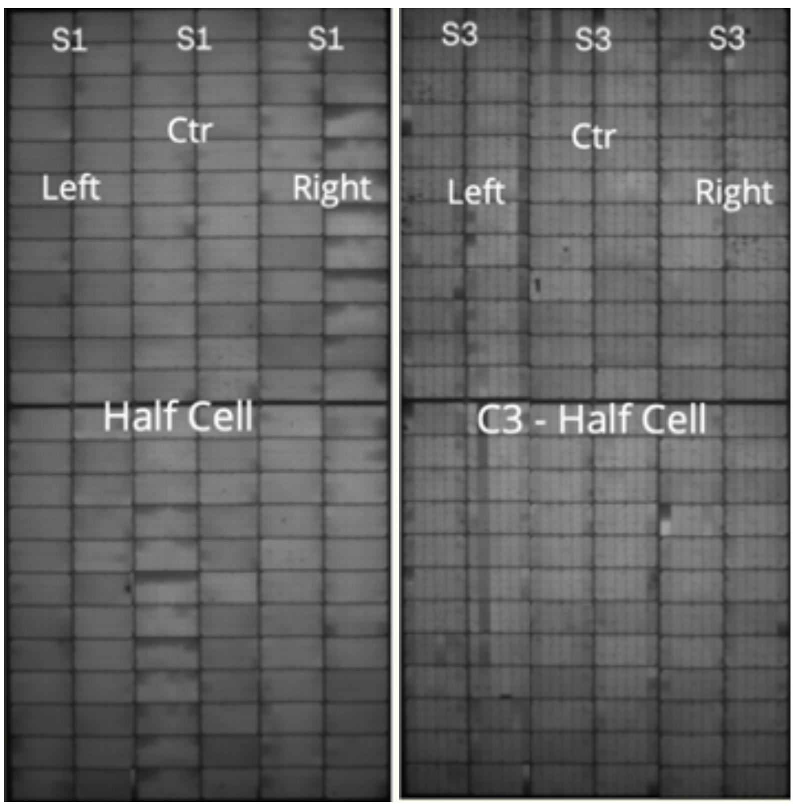


Figure 1. Electroluminescence image of a common half-cell module compared to a C3 enhanced half-cell module. Note the vertical segmentation for the C3 sample, which highlights the electrically isolated subcells.

C3 benefits include:

1. Reduced metal consumption: 3%-10% reduction in silver

Silver is one of the most expensive components in manufacturing solar cells. The pattern used by C3 to create subcells results in a net silver savings proportional to the number of busbars on the cell. A three-busbar "H" pattern reduces silver consumption and and a six-busbar pattern reduces it further. See Figure 2 for a control chart of silver deposition during a sample pilot production of a five-busbar cell design. In certain cell architectures, the reduction in silver materials is matched by reduction in aluminum.

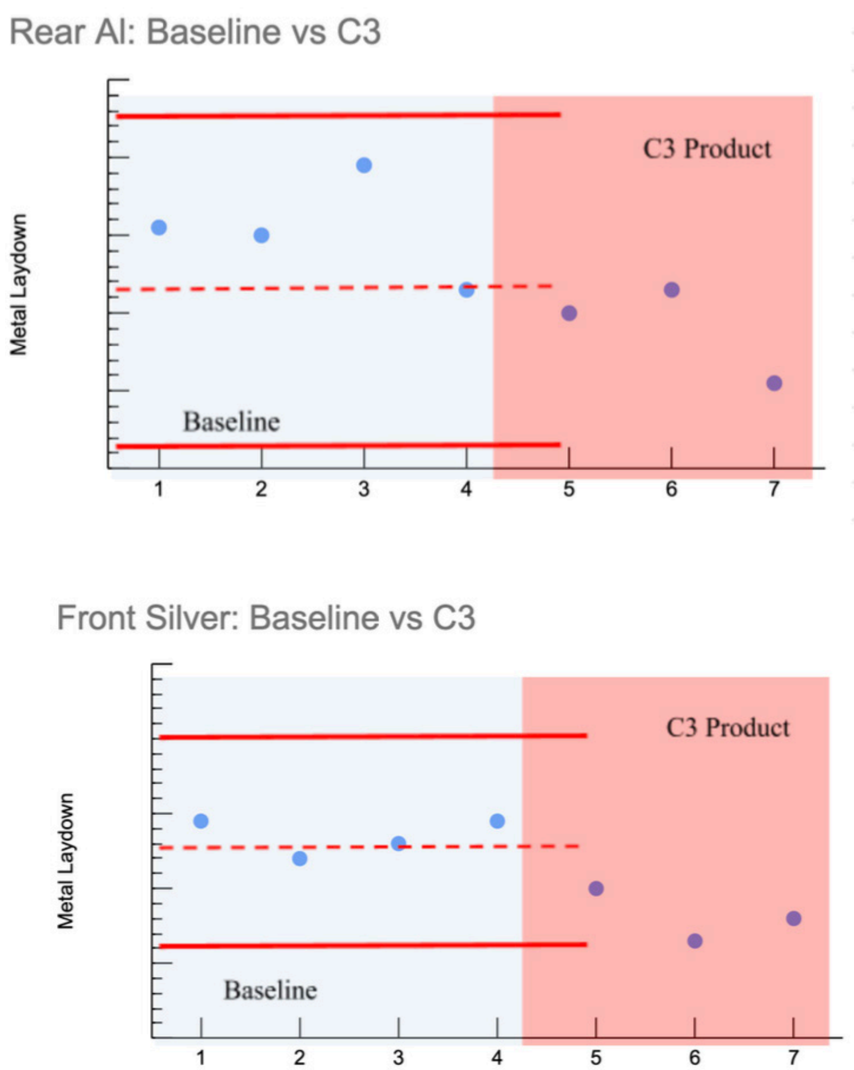
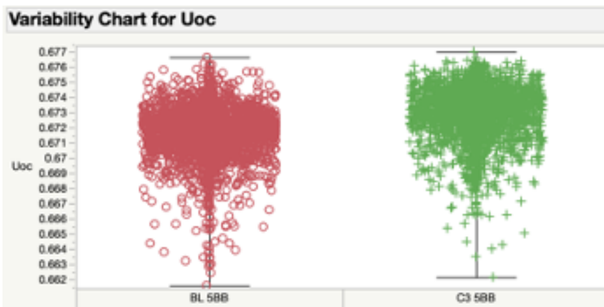


Figure 2. Process control chart measured during a 12-hour shift in a >500 MW solar cell fabrication plant, where the only change to production was a shift to C3 silver metalization on the front and rear side of the wafer. Both the front and rear side metalization were reduced by ~3% for a five-busbar "H" pattern.

2. Improved cell efficiency

In many cases, additional gains in cell and module performance are possible with C3. While these gains require additional R&D for each unique cell manufacturing line, select pilot tests and modeling have shown up to 3 watts panel, all without any additional cost or line changes.

The reduction in silver contact area acts to reduce the recombination velocity for metal on the silicon surface, resulting in a 1 mV-5 mV boost in open circuit voltage at the cell level. Figure 3 shows a data snapshot for C3 performance compared to the baseline group during the same production run for the silver savings shown in Figure 2.

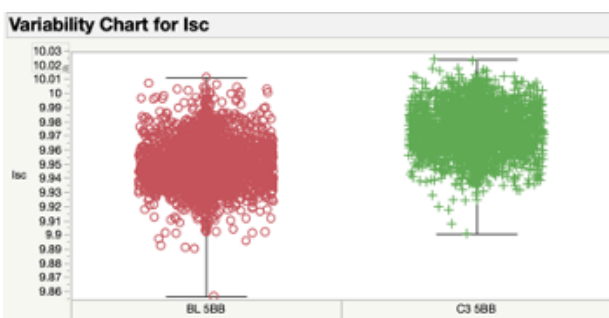


Variability Summary for Uoc

	Mean	Std Dev	Minimum	Maximum	Median	Observations
Uoc	0.672447	0.001717	0.661689	0.677092	0.672526	7632
Device Structure[BL 5BB]	0.671784	0.001536	0.661689	0.676736	0.671956	3842
Device Structure[C3 5BB]	0.673119	0.001627	0.662239	0.677092	0.673361	3790

Figure 3. Additional 1.3 mV of open circuit voltage for C3 enhanced mono PERC cells fabricated during the production run described in Figure 1.

The reduction in silver consumption also directly translates into less front metal shadowing, allowing more optical transmission into the bulk silicon for absorption and electrical current creation. Figure 4 shows the corresponding boost in short circuit current due to ~3% less front metal shadowing.



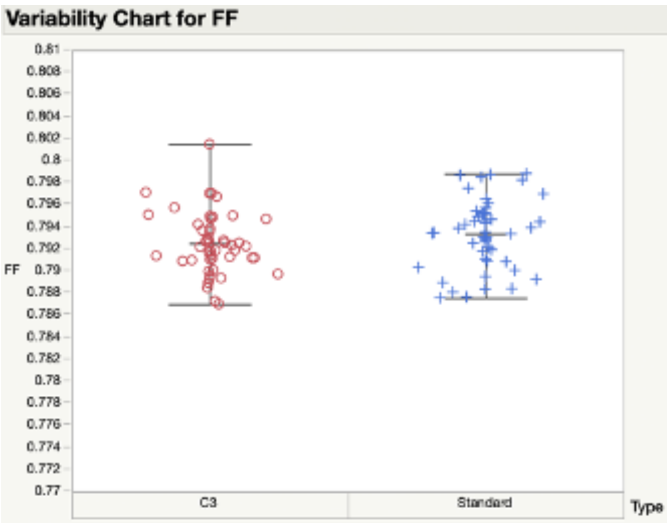
Variability Summary for Isc

	Mean	Std Dev	Minimum	Maximum	Median	Observations
Isc	9.9626	0.019619	9.857139	10.02454	9.961915	7632
Device Structure[BL 5BB]	9.950753	0.015619	9.857139	10.0118	9.949637	3842
Device Structure[C3 5BB]	9.97461	0.015533	9.901411	10.02454	9.97519	3790

Figure 4. Additional 0.02 amps of short circuit current for C3 enhanced mono PERC cells fabricated during the production run described in Figure 1.

3. Improved Cell-to-Module Ratio (CTM)

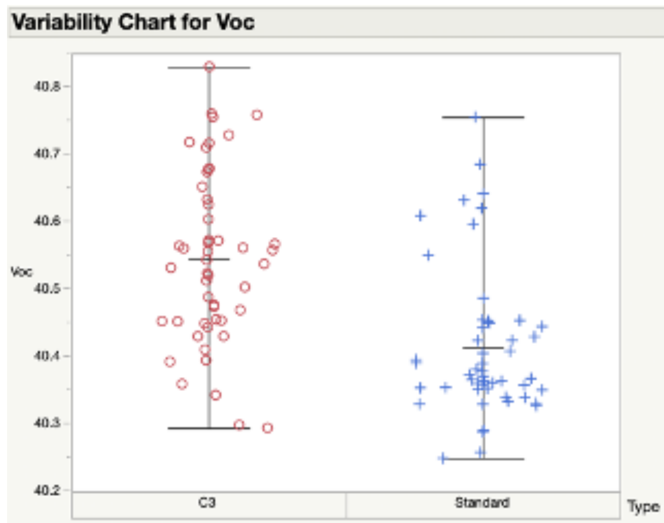
The improved open-circuit voltage and higher short-circuit current results in higher module-level power because the module fill factor (FF) is unchanged compared with a standard PV cell, which in turn reduces CTM losses due to the higher open-circuit voltage (VOC) for the C3 enhanced modules. The CTM benefits require no changes to the existing stringing and encapsulation equipment. Figures 5 and 6 show module level data for the same production run referenced in this white paper. Taken together, the higher VOC in C3 modules combined with an unchanged FF raises the overall CTM and power output of a module. Similar results have been obtained from multiple mid- to large-scale module manufacturers.



Variability Summary for FF

	Mean	Std Dev	Minimum	Maximum	Median	Observations
FF	0.792933	0.002905	0.786985	0.801476	0.792808	102
Type[C3]	0.792498	0.002728	0.786985	0.801476	0.792231	51
Type[Standard]	0.793368	0.003037	0.787549	0.798824	0.793462	51

Figure 5. Consistent fill factor for C3 enhanced mono PERC cells fabricated during the production run described in Figure 1.



Variability Summary for Voc

	Mean	Std Dev	Minimum	Maximum	Median	Observations
Voc	40.47981	0.135072	40.24915	40.83018	40.45242	102
Type[C3]	40.54547	0.125678	40.29426	40.83018	40.54357	51
Type[Standard]	40.41414	0.110736	40.24915	40.75537	40.37329	51

Figure 6. Increased open circuit voltage (~2mV per cell) for C3 enhanced mono PERC cells fabricated during the production run described in Figure 1.

4. Improved safety

The C3 electrical boundaries between each subcell slightly isolate the flow of current across the wafer, reducing current concentration around defects or small optical obstructions. The initial product release for C3 offers a mild improvement over baseline solar cells. Our next generation incorporates technology that substantially improves panel safety while decreasing power dissipation during a shading event.

5. Improved energy production compared to half-cells

The creation of subcells on a single silicon wafer without physically cleaving the solar cell maintains a smaller wafer perimeter compared to the wafer area of the individual solar cells. Each time a solar cell is cut in half, the ratio of the perimeter to the surface increases. This results in non-ideal diode effects and higher edge recombination velocity for individual "Half Cells." The C3 technology does not utilize a physical cleave and avoids the increased perimeter issue. Note that while C3 offers benefits over half-cells, it is entirely compatible with half-cells, offering improved power and safety benefits.

6. Reduced losses in large wafer sizes

The International Technology Roadmap for Photovoltaics (ITRPV) shows a trend toward larger wafer sizes. They are increasing past the standard 166mm, with factories starting to use wafers up to 210mm per square side. This increased size raises the cells overall short circuit current, but simultaneously increases the electrical heat loss (I^2R), reducing power. The most popular remedy is to cleave the cell into two or more physical pieces. This requires expensive equipment upgrades,increased material losses, and reduced cell efficiency to contribute to module power. Subcells and the C3 technology allow an additional layer of flexibility that permits these increasingly larger formats to reduce their virtual size without the need for cleaving.

Learning more about C3

The C3 technology is one of easiest, least risky, and least expensive (per watt) mechanisms for improving the profitability of silicon photovoltaic manufacturing. Solar Inventions offers licensing arrangements that are painless and 100% risk free. To learn more, please reach out to licensing@solarinventions.com and we will get back to you immediately with details on how to easily upgrade your manufacturing to benefit from C3. For qualified PV manufacturers, we offer pilots and proof of value at no cost.

About Solar Inventions

The founders of Solar Inventions have deep experience in the solar industry, early stage businesses, and technology licensing. The latest news and product information can be found at: **www.SolarInventions.com**

DR. BENJAMIN M. DAMIANI
CO-FOUNDER & CTO

LinkedIn

Ben has spent his career in solar. His innovations have enjoyed global reach through his work at early solar pioneers, Suniva and SolarWorld. He has worked across the world commercializing new solar technologies and building solar manufacturing facilities. Ben received his PhD in Electrical Engineering from Georgia Tech and did part of his grad work at the Fraunhofer Institute in Germany. After graduating he joined Intel's Process Technology Development (PTD) group and led the medium current ion implant group.

Bridging the technology from the integrated electronics industry into the solar industry, Ben was responsible for the first-ever implementation of Ion Implanted Solar Cells in high volume production for Suniva, Inc. Ben successfully realized this USA-born technology from concept and feasibility to 180 MW's production capacity in less than 28 months, a process that normally takes 6 years. As the Director of Industrial Technology Development for Semco Engineering in France he developed new processes for plasma enhanced chemical vapor deposition, low pressure diffusion and oxidation, bifacial solar modules, and n-type PhosTop solar modules. He holds several patents and has authored more than 30 papers.

BILL NUSSEY
CO-FOUNDER & CEO

LinkedIn

Prior to Solar Inventions, Bill spent most of his career as a tech CEO. Starting in high school, Bill co-founded and grew three software companies, the last of which had customers in 45 countries and was acquired by a public company. Afterwards, he spent several years as a venture capitalist with Greylock and later, he left the firm to run a portfolio company which he took public and grew to almost $500 million in revenue. His company prior to Solar Inventions, Silverpop, was sold to IBM where he later served as IBM's VP Corporate Strategy out of their world headquarters in New York. Bill's companies have created thousands of jobs and billions of dollars in value.

Bill received a degree in electrical engineering from North Carolina State University and an MBA from Harvard Business School. He holds several patents and has published three books, including a new one called **Freeing Energy,** which describes the how small-scale solar and batteries are disrupting the century-old electric power industry.

GREGG FREISHTAT
CO-FOUNDER &
CHIEF COMMERCIAL
OFFICER

LinkedIn

Gregg Freishtat is a technology executive with over 20 years of experience leading innovative and transformative companies. He founded five venture-backed start-ups, with four successful exits, and is now Co-Founder and Chief Commercial Officer of Solar Inventions. Deeply rooted in venture capital and management of technology companies, he has led several companies through acquisition and has had a hand in developing disruptive technologies at the convergence of telecom/internet, personal finance/online banking, web-based analytics and digital media/online marketing, and currently solar energy.

Freishtat is an active private equity investor, is the inventor on 18 patents, and has served on many Boards including: Greensky (GSKY), Telet, Proficient Systems, VerticalOne, Vertical Acuity, Marketworks, Relevant Knowledge, OutWeb, Camp Kudzu, Jewish Federation, Juvenile Diabetes Research Foundation, S1, USA.net, Saleswise, and others.

Freishtat received an undergraduate degree from Boston University and was awarded his J.D. from the University Of Maryland School Of Law.

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Advisory Board

Dr. Aba Ebong, PhD, UNC Charlotte professor and head of PV lab

Abasifreke Ebong received a PhD in Electrical and Computer Engineering from the University of New South Wales, Australia in 1995. His PhD dissertation dealt with low-cost, double-sided buried contact silicon solar cells. Dr. Ebong served as a Postdoctoral Fellow at Samsung Electronics, South Korea. In September 1997, he joined the University Center of Excellence for Photovoltaic Research and Education (UCEP), Georgia Tech., Atlanta, as a Research Faculty, where he worked on the development, design, modeling, fabrication, and characterization of low-cost, high-efficiency belt line multicrystalline, Cz, and Fz silicon solar cells. In 2001 he joined GE Global Research as Electrical Engineer, working on Solid State Lighting (LED-light emitting diodes) based on III-V semiconductors. In 2004 he returned to the University Center of Excellence at Georgia Tech as the Assistant Director, responsible for sponsored research in crystalline and amorphous silicon solar cells. Dr. Ebong joined the Faculty of the University of North Carolina at Charlotte as full Professor in February 2011. He has published over 140 papers in the field of Photovoltaics. His current research interests include: high throughput, low-cost and high efficiency silicon solar cells based on comprehension of fired-through contacts (screen-printed, inkjets etc) on homogeneous high sheet resistance emitters. He is Director of the Photovoltaic Research Laboratory at UNC Charlotte, which is supported by industrial partners from all over the world. Lab info and LinkedIn

Dr. Frank Faller, PhD, Strategic Technology Planner, EDP Renewables

Frank is a solar PV industry veteran with over 25 years of experience in research, manufacturing, sales, business development, and management across the PV value chain, including crystalline-silicon wafer, solar cell and PV module technology, starting with industry pioneers like Astropower and Shell Solar.

Frank is a physicist by training and holds a Ph.D. from the University of Freiburg, in conjunction with the renowned Fraunhofer Institute for Solar Energy, ISE in Freiburg, Germany. Prior to his career in PV, he was also a researcher at two laboratories for elementary particle research, at Fermilab near Chicago and CERN near Geneva, Switzerland. LinkedIn

Andy Klump, CEO, Clean Energy Associates

Andy Klump has over 20 years of high-tech and renewable energy sector experience, with 12 years in solar PV. He founded Clean Energy Associates (CEA), one of the world's leading solar consultancies in the areas of quality assurance, supply chain management, and engineering services, in 2008. CEA is based in Shanghai, China, with operations across eight other countries including the U.S., over 60 experts on staff, and clients in 35 countries.

Andy was previously Vice President of Business Development for Trina Solar, supported US$500 million of debt and equity financing through IPO and post-public offerings, and led a supply chain and operation strategy team to develop Trina's supplier co-location park in Changzhou, China. He had management roles in sales and business development in China for Dell and Intel. He holds an MBA from Harvard Business School, and a BA in Economics from Northwestern University. LinkedIn