

The next-generation utility-scale PV plant

Utility solar | A next-generation PV plant architecture based on increasing direct current system voltage from 1,000V_{DC} to 1,500V_{DC} holds the promise of a more cost-effective and productive utility-scale plant due to lower installation and maintenance costs. Mahesh Morjaria, Kevin Collins, Michael Stavish of First Solar and Greg Ball of DNV-KEMA Renewables explore some of the challenges associated with the development of the technology and the efforts to address some of those challenges

Over the past several years, the rapid drop in PV module price has made a significant dent in reducing the cost of utility-scale PV plants and in making solar energy affordable. However, further cost reductions are necessary to reach the goal of making solar-generated power fully cost-competitive with traditional power sources. For example, the US DOE's SunShot programme has set a goal to reduce the installed cost of a utility-scale PV system to less than US\$1/W, resulting in less than US\$0.06 per kilowatt hour (kWh) solar energy production costs by the end of the decade.

Since the SunShot programme's inception in 2010, the average cost per kWh of a utility-scale PV project in US has dropped from about US\$0.21/kWh to \$0.11/kWh. For a typical utility-scale PV system that feeds power directly to the grid, the balance of system (BOS) cost now represents between 60-70% of the total cost of the system from a previous value of less than 50%. Therefore, a significant opportunity for further cost reductions lies in improvement in the BOS.

Major cost and efficiency improvements have been gained in the past decade as utility-scale PV plants in the US

have moved from 600V_{DC} to 1,000V_{DC} architecture. Similarly, the transition to 1,500V_{DC} provides still greater efficiencies and cost reductions. The higher voltage operation translates to greater power throughput for the same ampacity (current carrying capacity) of DC components such as cables, combiner boxes and inverters. It enables greater consolidation of low voltage to medium voltage transformers and related switchgear. It further enables greater flexibility in general to design systems optimally for efficiency and/or cost.

Table 1.
Engineering
assessment
results

System Aspect	1,500V _{DC} relative to 1,000V _{DC} system implementation
Electrical design: DC wiring, grounding, and protection	Meaningful differences are limited to the voltage rating of overcurrent protection and switching components. The vast majority of design fundamentals match those of the 1,000V _{DC} systems.
Electrical design: AC	No fundamental difference in the design of medium voltage AC collection systems or interconnection
PV module	FS Series 4 modules certified to IEC standards to 1,500V _{DC}
Inverter	Overall cost-efficiency improvements can be demonstrated using larger 1,500V _{DC} inverter due to higher power density. Certifications to IEC 62109 and ultimately UL 62109.
Other DC BOS equipment	No issues with majority of components. Some parts such as string and module connectors, and harnesses cannot be officially listed to UL standards due to 1,000V _{DC} scope limitation, but are equivalently tested based on the higher voltages for UL 'recognised' status.
Safety in the DC system design	No salient differences. First Solar incorporates a high level of safety-driven design aspects.
Regulatory risk	Some regulatory risk inherent for early adaptors of 1,500V _{DC} platform. Risk in the US in general higher than in select international markets evaluated because of NEC preference for US-based product standards.
Cost performance	Design takes advantage of opportunities for cost-performance optimisation with electrical losses and greater array scale, enabling fewer inverter-MV transformer pads. No inherent reduction in performance from increase voltage.
Module PID	Third-party tests certify PID within limits similar to 1,000V _{DC} -rated modules
Installation/qualified personnel	Little difference in electrician training and qualification for 1000/1500V _{DC} systems. May be some jurisdictional dependency.
Arc-flash protection requirements	For some equipment, higher-rated arc-flash PPE required for maintenance personnel compared to 1,000V _{DC} systems.
O&M procedures and cost	Reduced O&M costs due to reduced number of components per megawatt of installation. Similarly reduced number of repetitive O&M tasks
Pilot site installation	Significant installation efficiencies demonstrated despite little apparent difference in 1,000V _{DC} and 1,500V _{DC} array segments. No design element changes required as result of AHJ review.

1,500V_{dc} products and standards

The adoption of 1,000V_{dc} utility-scale systems in the US was enabled by the availability of international products and the precedence of installations, mostly in Europe, during the early to mid-2000s. These products were initially only available with international certifications but over time, more and more have been certified to US standards to meet demand. Recently the 2014 edition of the US National Electrical Code has bumped its low voltage threshold from 600V DC to 1,000V_{dc}, eliminating unnecessary distinctions in the installation requirements of 600V_{dc} and 1,000V_{dc} projects. As in the past, the current move to 1,500V_{dc} is again partially enabled by International Electrotechnical Commission (IEC) standards that classify 1,500V_{dc} in the low voltage range, making components and products readily available.

As a vertically integrated company with PV module manufacturing among as its core competencies, First Solar has the unique ability to 'tune' the output characteristics of its modules to support this new 1,500V_{dc} standard. An unintended benefit was derived during

the development of these next generation thin-film CdTe modules (Series 4) in that additional conversion efficiencies were realised. Effectively, modules optimised for 1,500V_{dc} offer better performance with respect to efficiency and maximum output power compared to the 1,000V_{dc} predecessor.

Additionally, First Solar and its BOS component suppliers are collaborating to develop the next-generation 1,500V_{dc}-based plant capability. These technologies, which have been used widely in the wind power industry, have been adapted to suit the characteristics of PV DC systems. For example, GE has developed a new 4MVA ProSolar inverter/transformer system based on the previous 1MVA ProSolar platform that was introduced in Europe in 2009 as a derivative of its wind converter products. Compared with 1,000V_{dc} plants, these products enable a power plant design platform with significant flexibility to increase the size of the solar array served by each inverter or maintain the solar array size while reducing wire and cable sizes. The 1,500V_{dc} plant design platform maintains high power delivery while lowering installation and maintenance costs.

Technical and regulatory challenges

There are several technical and regulatory challenges associated with approvals and adoption of the proposed next-generation plant into the North American as well as other international target markets. Some of the challenges are inherent with early adoption of any new technology.

In this case, both the modules and the inverters have limited field history. The regulatory challenges in many places, particularly outside of North America are lower due to existing International Electrotechnical Commission (IEC) standards, which address 1,500V_{dc} design and safety. Greater challenges are faced in the US, where the lack of established standards that address 1,500V_{dc} applications often make it challenging to obtain plant construction permits from local authorities having jurisdictions.

However, much like the earlier transition from 1,000V_{dc} architecture, these issues are addressable and no long-term barriers to adopting this architecture are expected. Active steps are underway in the standards and codes community to address the needs of the growing large-scale PV plant market. The recent announcement by UL

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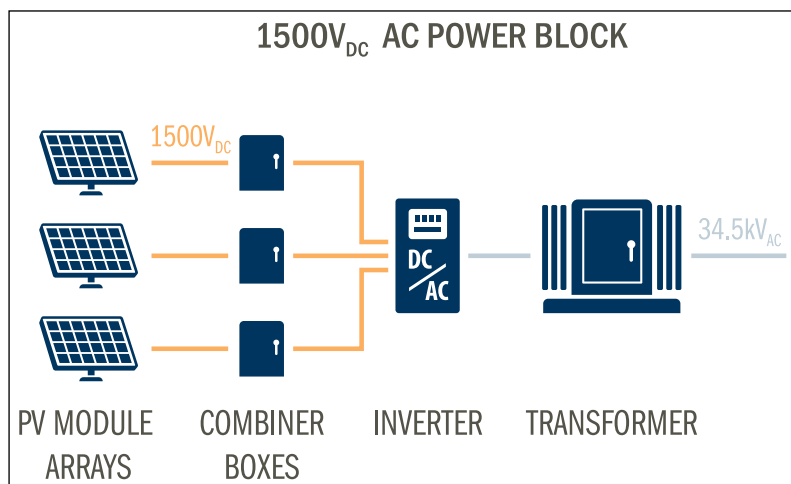


Figure 1.
Illustration of
1,500V_{DC} AC
Power Block.

to adopt ANSI/UL 62109-1 as the American National Standard for Safety of Power Converters for Use in Photovoltaic Power Systems enables US-based certification of 1,500V_{DC} inverters, and is a step in the right direction. UL is working towards the adoption of similar standards for modules and other DC BOS equipment, and in parallel, changes to the National Electrical Code (NEC) are anticipated that will better accommodate the unique aspects of design platforms utilised in large, utility-scale PV plants.

Independent engineering assessment

An independent engineering study was conducted by DNV GL to review the design and 1,500V_{DC} systems. The assessment of various relevant aspects, with emphasis on salient distinctions from 1,000V_{DC} systems, is summarised in Table 1. In general, the 1,500V_{DC} system architecture was found to be very promising with respect to performance, value and overall technical merit. Some risks and uncertainties are identified that are inherent with

early adoption of any advanced architecture, but no issues have been identified that are a long-term concern.

PV plant system design

A typical 1,500V_{DC} PV plant designed around an 'AC Power Block' of either fixed-tilt or tracking arrays ranging in size from 1 MW DC up to 5MW DC is described next (see Figure 1). The key plant components are similar to what have been deployed previously on the 1,000V_{DC} utility-scale PV plants – modules, DC wiring, combiner boxes, inverters and pad-mount transformers to step up the AC voltage. However, in this case the components are specifically designed to meet 1,500V_{DC} requirements.

The modules are connected in series strings of 15, up from the 10 per string used in the 1,000V_{DC} systems. The strings are connected to harness cables with in-line fuses, which are in turn combined in harness combiner boxes. A typical harness combiner box delivers the power of 96 strings (133kW) to the inverter via underground feeder cable pair. The

1,500V_{DC} inverter is equipped with dedicated fused inputs for each of the harness combiner boxes and can be configured for grounded or ungrounded arrays.

The increase in DC voltage and use of large-scale 4MVA inverters leads to a significant increase in the DC array size. The typical 1,500V_{DC} system design will incorporate between 5 and 5.3 MWp DC of PV capacity, corresponding to a DC/AC ratio between 1.25 to 1.33. The inverter converts the input DC power to 60Hz AC at 550V_{AC}, which is stepped up via a close-coupled transformer to 34.5kV for aggregation with other inverters throughout the plant. The aggregated inverter outputs are ultimately stepped up again to a selected transmission voltage for interconnection to the utility power grid.

The impact of array size increase and reduction in the number of inverters is very apparent when two plant layouts are compared side by side as illustrated in Figure 2. The figure on the left consists of typical 2.0MW_{DC} arrays of modules while the figure on the right consists of typical 5MW_{DC} arrays of modules. In this illustration the number of power conversion stations is reduced from 10 to 4 (60% reduction). There is also improvement in land utilisation with fewer access roads and less area occupied by the power conversion stations.

1,500V_{DC} inverter

Inverters for 1,500V_{DC} plants currently range in capacity from <1MVA to 4MVA in modular rating increments. This facilitates the flexibility of ensuring plant cost optimisation, depending on plant size, while closely matching plant capacity and availability requirements. 1,500V_{DC} inverters deliver almost 50% more power for each ampere of current from the array, meaning higher power density that reduces the overall installed cost compared with same 1,000V_{DC} inverter capacity.

By and large, 1,500V_{DC} inverters have the same fundamental converter topology as 1,000V_{DC} inverters – with power semi-conductors and DC power circuit components appropriately rated for the higher DC voltage. These components are covered by the existing IEC standards and readily available as they are similar to those components used in wind converters and industrial drives. 1,500V_{DC} inverters have the same AC grid interface circuits, controls, protection, and grid management features as 1,000V_{DC} inverters.

An example of 1,500V_{DC} inverters is the

**Figure 2. Sample
1,000V_{DC} and
1,500V_{DC} plant
layouts.**

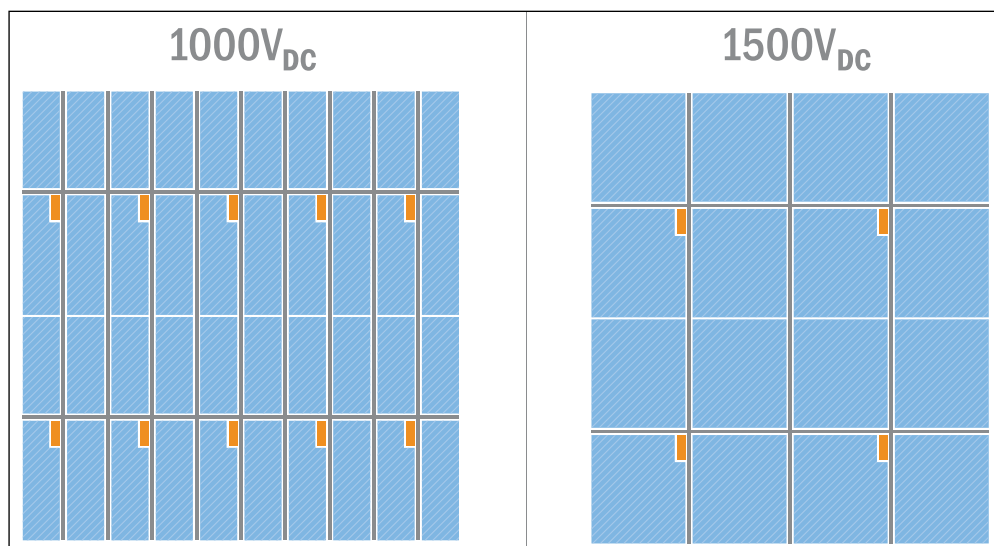


Figure 3. GE ProSolar 4MVA inverter with close-coupled transformer at a field site.



GE 4MW ProSolar unit shown in Figure 3, which is installed at a field site. The unit includes a transformer that is specifically designed to couple with the inverter and provide medium voltage output. The inverter has been developed as a derivative of GE's 1MVA ProSolar product introduced to the European market in 2009, leveraging the field experience and relative maturity of the technology platform.

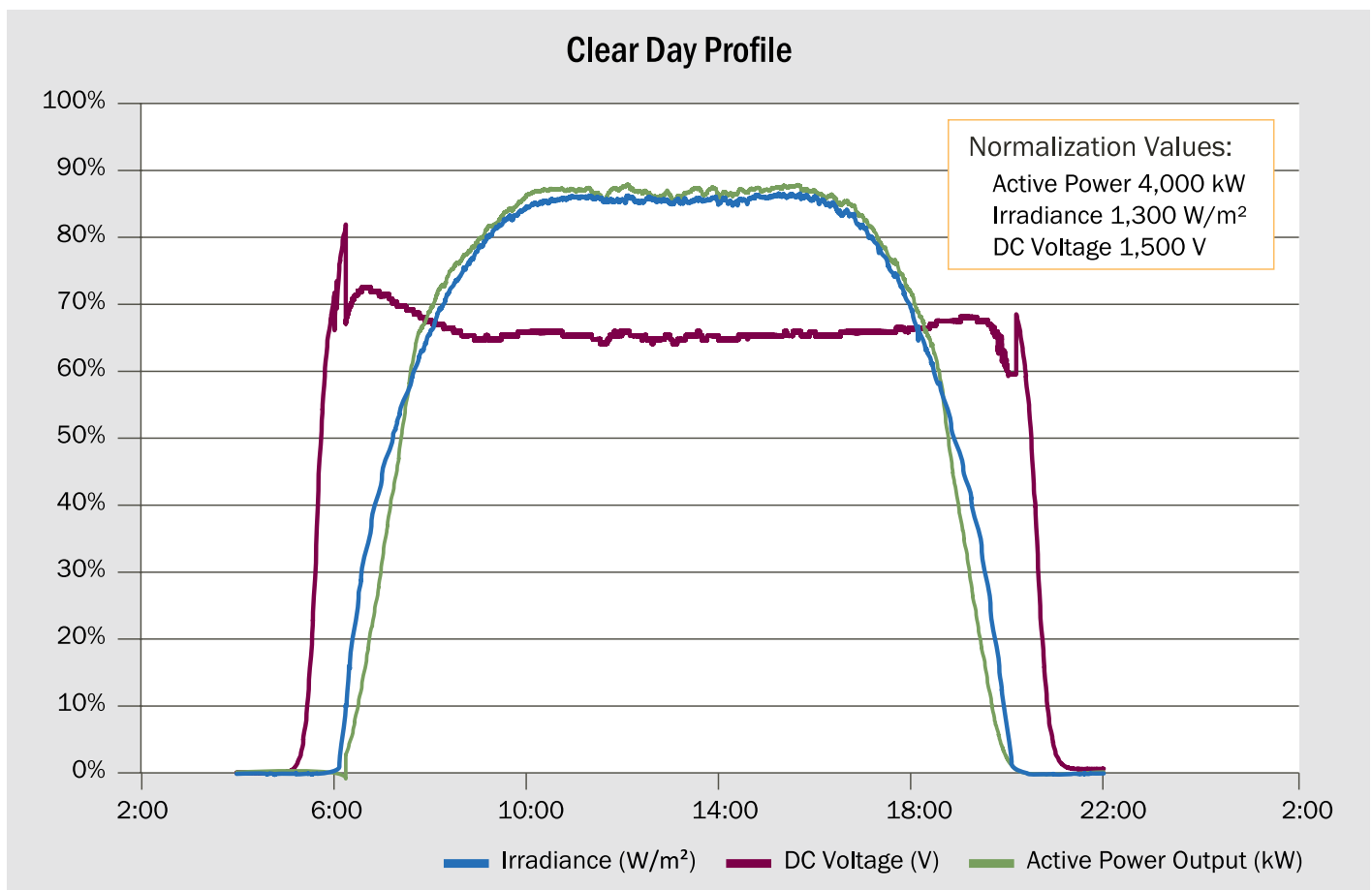
Figure 4. Inverter performance on a clear day.

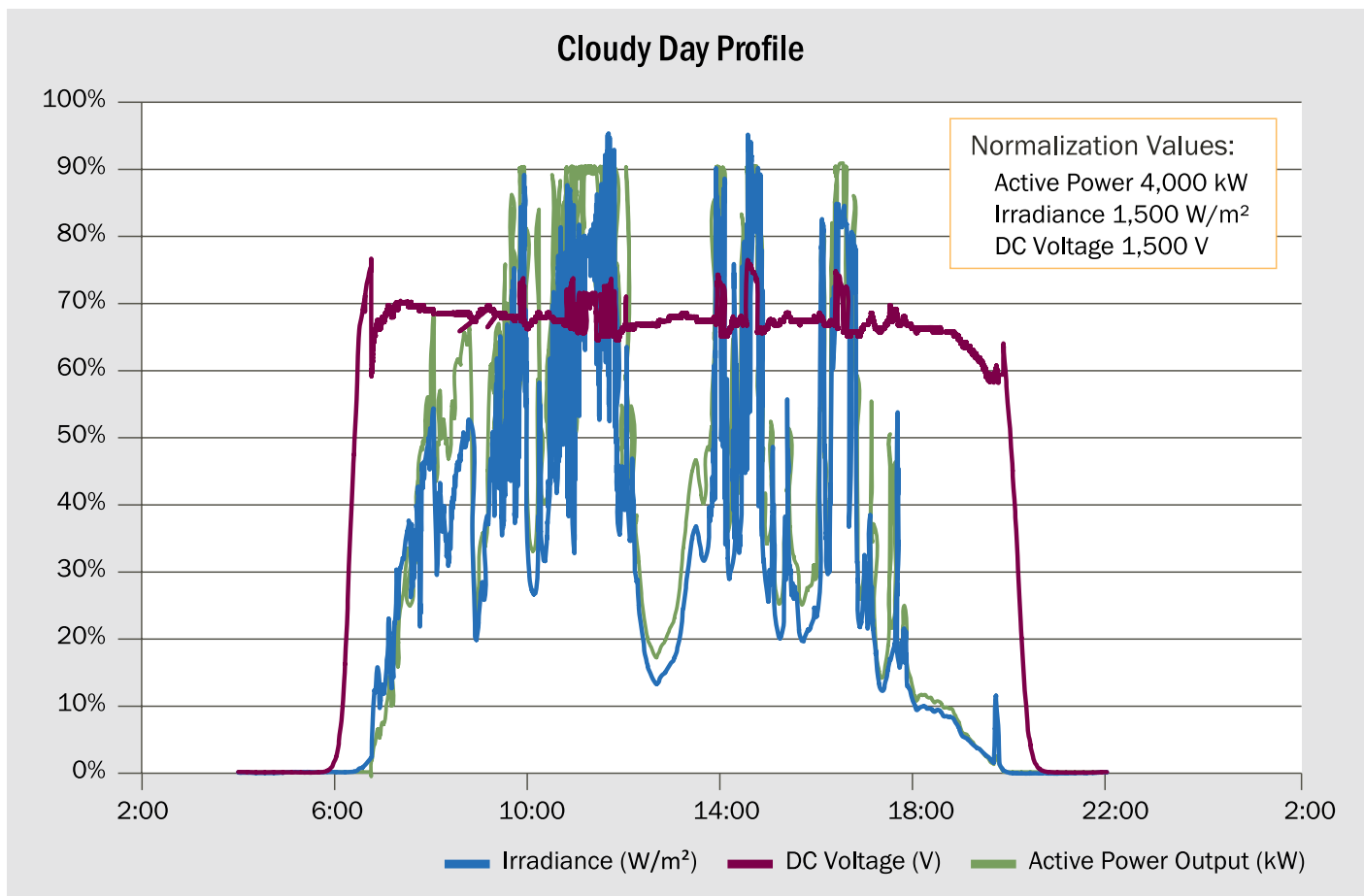
1,500V_{dc} modules

There are many module suppliers that are developing products to support 1,500V_{dc} applications. First Solar has developed the next-generation thin-film CdTe modules called Series 4, which is specifically optimised for such applications. The modules are IEC certified. They have gone through rigorous testing including TUV LST (Long Term Sequential Sandstorm and PID test) to ensure high reliability and performance.

Field experience

In the spring of 2014, First Solar commissioned its first 1,500V_{dc} AC Power Block at the Macho Springs Solar Plant in Deming, New Mexico, M, operated by First Solar and owned by Southern Company. The PV plant, with an overall capacity of 52MW, has 34 arrays that utilised 1,000V_{dc} architecture. An additional array using 1,500V_{dc} architecture was added to the plant to demonstrate the viability, commercial readiness, and accept-





ability of this new industry standard.

It consists of a 3.6MW_{dc} array using First Solar 1,500V_{dc} CdTe modules and a GE ProSolar inverter and transformer. Due to the specific project (land) constraints, the array size was designed smaller than an optimal design. Enhanced commissioning procedures and field tests were performed to verify performance and operational characteristics. The field tests included PQ curve validation, harmonic compliance verification, check of audible sound limits, DC ripple current check and high irradiance start up.

Data collected by the plant SCADA is being analysed by First Solar on an ongoing basis to validate performance and reliability. In particular, ground leakage testing was performed on the array and base-lined against 1,000V_{dc} arrays within the Macho Springs plant with comparable results. Plant operations and maintenance procedures are largely unchanged from that of the 1,000V_{dc} platform, and there are fewer components per megawatt to service.

A typical performance of the inverter on a clear day is shown in Figure 4. As expected the inverter output closely follows the irradiance measurement taken at the plant. The DC voltage is consistent with the

module IV characteristic when the inverter is producing power.

A typical performance of the inverter on a cloudy day is shown in Figure 5. Again as expected the inverter output closely follows the irradiance measurement taken at the plant and the DC voltage is consistent with module IV characteristic.

First Solar plans to build two more 1,500V_{dc} AC Power Blocks at the Barilla Solar plant in Texas, owned and operated by First Solar. Each of these arrays will be 5MW_{dc}/4MW_{ac} and will utilise GE inverters that are further refined, offering improved efficiency and "overdrive" operation at temperatures below 50C. These arrays are planned to be installed and operational by the end of 2014 to gain further operational experience on a small scale prior to a large-scale commercial deployment in 2015.

Summary

The next-generation utility-scale PV plant based on 1,500V_{dc} architecture has a significant impact on the plant costs and its efficiency. This is illustrated through a number of utility-scale PV plants that First Solar has developed or is in the process of deploying over the next several years. Some of the key elements that contributed to

Figure 5. Inverter performance on a cloudy day.

this accomplishment include First Solar's development of high voltage-capable thin-film modules and GE's development of the world's largest PV inverter (4MVA). The ability to install significantly larger solar arrays served by each inverter reduces the installation and maintenance costs of the plant. This BOS cost reduction in turn contributes to the primary goal of making solar energy affordable. As in the case of the previous transition of 1,000V_{dc} architecture, the industry is poised to take this next step as some of the technical and regulatory barriers are overcome. ■

Authors

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