It’s Not the Heat, It’s the Electricity

Why hot spots are a problem, and why they’re getting worse

Marc Stewart, IdealPV

Abstract

Driven by a recent breakthrough, solar module power will double as cost halves within five years. The breakthrough, developed by idealPV™, is Forward Only, Zero Hot-Spot™[1], or FOZHS™ technology. Solar cell hot spots are caused by reverse-bias events and are a problem that has plagued the solar industry from its very early days. The remedial measures that worked reasonably well decades ago (bypass diodes and improved factory inspection) are no longer adequate. This paper presents a mathematical analysis as to why the problem has become increasingly severe, and introduces the new FOZHS technology which, rather than seeking to mitigate the damage caused by hot spots, prevents them entirely. Eliminating the hot spot issue will release multiple new technologies for lowering costs, improving safety, and increasing efficiency.

The Future of Solar

By 2025, typical solar modules will generate over 500 watts and cost a fraction of what they cost today. Gone will be the self-inflicted temperature rises of hundreds of degrees Celsius, along with sustained plasma arcs and dangerous residual voltages after shutdown.

Heavy glass and expensive precious metals will be replaced by shatterproof plastic and plentiful aluminum. Complex soldering and lamination manufacturing processes will be replaced by conductive adhesives and UV-cures polymers. This future is now in sight, thanks to the introduction of the world's first Forward Only, Zero Hot-Spot solar panel this year.

What follows is a discussion of the so-called “hot-spot problem”: what causes hot spots, how serious the problem is, why it is getting worse rather than better, and how Forward Only, Zero Hot-Spot (FOZHS) technology solves the problem once and for all.

Introduction to the Hot Topic of Hot Spots

To the casual observer, concern about hot spots in solar modules (or “solar panels”) may seem akin to worrying about snow on Mount Everest. Solar modules spend all day out in the Sun, so of course they’re going to get hot, right? Well, hot spots get much hotter than any object just sitting in the Sun, and they can cause considerable damage. This destructive heat comes primarily from *electrical* power that is forced into a victim solar cell, which can exceed the photon (light) power from the Sun many-fold.

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[1] “idealPV,” “Forward Only, Zero Hot-Spot,” and “FOZHS” are trademarks of idealPV, LLC

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Hot spots occur when cells deliver their electrical power to another cell instead of to an external load, a condition called “reverse bias.” Solar panels are internally divided into 3 sections by semiconductor devices called bypass diodes, and within each section one cell can be forced to “eat” the electrical power of the remaining cells, in addition to what it is receiving from the Sun. In a 60-cell module, 19 cells can force electrical power into one cell; in a 72-cell module, it can be 23 against one.

A full-sized solar cell is about 6 inches square and receives 25 watts of photon (light) power[2] in full sun (direct sunlight). *Each watt of power warms a full-size solar cell by about one degree Celsius*, so a solar panel sitting in full sun gets about 25°C warmer than the air around it (the “ambient temperature,” in techno-speak).

A cell of 20% efficiency will convert 5 watts of those 25 sun-watts into electric power. If the cell’s electric power is removed from it (i.e., if the panel is connected to a load), the cell will cool by about 5 degrees Celsius—one degree for each watt removed—and run only 20°C warmer than the ambient air instead of 25. Thus a power-producing module runs *cooler* than one that is disconnected from a load (it surprises most people to learn this).

The same math works in the other direction: removing power from a cell cools it, and adding power to it heats it up. In a hot-spot situation, one victim cell receives electrical power from 19 or 23 cells (depending on the panel cell count) in addition to the 25W it receives from the Sun. In a 300W, 60-cell panel, the 19 aggressor cells can push 95W into the victim cell, raising its power dissipation to as high as 120W. In a 72-cell panel of the same efficiency, 23 cells can push 115W into the victim cell, raising its dissipation to 140W. In summary, the numbers look like this:

> 20 watts: a load-connected solar cell in full sun, runs about 20°C above ambient
> 25 watts: an unloaded solar cell in full sun, runs about 25°C above ambient
> **120** to **140** watts: a reverse-biased solar cell in full sun. Temperature skyrockets.

As we’ll see, hot-spot temperatures are high enough to damage the plastic insulating materials in the panel which are vital to safety. A typical panel sandwiches the cells between two clear layers of ethylene vinyl acetate (EVA), laminating them to a piece of tempered glass in the sun-facing side and weather-toughened plastic to protect the back side (it is usually white and called a backsheet). The EVA material is similar to hot-melt glue, and is raised to a temperature (about 140°C) sufficient to soften it so it conforms around the cells during vacuum lamination. The EVA acts as both an adhesive (to the glass in front and to the backsheet behind) and as the primary insulator for the electrified solar cells and wiring.

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[2] Photon power (sunlight) and electrical power create the same amount of heat per watt, and may be considered interchangeable in our analyses.

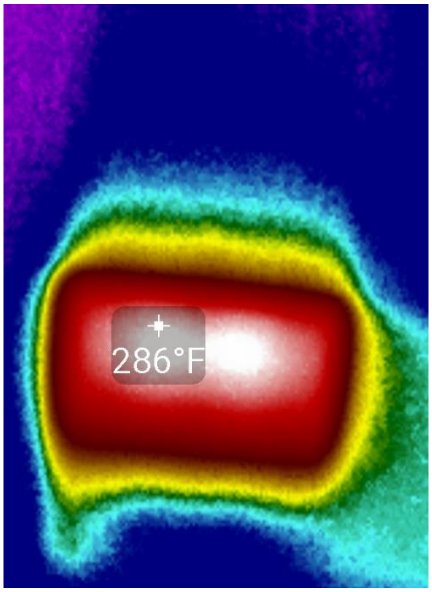

Figure 1 UL1703 Conditions, No Flaws

On November 13, 2017, at solar noon on a 22°C day in San Jose, CA, this author performed the UL 1703 hot-spot test on a 285W, 60-cell commercial panel made by a top-tier manufacturer. (The UL 1703 test was the industry standard test at the time, but has since been superseded by the more rigorous IEC 61730.) Here is a thermal image taken after about 15 minutes:

286°F is equal to 141°C, and represents a 119°C temperature rise above ambient. There are no backsheet materials that can withstand continuous exposure to temperatures this high. Even brief excursions above rated temperature will degrade the plastic and cause premature failure. Typically, the material will turn brittle and possibly crack or split. Delamination and bubbling Is another hazard, since the heat can melt the adhesive layers. An Internet image search for “hotspot backsheet damage” will bring up a number of scary-looking pictures like these:

Figure 2 Left backsheet failure, Right multiple cell backsheet degradation

The backsheet is a vital insulation barrier to protect against arcing and fires; this is why hot spots are such a problem. The pictures above are just two of hundreds and hundreds like it. It’s a huge problem, and the problem is getting worse. The reason is a bit ironic: it’s because solar cells are getting better.

Over the past few decades, solar cells have been getting steadily more efficient, which is great for power production, but it magnifies the hot-spot problem. Yesterday’s top-of-the-line 180 watt panels produced 40% less power than today’s 300-watt (and higher) panels, so they had 40% less electrical power to contribute to heating up the victim cell. Since heat-induced backsheet degradation often takes time to reveal itself, the relationship between higher efficiency and reduced field lifetimes has not been obvious, except in hindsight.

Not all damage is catastrophic. Plenty of modules in the field have developed brown discoloration in the EVA; the stains block light and reduce their power output. The source of discoloration can be traced to heat by the telltales left behind: 1) the regions between cells stay clear, 2) browning is worse over cells that have been shaded repeatedly, and 3) spot-heating due to poor solder joints create obvious bulls-eye brown spots. But even outside these obvious brown spots, EVA yellows over time. We are left to ponder how much of this yellowing is due to transient reverse-bias conditions (due to clouds, birds, planes, etc.), which happen on average several times per day. Based on long term studies on modules made with EVA, the mainstay encapsulant for decades, the industry's standard for expected power loss due to aging has been -0.5% per year; in other words, down 10% after 20 years. (In systems with solar concentrators, which run hotter by nature, the loss can be 10% *per year*.)

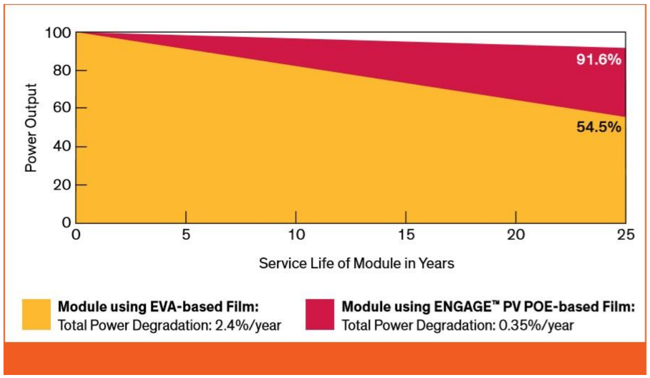

Figure 3 Projected Power Output of Modules Using Selected PV Encapsulant Films Over 25 Years.
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Because long term studies take decades to complete, the solar cells used in those studies are at least 40% less powerful than cells are today. With conventional hot-spot mitigation, peak temperatures in solar panels have increased substantially.

In light of this, a recent shorter term (three year) study reports that degradation is now five times worse, -2.4% per year, for an expected degradation of 40% after 20 years.

Given the severe impact of current heat levels, new materials have been proposed.

Over the decades, EVA has been proven stable under intense solar input in all climates. Because increases in temperature effect materials exponentially, the long term impact of hot-spot mitigation heating and cell improvements caused unforeseen problems.

Early results on some new materials are promising, it will take decades to conclude if these materials can match EVA's proven long term solar input stability and stand up to current and future cell power using current hot-spot mitigation technology.

The images below show what happens over decades in typical installations. Left, 10 year old polysilicon module, Right, 20 year old monosilicon module. Both are consistent with -0.5% per year industry standard expectations for degradation. The centrally brown cell in the right-hand image was measured to be 15º to 20ºC warmer than adjacent cells, consistent with normal, slight cell mismatch. The EVA between the cells and the cooler outer edges (See Figure 1 for heating profile) shows no degradation The EVA over the center of neighboring cells shows subtle discoloration. The same is true in the left-hand image. In this case, a slight contact imperfection that developed over time on one busbar (top slightly left of cell center) may have resulted in the cell producing slightly less power. The images below document that preventing even subtle electrical warming over normal sun optical heat input eliminates long term EVA aging. Solar cells producing power cool. Conventional hot spot mitigation causes heating.

Figure 4 Left 10 year old polysilicon, Right 20 year old Monosilicon

Reverse Bias Events Are Why Hot Spots Happen

The “reverse bias” condition which causes hot spots happens when one cell cannot provide the same electrical current as its neighboring cells. This typically happens when a cell gets partially shaded by the moving shadows of fixed objects such as standpipes, by dirt or other debris, or (infamously) by bird droppings. All the cells in the module are connected in what is called a “series circuit,” where each cell contributes voltage (potential energy) to a flow of current that is passing through all of the cells. A good analogy is a series of water pumps adding incremental pressure to a flow that is passing through all of them.

The amount of current (measured in amperes, or amps) a solar cell can “pump” is directly related to the amount of sunlight it receives. If part of the cell becomes shaded, it may be unable to pump the required amount of current. In this case the current flowing through the rest of the system is shunted through an alternate path (the bypass diode), so the overall array power isn’t adversely affected too much. A typical module has 3 bypass diodes, each bridging across one-third of the cells. If the solar array’s inverter demands more current than one of the cells can provide, the bypass diode takes over and shunts the current around the cells it bridges. This has the effect of essentially shorting out that portion of the panel, and the strong cells in the shorted sub-string force their combined voltage across the shaded cell. This voltage is inverted in polarity from normal (plus becomes minus, and vice-versa), which is where the term “reverse-bias” comes from.

The sunlight striking the unshaded portion of the victim cell still generates photo-current, but the current is now a power source heating the cell. The potential energy of that current is raised by all the other cells in the bypassed section of the panel, which is why the induced power is so high. The shaded cell essentially turns into a hot plate where much of the electrical power from the other cells is converted to heat.

So far we have been calculating heating based on an entire cell being illuminated and in reverse bias. Figure 1, for example shows 50% of the cell shaded so the obvious next question to ask is: what happens if more of the cell is shaded? From a temperature-rise standpoint, not much because heat flows so poorly sideways through the very thin cell. True, the amount of power is reduced by the amount of shading, but the dissipation area is reduced by an equal amount; the power *per unit area* isn’t much different, and that is the primary determinant of temperature rise.[3]

Bypass diodes were (barely) adequate protection when solar cells were only able to produce about 2 watts each, but now that their efficiencies are up, so are the levels of damage. The numbers show that each percentage point of efficiency improvement adds roughly 5 degrees Celsius of reverse-bias temperature rise. Cell efficiencies have improved 12-14 percentage points since bypass diodes were first employed, and hot-spot temperatures have since gone up 60+°C as a consequence. Let us state it now and for the record: *Bypass diodes are no longer adequate protection against hot-spot damage in solar panels, and they haven’t been for some time.*

The Bad News Gets Worse

The numbers we’ve seen so far are alarming, but what’s worse is that they represent a best-case scenario: evenly-distributed heat over the surface of the cell. In actuality, some areas get even hotter than the numbers predict. There are always variations in the material which cause some of the current to flow to what are called the “paths of least resistance,” and those paths get the hottest. For this very reason, silicon cells are sorted in the factory to minimize these non-homogeneities. But there is always uneven heating, as seen in the thermal image in Figure 1.

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[3] There are secondary effects which cause the cell to get hotter with smaller amounts of shading. More recent testing standards have changed accordingly: the older UL 1703 test shaded 50% of the cell under test, while the newer IEC 61730 test shades only 20% of the cell.

These low-resistance paths have almost no deleterious effect if the cell is never forced into reverse-bias. Without getting too deep into the math, the level of harm due to low-resistance paths goes up as the *square* of the applied voltage. Forward bias rarely reaches 0.71 volt, while reverse bias regularly exceeds 10V. The ratio of the squares of those two numbers (0.5 and 100, respectively) is 1 to 200, making reverse bias at least 200 times more stressful than forward bias.

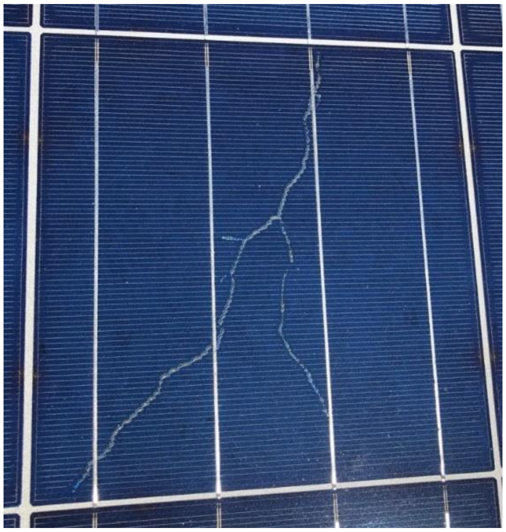
Figure 5 Micro-crack

But every solar cell, no matter how perfect, is subject to damage in the field. Handling, vibration, wind loads, thermal stresses due to hot spots—all of these can cause solar cells to develop cracks that are usually too small to see (appropriately enough, they are called micro-cracks). When a micro-crack forms, it is usually short at first, intruding from an edge toward the middle of a cell. At the tip of the crack, bad things happen under reverse-bias. The externally-applied voltage creates an uneven electrical field that concentrates current into that tiny spot, which gets it very, very hot. The strong thermal stresses cause the crack to propagate across the cell, burning all the way, leaving behind a tell-tale path of bubbled EVA insulating film (Figure 2). This rather dire side-effect of reverse-bias is a complete non-issue in forward-bias, because there is no externally-imposed electric field to force current into the tip of the crack. As long as the metal contacts still bridge across the crack, it doesn't even cause power loss. If a piece of the cell does become separated from the rest, the module power will drop, but there will be no reverse bias, no heat, no danger.

The Solar Industry Tries to Live With the Problem

At this very moment, there are probably hundreds of aerial drones with infra-red cameras zipping over solar installations looking for hot spots. This is the new norm in the industry: try to find hot-spot problems before the damage gets too bad. A document search for hot spot research will yield paper after paper on efforts toward *mitigating* the problem, but virtually none about *preventing* it. The industry seems to have accepted as axiomatic that reverse-bias is unavoidable, and the only thing to be done is to try to minimize the damage.

Unfortunately, even the most diligent inspection regime will not and cannot solve the problem. A micro-crack can form at any time, and the typical time between reverse-bias events is only a few hours. Micro-crack hot spots can burn through the insulation in a matter of milliseconds or less, and if an arc forms, it will be unlikely to extinguish as long as the Sun is up.

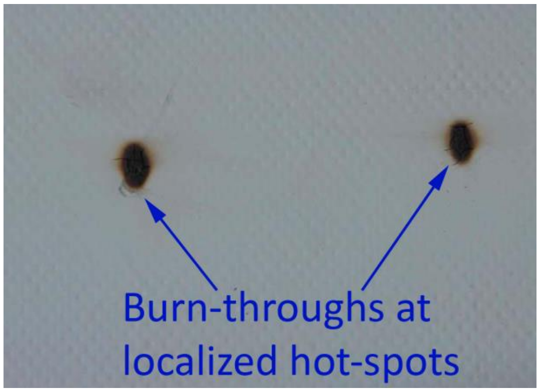

Figure 6 Backsheet burn-through

Here is an example of an otherwise pristine backsheet that has been burned through in 2 places by hot spots. The intense heat occurs when moderate amounts of power get concentrated onto small areas.

Figure 7 Sequential arc-fault

If a burn-through or other failure of a backsheet occurs anywhere near the panel's frame (which is grounded for electrical safety), a spark can ignite. An arc of plasma immediately forms and starts consuming the silicon, glass, and plastic, being fed by the remaining silicon cells. The aftermath often looks like this (assuming the building is still standing):

The thing to understand about solar-fed arcs is that they are *not* inherently self-extinguishing. The reason is because they are direct-current arcs: the flow of electricity is constant as long as light is striking enough cells to keep current flowing.

An alternating-current arc flips polarity many times per second (most grid current operates at 50 or 60Hz). The voltage polarity reverses with a smooth waveform that crosses zero-volts twice per cycle, or 120 times per second at 60Hz. When the voltage drops to zero, the arc has a chance to go out, and having gone out, it might stay out.

A direct-current arc keeps going and also feeds itself. An electric arc is so hot, it rips electrons loose from the atoms it passes through (ionizing them), creating the tell-tale glow. Those electrons can carry current just like a wire, so as long as the arc keeps ionizing the material around it, it keeps creating new current paths; new “wires” to flow through. The modules in the above picture look as though they have been consumed from within because they have. The arcs chewed their way right through non-combustibles like glass and silicon, melting or even vaporizing it. Meanwhile, the aluminum frames (which have much lower melting points) are left behind because they are not supplying any current.

We cannot claim that every solar fire starts with backsheet burn-through; there are other places an arc can form, like at a faulty cable connector. But we can certainly state categorically that backsheet damage raises the danger level to catastrophic levels. FOZHS will eliminate the primary cause of module insulation damage: heat. Additionally, the intelligence built into every FOZHS controller can detect the tell-tale electrical noise of an arc and do an orderly shutdown in fractions of a second.

Reverse-Bias and Hot Spots Can Happen Anytime, Anywhere

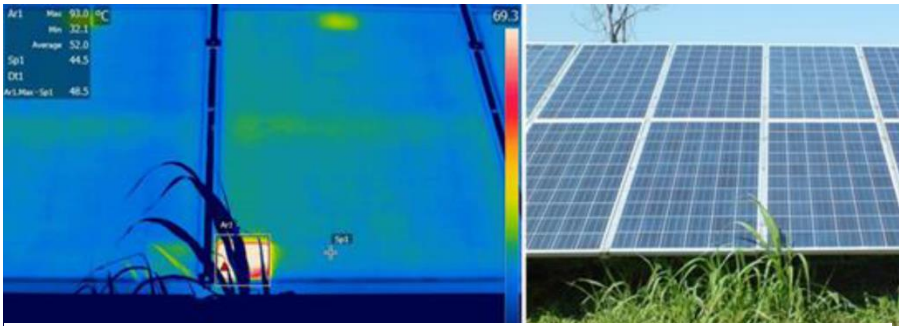

Figure 8

These images illustrate how common the hot-spot problem is. Here is a ground-mounted installation where grass grew in front of the lower edge and created elevated the cell temperature about 60°C hotter than the rest of the module. The yellow rectangle near the top of the thermal image is the junction box on the back; the bypass diode inside it gets hot also, and that heat is telegraphing through the module:

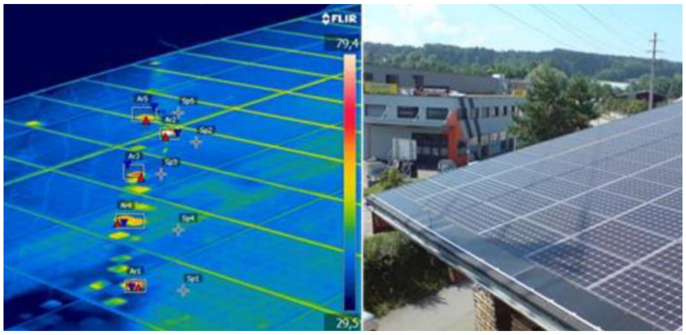

Figure 9

Even the thin shadows of overhead power lines can create serious problems, as seen in this image (the modules in foreground are being hit by a pylon’s shadow, but the ones at rear only have narrow shadow bands crossing them):

In both of the above situations, FOZHS would prevent any cell heating at all.

Forward Only, Zero Hot-Spot Science

The key to stopping hot spots is to stop reverse-bias, and the key to stopping reverse-bias has been waiting to be discovered for over 100 years. Way back in 1906, Albert Einstein provided the key to zero hot-spot science when he described the physics behind the photoelectric effect. Without getting into all the whys and wherefores, suffice it to say that a solar cell goes through a rather significant change in behavior as it approaches reverse-bias. This is key: as it *approaches* reverse-bias. We don't have to wait until reverse-bias happens and try to do damage control; we can stop it from happening before it even comes close. With high-speed, smart electronics, we can watch every cell in a module at once, and if any one of them shows signs of transitioning from power production to power consumption, we immediately reduce the current load so the weakest cell isn't overloaded.[4]

Forward Only, Zero Hot-Spot technology uses intelligent, fault-tolerant electronics on every panel to keep them all running safely. The panels themselves use quarter cells to reduce the current in the panel by a factor of four. Wiring losses drop as the square of current reduction, so a 4x drop in current is a 16x drop in losses.

Figure 10

Losses are so low, we can switch from expensive silver plating on contacts to aluminum. Silver is deposited on the back sides of cells for its solderability and low resistance, but a lot of silver goes into every solar panel: over 0.6 troy ounces. To put that in perspective, this 1000-oz silver ingot is about enough for 100 homes' worth of panels.

The use of a limited commodity like silver restricts the rate at which we can build solar modules. Changing to all-aluminum (for cells and ribbons) will remove that restriction. Aluminum is over 1 million times as abundant as silver, and aluminum production outpaces silver production by over 2 million to one.

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[4] It may seem like 10% shading on one cell would cause the entire panel to run at only 90% power, but that is not the case. The reduction in power is less than 2%. The panel current doesn't have to drop a full 10% to keep the shaded cell in forward bias, and the fully-lit cells raise their voltage a bit as the current is dialed back. The net result is only 1-2% power drop, if that. For the same reason, a cell has to be covered at least 40% to reduce the module output by 33%. With bypass diodes, however, a single cell covered only 5% can cause the same power loss because the bypass diode switches on and shorts out one-third of the module's cells.

The Power of Intelligent Thinking

FOZHS modules use an advanced architecture to optimize in ways conventional modules can’t. As solar cells have gotten more efficient, they have been producing higher and higher amounts of current. That current has to be somehow carried from the cells out to the wires outside, and that is becoming increasingly difficult. The metal ribbons in solar modules are kept as thin as possible so they don’t block too much of the sunlight, but must be thick enough to carry all that current.

Smaller cells would reduce the current, which would have great benefit because the losses due to wiring go up with the square of the current. Cut the current in half and the wiring losses drop by a factor of four. Unfortunately, the voltage goes up at the same time, and modules have had an output of about 30V for a long time because it’s a pretty convenient number. In an array, the voltage of all the modules adds up, and the sum of the voltages has to be kept within safety limits. Home rooftop systems are typically rated to 600V maximum. Fifteen 30V modules can be strung together and operate at 450V nominal, with assurance the voltage will stay below 600V at all times. If the modules are rated at 300W each, your system will produce a healthy 4.5 kilowatts (kW).

If you want to design a similar system with half-cell modules, the string will have to be split in two to keep the voltages within limits. The inverter will be more expensive because it will have to control two strings separately. The wiring will be more expensive because two runs must be made to the inverter. But even with these drawbacks, half-cells are looking better and better as efficiencies (and currents) go up. Many new modules are being introduced with half- and even third-cells.

The FOZHS uses quarter-cell modules, and has since the very first design. We can do that because we convert the module voltage down to mimic an idealized 60- or 72-cell module at each converter output. The same converter also has the intelligence (digital signal processing) to run the forward-only algorithm in real time. Measurements are taken hundreds of times per second to keep all the (quarter) cells in the module running safely in forward-voltage mode. Using quarter cells reduces cell current by a factor of four, which reduces resistive losses by a factor of 16. Operating at such a low current eliminates heating due to poor solder joints (see left-hand image in Figure 4)

Once you combine processing power with sophisticated measurement circuitry, you can do a lot of things to enhance safety. One of the most important is automatic shutdown. Systems are being put in place to send signals to module disconnect boxes to get them to shut off within 30 seconds of being commanded to do so. Our electronics can detect the presence or absence of an inverter; if the DC disconnect switch (located next to the inverter) is manually pulled, or if the inverter is commanded to disconnect, an FOZHS module will shut down within *milliseconds*, immediately reducing the string voltage from hundreds of volts to less than 30.

Looking Toward the Future

Cooler Temperatures Allow New Cell Chemistry

The reverse-bias problem has been a huge impediment to solar technology advances. Any cell chemistry that cannot handle the applied voltages and/or the hot-spot temperatures has a real problem ever being fielded. One new chemistry that shows a lot of promise is perovskites. A perovskite is a particular crystal structure of multiple elements, and some combinations of elements are achieving pretty impressive efficiency levels in the lab. The problem is, they are fragile against elevated temperatures and against reverse-bias voltages. Work is ongoing to make them more rugged, but eliminating both adverse conditions would free up research efforts in other directions. Silicon works most efficiently with red light, but a perovskite solar cell could be layered on top of a silicon cell to harvest blue light efficiently, then pass the red down to the silicon cell below it. This type of cell, called multi-junction or hybrid, is a proven means to greater efficiency. The only problem is: silicon hot spots are too hot for perovskites to withstand. With FOZHS, everything is cool.

Forward Only, Zero Hot-Spot Reduces Manufacturing Energy Burden

As mentioned earlier, defects in silicon cells create low-resistance paths that can markedly elevate the temperature of hot spots. For this reason, silicon must be refined to very high purity to cut down on these defects. Such refinement is very energy-intensive, which pushes out the time it takes for a silicon cell to generate more energy than it took to make it. Even with extensive refinement, about one in 20 cells has a defect that sends it into the reject bin, where they either have to be re-refined or sold at a loss. Shunt defects are *only* a safety problem if they are reverse-biased. As long as the cell remains in forward bias, the only cost is a minor drop in efficiency. With reverse-bias eliminated, the purity standards can be relaxed a bit, reducing the energy burden of cell manufacture.

Toward Low-Cost, Lightweight Front Sheet

Solar modules use tempered glass, which is expensive, heavy, and breakable. If we could replace it with shatterproof plastic, we could save weight for certain, likely reduce hail damage, and even increase efficiency (anti-reflective polycarbonate, for example, transmits more light than glass). So far, the high temperatures of reverse-biased cells have kept plastics off the table for front sheets; FOZHS would remove that impediment.

Smaller Cell Size, Flexible System Architecture

As mentioned earlier, IdealPV modules use quarter cells to minimize wiring losses and improve safety (the current is low enough that a single ribbon can carry all of it, so the wiring is fully redundant). The advantages of lower module current are not lost on the industry, and half-cell and third-cell modules are being introduced as options. The lower current makes for lower wiring losses, but the attendant higher voltages make system design less flexible. Total string voltage must be kept below safety limits in all conditions, and smaller cell size (higher module voltage) makes for larger voltage steps. To add to the difficulty, module voltage changes with temperature and load, and must remain below limit in all conditions.

The IdealPV FOZHS module uses a high-efficiency power converter to create an output voltage that mimics that of conventional 60- or 72-cell modules to maintain design flexibility. Further, the output voltage is stable over temperature, unlike conventional modules. Full power is available across a wide voltage range and a wide current range, which allows multiple module orientations within a single string. The FOZHS controller constantly monitors its attached cells and keeps them all in forward bias at all times.

Conclusion

Reverse-bias events and the damage they cause have been a major impediment both to solar safety and to technology advancement. Industry efforts have heretofore been directed toward limiting the damage caused by reverse-bias, but with reverse-bias itself eliminated, those efforts can be directed in more productive avenues. And while upside potential is great, FOZHS is ready *right now* take us on a giant leap forward in safety, with improvements in efficiency and reduction in cost as extra bonuses.

References

Figure 1 UL1703 Conditions, No Flaws
idealPV

Figure 2 Left backsheet failure, Right multiple cell backsheet degradation
Left: https://pv-magazine-usa.com/2016/09/06/melting-backsheets-broken-cells-and-hotspots/
Right: https://www.researchgate.net/figure/20-left-shows-a-rear-side-of-one-PV-module-with-burn-marks-Both-left-and-center_fig19_274717790

Figure 3 Projected Power Output of Modules Using Selected PV Encapsulant Films Over 25 Years. ENGAGE™Trademark of The Dow Chemical Company (“Dow”) or an affiliated company of Dow
The Material of Choice for Photovoltaic Encapsulant Films
https://www.dow.com/content/dam/dcc/documents/en-us/mark-prod-info/868/868-00151-01-the-material-of-choice-for-photovoltaic-encapsulant-films.pdf?iframe=true

Figure 4 Left 10 year old polysilicon, Right 20 year old Monosilicon
Left-hand image: https://sinovoltaics.com/learning-center/materials/eva-browning/
Right-hand image: Energy performance and degradation over 20 years performance of BP c-Si PV modules
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Figure 5 Micro-crack
https://www.reddit.com/r/solar/comments/av8urh/any_solar_professionals_out_there_studying_the/

Figure 6 Backsheet burn-through
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Figure 7 Sequential arc-fault
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Figure 8
Review on Infrared and Electroluminescence Imaging for PV Field Applications
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Figure 9
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Figure 10
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