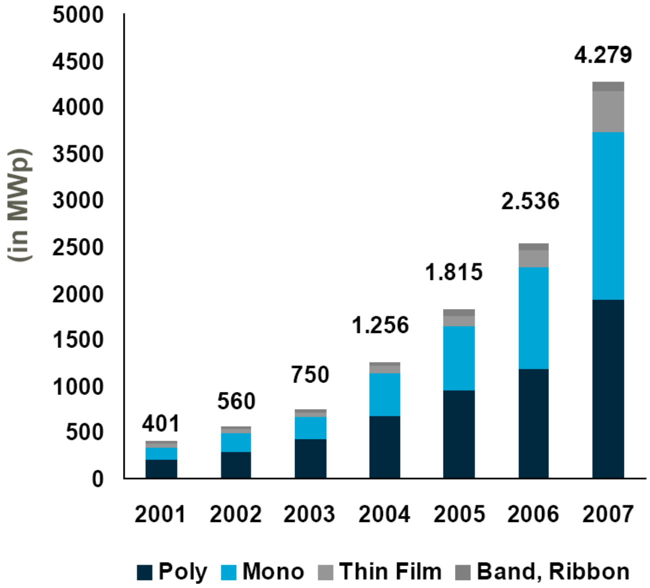
Solar Power Shines

The photovoltaic energy market appears to be very sunny, with impressive growth rates and a lot of innovation, but the market drivers vary significantly from country to country. One thing that all of these markets have in common is the need to deliver the highest efficiency, making solar cells and photovoltaic inverters a fine example of high technology. This article explores the implications of different solar panel technologies and system power ranges, and breaks down the inverter into a front-end boost converter and a back-end frequency inverter, to explain the tremendous differences in requirements and how to solve them.

Solar power is a fast-growing market, with around 35% CAGR over in the last two years. This is not surprising, since it is driven by strong improvements in panel efficiency, guaranteed feed-in tariffs in more and more countries, and last but not least by the fact that it represents “clean” energy, with no noise or pollution during usage. Compared to other renewable energies, it has significant advantages. Solar energy is available almost everywhere; the installations are scalable from small systems for individual houses to large-scale plants; no supplies are required to keep it operating, and there are no moving parts that significantly impact reliability. Other alternatives used today, like oil, coal, or nuclear energy have disadvantages such as availability and sustainability, even with the environmental side effects aside.

So it is not unexpected that growth rates are forecast to remain strong for many years to come. Solar electricity clearly represents a market in full upswing. The picture below shows the panel production capacity in the last years by cell type:



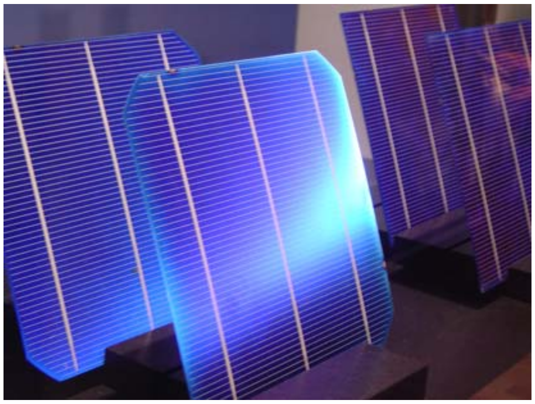
(Source: Photon)

All the large solar cell manufacturers are building large factories to participate in the strong momentum that this market shows. But as much as external factors are driving the market, this market is, at the same time, characterized by immense technological developments, and improvements in cell efficiency. In fact, market development has been so strong that a shortage in one of the basic materials has happened, in raw silicon, the same base material the semiconductor industry also needs. Silicon is one of the most common elements on the earth, but the process to clean this element is extremely time-consuming and expensive. As shown in the diagram below, thin-film cells that use much less silicon (or other materials) have gained in momentum, despite the fact that their efficiencies are lower than the mono-crystalline cells.

The biggest market in Europe for solar cells today is Germany. However, solar electricity in Germany represents only roughly 4% of all renewable energy sources in 2007, which equals about 0.6% of the total electricity consumption in this country. The German government, like many other European governments, has clearly defined goals to increase their share of renewable energy, and the space and potential for wind, biomass and water energy is limited. With this consideration in mind, it is increasingly clear that solar electricity has great growth potential. Comparing the German market with the Spanish market (the second biggest in Europe), there are important differences:

- The solar radiation density is much higher in Spain
- Predominantly direct radiation (versus indirect radiation in Germany)
- Population density is lower

Consequently, the type of systems installed is very different, whereas in Germany many individual home-owners are operating smaller-scale systems on their roofs (in a power range of 5kW to 20kW) and conversely, the predominant type of installation in Spain consists of large power plants in the megawatt range, with tracking systems to follow the sun’s movement and optimize the yield, combined with large inverters. For these power plants, the large pieces of land that are required are easier to find in Spain. The differences also imply a difference in cell types, with large concentrator cell plants being an interesting new concept for Spain, since these cells can easily handle higher illumination densities



Monocrystalline solar cells

Today, four different panel types dominate the market:

	Efficiency
a-Si, or polycrystalline silicon	10%
CdTe (Cadmium Telluride)	12%
CIGS (Copper-Indium-Gallium-Sulphur-Selenide)	14%
c-Si, or monocrystalline silicon	16%
CPV (concentrator PV using triple-junction cells)	25% (prototypes)

The efficiency values are industry-average estimates for mass production, and as such can only give a relative indication. Today, around 85% of all panels are built with c-Si. As mentioned before, raw silicon as a base material has become rare, but a recent breakthrough may change that. Various companies have developed a process to provide umg-Si (short for “upgraded metallurgical silicon”), which is not as pure as the silicon used for semiconductors, but may be good enough for solar cells, and is more cost-effective and easier to produce. This fact could mean that solar panels might become less expensive, putting significant cost pressure on the other components of the solar systems, namely, the inverters, to follow a similar cost-reduction path.

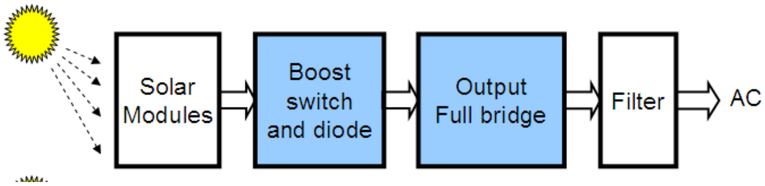
The output of PV systems can suffer from various issues. Most of them have to do with the way the light reaches the cells, like cast shadows, diffuse shading, or dirt or other particles on the modules. The picture below shows how even small plants can cause a significant loss in output power:

Shading caused by trees

Why is this a challenge? The typical panel output voltage of 50V can only be reached by series-connection of many cells, all acting as current sources. If one of the cells is shaded, its source impedance rises significantly, *and only little current can flow through the whole chain* – one cell is effectively shutting down a whole string of cells. At panel level, by-pass diodes can prevent this from becoming a larger issue, but the panel itself has significantly reduced power output.

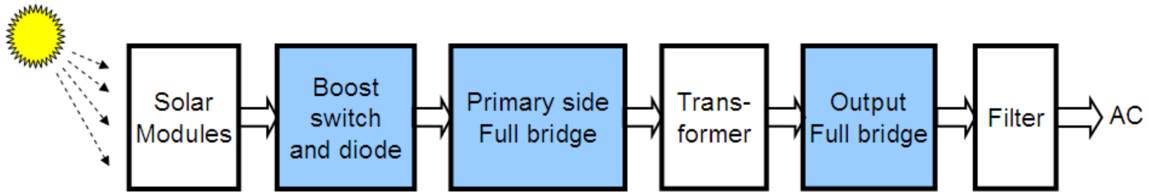
The second large category of challenges has to do with the cells, either broken or mismatched within the panel. And, the matching of the cells to the inverter is critical to ensure that the system operates at maximum efficiency most of the time.

Thirdly, corrosion can be a significant issue, since the lifetime of the systems can usually exceed 20 years. Water or dust entering the panels, connectors or the inverter can cause early failure.

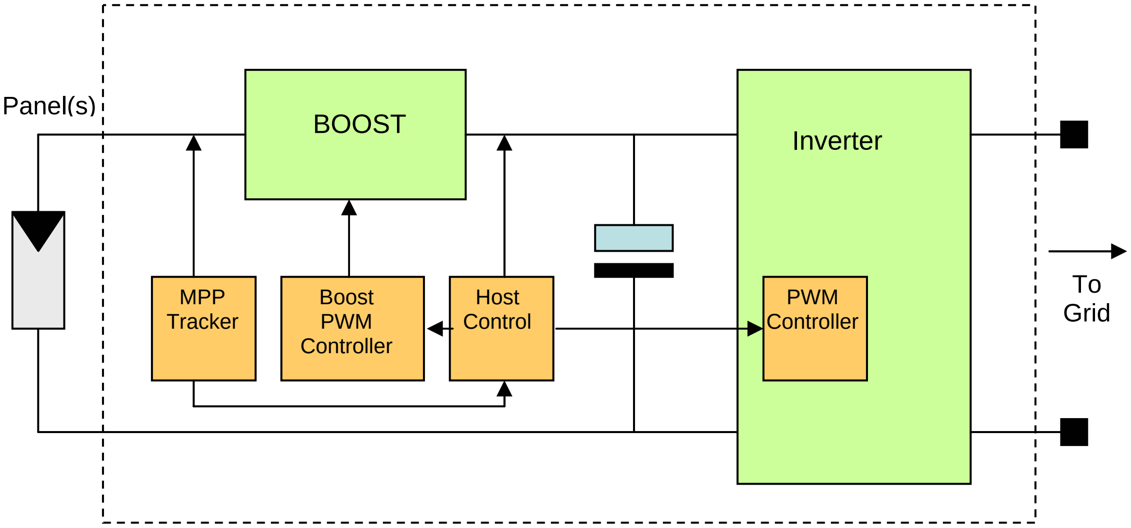


The picture above shows the block diagram of a PV system, with the panels on the left side providing a DC input, and the connection to the grid on the right hand side. Most systems today are connected to the grid, and feeding the generated power into the mains. Some systems in more remote locations are not connected to the grid but usually provide the same output as normally found on-grid.

Inverters come in different topologies, depending on whether isolation is needed or not. The above block diagram shows a transformer-less topology that is instrumental in optimizing efficiency. When isolation is required, a transformer needs to be introduced:



In order to keep the transformer small, another full bridge is used to drive it at high frequency, reducing the overall efficiency somewhat.



The inverter is the main element between the panels and the grid. It provides proper loading to the cells, to draw the maximum power, and converts this energy into an AC output current. To do this, an MPP tracker is used ("Maximum Power Point"). The cells can be thought of as a voltage source with a non-linear source impedance, and the MPP tracker varies the loading until the product of voltage and current is maximized, by changing the input impedance of the boost converter. In a second stage, this DC current is then converted into the required AC output current. For this, the inverter will monitor the grid voltage and frequency, and its own output current, to control the inverter stage appropriately. The inverter really works as an AC current source, driving the grid impedance. The intermediate voltage has to be higher than the desired peak output voltage, plus some margin – at 220V_{RMS}, the peak voltage is 308V, so the intermediate voltage is usually chosen to be 350V-390V. This means the second inverter can act as a pure step-down circuit, simplifying the topology. It is not uncommon to find several boost converters connected in parallel, to be able to connect multiple strings of panels. They all "feed" into one inverter.

Small inverter for 3kWp output power

The above picture shows an inverter, with the main PCB dedicated to the power conversion. In the center, power IGBTs can be seen under clips that press them to a heat sink. On the right, electrolytic caps are used as intermediate caps between the boost converter and the inverter, to store the energy needed to bridge individual 50Hz cycles. Here, many caps in parallel are chosen over one large cap, in order to minimize the equivalent series resistance. The flat cable in the middle connects to the microcontroller placed at the front of the case, where also the display is located. This is a transformer-less inverter, and the two big inductors on the top are the output inductors.

In a typical smaller-scale installation with an output power of 5kW to 10kWp, a separate electricity meter may be used to count the Kilowatt-Hours the system is producing. In larger solar power plants, the inverter can be used for this purpose, since it is measuring voltages and current anyways. Here, a remote host is communicating with the inverters and tracking the yield of each part of the system. Web-based interfaces allow easy checking even from a distance.

Rack with several higher-power inverters working in parallel

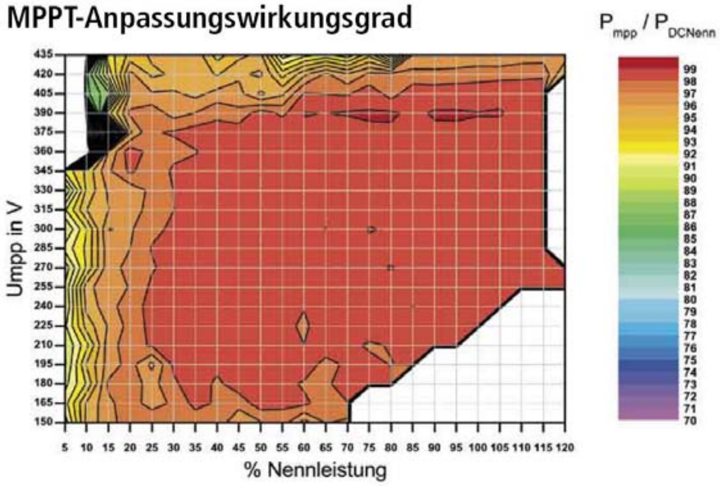
In this larger-scale system shown above, several inverters are combined in multiple racks for a total output power of 500kW. One of the inverters is pulled out of the rack, demonstrating the easy replacement. The unit in the middle is the monitoring unit, used to control all inverters and monitor the performance of the subsections of the solar power plant. There are also systems that can handle up to 200kW in one (larger) rack unit, at increased power density.

As shown above, the front end of the inverter has a distinct task. In order for the back end to perform the DC-to-AC conversion with high efficiency, it is best to “feed” it with a DC voltage that is by a certain margin higher than the maximum required output voltage, so that the backend only needs to perform a step-down function. But the output voltage of one panel is typically 50 to 80V, so several panels must be connected in a series to achieve a high input voltage. And, the voltage will depend on the solar radiation density – very quickly, a pretty complex situation is achieved. The challenges are:

- The input voltage can vary over a wide range. If the number of panels chosen and connected in series is so high that the input voltage is higher than the output voltage under all conditions, then the maximum input voltage is so high that power switches with very high breakdown voltages are needed (which is expensive and lowers efficiency), and the handling and cabling is more difficult (making the system less reliable). A compromise is to choose a smaller number of panels in series, so that the voltage cannot become so high, but in order to provide output power at lower radiation levels a boost converter is needed. The total efficiency and the yield of the system can be shown to actually be higher, even though the system is more complex.

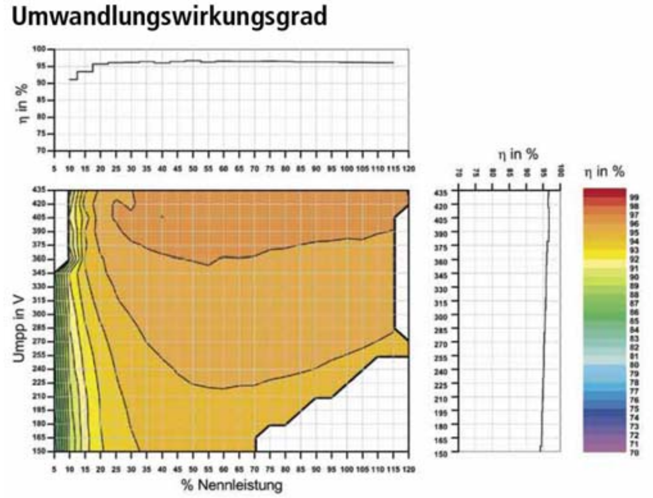
- In a larger system, several strings of series-connected panels are connected to an inverter. If one of the panels is shaded or the cells have a lower yield to begin with, the output voltage of this string will be lower. In order for this string to contribute to the output, individual boost converters are used for each string, compensating individual variations, and operating each string in its maximum power point
- As individual panels have different MPPs, they must be sorted before connecting them together, to ensure their MPPs match, or even the best inverter in the world will not be able to maximize the yield.

The MPP tracking function requires a multiplication of the voltage and current, to calculate the output power. Then, the load impedance is varied slightly, and the system moves in the direction of higher power drawn from the panels. This algorithm is then repeated. As the radiation usually changes slowly, a high speed loop is not required.



(Source: Photon)

This picture shows an example of the MPP tracker matching at the input, that means, how close the front end converter is able to match its input impedance to the output impedance of the panels. The horizontal scale is the nominal power; the vertical scale the input voltage. Higher efficiency areas are shaded in red. The input impedance is controlled within the feedback loop of the MPP tracker, so any deviation is signaled through a lower efficiency and implies something this control loop cannot regulate away – an implicit limitation of the inverter, and the topologies and components chosen. Another root cause can be measurement errors in determining the input current and voltage, as well as limitations in the resolution of the A-to-D converters and controllers.



(Source: Photon)

This diagram shows the total conversion yield of the same inverter, disregarding the mismatch at the input, but purely looking at the AC output power versus the DC input power. The horizontal scale is the nominal power, and the vertical scale shows the input voltage. This example shows an inverter that actually works quite well, particularly with high input voltages, but as the voltage drops the yield also goes down. On the left hand side the inherent energy consumption of the inverter can be seen to reduce the yield. The input overcurrent protection can be seen in the lower right corner.

As can be seen from the diagram, the “harder” the front end converter needs to work, the lower the yield. At high input voltages, very little additional boost needs to be provided, so the corresponding power dissipation is lower. However, at lower input voltages, a high AC current ripple in the input translates to larger losses. Improvements in the boost converter would first of all improve the overall efficiency, and secondly, move the area of maximum efficiency to lower input voltages, providing a better match to the panels. As panels do have a non-zero source resistance, the output voltage under load can be significantly lower than the no-load voltage, particularly for thin-film panels. So, this reduced voltage level is where the maximum yield of the inverter should be and not at very high input voltages as the yield will be wasted with this mismatch.

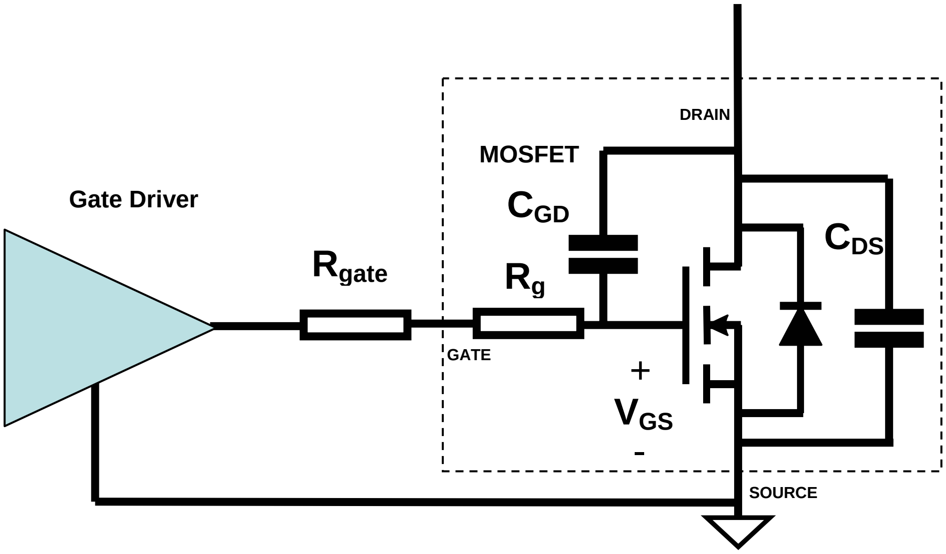
It is interesting to note that the best tracking is achieved at an input voltage of 390V, precisely the voltage chosen at design to turn-off the boost converter, and a clear distinction can be seen at the handover point between the two-stage and the single-stage operating mode. The inefficiencies in the tracking as well as power conversion are due to a sub-optimal inverter, that cannot transform a required input impedance value well enough to a certain output impedance. In the upper left hand corner, a lower tracking and also efficiency is visible, indicating the main inverter cannot handle low input currents at high voltages very well. This may be caused by power switches with too high output capacitances, as the losses are proportional to $C*U^2$. As the current in the inverter increases (moving in the diagram to the right), the proportion of switching losses is getting smaller compared to the conduction losses, so the efficiency actually improves, although the power dissipation goes up.

As can be seen on the left hand side with the vertical yellow areas, the yield is lower at low power, probably due to this inverter having higher than necessary switching losses in the boost converters. At the lower right corner, at a combination of low input voltage and high power, the input current becomes very large so the input DC over current protection will switch off the inverter. On the right hand side, at power levels over 115%, the inverter will turn off as well.

In order to improve the performance, and have larger parts of the diagram “red,” various measures can be implemented. Apart from the obvious optimization in passive components, the boost diodes need to be carefully selected for low switching losses (improving the performance at low input power, the left side of the diagram), and for low forward voltage drop (to improve the yield at high input currents, the lower part of the diagram). The Stealth^{TM} II diodes from Fairchild Semiconductor or silicon carbide diodes can provide this optimization. The power switches in the boost converter, usually MOSFETs, also need to be carefully chosen. At low input voltages, the current through the switches is causing conduction losses due to the high duty cycle, so low R_{DSON} is important – in fact, it is not uncommon to see several large MOSFETs in TO-247 packages connected in parallel.

Further improvements can be gained with a careful choice of operating mode of the boost converter. Continuous mode conversion is chosen, to minimize AC losses, and the lower ripple currents allow for reduction of unwanted overhead in the system. However, this is a hard-switching system, so power MOSFETs with a low output capacitance should be chosen. This, however, contradicts somewhat with the requirement for low conduction losses in the switch, to be obtained with a larger device. Here, a good compromise can be found in Fairchild's SuperFET™ devices that can at the same time provide a "fast" body diode at no R_{DSON} penalty. This also helps at the lower right hand corner of the diagram, as at low input voltage and high power the duty cycle of the converter is quite long, with high currents in the switch.

The correct gate drive of the power switches is crucial in many respects. Below schematic shows the typical setup:



The value of R_{gate} plays a significant role in the performance of the system. The lower this resistor becomes, the faster the MOSFET will be switching (provided the gate driver has sufficiently low output impedance). Faster switching corresponds to higher dI/dt and dv/dt, increased electromagnetic emission (EMI), and can lead to breakdown of the components, reducing reliability. If the gate resistor value is increased, the switching speed is reduced, but this means the overlap between current in the device, and voltage across the device, is increased, and so are the switching losses. In other words, the switch behaves less and less as a switch, but spends more and more time in the linear region, causing power dissipation. In conclusion, the gate resistance values need to be finely tuned for lowest power dissipation and EMI.

To improve performance even further, resonant or quasi-resonant topologies can be used, although they can be challenging to implement for a wide input voltage range and still operate at ZVS (“zero voltage switching”) or ZCS (“zero current switching”). Another topology to improve performance is the interleaved boost converter. Here, multiple converters are working in parallel, out-of-phase with each other, and it can be shown that the ripple current in the output can be reduced. And, if the input voltage is high enough, the boost converter can be turned off completely and bridged e.g., with a relay, to further reduce losses.

The inverter or DC-to-AC section of the inverter can be built with many different topologies, quite a few of them proprietary to some of the companies building inverters. One of the “classical” topologies consists of using a full bridge, driving output inductors to reduce EMI. Here, some of the devices can be switched at line frequency whereas others are switched with the conversion frequency – if done cleverly, the first devices can be chosen for lowest conduction losses, like the Non Punch Through (NPT) Fieldstop (FS) IGBTs from Fairchild Semiconductor, whereas the latter should be chosen for lowest switching losses, e.g. the new NPT Field Stop Trench devices from Fairchild Semiconductor. Here, a combination of different IGBTs or even IGBTs and MOSFETs can help to improve the overall yield. And to properly drive the power switches, optically isolated gate drivers like Fairchild’s FOD3180 can be used, improving the system reliability where high dv/dt can suddenly occur, e.g., in the case of a grid fault.

In applications such as solar inverters, where the key performance parameter is the conversion efficiency, improvements in switching device performance, through the use of IGBTs, MOSFETs and diodes, is very important. Here, the voltage drops and switching energy losses can still be improved, although in order to realize the potential gains, more brainpower has to go into how to drive the switches properly, to avoid parasitic oscillations and overvoltages: the two biggest enemies of high efficiency and robustness. Here, integration of subsystems into intelligent power modules can really help! Due to the close proximity and ideal matching of driver and power switch, the best possible switching behavior can be realized repeatedly. Fairchild Semiconductor is driving the state-of- the-art in both power switch technologies as well as module integration to support further performance improvements in these green high-tech applications.

About the author:

Alfred Hesener is director for applications and marketing for Fairchild Semiconductor, responsible for the European market.