Application Report

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Supplying TPS61200 With a Single Solar Cell

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ABSTRACT

This application report explains how to use the TPS61200 in combination with a single solar cell to charge a battery or storage device. A characteristic of solar cells is the internal resistance that can vary from less than 10 Ω up to more than 100 Ω. Therefore, it is important to control the load placed on the solar cell to ensure a reliable start-up of the application. This report describes an application that avoids the solar cell output voltage breaking down and manages the load as the solar cell power changes. The solution provides a reliable start-up of the TPS61200 using solar cells that can deliver at least 3 mA at 0.5 V.

Solar Cell Knowledge

In general, solar cells can be classified into two types, crystalline silicon solar cells and amorphous silicon solar cells on float glass. Both types have certain benefits in specific applications as a power source.

Usually, the crystalline silicon solar cell has better efficiency compared to the amorphous silicon solar cell. On the other hand, the amorphous silicon solar cell is more sensitive to stray light than the crystalline solar cell. This does not totally compensate the lower efficiency but brings both types close together. The amorphous silicon solar cells cost less than crystalline solar cells.

The power that can be drawn from a solar cell depends on the physical size and type of the cell – the smaller the solar cell, the less power it can deliver. For some applications, it can be beneficial to use solar cells in series to increase the module output voltage instead of boosting from a single solar cell. For ultralow power applications, this yields better efficiency numbers compared to what is achievable with a single-cell configuration with a nominal output voltage of 0.5 V.

When using solar cells, it is important to consider what kind of light source is available. Sunlight delivers much more energy than artificial light. A bulb lamp is better than a fluorescent lamp. Therefore, it is necessary to match the solar cell with the application and the light condition for which it is used . Crystalline silicon solar cells work best if used outside with sunlight. For indoor use, amorphous silicon solar cells are more suitable. This type of solar cells has a different light sensitivity which fits the spectrum of artificial light much better than crystalline solar cells. Prepared for both light conditions is the stacked type of solar cells. It is build of two thin layers of amorphous silicon with a different spectral light sensitivity and stacked on top of each other. This kind of solar cell is working with a much wider spectrum of light than any other type. Therefore it is ideal for hand-held devices which can be used indoor and outdoor.

Solar cells are typically specified at certain light intensities. For crystalline solar cell and outdoor amorphous solar cells, the reference intensity is 1000 W/m^2, which represents sunlight on earth at noon and close to the equator. For indoor solar cells, the reference is mostly 100 and 1000 lux, which covers most indoor light conditions from a single bulb lamp to indirect sunlight through a window. For comparison, 1250 lux is approximately 1 mW/cm^2.

I-V Characteristic of a Solar Cell

For high-impedance sources, it is important to keep the maximum load in the range of the output impedance R_I (see Figure 1). This ensures that the application operates at a point that offers most power and good efficiency. For a solar cell, especially if small form factors are applied, this means that the voltage generated by light must not fall below 450 mV, and for best performance, it must be held at 0.5 V. The current that can be drawn from the solar cell is proportional to the intensity of light. Therefore, the power that can be delivered by a solar cell varies a lot due to different light conditions. To keep a connected circuit running due to the different light conditions, it is important to control the voltage that the solar cell is generating. The following sections describe how this can be done.

Figure 1 shows the typical I-V characteristic of a 12.5-cm × 12.5-cm (~5-in. × 5-in.) solar cell at a light intensity of 1000 W/m^2 and 500 W/m^2. The purple graph shows that the power that can be drawn from the solar cell and the maximum is slightly below 0.5-V cell voltage. The schematic shows the equivalent circuit diagram of a solar cell.

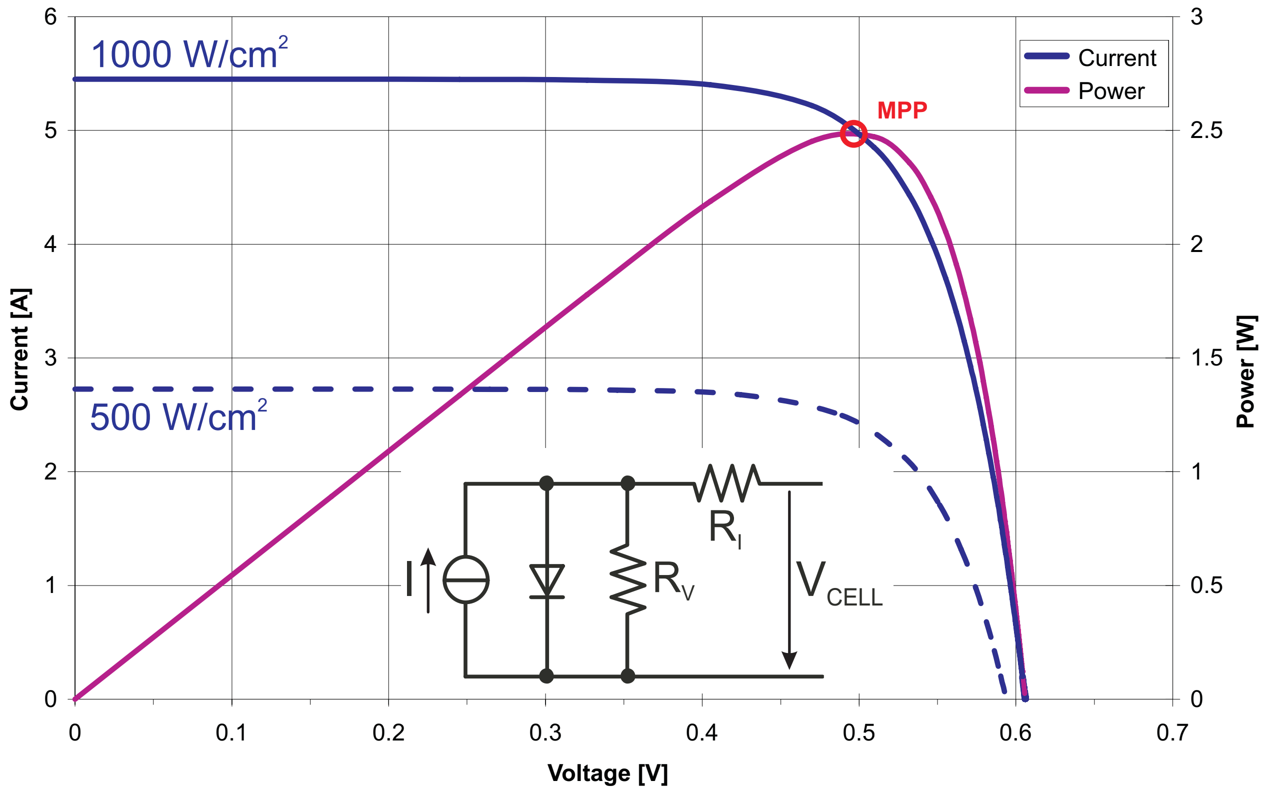


Figure 1. Typical I-V Characteristic of a Solar Cell With Equivalent Circuit Diagram

Boost Converter Topology

To understand the problems which occur when boosting from low input voltages to typical output voltages in the range of 3 V to 5 V, it is necessary to have a basic understanding of how boost converters work. Assuming that an ideal boost converter is used, physics states that the input power is the same as output power. This means that if an output voltage of 3.3 V is needed and the load current is 5 mA, the power at the output is 16.5 mW. The conversion factor from 0.5 V to 3.3 V is 6.6, and therefore, the input current is at least 6.6 times larger than the output current. However, with a real-world converter, the losses have to be added to this value. The TPS61200 data sheet (SLVS577) shows that the efficiency at 0.5-V input voltage is approximately 50%. This efficiency describes all losses and the current consumption that the converter needs to work. Returning to the example, the input current I_L is 66 mA, using Equation 1, where η is the efficiency (50% = 0.5).

$$I_L = \frac{V_{OUT} \times I_{OUT}}{\eta \times V_{IN}} \tag{1}$$

The input current is equal to the mean current through the inductor and therefore through the main switch. The additional ripple peak current ΔI_L can be calculated by Equation 2, where f is the switching frequency (1250 kHz) and L is the used inductor value (4.7 µH).

$$\Delta I_L = \frac{V_{IN} \times (V_{OUT} - V_{IN})}{2 \times V_{OUT} \times f \times L} \tag{2}$$

Performing this calculation gives a total peak current of 66 mA + 36 mA = 102 mA. This current flows though the inductor and the main switch and is important for choosing the right inductor. The calculation also impressively shows that the input current I_L is more than 13 times higher than the output current for this typical assumption. Therefore, it is necessary to keep this in mind when choosing a solar cell or any other high-impedance supply. The calculation only shows what current or power is needed during normal operation but does not show what happens during start-up. The start-up current can be much higher because at this time the output capacitor needs to be charged as well as the gate capacitors of the switches. The uncharged output capacitor at the beginning of the charge cycle can be described as a very low-impedance load and consumes a high current if no circuitry is able to limit the current flow. Because the internal current limit of the TPS61200 is designed for current above 1 A, an additional circuit is necessary to prevent the converter from pulling too much current from the solar cell.

Advantages of TPS61200

Two features of the TPS61200 ideally fit the needs of applications running from a single solar cell. The first and most important feature is the very low start-up voltage. The TPS61200 is able to start from a load of 0.5 V and will run down to voltages below 0.3 V. This feature differentiates this boost converter from other converters and makes it ideal for being supplied by solar cells.

The second feature offers a great advantage for additional circuitry that do not consume much power but needs to be started or running when the main circuit is disabled. The additional circuitry can run from the V_{AUX} output. This output already offers a voltage at very low input voltages (>150 mV typ.) and can drive currents of about 1 mA.

Device Description

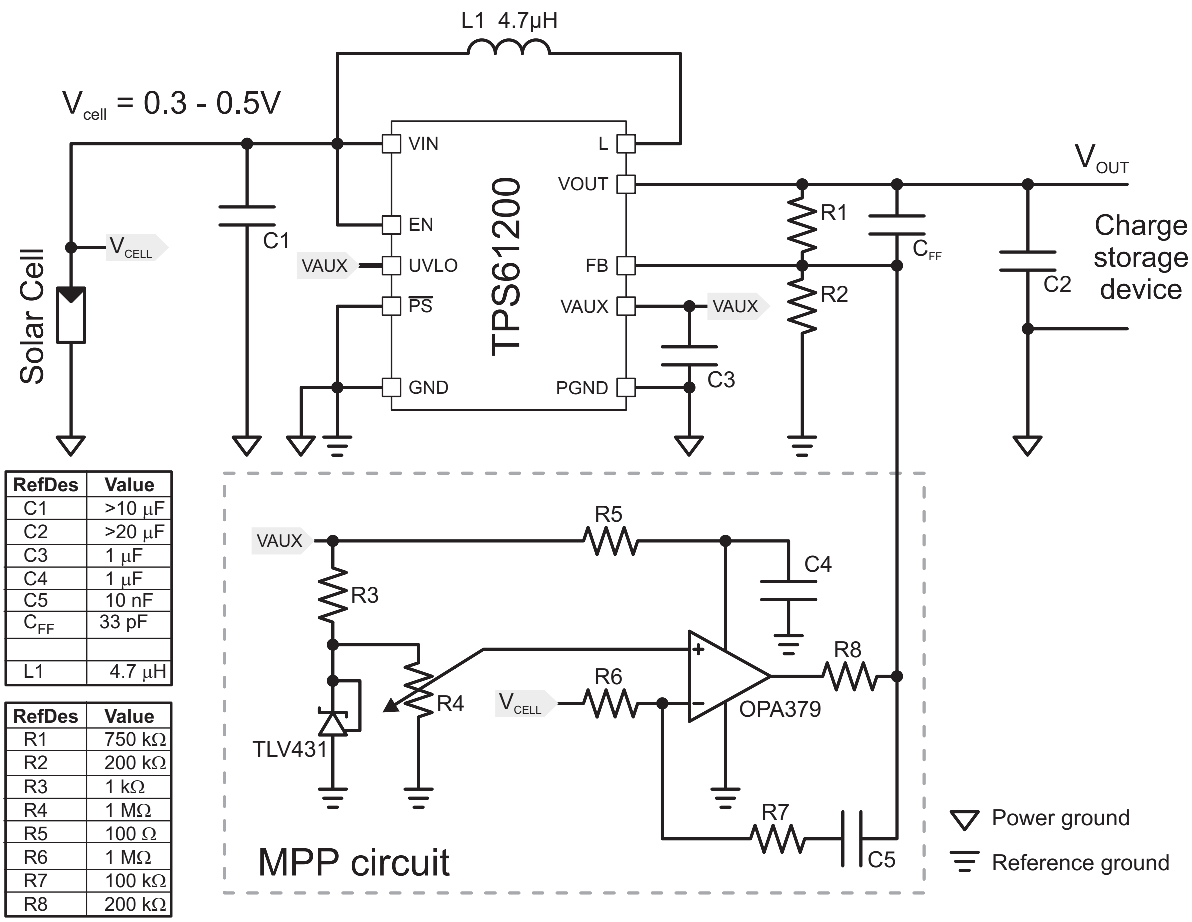
The TPS61200 devices provide a power supply solution for products powered by a single-cell, two-cell or three-cell alkaline, NiCd or NiMH, or one-cell Li-ion or Li-polymer battery. It is also used in fuel-cell or solar-cell-powered applications where the capability of handling low input voltages is essential. Therefore, the converter is designed to start at voltages below 0.5 V. Possible output currents depend on the input-to-output voltage ratio. The devices provide output currents up to 600 mA at a 5-V output while using a single-cell Li-ion or Li-polymer battery, and discharge it down to 2.5 V. The boost converter is based on a fixed frequency, pulse-width-modulation (PWM) controller using synchronous rectification to obtain maximum efficiency. At low load currents, the converter enters the Power Save mode to maintain a high efficiency over a wide load current range. The maximum average input current is limited to 1500 mA. The output voltage can be programmed by an external resistor divider or is fixed internally on the chip. The converter can be disabled to minimize battery drain. During shutdown, the load is completely disconnected from the battery. The device is packaged in a 10-pin QFN PowerPAD™ package (DRC) measuring 3 mm × 3 mm.

Obviously, the TPS61200 is designed for an application that consumes more than just a few mA of current. Nevertheless, the low input voltage makes this device suitable for applications powered by single solar cells as well as other low voltage supplies. Applications using this kind of power sources are mainly sensor applications where less power is needed and space is limited. Small-size solar cells are not able to deliver high currents like a standard size cell. The deliverable current is proportional to the area of the solar cell and greatly depends on the light source which is available. As an effect of this behavior, it is important to limit the current flow into the application. This can be done either by just limiting the current to a certain value, or by controlling the power supply circuit in such a way that it operates the solar cell in the most efficient manner. This is accomplished by keeping the input voltage at a certain value where the power that is delivered to the supply is at its maximum, called the maximum power point regulation (MPP). The following schematic shows an example of a circuit that monitors the supply voltage of the TPS61200 with an additional operational amplifier and compares this voltage with a reference voltage.

Before describing the circuits, three things must be considered.

- The following circuit can only be realized with a TPS61200. The fixed-voltage versions cannot be used because of the different internal connection of the feedback pin.

- The converter needs to work in power save mode. This mode is important for light load efficiency because it reduces the quiescent current of the converter and protects a connected chargeable device from overvoltage.
- To improve the power transfer from the input to the output at low input voltages, a higher inductance value is necessary. This supports the start-up circuit better than a lower inductance and increases the efficiency. Inductors of 4.7 µH to 10 µH have shown good results.



RefDes	Value
C1	>10 µF
C2	>20 µF
C3	1 µF
C4	1 µF
C5	10 nF
C_{FF}	33 pF
L1	4.7 µH

RefDes	Value
R1	750 kΩ
R2	200 kΩ
R3	1 kΩ
R4	1 MΩ
R5	100 Ω
R6	1 MΩ
R7	100 kΩ
R8	200 kΩ

Figure 2. TPS61200 Combined With MPP Circuit

Circuit Description

The TPS61200 is able to start at input voltages of less than 0.5 V. This is done by using a dedicated low-voltage start-up circuit inside the converter. This circuit is boosting the input voltage to charge the capacitor at V_{AUX} (C3). This works at input voltages as low as 300 mV. When a voltage above 2 V is reached at V_{AUX}, the main control circuit is started, supplied by the voltage at V_{AUX}. After activating the main gate drivers, the main switch starts switching and the converter charges the output capacitor C2. Due to the high conversion ratio which is necessary to boost from 0.5 V to a suitable supply voltage for the application in a range up to 3 V, the input current is increasing to hundreds of mA. Without additional control, the output voltage of the solar cell collapses. The DC-DC converter basically shorts the solar cell because it tries to draw enough current to maintain its output voltage. This current may be more than the solar cell can provide, and the system latches in this condition, which can only be cleared by turning off the converter or removing the load completely.

The TPS61200 V_{AUX} capacitor provides a power source that can be used to drive additional low-power circuits from a low-input voltage and before the main output is operating.

To dynamically control the input current, the additional MPP circuit (framed circuit) is added. The operational amplifier is connected to V_{AUX} as well as the additional voltage reference. The selected operational amplifier is a low-power-consuming, rail-to-rail amplifier that is able to work at low supply voltages. Also, the voltage reference has low power consumption and operates well at low supply voltages. Because this additional circuit is powered by V_{AUX}, it starts working before the main switch of the converter is turned on and the main power output becomes active. The operational amplifier output is connected to the feedback pin of the TPS61200 to control the output voltage of the converter depending on the supplied input voltage of the solar cell. The operational amplifier is working mainly as a comparator which compares the voltage at the solar cell to a voltage reference. This voltage reference is generated by the TLV431 and can be adjusted by changing R4. Using a potentiometer instead of a resistor divider offers the ability to adjust the circuit to different solar cell types and different conditions. This is necessary because solar cells behave differently under certain environmental conditions. Light condition and the cell temperature have a strong influence on the power available from the cell and therefore on the optimized voltage value for the MPP. In the final application, the potentiometer can be replaced by a fixed voltage divider after the ideal value for the MPP of the specific solar cell is found.

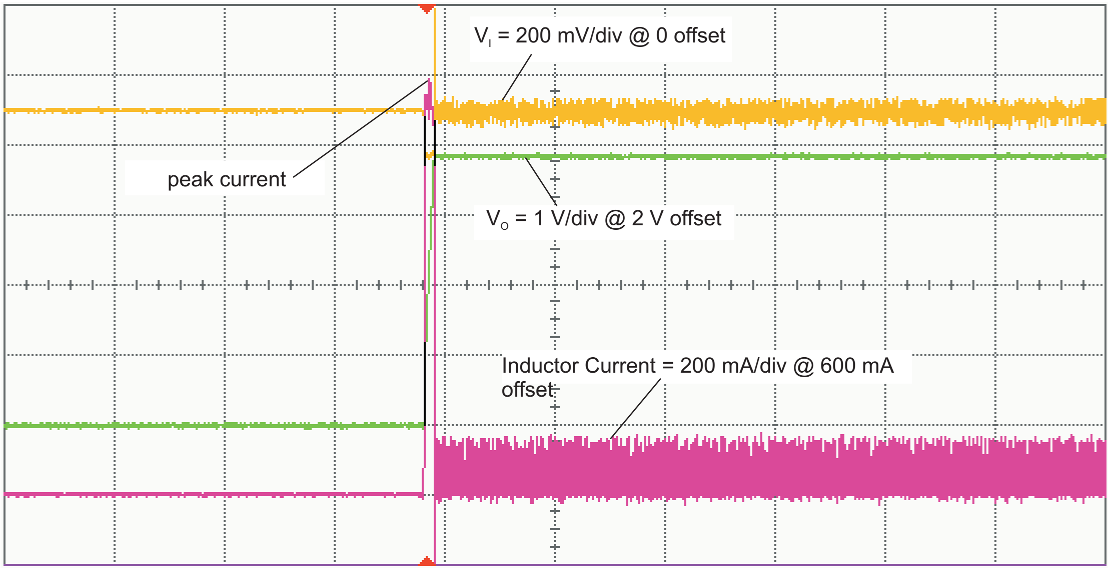
If the optimized voltage is set by R4 and light is applied to the solar cell, the TPS61200 starts to charge the capacitor at V_{AUX}. When the voltage reaches 2 V, the external MPP circuitry is ready to start working just before the main converter starts operating. Activating the main switch immediately increases the current pulled from the solar cell. During steady-state conditions, the input current is proportional to the output current by the conversion ratio set by the output voltage divider. To lower the input current, the MPP circuit reduces the set output voltage to a much lower value by injecting current into the feedback node.

As the converter output voltage is reduced, input current is also reduced. This decreases the current pulled from the solar cell and decreases the voltage drop due to the solar cell output resistance. The result is a smooth start-up without overloading the solar cell.

In addition, the MPP circuit increases the start-up time depending on the power available from the solar cell. This should be kept in mind but will not affect typical applications very much.

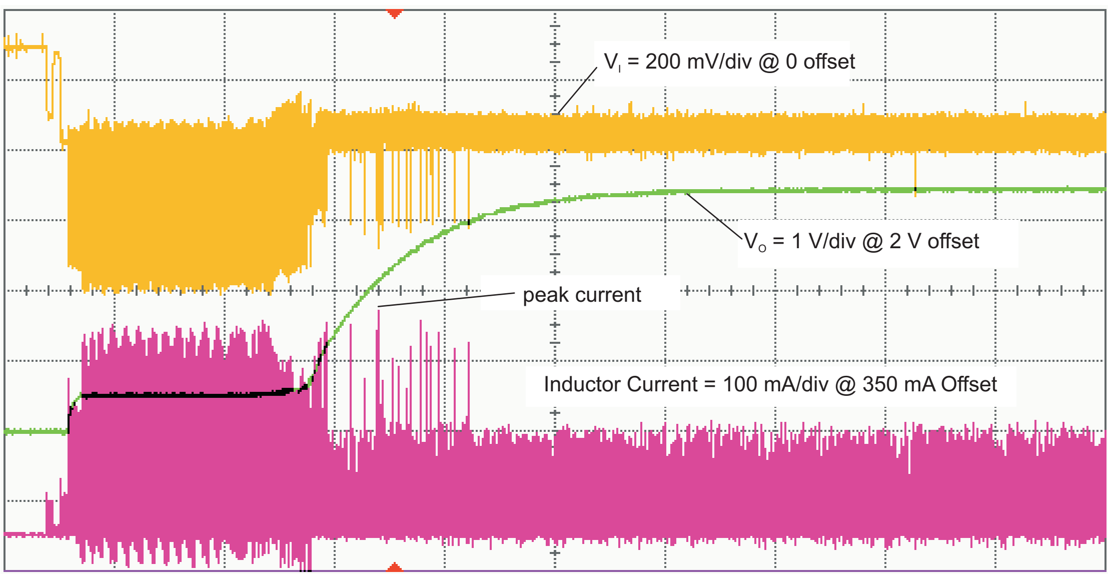
During operation, the MPP circuit maintains control of the input voltage. It reacts to changes of the load condition as well as to changes at the input conditions like changes in the amount of light applied to the solar cell. Even if the solar cell is unable to supply any useable voltage because of shade or darkness, the MPP circuit always ensures a reliable start-up and the recovery of the application as soon as the solar cell generates enough energy. Because of the extreme light changes that can happen for solar cell applications, it is important to use an energy storage device between the TPS61200 boost converter and the load. This prevents the connected load circuit from being re-started every time the light goes away. The chargeable device can either be a battery or a super capacitor. Both devices offer the opportunity to support the attached circuit with energy during the light-off period. The time gap that can be bridged depends on the time the chargeable device was charged, the capacity, and finally the leakage of the energy storage device.

The following illustrations show the TPS61200 start-up behavior with and without the MPP circuit. For both illustrations, the load current at the output of the converter is set to 1 mA. Figure 3 shows the TPS61200 boost converter start-up without the MPP circuit. Input voltage is 0.5 V and is boosted to 3.8 V. For a fast start-up, the current through the inductor increases above 1 A for a short time, but this cannot be supported by a high-impedance source like a solar cell. Figure 4 shows the start-up behavior of the TPS61200 with the MPP circuit. To simulate the output impedance of a solar cell, a 10-Ω resistor is put in series to a standard power supply. This simulates a solar cell under good lighting conditions. The start-up time is increased because of the reduced total power that can be delivered by the supply due to the increased output impedance.



t - Time - 20 ms/div

Figure 3. TPS61200 Device Start-up Behavior Without the MPP



t - Time - 20 ms/div

Figure 4. TPS61200 Device Start-up Behavior With the MPP

The circuit was tested with a variety of solar cells of many types. The MPP circuit is even able to support solar cells with an area of less than 1-cm^2 (~0.16-sq in) at bright light condition but with no load at the output. As described in the previous section *Boost Converter Topology*, the input current is 13 times higher than the load current. The chosen solar cell needs to support that current under the application's worst-case condition. Also, the current consumed by the MPP circuit must be considered and is calculated the same way as the input current using Equation 1.

Due to the additional current consumed by the MPP circuit and the high voltage conversion ratio of the power circuit, the overall efficiency is affected. For very low current applications, the efficiency can be below 50%, depending on the output voltage. The efficiency increases with the load current, assuming a suitable solar cell.