INNOVATOR IN ELECTRONICS

A Solar Energy Harvester for Wireless Sensor Networks

Application Note M1001

Solar provides an excellent source of energy for wireless systems that have no access to fixed power. Solar energy is abundant, present in all but the most northern-reaching climes and dependable for the foreseeable future (>1 billion years). Given the commercial interest in Green technology and alternative energy sourcing, Solar or Photovoltaic (PV) cells continue to improve at a rapid pace, both in terms of higher efficiencies and lower production costs.

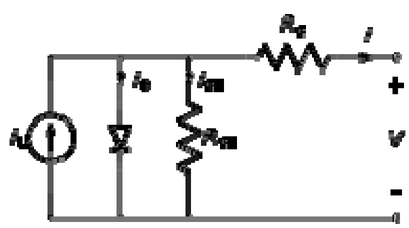
On average, the amount of solar energy falling onto a square meter at the equator of planet earth is 1000 w/m^2. This number varies wildly depending on circumstances and location but illustrates the point that solar energy can provide significant amounts of power for outdoor wireless applications.

Murata has designed two solar power energy harvesting supplies for our LPR2430ERA wireless module. The LPR2430 is a 100mW 802.15.4 wireless sensor module. This app note explains the technical approach and design choices used to design the harvesting supply. The circuits discussed in this app note have been implemented in prototype designs and have been working in an outdoor environment for more than 4 months.

Energy source: The PV Cell

At its most basic, the equivalent circuit of a PV cell is that of a photon-controlled current source in parallel with a diode. Figure 1 shows that basic configuration plus parasitic resistances. These model the various losses in the cell and are of secondary importance. For our purposes, the current source and the diode are the key elements to consider when designing the power harvester.

Figure 1.



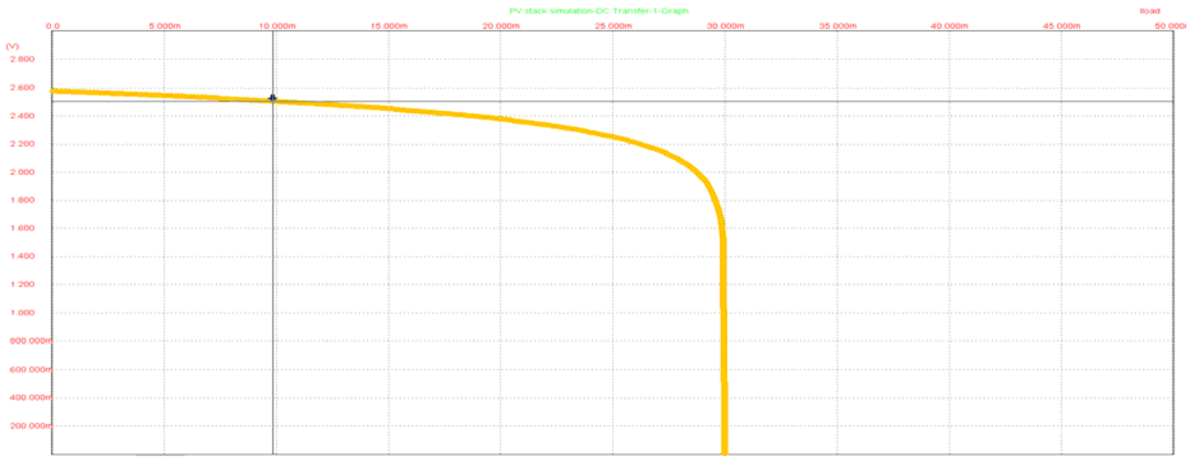
PV cells are rated to produce a given current and voltage output when illuminated with a standard light level (irradiance) of 1000 Watts/m^2 at room temperature. The current produced by the cell is directly proportional to the active area of the cell (in m^2), the amount of light falling in that area and the conversion efficiency of the cell.

The voltage across a single PV cell is a function of the current through it (I_d) and obeys the standard semiconductor diode equation. Open circuit voltage across a single cell is usually about 0.6 volts. Note that while one cell will suffice for many applications, most of the time, cells are stacked in series and/or in parallel to provide higher currents or voltage for a given light level.

Figure 2 shows the I/V characteristics of a series-stacked PV cell when illuminated with 1000 Watts/m^2. Note that the output voltage of the cell remains reasonably constant as current drawn from the cell is increased from 0 to 30 mA. Past that point though , the cell voltage collapses and the output voltage drops to 0 volts. Conversely, the cell voltage peaks at ~2.6 Volts at room temperature when no current is drawn from the cell.

This characteristic is typical for all PV cells and we've found it useful to think of the devices as current limited voltage sources. As long as the current pulled from the cell is somewhat less than its short circuit limit (30 mA in this case), the cell can be considered to be a constant voltage source with moderate internal resistance. Note that this characteristic will have some bearing on the choice of power conditioning circuitry following the PV cells.

Figure 2.



For the purposes of this app note, we'll simply state that PV cells come in only two flavors: thin film and crystalline silicon. Both differ in efficiency and form factor. This is a gross over-generalization but it is fairly safe to say that Thin film cells are flexible, fairly inexpensive but have low (3% to 5%) efficiency when converting photons to electrons. Crystalline cells are usually rigid (inflexible), higher cost and higher (15% to 20%) efficiency. The choice of cell is dictated by the amount of available sunlight, form factor (volume and area) and cost.

Energy Storage

Since our PV cells can only collect energy during the day, some provision for energy storage must be made to power the modules when no light is available. After considering many battery technologies, we chose to use a Lithium Ion secondary cell for our storage element. Li-Ion batteries have excellent energy storage capacity, long charge/discharge lifetime characteristics, low internal resistance and exhibit very little self-discharge. They have the additional virtue of providing 3.6 volts – a very handy value for powering 3.3 volt modules.

The size of the battery is completely dependent on the current drawn by the wireless module. The battery sizing calculation is straightforward:

$$Battery\_Capacity(Ahrs) = Current\_Consumption(A) \times Dark\_Hours(hrs)$$

Extra capacity is always thrown in to cover the very real probability of successive dark days. We found that rechargeable AA Li-ion cells were fairly inexpensive, readily available and, at ~800 mA-hrs of capacity, had sufficient capacity to power our modules over many successive dark days and nights.

Energy Conversion Circuitry

The type of circuitry used to convert solar energy to electricity to power our wireless module is driven by the voltage rating of PV cell and the voltage requirements of the wireless module. RFM's LPR2400ERA wireless module requires at least 3.3 volts for proper operation. PV cells come in all flavors and the choice of voltage ranges from 0.6 volts to tens of volts. [Futurlec[1] carries a wide range of crystalline cells suitable for powering wireless modules. Powerfilm Solar[2] is a good source for Thin Film cells.]

1 http://www.futurlec.com/Solar_Cell.shtml

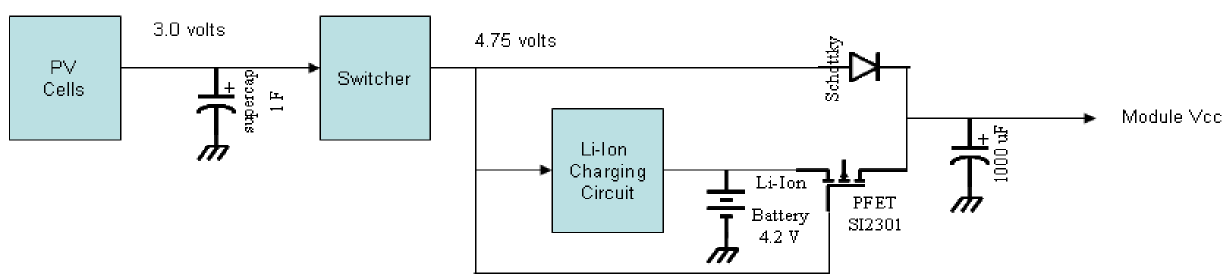
2 http://www.powerfilmsolar.com/oem-components/module-series.php

If the cell voltage is rated below 3.3 volts, then a boost switcher will be required. Conversely, if the PV voltage is higher, either an LDO or buck switcher is required. In both solar harvesters we constructed, the PV cell voltage was lower than what was needed to power our module and charge our battery so we used boost regulators.

Basic Circuit Implementation

Figure 3 shows the basic block diagram of our first solar powered energy harvester. A detailed schematic and BOM of this circuit is included at the end of this app note.

Figure 3



When adequate sun is present, the PV cells supply power to the switcher at a nominal 3.0 volts. The particular PV cells we chose for the first harvester prototype produced a composite 125 mA output current. We needed at least 4.5 volts to operate our Li-Ion charging IC so we used a voltage boost IC to translate the PV cell voltage up to 4.75 volts to provide some head room. Peak current for our wireless module was 125 mA so the switcher was sized appropriately. The Li-Ion charging circuit was set to provide a constant charging current of 10 mA to the battery.

The Diode and P-channel FET circuit on the right side of Figure 3 selects either the switcher output or the battery voltage depending on time of operation. During the day when the PV cells are operating, the switcher produces 4.75 volts. This is higher than the 4.2 volts across the Li-Ion battery so the P-channel FET is back-biased and the Schottky diode provides current to the load.

After dark, the PV cells are off and the switcher produces 0 volts. The 4.2 volts across the battery is now higher than the switcher output. The P-channel FET switch turns on, the Schottky is back-biased and power flows from the battery to the load. Next morning, the PV cells crank up at first light, the switcher starts producing 4.75 volts, the P-channel FET turns off, the Schottky turns on and the circuit is again solar powered.

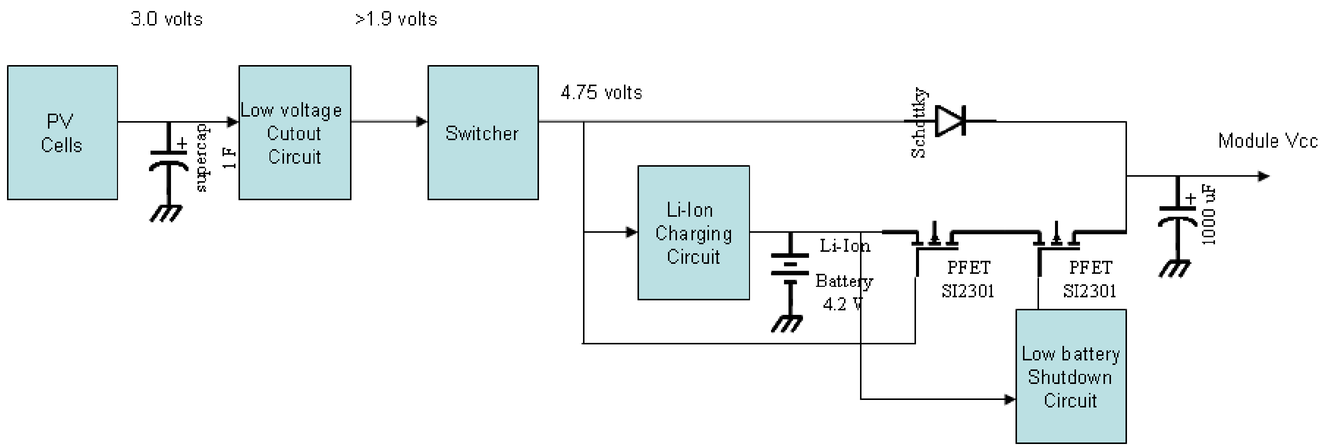
The 1 Farad supercap on the left and the 1000 uF electrolytic capacitor on the right serve as charge reservoirs to buffer current spikes produced when the module transmits an RF signal. The Supercap reservoir allows us to use PV cells rated at 125 mA to power circuitry that consumes higher peak currents. As long as the transmit bursts are reasonably short, the supercap will fill the gap and provide the necessary energy.

Finally, note that most supercaps are rated to 2.5 volts. We used two in series to handle the 3.0 output voltage from the PV cells.

Enhancements to Basic Circuit

Figure 4 shows two additions we made to the basic harvester circuit. The first is the low-voltage cutout circuit between the PV cells and the switcher.

Figure 4 – Enhanced Harvesting Circuit



The Low Voltage Cutout circuit fixed a problem we found early on with the first prototypes of this circuit. When the harvester started up under low light conditions, the boost switcher would initially draw excessive current from the cells and the cell's output voltage would collapse to ~0 volts. With the PV cells shorted out, the boost switcher couldn't start properly and the circuit was locked down tight. This condition would continue until the cell was disconnected from the switcher. Start up under brighter light was more reliable as the PV cells could source the current needed by the boost switcher at start up.

We got around the lock up problem by using a low-voltage cut out circuit. While not very elegant, it did eliminate the start up problem with very little added cost and complexity. We simply allow the voltage across the cells to rise to a certain level before the cells are connected to the switcher. At the higher voltage, the supercap in parallel with the cells holds enough charge to support the boost regulator when it starts up. Once the boost switcher is up and running, the required input current decreases to the level required only by the load. If the current produced by the PV cells is still inadequate to support normal operation, the voltage across the PV/supercap combination will fall until the cut-out circuit breaks the connection once more.

In fact, this is exactly the behavior we see when the prototypes first wake up in the morning. The morning's first light produces low levels of current in the cells. The voltage across the Supercap slowly rises as the cells dump current into them. Finally, at one point the voltage across the Supercap exceeds the trip point of the low-voltage cutout circuit and the switcher is connected. If the current from the PV cells is still insufficient to power the load, the voltage will start to fall, the switch will open and the cycle begins again.

As the morning progresses, the light level will at one point be sufficient to continually power the unit and the switch will maintain connection between the PV cells and the switcher. The important point is that the cells are never shorted out by the switcher and the harvesting circuit never locks down. It may toggle on and off a dozen times but eventually it settles down and maintains standard operation.

The appropriate cut-in voltage was determined empirically. We found that any voltage above 2.2 volts avoided the lockup problem. We used a standard voltage monitoring IC to measure the PV cell voltage and a P-channel FET to act as series switch. The schematic and BOM has details of the actual implementation.

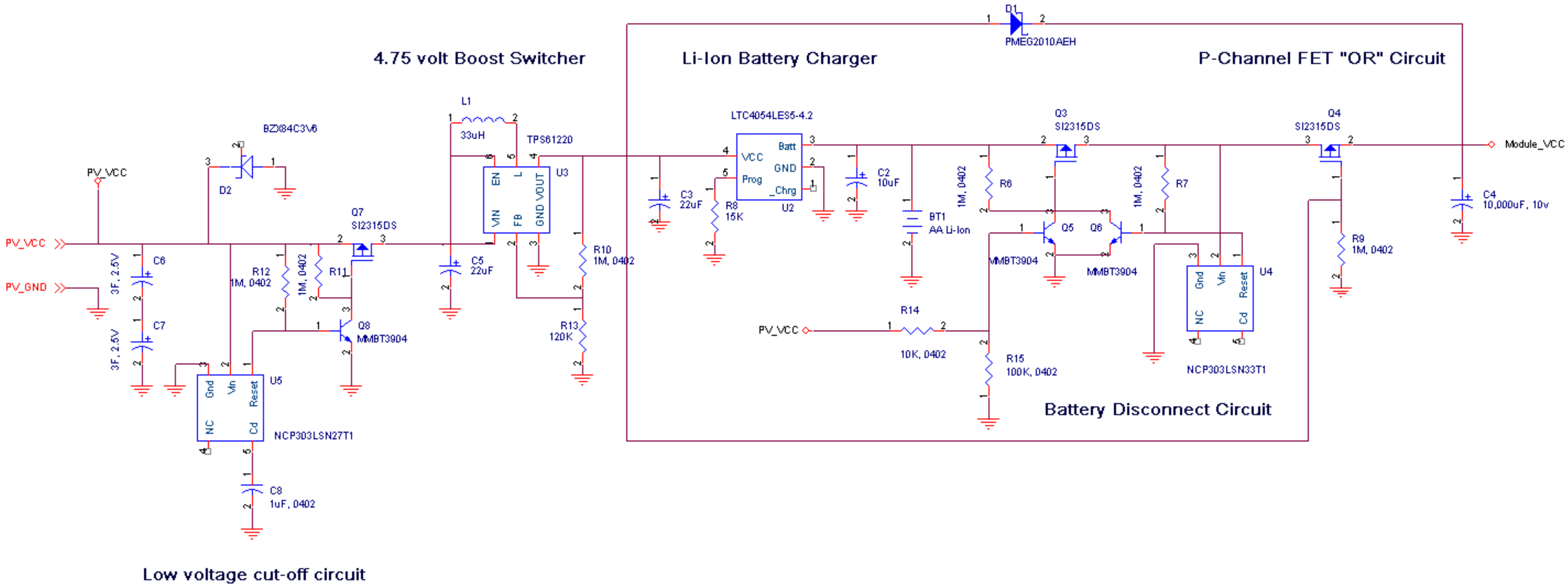
The other circuit enhancement added in Figure 4 is the low-battery disconnect circuit. Li-Ion cells are reasonably forgiving compared to other battery families. However, they will not tolerate excessive discharge below a certain voltage. When the cell voltage drops below roughly 2.7 volts (sources differ as to the exact value), it must be disconnected from the load to avoid damage to the cell. We implemented the disconnect function with a circuit very similar to that used in the low-voltage cut off circuit. Ultimately, we decided to use a 3.3 volt cut-off to disconnect the battery since the modules would not operate reliably at lower voltages.

There is one slight trick to the battery disconnect circuit. Refer to the schematic in the appendix and note that after the NCP303 voltage monitor turns off FET Q3, it will never turn back on until the PV cells start producing power again. This ensures that the battery stays disconnected from the load until power is available. See the schematic and BOM for exact implementation.

Summary

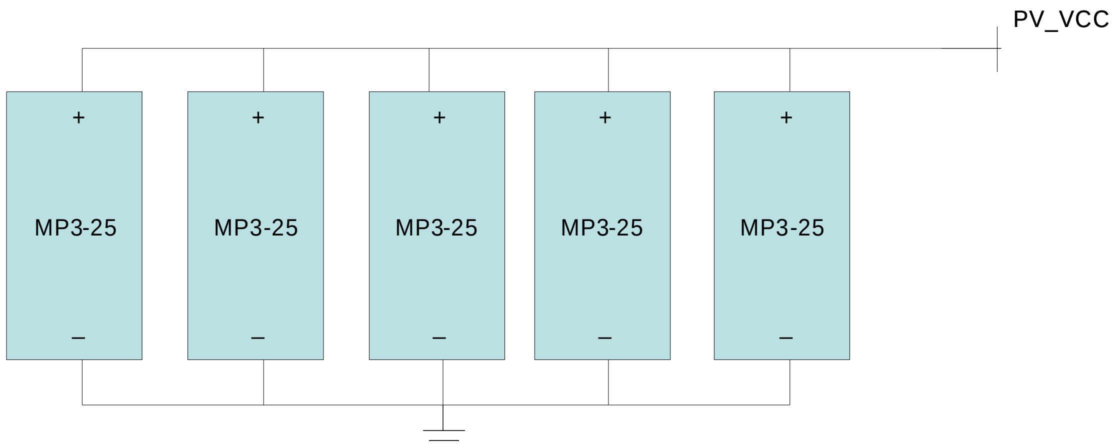
The Murata Engineering group has built two solar powered sensor radios using the techniques outlined in this app note. Both units have been running continuously since November of 2009. Each unit was designed slightly differently so we could investigate technology differences between PV cells and batteries. Unit One uses 5 Thin Film PV cells and 1 coin-cell Li-ion battery. Unit Two uses 4 crystalline PV cells and an AA Li-ion battery. After 4 months, both systems continue to perform well. The Crystalline and Thin Film PV cells appear to be sized about right for our energy consumption needs. We have decided that a product based on these prototypes would probably use the AA battery to provide greater energy storage in case of extended dark weather.

Appendix 1 - Solar Energy Harvesting Schematic

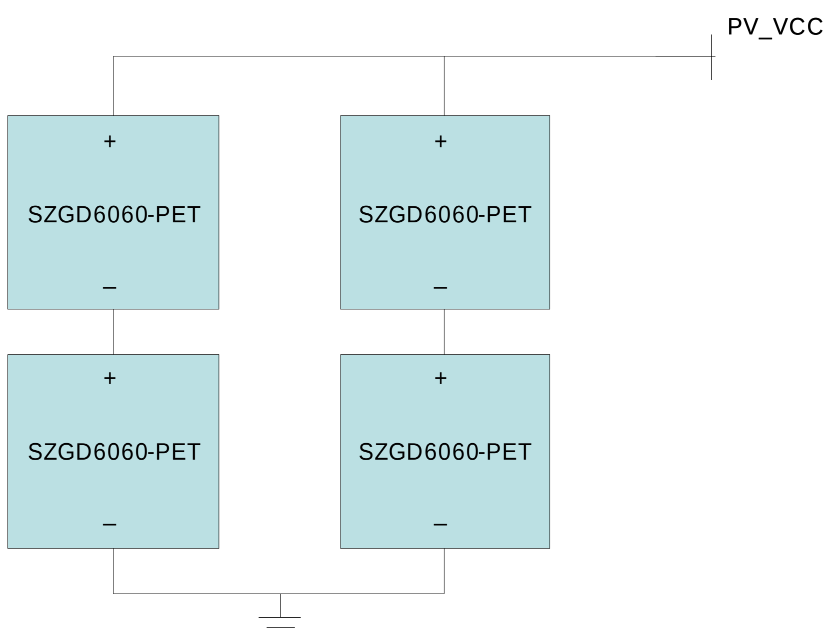


Appendix 2 - PV Cell Stack-up

Thin Film PV Cell Stackup



Crystalline PV Cell Stackup



Appendix 3 - Bill Of Materials

Item	Quantity	Reference	Part	Vendor
1	1	BT1	AA Li-Ion	Various

(http://www.onlybatteries.com/cat_featured_items.asp?cat1=27&cat=2&id=162&uid=1106)

2	1	C2	10uF, 10v	Various
3	2	C5,C3	22uF, 10v low ESR	Various
4	1	C4	10,000uF, 10v	Various
5	2	C6,C7	3F, 2.7V	ESHSR-0003C0-002R7

(http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=589-1000-ND)

6	1	C8	1uF, 6.3v	Various
7	1	D1	PMEG2010AEH	NXP
8	1	D2	BZX84C3V6	Diodes Inc
9	1	L1	33uH, CTDO3316PF-333	Central Technologies
10	3	Q3,Q4,Q7	SI2315DS	Vishay
11	3	Q5,Q6,Q8	MMBT3904	On Semiconductor
12	6	R6,R7,R9,R10,R11,R12	1M	
13	1	R8	15K	
14	1	R13	110K	
15	1	R14	10K	
16	1	R15	100K	
17	1	U2	LTC4054LES5-4.2	Linear Tech
18	1	U3	TPS61220	TI
19	1	U4	NCP303LSN33T1	On Semiconductor
20	1	U5	NCP303LSN27T1	On Semiconductor
21	5	Thin Film PV cells	MP3-25	

(http://www.powerfilmsolar.com/oem-components/module-series.php)

Or -

21	4	Crystalline PV cells	SZGD6060-PET	

(http://www.futurlec.com/Solar_Cell.shtml)