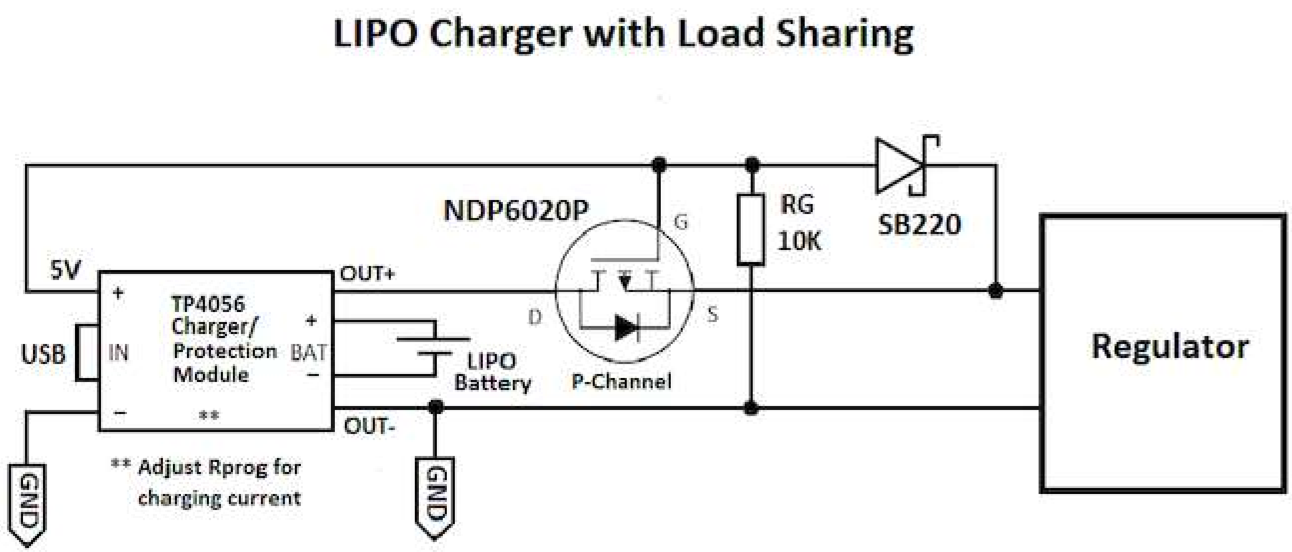
V2.0

Solar Charger Load Sharing

TLDR: A typical 5V USB-powered lithium battery backup with charger should have a "load sharing" circuit added, which allows the input supply to power the load directly rather than going through the charger. But such a circuit does not work well when using a solar panel to power the circuit. That's because the input voltage varies with sunlight intensity rather than being fixed at 5V. In the daytime, the circuit acts like a two-diode model, with the second diode being the mosfet's body diode, and this causes a significant Vf voltage drop in the battery line. It's only at night that the mosfet turns on and the Vf is bypassed. The Vf drop can be reduced if a second Schottky is connected across the mosfet in parallel with the body diode. However, a circuit which uses an opamp to control the mosfet gate produces no voltage drop at all, so the circuit output voltage is never lower than the battery voltage.

There are many inexpensive 5V-powered charger modules available for single-cell lithium batteries. Here's an example which also includes battery protection circuits. It uses the TP4056 charger IC:

However, if such a module is used in a battery backup system which powers a project load, a "load sharing" circuit (also called "power path") should be added so power for the load will be provided directly by the 5V supply when it is plugged in, rather than powering the load through the charger. The load sharing circuit consists of a logic-level P-channel mosfet, a Schottky diode, and a resistor. Here's an example circuit:



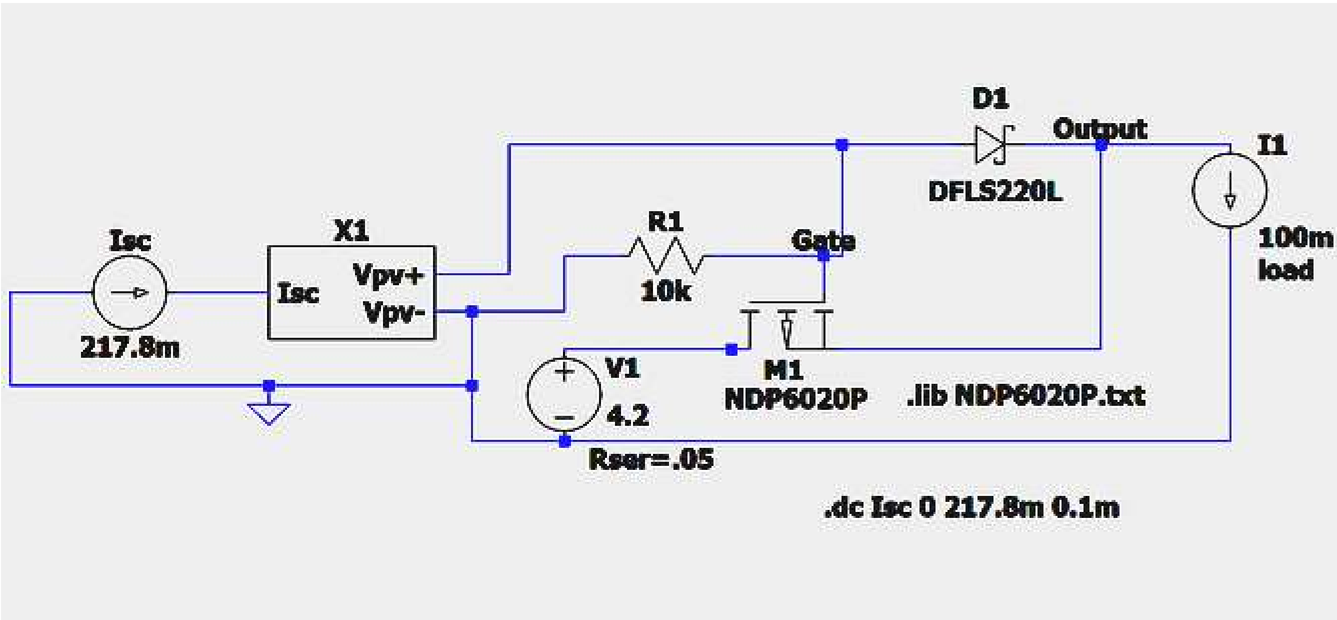
The mosfet takes the place of what would be a second diode in the battery path, and has almost no voltage drop. All of this is explained in a video I contributed to my local Open Source Hardware Group:

https://www.youtube.com/watch?v=T70mBHeIOZA

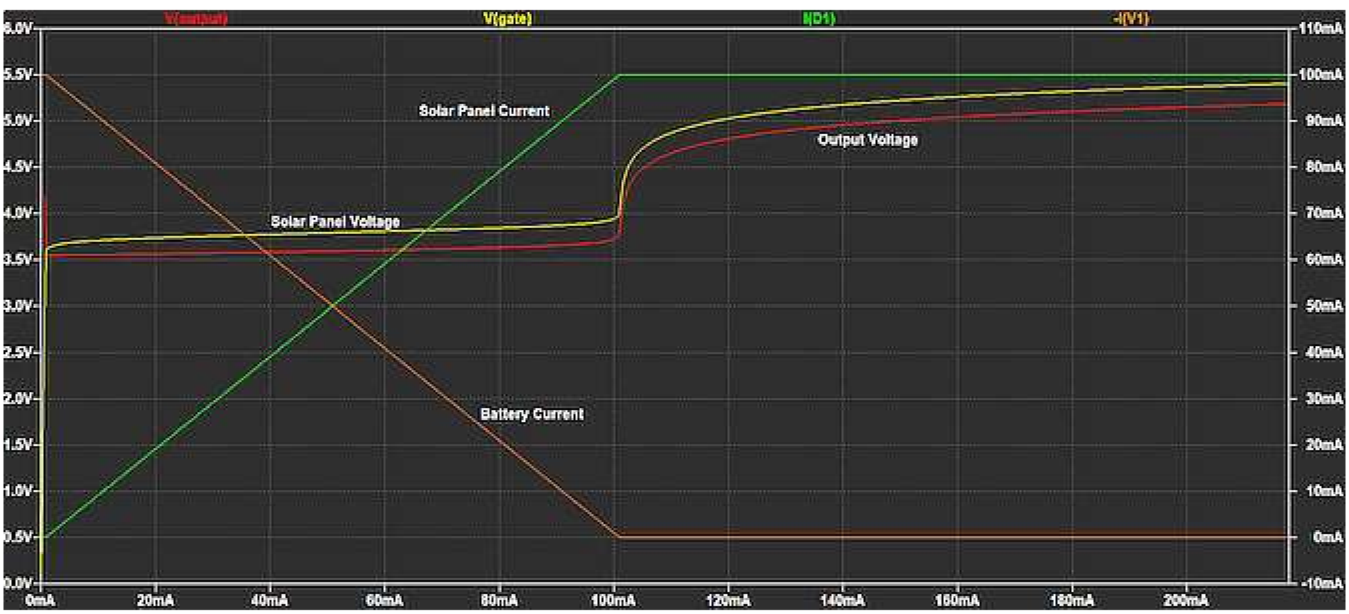
The load sharing circuit works with a standard 5V power input (USB or equivalent) because that power is either connected and supplying 5V with enough current to charge the battery and power the load, or it is completely absent. There's no in-between. The mosfet is either on, with the battery supplying all the load current, or off, with the input power supplying the load and independently charging the batttery if needed..

In the video I suggested that this circuit should not be used with solar power because the input power could wander, and it was unclear what would happen with the mosfet at intermediate supply voltage and current levels. Shown below is an LTspice simulation of the load sharing portion of the circuit when powered by a 5V solar panel. It shows what happens when the input current (Isc), which is proportional to solar illumination, is swept from zero in the dark to the panel's short circuit current in full sunlight. The model for the solar panel ("X1" in the schematic) was obtained from a Youtube video, with adjustments made to match a specific panel available from Digikey.

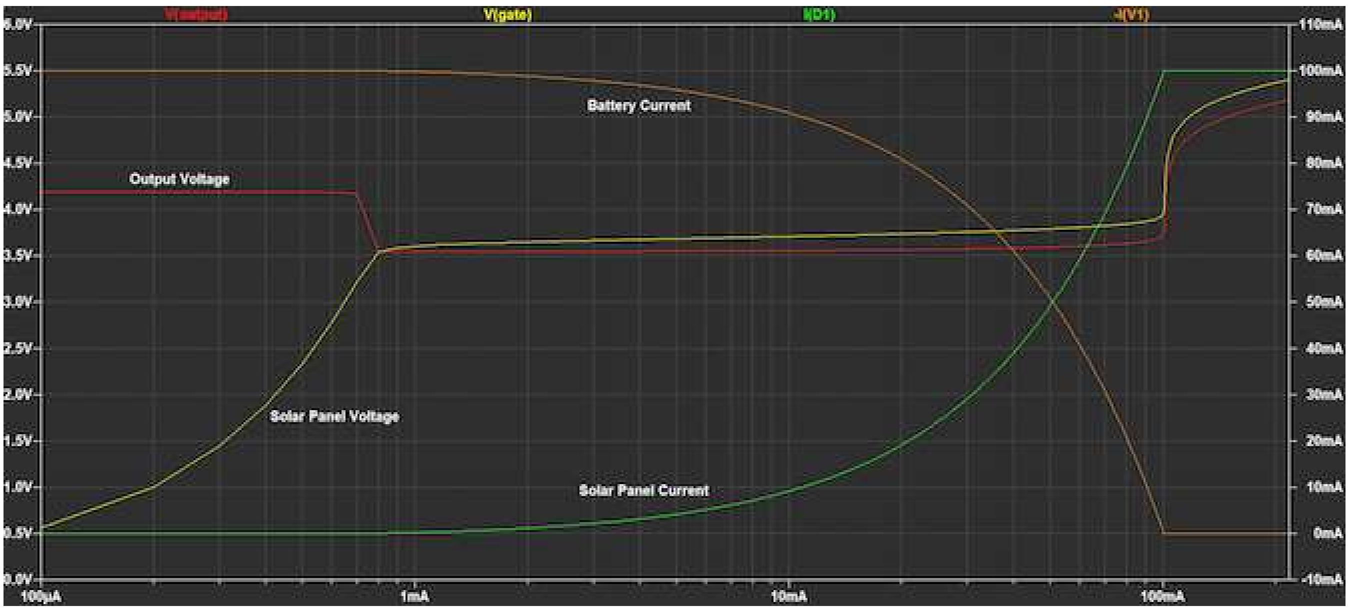
This is the schematic used. The charger is not included because I don't have a simulation available for the TP4056 charger. The battery is assumed to be fully charged at 4.2V, and the load current is fixed at roughly half the maximum short-circuit current of the panel.



And this is the DC sweep simulation with the illumination current on the X axis, and plots of the output voltage, solar panel voltage, battery current, and solar panel current:



Overall, the simulation shows that with increasing illumination the solar panel supplies more and more of the load current, and the battery supplies correspondingly less current. Barely visible at the very far left, when illumination is near zero, the output voltage is 4.2V, which is the battery voltage with the mosfet fully turned on. The entire load current is provided by the battery. But as the solar panel even begins to supply current, the output voltage drops to about 3.5V. That happens because the mosfet switches off, and all of the battery current now passes through the mosfet's body diode. Looking at a logarithmic display of this same simulation, we can see more clearly what happens on the far left:



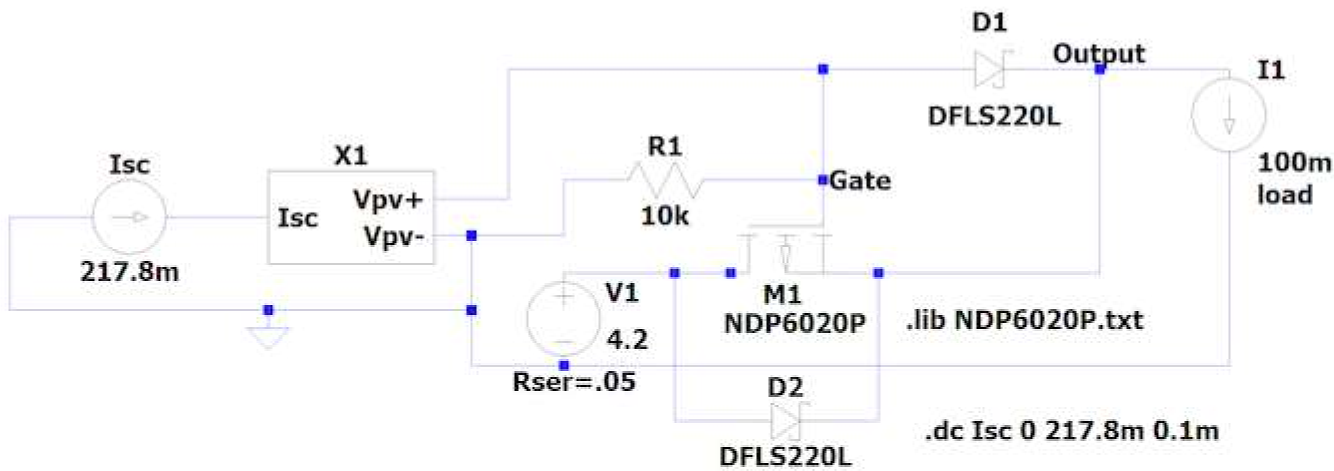
Remember that the solar panel voltage is also the mosfet's gate voltage, and the circuit output voltage is also the mosfet's source voltage. The 10K gate pulldown resistor current briefly delays the rise of the solar panel voltage. But when panel voltage gets closer to the output voltage, the Vgs threshold voltage (about 1V) is no longer met, and the mosfet shuts down. Battery current then passes through the body diode, which accounts for the 0.7V drop in output voltage.

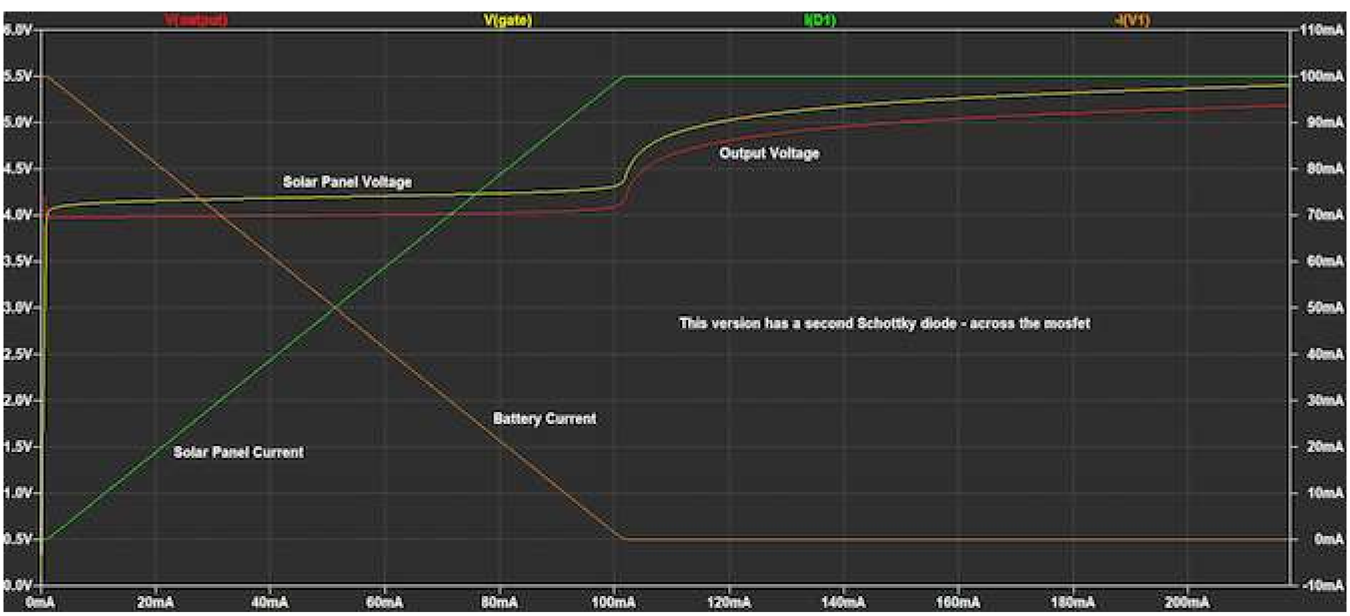
This means that when the solar panel is providing any amount of current to the output through the Schottky, the mosfet will be turned off, and any current supplied by the battery will flow through the body diode. We know that must be true because if current is flowing from the panel through the Schottky diode, the diode's anode voltage must be 0.3V higher than its cathode voltage, and that means the mosfet's gate voltage must be 0.3V higher than its source voltage, so the mosfet must be off.

The bottom line is that for solar power this circuit is the same as a two-diode model - except at night. In total darkness, the mosfet turns on, and the diode voltage drop is bypassed. But in daylight, it's just the Schottky and the body diode carrying the current.

Added Diode

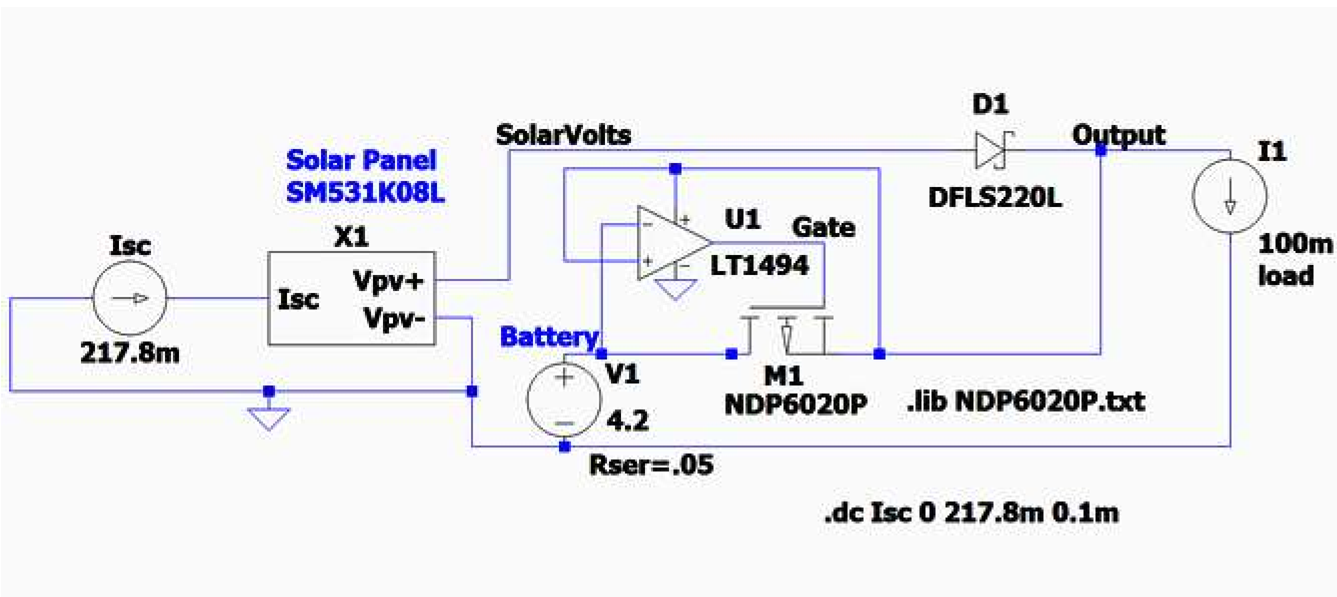
If avoiding the night time Vf drop is felt to be important, one should at least make the two-diode operation at all other times as efficient as possible. That can be done by installing another Schottky diode (D2 below) across the mosfet in parallel with the body diode. That effectively replaces the body diode with one which has a much lower Vf, so the output voltage under partial illumination would be almost 1/2 volt higher. Shown below are the schematic and simulation of this version. The only difference is the lower voltage drop under partial illumination.

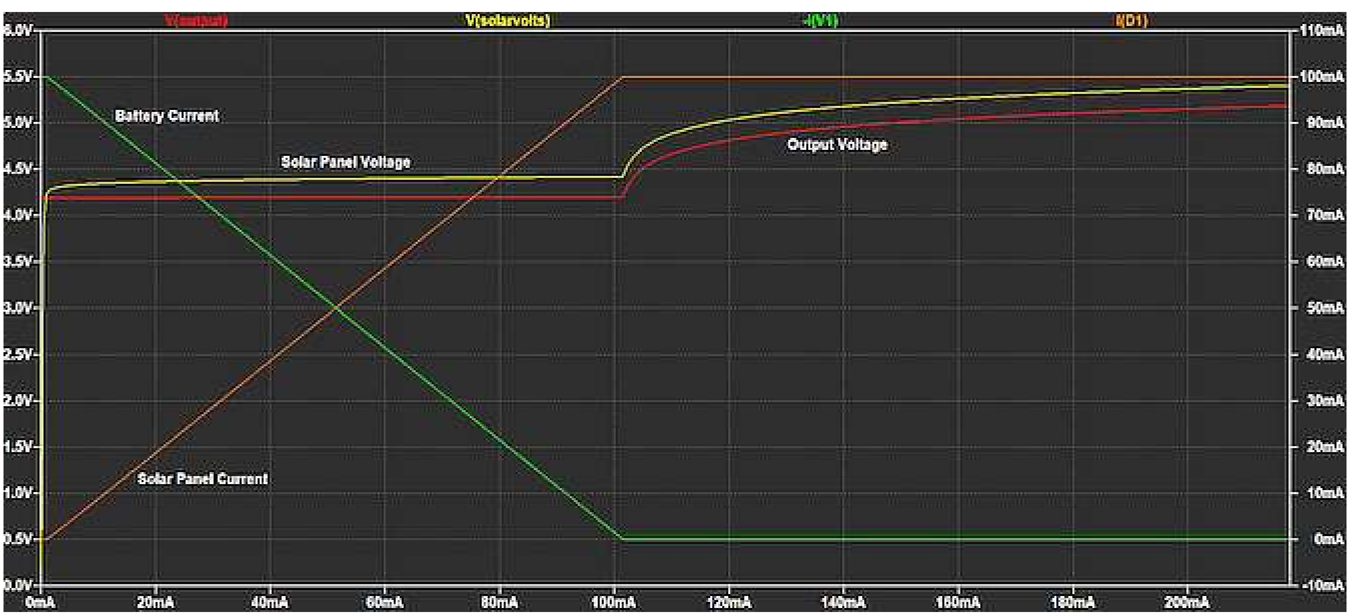




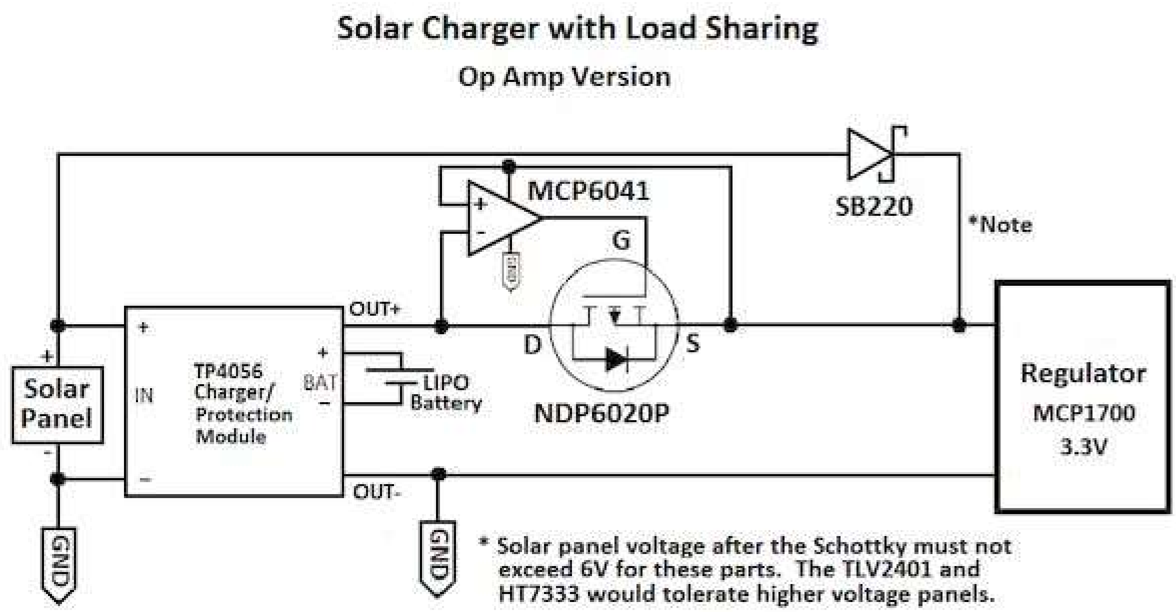
<u>OpAmp Version</u>

The diode voltage drop can be eliminated entirely if an opamp is used to control the mosfet gate. The opamp non-inverting input is connected to the circuit output, which is also the mosfet source terminal, and the inverting input is connected to the battery, which is also the mosfet drain terminal. If output voltage is lower than battery voltage, the opamp drives the gate to ground, which turns on the mosfet. Otherwise the opamp drives the gate high, which turns the mosfet off. Here are the schematic and simulation for this version. The simulation shows that the output voltage never falls below battery voltage, which maximizes battery life.





The opamp shown in the simulation is the LT1494. It has ultra-low supply current - about 1uA - and the common mode range of its inputs extends to just above the upper rail. That means there's no need for resistor dividers or biasing of any kind that would draw current. The LT1494 is quite expensive at about $5.00, but all physical testing of this circuit was done with the MCP6041, at $0.66, which has the same characteristics. However, the MCP6041's maximum permitted power supply voltage is 6V, which only works for 5V solar panels. The TLV2401 has a 10V limit, and should work well with 5.5V and 6V panels. It costs about $2.60. The LT1494 was used in the simulation only because Spice models that work in LTspice aren't available for the two primary choices, both of which come in DIP packages and in the usual SMD packages.



OpAmp Circuit Testing

Testing of the opamp circuit was done using a 5V solar panel with 5.85V open-circuit voltage and 550mA short-circuit current. The unprotected TP4056 module, an NDP6020P mosfet, an SB220 Schottky diode, and an 18650 lithium battery were used. A 3.3V LDO regulator was also used with a fixed load of 25mA on it.

The performance of the circuit seemed very smooth. At night, the opamp drives the gate low, which turns on the mosfet, thus providing no-drop battery power to the load. As illumination increases, the mosfet stays on, the output voltage is essentially fixed at the battery voltage, and the solar panel provides what current it can at that voltage, with the battery providing the remaining load current. When illumination has increased to the point that the solar panel is providing all of the load current, the output voltage then begins to rise above the battery voltage, which causes the opamp to drive the gate high, which turns off the mosfet. The charging system and battery are now isolated, and charging can proceed to termination.

There was no observable tendency to oscillate. The opamp output is biased low even when the mosfet is wide open. I believe that's because there is always at least a tiny voltage drop across the mosfet because of the RDSon resistance, which never completely goes away. So everything seems stable. Then when the voltage on the source does actually go higher because of increased illumination, that occurs when the current contributed to the load by the battery is already zero, so the panel doesn't see any additional load when the mosfet turns off, and there's nothing to make it oscillate.

The Programming Resistor

The typical TP4056 module comes populated with a 1.2K programming resistor, which sets the full charge current during the constant current phase to about 1A. That's the maximum charging current the TP4056 can handle. In a recent Youtube video on adding a power path circuit to a TP4056 solar charger, it was suggested that the programming resistor should be changed so as to reduce the charge current setting to the approximate MPP (maximum power point) of the solar panel being used - this would allow the panel to deliver maximum power to the charger.

But that's not correct. If the TP4056 were a switch-mode charger, then indeed the MPP of the panel would be relevant. But the TP4056 is a linear charger. If the solar panel cannot provide the full 1A of current, it will automatically provide as much as it can - at the minimum voltage required for that. Reducing the current setting to a lower value that corresponds to the MPP, which would also produce a higher voltage, would only reduce charging current, extend charging time, and increase heat dissipation in the charger. There is no point in increasing the power delivered to the charger if the extra power is just dissipated as heat. Without reducing the charge current setting, the battery is already performing optimally, and any attempt to operate at the MPP will only reduce performance.

So generally there is no need to change the programming resistor to reduce the charge current setting to match the solar panel's capability. The panel will provide as much current as it can anyway, and for a linear charger it's current that matters, not power, so the MPP is not relevant. However, remember that you always have to reduce the charge current setting if what the panel can deliver is too much for the battery.

Since reducing the charge current setting also reduces the termination current setting (always 1/10th of the full current), then in theory reducing the charge current setting to something closer to the panel's maximum current would also reduce the termination current, which would extend charging time and result in a more fully charged battery. However, I tested a 50mA panel with charge current set to 1A, then with charge current set to 130mA, and didn't detect any difference, to two decimal places, in the final charged voltage of the battery. In theory, setting the charge current to the maximum current of the panel, or slightly above that, should lower the termination current and maximize the battery charge without slowing things down. But in practice the difference may not be worth the trouble of changing out that SMD 1.2K resistor.

Conclusions

The opamp version is clearly the best performer. It would be more complicated to work into an existing TP4056 charger module, but the DIP opamp can be mounted right on the TO220 mosfet body, and wired to its pins. The non-inverting input and the Vcc pin connect to the source, the inverting input connects to the drain, and the output connects to the gate. All that's left is a ground line that needs to be connected somewhere on the module. The three NC pins can just be cut off. And the resistor isn't needed at all.

A two-Schottky circuit, with or without the mosfet, also works pretty well with a modest Vf drop, and if battery life isn't critical, that might be the best option. The mosfet decision may depend on what's downstream from this circuit. The mosfet's no-drop contribution during the night doesn't really help if the regulator is linear because the current draw will be the same no matter where the voltage drop occurs - as long as it doesn't actually drop out. But using a switching regulator would mean that any voltage drop in the battery line at any time of day or night has a real cost in terms of battery life. In that case, even a 0.3V drop will draw down the battery faster because with a lower input voltage the switching regulator will need to draw more current to produce the needed output power.

The biggest challenge to the battery in the standard circuit would be in the morning when the battery voltage is at its lowest and partial illumination switches off the mosfet and reimposes the Vf drop before it's bright enough to begin charging. If that's critical, then using the opamp version would provide the best chance of preventing dropout since it imposes no voltage drop at all.

One can also use one of the newer chips that are designed for solar power and have load sharing built in (the MCP73871 looks promising). But most of those are not available in hobbyist-friendly packages, or in convenient modules. So it's good that a proper circuit can be rigged up using readily available parts if that's needed.