# Justifications for design choices

Any figures that do not have sources have been created by the authors.

To do now:

Implement CV

SOC

MPPT, for testing the different configurations.

Schematic:

Connections directly between SMPS and Arduino shield have been omitted (internal connections), this is a simplified schematic.

Need to make a state diagram

**Characterising components:**

When designing a system it is necessary to know the behaviour and limitations of its constituent components. There are three main components that make up the energy subsystem: the battery cells, the PV panels and the SMPS.

**Battery cells:**

WHAT IS THE BATTERY CELL NUMBER (ID) AND SUCH?

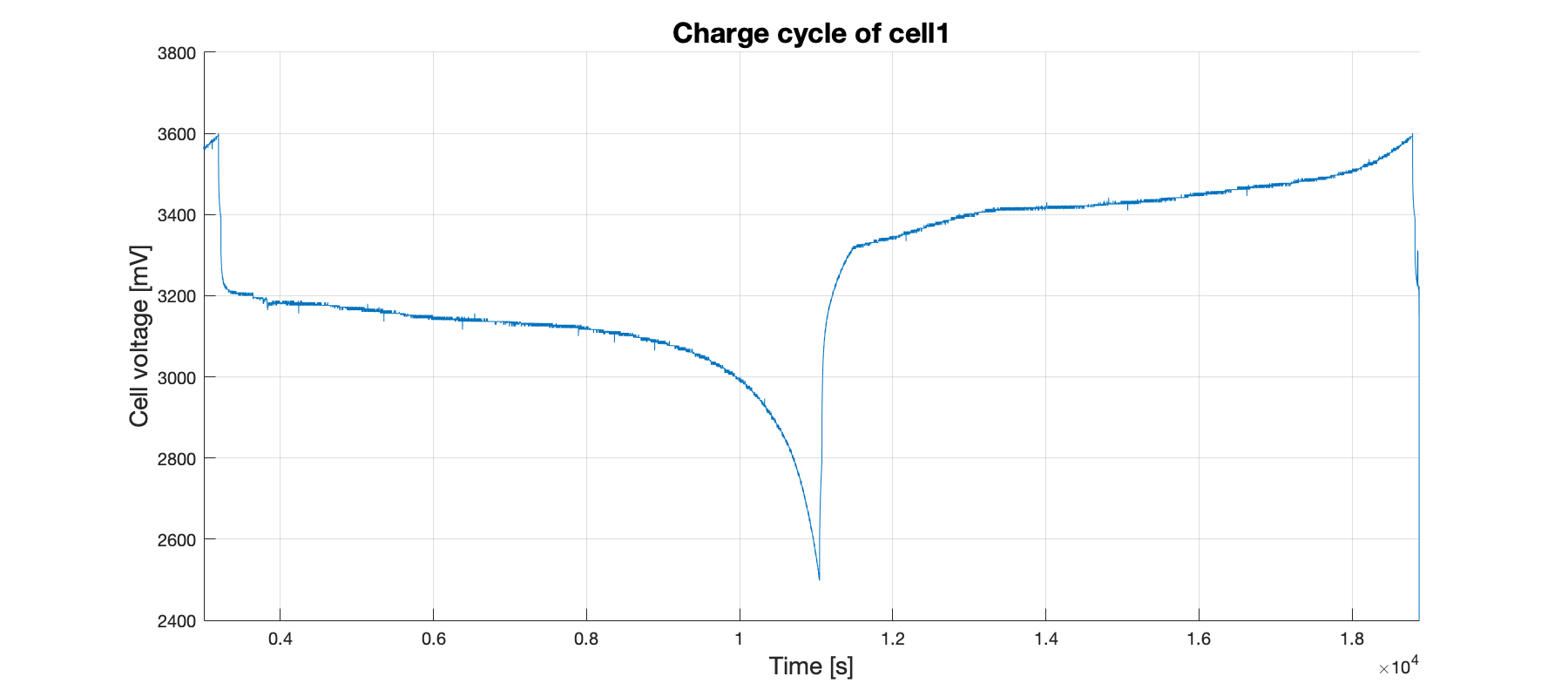
To determine the behaviour of the battery cells they were all tracked through a full charge cycle using the provided “Battery\_Charge\_Cycle\_Logged\_V1.1.ino” code. Every cell behaved similarly in terms of the cell voltage compared to time. The cell voltage of cell1 over a full charge cycle is shown below:

Figure 1: One full charge cycle of battery cell1. Note that the time axis starts at 3000 seconds.

Note the following important points on the graph. At 3190 s the cell is done charging and enters an idle state for 30 s after which it starts discharging. At 11000 s the cell is done discharging and enters an idle state for 30 s after which it starts charging. Finally, at 18800 s the cell is once again fully charged and the charge cycle is completed. The specific behaviour in each region of the graph will be discussed in later sections.

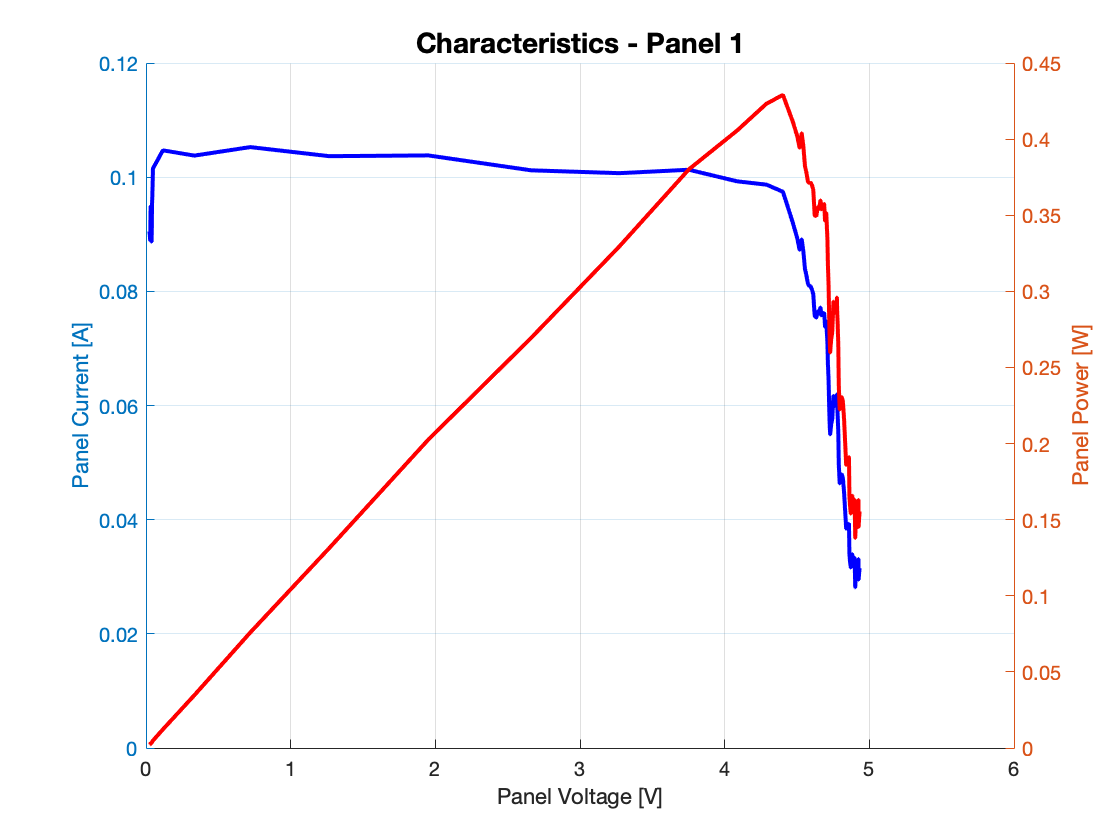
The provided charging algorithm also logs the current into the cell. By integrating said current for a full charge or discharge section it is then possible to determine the cell capacity in terms of mAh. The results of this analysis is presented in the table below:

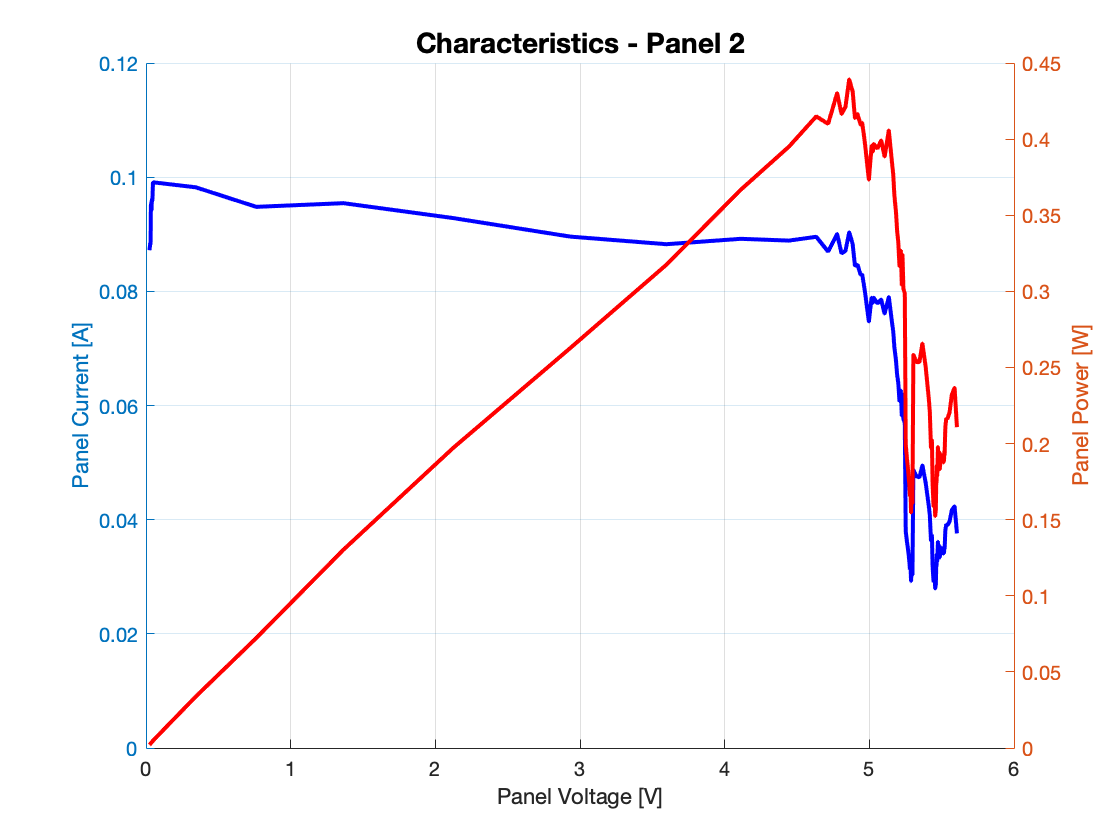
|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Cell number | 1 | 2 | 3 | 4 | 5 |
| Capacity (mAh) | 542.7 | 526.1 | 519.5 | 530.1 | 543.7 |

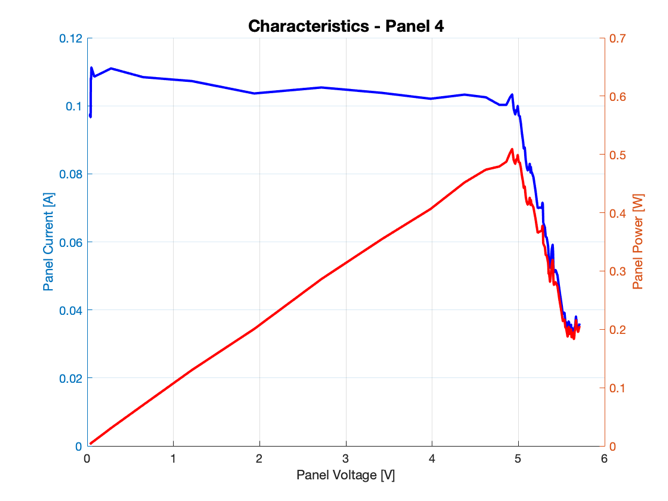
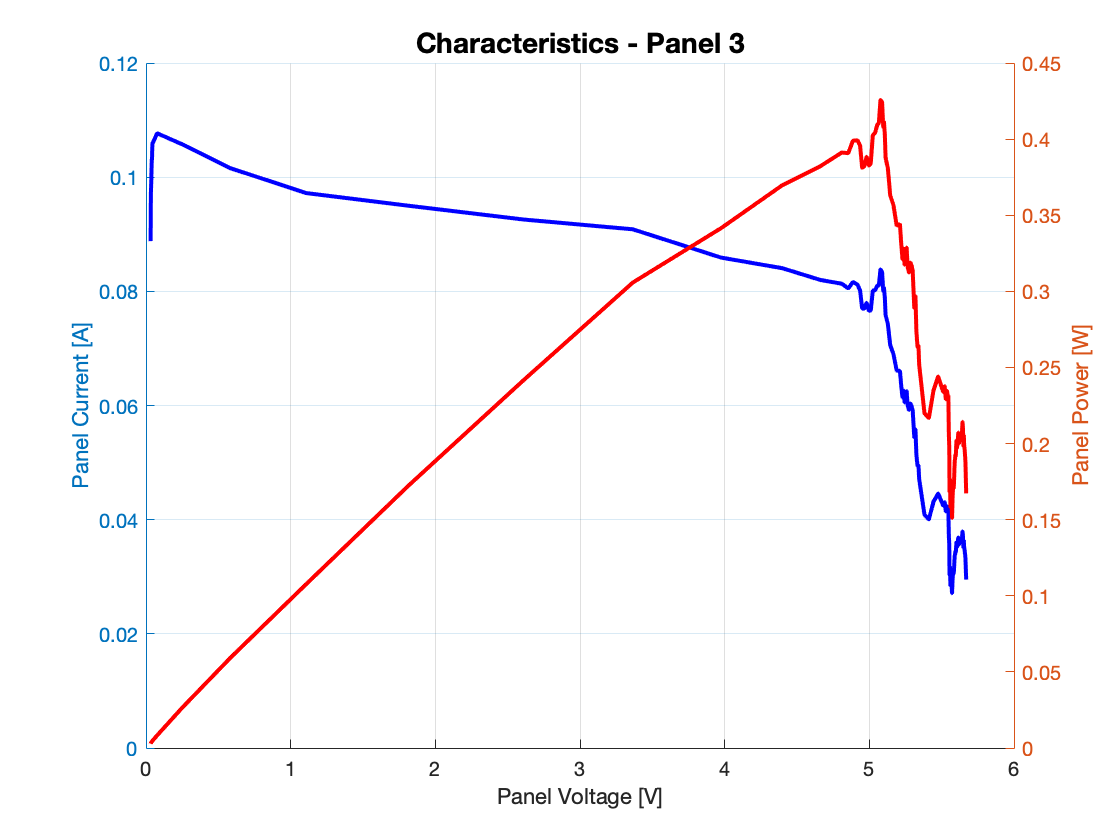
What is important to notice is that the cells all have different capacities. Also behavour at nearly charged an nearly fully discharged. Behaviour in rest part.

**PV panels**

The provided PV panels are each rated for a maximum power of 1.15 W at a voltage of 5.0 V and current 230 mA. Away from the maximum power point the performance of the panels can be determined from their I-V curves. To find the I-V curves each panel was connected to the SMPS operating in non-synchronous boost, they were then lit by the lamp and the duty cycle of the SMPS was varied while measurements of panel current and voltage were taken. After processing the resulting data it was plotted in figure ?:

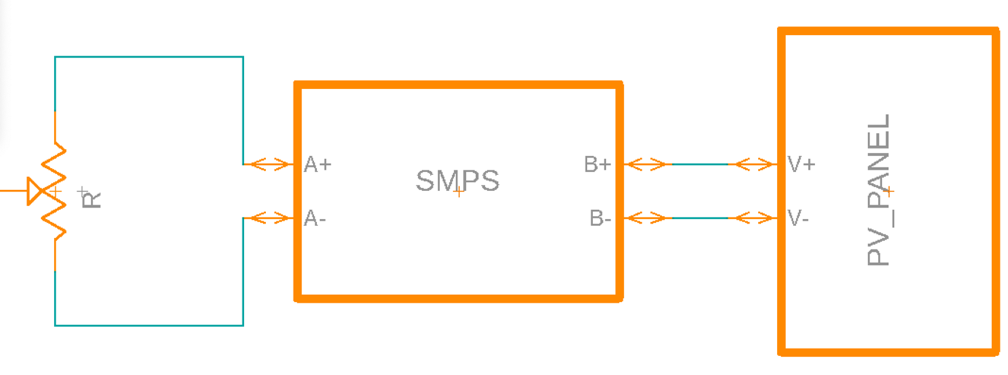






Though the data is noisy, it is clear that all panels exhibit the standard I-V characteristics of a PV cell. That is, they behave as non-ideal current sources with a nearly constant current at low voltages and a rapid current reduction at high voltages (2). Moreover, we see that the provided lamp activates the panels poorly as the peak power for each of the panels is only ~0.5 W.

To determine their performance away from the maximum power point we can find the I-V curves of the panels. To do t



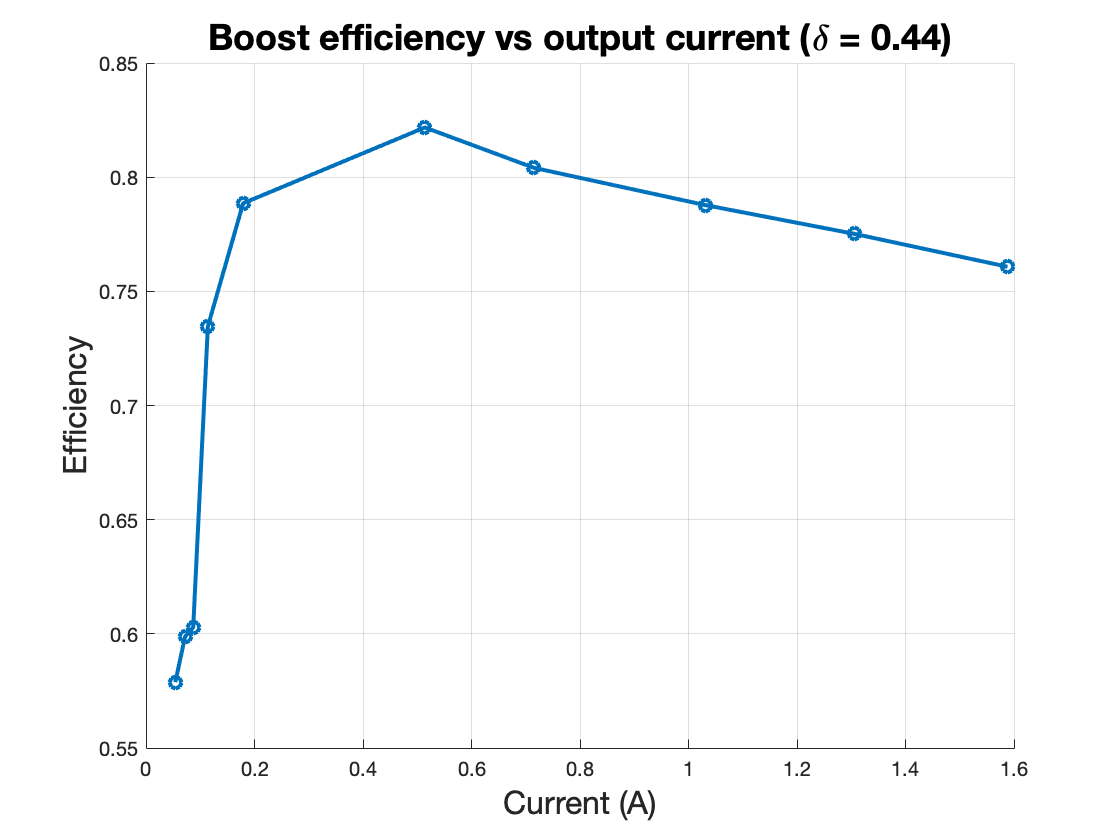
…, they are rated for … at … What is rated power etc?

The PV panels are characterised by their I-V curves. To determine the I-V curves each panel was connected to the SMPS in the manner shown below. To get consistency between panels, each panel was activated using the provided lamp and not direct sunlight.

The SMPS was used in a boost configuration such that the voltage and current of the panels could be measured directly. Using the “PV\_characterisation.ino” code (1), the input current was swept and the corresponding input voltage logged. The resistance on the output was changed at set currents such as to not exceed the maximum output voltage of the SMPS. The produced I-V curves and power output graphs are shown below:

Though the data is a noisy, it is clear that all panels exhibit the standard I-V characteristics of a PV cell. That is, they behave as non-ideal current sources with a nearly constant current at low voltages and a rapid current reduction at high voltages (2).

**SMPS**



The SMPS has been thoroughly characterised in 2nd year labs. Its characteristics vary with mode of operation, input power, output voltage and many other factors. As will be discussed in later sections, for the energy submodule the SMPS will be operated in non-synchronous boost mode. The most important part of the SMPS performance for the energy submodule is its efficiency. attribute *efficiency* is

only non-synchronous boost mode will be most important.

SMPS will be operating in non-synchronous boost mode. For this project the

The SMPS will be controlled by a closed loop controller and as such

buck mode with an output voltage in the range 2.4 - 3.6 V.

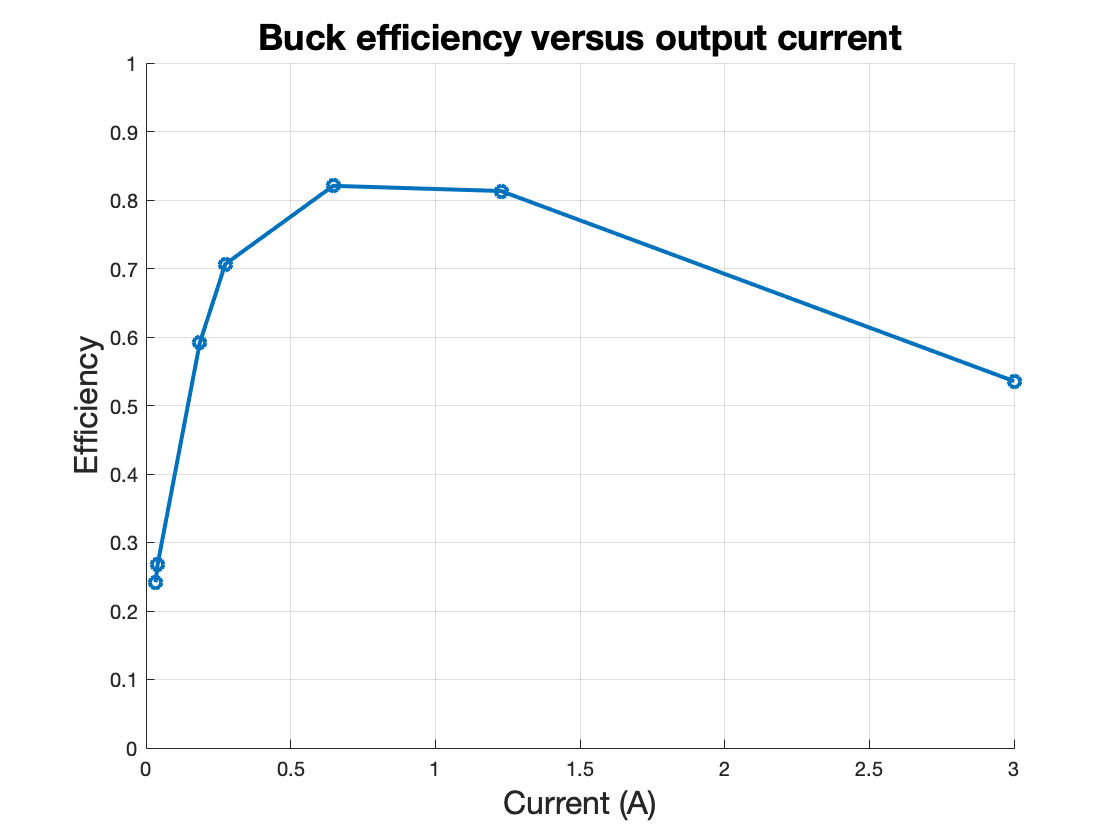


Figure 2 details the efficiency of the SMPS in closed loop, synchronous, buck mode, 5 V input with a target output voltage of ~2.7 V (3). The efficiency of the buck SMPS varies greatly with the output current, with very low efficiency at low output currents.

The SMPS has a power rating of 10 W and maximum input/output voltage of 20 V. When run of the USB power supply the input current is limited to 2.5 A. (4). However, when power is being provided directly at the SMPS ports the current limit is far higher at in our out, and as such is unlikely to impact the operation of the circuit.

Figure 2: Buck SMPS efficiency at V\_out = 2.685 V

**Configuration of PV panels:**

CAN THE SMPS TAKE OVER 20V IF THE POWER IS FLOATING?

The PV panels will provide the power used to charge the battery. The PV panels will perform their job well if they:

1. Provide a high average power output. This will allow us to charge batteries faster.
2. Provide a stable power supply. As will be discussed in later sections, for most of a charging cycle the battery will be fed a constant current. This will need close to constant power.
3. Can interface appropriately with other circuit components.

As we want the PV array to have a high average output all four PV panels will be used. Using all four PV panels there are four different ways that the panels could feasibly be connected.

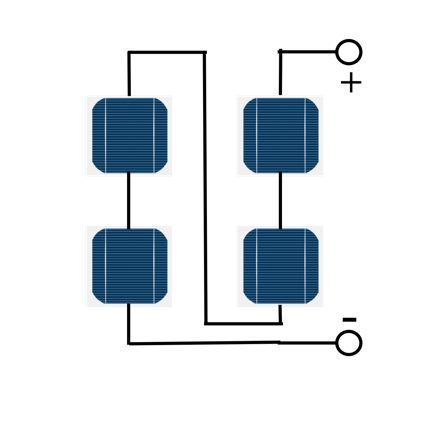
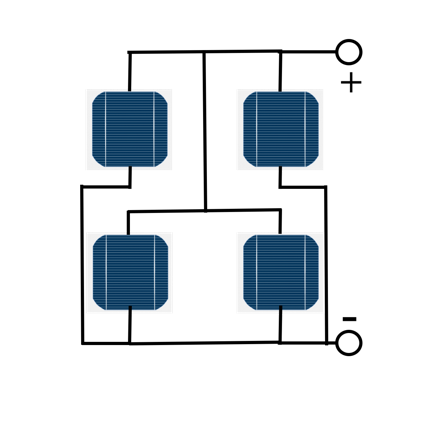
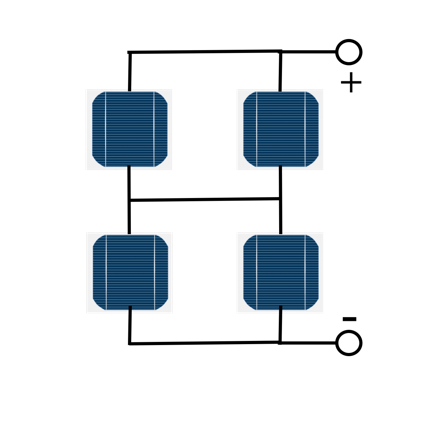
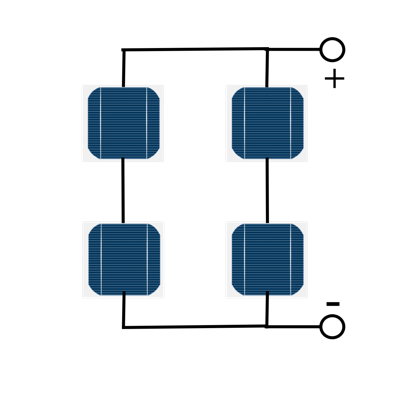


Figure 3: From left to right: Series (S), Series-Parallel (SP), Total-Cross-Tied (TCT), Parallel (P)

Of the four proposed configurations we can readily reject a pure series connection. Though the PV panels are rated at 5 V, the measured I-V curves reveal that even under illumination purely from the provided lamp, the output voltage can go significantly above 5V. In that case the total voltage of the series connection would be 20+ V, which is higher than what the SMPS power converter is rated for. A pure series connection is therefore not a suitable configuration of the PV panels. (Can actually handle 100 V if connected the right way?)

This leaves three configurations, all of which produce voltages and currents that the SMPS can handle (integrate well with the SMPS). Assuming identical illumination and identical panels, all of the configurations produce the same amount of power. However, most likely each panel will not experience the exact same illumination. Especially on Mars where the deposition of dust over times leads to partial shading of each panel (6). In partial shading conditions a TCT configuration consistently outperforms the SP configuration in terms of power output, and is therefore preferred over and SP configuration (7). (Also makes power output more stable)

Research on the partial shading of solar

TCT has a problem with voltage, after leaving headroom on the power output for inefficiencies in the SMPS; the solar panels are only able to charge 4 cells at standard charging current. 4 cells in series give voltages in the range [10, 14.4] V, might not work well with voltages of solar panel.

Non-uniform shading, lamp does not activate array well. 8 days of consecutive rain in London, could not test outside.

Mismatch losses in Series are far higher:

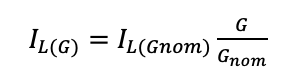
<https://ieeexplore.ieee.org/abstract/document/6104128>

How will series battery pack impact what voltage we need?

However, not only are all panels slightly different as can be seen on the I-V curves. Nor are they likely to experience the same illumination.

Moreover, for the TCT configuration no current would flow through the central wire and the array would therefore be identical to the SP configuration.

PV cells should not be connected directly in series. In a series connection partial shading can have a huge impact. From lectures we have:



Meaning that if a single PV cell has an incoming irradiance of half the others then the current will be halved and the power of the array will drop to almost half of peak power. On Mars partial shading is expected to occur as dust covers parts of the solar array.

This leaves two configuration total-cross tied connection (TCT) and full parallel. Both configurations are shown below:

Et bilde som inneholder tekst, klokke

Automatisk generert beskrivelse

TCT has the advantage over series connection that the drop off in the current of one cell has a far smaller impact on total output power.

Could also have done two parallel connections of two PV panels in series, but this has the disadvantages of series connection without the advantages of TCT. See linked article to see comparison.

Disadvantage of pure parallel connection is that voltage is lower. To charge the batteries we use the SMPS in a buck configuration, and the voltage is therefore stepped down. Thus, if the voltage of the PV array is not higher than the charging voltage of the battery then we won’t be able to charge at all. The advantage of parallel connections is that a change in the current of one cell will not impact the current of other cells. However, at the maximum power point of the array as a whole, each individual cell might not be operating at its own maximum power point. Disadvantage, SMPS losses might be high at low voltages.

Remember that capacitor on SMPS input will be able to hold some energy. At 62.5 kHz it holds enough power that input power is constant no matter the duty cycle.

What is the maximum power drawn by the batteries? There are 5 batteries and we charge at 250 mA:

In addition to this there will be losses in the circuit. However, the rated power of the PV cells together is:

So we need to draw as much power as possible out of the solar panels. Might not be able to use the full 5 battery cells.

<https://www.sciencedirect.com/science/article/pii/S0360544211001484?casa_token=aN6AlhJsx9IAAAAA:yUMOdvzscbw5ltokpvOcWVfY8IOHd0nr_6eLwivW_ZHVWAsjFMjRJ7ihyQtg2kn25_U9QIG5yg> , configuration of solar panels

<https://www.sciencedirect.com/science/article/pii/S0038092X16300111>

Testing both configurations and comparing them. Test each multiple times.

**Configuration of battery cells:**

We want to capture as much as possible of the solar power

The rover has a quite high power consumption and drive alone can reach a peak power of ~10 W. 12.75 W. For high power output we need many cells

USE THE LED ON THE ARDUINO ITSELF TO GIVE STATE, number of blinks indicate state\_num. Got rid of LEDs to get more ports, (or maybe I will just use 3 batteries?)

Using boost also has the advantage of being able to test the charging part of the system with the power supply rather than with the solar panels, which do not perform that well when not directly lit with sunlight.

Two choices: either use 0.5 ohm load as current sensor or have parallel battery pack with pulse charging. Or use series connected pv panels (Choose one based on what leads to the smallest loss, using series connected PV panels or using 0.5 ohm resistor as current sensor. Use an op-amp unit gain to give voltage difference, what is it powered by? Simply power it from 5V output of Arduino. 0.5 ohm load current sensor is very hard to implement in a way that gives accurate measurements for both positive and negative currents (with the equipment we have available).

Actually use internal current sensor, assuming the inductor current is constant, which it is on the time scales we are working on. Use formula I\_out = I\_L\*duty\_cycle

<https://www.electronics-tutorials.ws/opamp/opamp_5.html>

How much energy can the batteries hold and how much energy can be produced in a sol. What is the maximum power output of solar panel versus how much power is needed to charge batteries.

Maybe not use the full 5 because then there are no spares. Probably going to use 4. Use the cells with the highest capacity. Also not enough Arduino outputs anyway

In design brief we have been advised as to not mix parallel and series connection and will abide by the advice.

Check if charging at a lower current has any effect on capacity, if not, then we can charge more cells, just at a lower rate. Then we can use the full battery-pack.

Can also provide less power if in series, as maximum current is far lower, no because voltage is higher.

In parallel we can disconnect a faulty cell, in that way the battery pack as a whole can keep functioning at a reduced capacity, even if one or multiple of the cells die.

No way to detect over-current in parallel

In series can’t measure cell voltage while charging as current has nowhere to go.

**Charging algorithm**

Constant voltage is not very power hungry and is only used to top up on the charge.

CC/CV is the recommended charging method mentioned on the datasheet:

<https://www.ampsplus.co.uk/ampsplus-14500-3-2v-500mah-battery-button>

Pulsed CC/CV, for CV charging in a battery pack the voltage across individual cells are not necessarily constant due to different impedances responding differently to current decreasing. Would lead to some cells racing away from 3600 mV, often hitting more than 3700 mV triggering an error. Switched from keeping the output voltage stable to try to keep the individual cells voltages stable at 3600 mV.

In balance state, we first try to get every cell up to 3600 mV, then we keep them at 3600 mV until the current has fallen below 30 mA, which is about the current that maximum can be dissipated by the internal resistances. Current slowly decreases.

Actually measured higher capacity for pulsed! Charging time is the same

There are many ways to charge batteries: (can I call it a lithium-ion, don’t think so)

<https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6360973>

However, many of them are hard to implement directly in software and either need hardware, which we do not have available, or need extensive knowledge of the battery behaviours, that could be a project in itself in determining. Easy to implement and widely used is, CC/CV.

Maybe do pulse charging for parallel cells. Maybe offset relay switching by a couple of milliseconds as to limit current drawn from Arduino. (staggered switching)

Probably do some integral thingy to determine if a cell is consistently higher voltage then other cells, which will then trigger the disp output and initiate passive balancing.

SMPS more efficient at higher currents?

Relay: <http://www.farnell.com/datasheets/1717878.pdf>

6 ms to turn on, 8 ms to stabilise voltage, 2ms hold time, 4 ms to turn off

Constant current is used to eliminate imbalance of cells.

Actually need to measure Vb as well so that we can use it for constant voltage.

Could probably tell if light on solar panels increase by looking at the duty cycle. Maybe change reference if under 90% of current reference current after some time.

<https://pubs.rsc.org/en/content/articlepdf/2018/ta/c8ta00962g>

pulse charging

Even improves charging speed:

<https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6646717>

As shown in this paper pulse charging can be combined with constant voltage at the end, but still pulsating. Little negative impact. A lot of good stuff in this article.

<https://www.researchgate.net/publication/224326763_Design_of_Duty-Varied_Voltage_Pulse_Charger_for_Improving_Li-Ion_Battery-Charging_Response>

More efficient charging, but a bit lower capacity

<http://www.kohl.chbe.gatech.edu/sites/default/files/linked_files/publications/2001_The%20effects%20of%20pulse%20charging%20on%20cylcing%20characteristics%20of%20commercial%20lithium-ion%20batteries.pdf>

Faster charging, and longer lifetimes.

1 Hz frequency: (This uses lead battery, so depending on chemistry of battery), 0.8 duty cycle is used here.

<https://core.ac.uk/download/pdf/61010268.pdf>

50% duty cycle is the best

<https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8294255>

Should do with multiple duty cycles and see if 80% is better.

Everything from 1 Hz, to many kHz

<https://www.researchgate.net/figure/Optimal-pulse-charge-frequency_fig7_3218839>

Change to a Mealy machine, so that outputs can change at a faster frequency than state.

Measure voltage only at certain times, but measure current all the time.

Stop constant voltage charging when average current is less than 3% or something of normal current.

**0.5 Ohm current sensor**

Need to low-pass filter either digitally or in circuit.

**SOC:**

Would have logged more often but gave issues with speed of programme. 17% slower than it should be. Log the average current for the past second instead of actual current at any given point.

Voltage measurements only have a accuracy of ~4 mV

Method for SOC:

<https://www.sciencedirect.com/science/article/pii/S2352146519301905>

Methods relying solely on the cell voltages does not work well due to the flat part of the voltage curve during charging/discharging.

Impedance method could have worked, but SMPS might not be quick enough to give the current accurately in 10ms. Very hard to measure the internal resistance accurately.

Coulomb counting is good and easy to implement, the problem is that it gives the charge stored, not the energy, which we need to estimate the range of the rover and other stuff. Energy stored is more useful than current stored. We therefore use a hybrid method combining current and voltage.

Note however, that energy in is not necessarily equal to energy out. Measure how much energy we are able to draw from the battery. The problem with having the SOC rely on voltage measurements is that the voltage depends heavily on what current is currently being drawn or has recently been drawn. We see this from the characterisation of the batteries for which in the charging rest state the battery voltage drops immensely even though power is being drawn from the battery. However, it still holds true that the charge towards the end of the cycle has less energy as the cell voltages are lower, by as much as 1/3 compared to the maximum voltage. (i.e. maximum voltage is 50% larger). Thus, we can make the estimation better by making SOC table non-linear. (BUT WE NEED TO KNOW HOW MUCH ENERGY IS LEFT DO RANGE ESTIMATION).

Adaptive system, 1% update each cycle

Range estimation

**SOH:**

Many different way to estimate SOH:

<https://onlinelibrary.wiley.com/doi/epdf/10.1002/er.3598?saml_referrer>

However, most methods require a lot of data about the battery cells, especially lifetime measurements which we do not have access to as there is not enough time in the project to go through a full life cycle of even a single cell.

Coulomb counting, i.e. comparing current capacity to initial capacity is good and easy to implement.

OCV does not work due to the large amount of data about the battery cells needed.

Maybe interpolate inbetween.

Other sign of health is whether the cells are balanced which is why we store data about this.

We store:

How much capacity has already been used, assuming continuous operation or only brief interruptions so this will work well, we can reset once we are fully charged or discharged.

Number of cycles,

Current maximum capacity

Initial maximum capacity

Cell1 voltage

Cell2 voltage

Cell3 voltage

Cell4 voltage

Write every ten seconds just in case the system loses power, that way information will still be retained.

**Cell balancing:**

Balancing state is only used if there is a severe unbalance between the cells (more than 50 mV difference between the cells), if the unbalance is small we move on to the constant voltage state where some balancing is also done.

Only for when charging:

<https://www.batterypoweronline.com/blogs/why-proper-cell-balancing-is-necessary-in-battery-packs/>

Cell balancing during discharging would just use energy and decrease usable power.

Discharging stops when the first cell reaches the minimum acceptable voltage.

Gives a higher capacity and allows us to extract more energy from the battery pack.

Hysterisis loop is not very computationally expensive (was already pushing Arduino to its limits), very easy to implement.

At a balancing coefficient of 0.1, there is no net current through cells with too high a voltage, but current flowing through other cells.

<http://www.amarketplaceofideas.com/wp-content/uploads/2018/09/Topic20220-20Battery20Cell20Balancing20-20What20to20Balance20and20How1.pdf>

Unbalanced cells gives:

Premature cell degradation

Safety hazard

Reduced capacity

Early discharge termination

* **Balancing at high states of charge only** is used to decrease the effect on SOC balancing that can come from impedance unbalance.

Will probably have very similar charge profile as last time, which will hopefully get us to the correct voltage without balancing.

**SMPS configuration**

Can’t be in synchronous mode due to high output voltage?

Also if power to Arduino is lost then immense currents would flow, destroying the batteries.

**Safety mechanisms:**

Needs to shut itself down when too much power has been drawn, if not we might damage batteries.

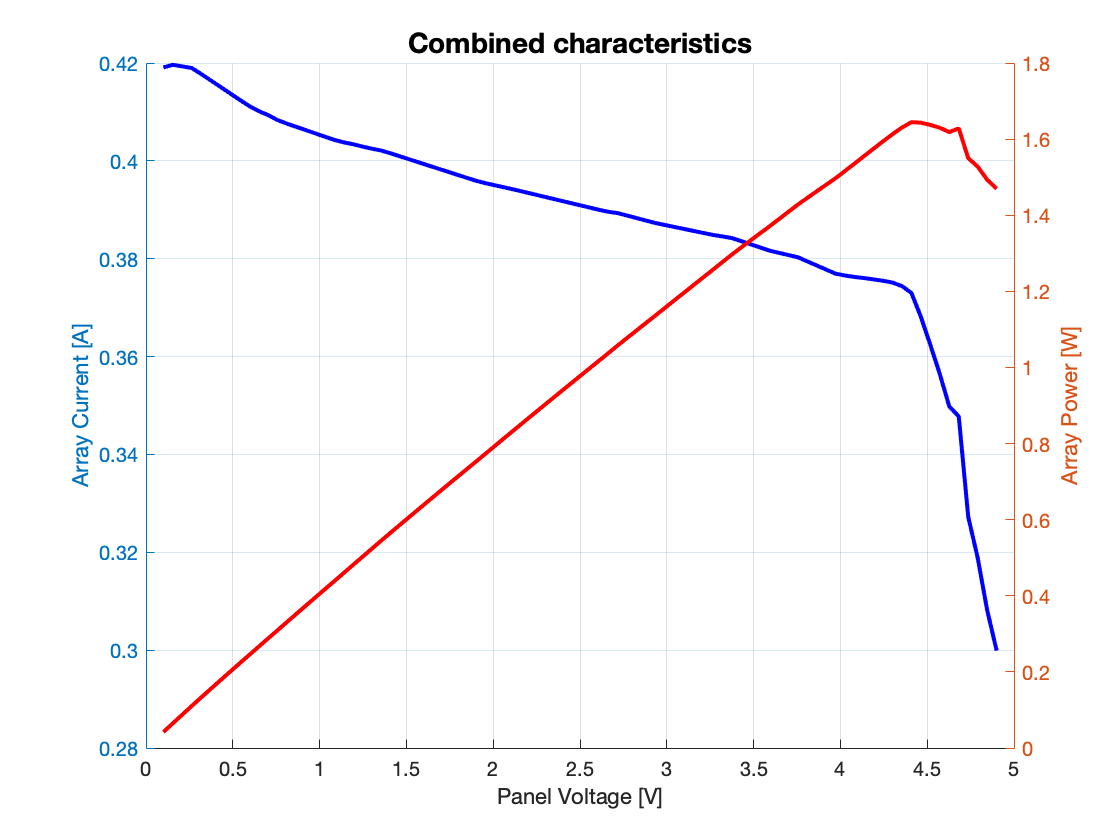
Switch one of the cells out of circuit if current is too high for too long. Or simply stop charging, then wait until balanced using internal resistors.

**MPPT:**

When power is provided by solar panels it is common to use two-stage power conversion before exporting the power. The first stage of the power converter does maximum power point tracking, so that we can get the most power out of the solar panels, the second stage conditions the power to the correct voltage or current (2). For the energy submodule only one SMPS device was available. Therefore it was not possible to implement the standard two-stage power converter. However, this is not a problem seeing as the goal of the PV panels is not to output the maximum amount of power.

For the charging algorithm for the most part the output power is fairly constant. It then does not matter to us if the solar panels can provide a bit more power than they do currently. In total the provided power is:

This is for parallel



Though we do not need maximum power point tracking, we still need some way to determine the necessary duty cycle. The charging algorithm has two parts for which we need to consider the operation of the SMPS: constant current mode and constant voltage mode.

Assuming boost configuration:

Now let us make the following considerations; in constant current mode, if the current is a bit low we would try to increase the current by increasing the output voltage, by increasing the duty cycle. As both the current and the voltage increases on the output, the output power increases. Assuming 100% efficiency, so too must the power on the input increase. If the duty cycle of the SMPS increases that means that the input impedance decreases, no matter if it is buck or boost. When the input impedance decreases, the input current will increase.

Likewise for constant voltage mode, if the voltage is a bit low, we would increase the output voltage, by increasing the duty cycle, which would increase the output current. As both output current and output voltage increases the output power must increase. When the duty cycle increases, the input impedance decreases and so the input current will increase.

In both situations the output power increases with increased duty cycle, while the input current increases. Assuming 100%, the increase in output power means that the input power must increase. Now let us inspect the curve above. If more current is drawn, then the power only increases if we are to the right of the maximum power peak. If we are to the left of the power peak the increase in current will cause the input power to decrease, which will cause the output power to decrease, the opposite of what we wanted.

From this analysis we see that we want to operate to the right of the power peak, then any time the current reference increases we will move closer to the power peak. If we try to demand more power from the solar panels than they can increase, then the duty cycle will raise to 1. By detecting whether the duty cycle is 1 then we can determine whether the PV array is able to supply the demanded power. If the duty cycle is 1, we know that the PV array cannot supply the demanded current. What we do then is set a lower current reference and reset the duty cycle to 0 for which the output power is 0, the duty cycle will then increase until we find an equilibrium. If we find an equilibrium, great, if not the duty cycle will go to 1 again and we need to set an even lower current reference.

Also every now and then we can check if we can use a higher current by doing simply setting a higher current reference and seeing if an equilibrium exists. The test should come less and less frequently if stepping up the power has failed many times before.

(Maybe roll duty cycle all the way back to 0, when searching for another current which works!, this might be the easiest to implement, if duty cycle is 1 then we need lower current-reference, maybe use a current reference multiplier)

<https://www.sciencedirect.com/science/article/pii/S1364032117305750>

**Statement of own performance**

Energy was pretty separate, for the most part needed access to hardware to do stuff.

**Integrating with the rest of the rover**

Need 3 SMPS devices due to bad part selection. Arduino can’t run directly of battery pack either in series or parallel. An easy fix would be to simply buy an H-bridge which supports speed control directly. Actually, could do a PWM signal from the H-bridge to the motors and have it run of 5V, then we would only need 2 SMPS devices.

Everything might actually be able to run directly of 4 cells in series. No, think I need 5V for FPGA.

In real life would connect through UART, but as we can’t make physical connection we need to connect to database or something. USE UART CONNECTION ON USB, this will control section.

Would not use a Buck-Boost configuration, but simply a buck configuration. That way we could take the full 14 V input voltage.

Would have used the UART ports and not relayed through the computer.

**Communicating with Other Modules**

Though it is not necessary to fully integrate the energy module with the rest of the rover, other submodules, specifically command, needs access data such as the battery SOH and SOC. For communicating with other modules the Arduino shield has a set of UART ports. However, as group members were not in the same location it was not possible to physically connect the energy module to the rover, which is necessary to use UART. As such, an alternative approach was employed. First the Arduino was connected to a computer via USB. On the computer a Python script was run [8]. At the start the Python script establishes a connection to a server created by running a similar script on the command module [9]. After a connection has been established the Python script starts reading the serial data coming from the Arduino and transmits it using TCP to the command module. Each message coming from the Arduino is in CSV form where the first entry is the message ID, which allows the command script to decode what type of data is being sent.

Send information about the estimated amount of joules left in the system. Command takes power usage and speed from drive and estimates range.

**Sources:**

(2) <https://bb.imperial.ac.uk/bbcswebdav/pid-2060823-dt-content-rid-8486224_1/courses/10435.202020/2%20Notes%20-%20Photovoltaic%20Energy%20-%20ELEC50012%2020-21%281%29.pdf>

(3) Edvard’s power logbook

(4) Power lab instructions v0.99

(5) <https://static.rapidonline.com/pdf/502676_v1.pdf>

(6) <https://d1wqtxts1xzle7.cloudfront.net/1759451/2006Pruessner_Solar_Panel_book_chapter.pdf?response-content-disposition=inline%3B+filename%3DSolar_Panel_Obscuration_by_Dust_and_Dust.pdf&Expires=1621616316&Signature=JwZzU8EQLWboK57iyasZbxDiV4Gi8jSoq9Hr0M5q4eA6G4VtWfkDxhSe~-OG~xerMmS24AdTGWpZV-74hYKt-0jOZhFXLNZr6K3B69Sck5HvhhblMlI1oGC5PrtGi8LDKh5l1iYvNsZH8DMIaob79VVOwP8g3U0nrq1o4Gtwb0xvh3WuWcMH0wNe4URsHGrHGn5v2sfjwVHGhK6fvdrRrJDwEG6BtQcN7CWz3P1~kBeSSwQ10eY8YVsLAR1~xGbJ2yLayR4rAZWIZZCo1EB7MTZxJ3TLOS-4bcaX1l7pdJ4Xu2jjsYqX32gh6FUBdbKnykJ1ZO0CThi9MIXMIS-a3w__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA>

Dust on Mars

(7) <https://www.sciencedirect.com/science/article/pii/S0038092X16300111#s0055> Solar panel, partial shading

[8] Raghav’s Arduino script

**Appendix:**