T005: Battery Tradeoff Study
Jason Mills
Derek Alley

For our PV system, multiple energy storage options need to be researched and compared in order to find the best solution for our needs. This does not necessarily mean the cheapest solution. We need to take into account safety, complexity, and life time to make sure the batteries meet all required specifications from the statement of work.

Below is a table comparing six energy storage technologies; five of them are chemical storage devices, while the last one is mechanical.

	SLA (Sealed Lead Acid)	**NiMH**	**Li- Ion**	**LiFePo4**	**Super Caps**	**Flywheel**
Working Temp (Celsius)	-20 - 40	-20 - 50	-20 - 60	0 - 60	N/A	N/A
Wh/kg	>35	>80	>210	>120	>6	~130
$/Wh	0.10-0.30	0.50	1	0.77-1		
Charge Rate	1C (decreasing until full charge)	1C (mostly constant current charging)	1C (decreasing until full charge)	C/4 (decreasing until full charge)	Much Higher than Batteries	15 minute fast charge
Discharge rate	0.7C	~1C	~1C	~1C	Much higher than batteries	Much Higher than batteries
Charge Complexity	Medium	Medium	High	High	Low	Low
Safety Level	Safe	Safe	Unsafe (can explode from over charging)	Safe	Safe	Less safe (can explode from over charging)
Environmental Hazard Level	High	Low	Medium	Low	Low	Low
Memory effect	Yes	Yes	No	No	No	No
Self discharge rate (%/month)	3%-20%	30%	5%-10%	5%-10%		
Cycles	>200	>500	>500	>2000	10^6	10^5 – 10^7
Cost based on cycle life * Wh of SLA	1	1.2-1.4	1.5-2.0	0.15-0.25		

Note: A rate of 1C is in terms of the battery's Ah rating. For example if a 5Ah battery discharges at 1C, it is discharging at 5Ah and will theoretically be dead in 1 hour. If a battery is discharging at C/20, then the battery will theoretically be dead in 20 hours.

The most important properties to look at for our application are the price, charge complexity, safety level, and cycles. According to price, lead acid is the winner. It is extremely cheap for the amount of storage it offers. Its charge complexity is on the same plane as NiMH batteries and its safety is of no concern as long as proper care of the batteries is observed. Although this is a great battery, it is not environmentally safe and therefore is not allowed in our design as per the Statement of Work.

The next best chemical battery options are Nickel Metal Hydride and Lithium Ion. They offer a higher energy density and longer cycle life. Unfortunately, the lithium ion chemistry doesn't handle overcharging well, often resulting in fire and/or explosion. This safety risk paired with the more complex charging algorithm required makes it a less desirable solution. NiMH, on the other hand, is more robust when it comes to overcharging and has a slightly simpler charging algorithm. At half the price of lithium ion, NiMH is a good choice. Even better than NiMH, is LiFePO4. This new lithium battery is robust; it has high energy density and does not suffer from the high self-discharge rates of NiMH. This battery option is the best, but the limiting factors are higher price and lower availability than NiMH.

Batteries aren't the only energy storage devices that are possible. Two less common long-term energy storage devices are electric double-layer capacitors (super caps) and flywheels. Although super caps are able to charge and discharge extremely fast, they do not store enough energy for feasible long term storage applications. Flywheels are also able to charge and discharge very quickly, and have no memory effect. If this technology was more developed, it would be a great alternative to batteries.

It comes down to LiFePO4 and NiMH as the best battery choices. The rest of this paper explains the intricacies of each.

<u>Storage system Requirements:</u>

This system and load will need a certain amount of voltage coming out of our batteries. We have estimated that the George Foreman grill will consume approximately 1KW of power from the system. We assume that approximately 30 students and guests will be at our final presentation and are subject to eat only 1 burger. The approximate cooking time of a burger is 10 minutes and we can fit 4 burgers on the grill at one time. The numbers come out to be that we will need approximately 80 minutes in order to cook enough burgers, including the warm up time. Just to be on the safe side we will assume 2 hours of continuous running time of the grill, so we will assume it will take 2 KW of power in a 2 hours time frame. We can also expect that the inverter operates at approximately 80% efficiency so we will be expected to hold approximately 2.5KW of energy in order to run this demo. We have decided that the load will run off the large battery storage system, system1, while the SCADA system and control boards alogn with other system power, will run off a separate battery system, system 2. The system 1 topology is not yet agreed on, due to some varying inverter topologies but the main topology focuses on a battery voltage around 190-230 volts DC. We plan to put a 8-10 12Ah batteries series in order to maintain that voltage. System 1 will run off the NiMH batteries because of LI-ion difficult charge rate, lack of safety, and other issues. The Li-Ion Battery also dislikes charging in a series connection, which will definitely hurt battery cycle life and project sustainability life. System 2 will most likely run off one of the other alternatives between Li-ion or LIFePo4 rather than NiMh because it will be a smaller system. System 2 requires a battery which has a slow self discharge rate in order to maximize duration which these two options give us that NiMh does not. The system 2 battery size will range according to final hardware parts chosen by the SCADA group. They approximate a 10-30 W system, plus some minimal power consumption by the circuit boards. Due to insulation projections we has assume that during the demo we could be getting as much as 12-16 hours of darkness during a day, so we are going to chose a batteries system in the range of 16 hours * 30W = 480W which can be done with a 48 volt 12Ah battery which are easily available. Slight adjustments in numbers are still debatable at this point. The batteries will also need there own containers, which will need to hold and insulate a large size and weight of batteries. Placement and fire safety of this container will be an issues to consider when closer products decisions can be made.

NiMH Battery Research

Charging Characteristics

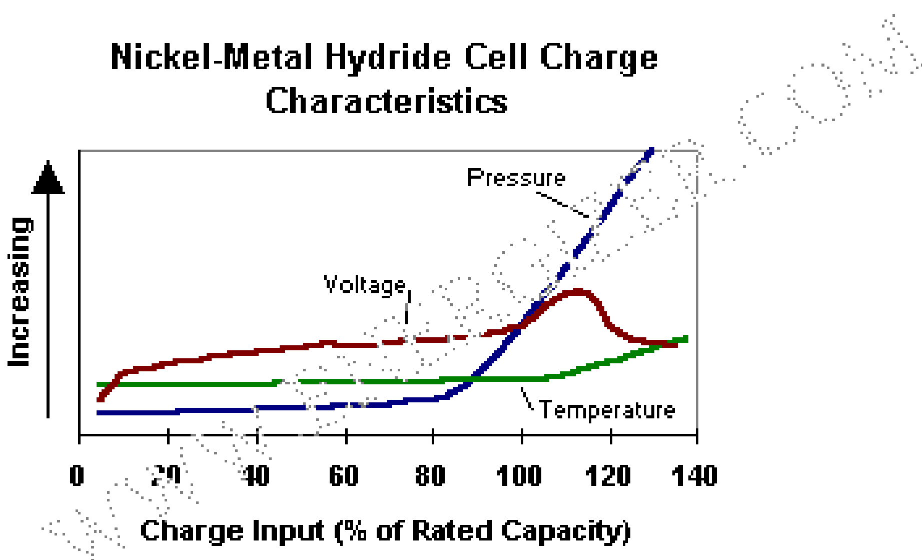


Figure 1: NiMh voltage, internal pressure, and cell temperature as a function of charge time

Charging methods:

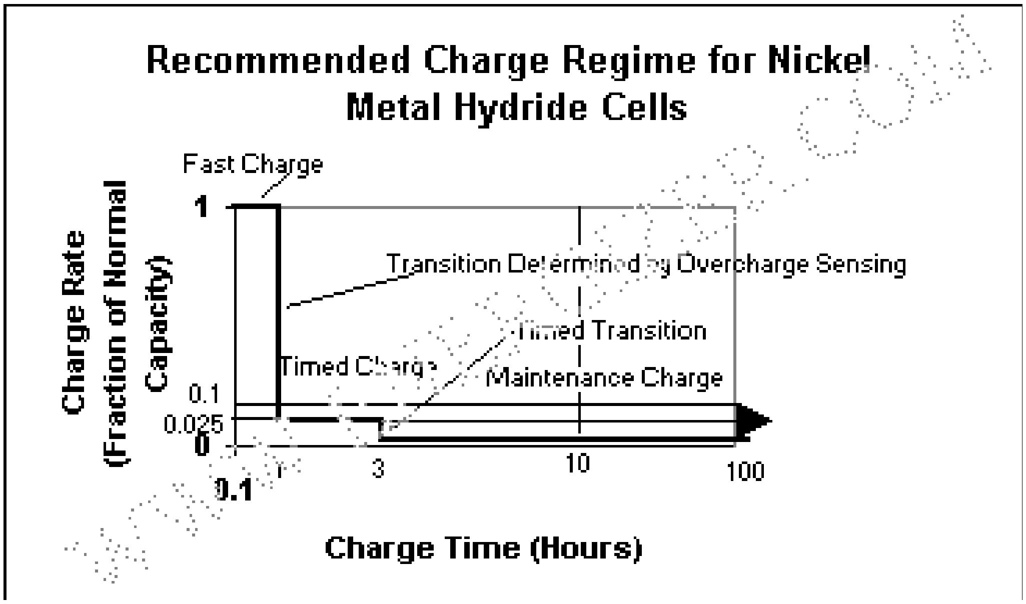


Figure 2: 3-stage charging of NiMH cells

The three stage charge method begins with a fast charge rate of 1C to fill the batteries to 90% capacity, and then is followed by low level timed charge to finish off the battery. Finally the charger trickle charges the battery to counteract self discharge. Trickle charge at 0.025C to avoid damaging batteries. This method is complex, but is the best way to protect the cells from overcharging damage.
http://data.energizer.com/PDFs/nickelmetalhydride_appman.pdf

ΔV overcharge detection:
In this method, the charger looks for the voltage spike that occurs once the cells have entered the overcharge region and appropriately limits charge afterwards. The voltage spike can be seen in figure 1.
http://data.energizer.com/PDFs/nickelmetalhydride_appman.pdf
The ΔV method is preferred, but is not reliable at slow charge rates because the voltage spike shrinks as charge rate decreases.
http://en.wikipedia.org/wiki/Nickel_metal_hydride_battery

ΔT overcharge detection:
This method of charging looks for a sharp increase in cell temperature which indicates entry into the overcharge region. The charger then limits further charging. The Temperature profile can be seen in figure 1.
http://data.energizer.com/PDFs/nickelmetalhydride_appman.pdf

Δt overcharge detection:
This method uses a timer. When the timer is done, the charging stops. This method is very simple, but unreliable in protecting the battery from being overcharged.
http://data.energizer.com/PDFs/nickelmetalhydride_appman.pdf

Cells have a vent to release hydrogen gas so a fan will be needed for ventilation. Cell capacity declines with temperature.
http://en.wikipedia.org/wiki/Nickel_metal_hydride_battery

The higher the charge rate, the better the charge acceptance. This means charging at the C rate or slightly higher provides the best charge efficiency as seen in figure 3.

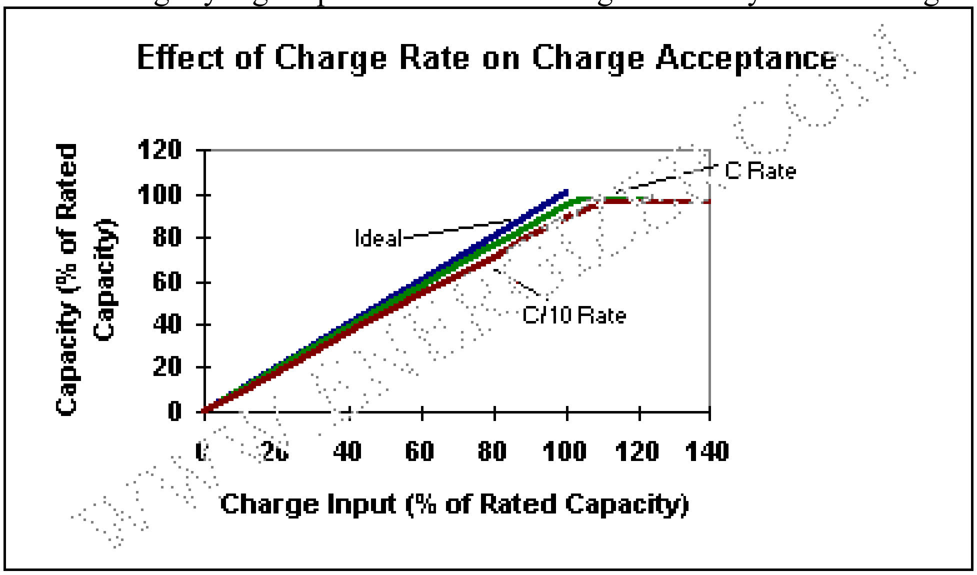


Figure 3: Pictorial representation of charge efficiency vs charge rate

Discharging:

The discharge voltage of NiMH cells is very stable. It averages at about 1.2V per cell. At full charge it begins at 1.4V and quickly drops to 1.2V after loaded. The ending cell voltage is 0.9V. The rate of discharge affects the capacity of the cell. The higher the discharge rate, the lower the capacity of the battery as illustrated by figure 4 below.

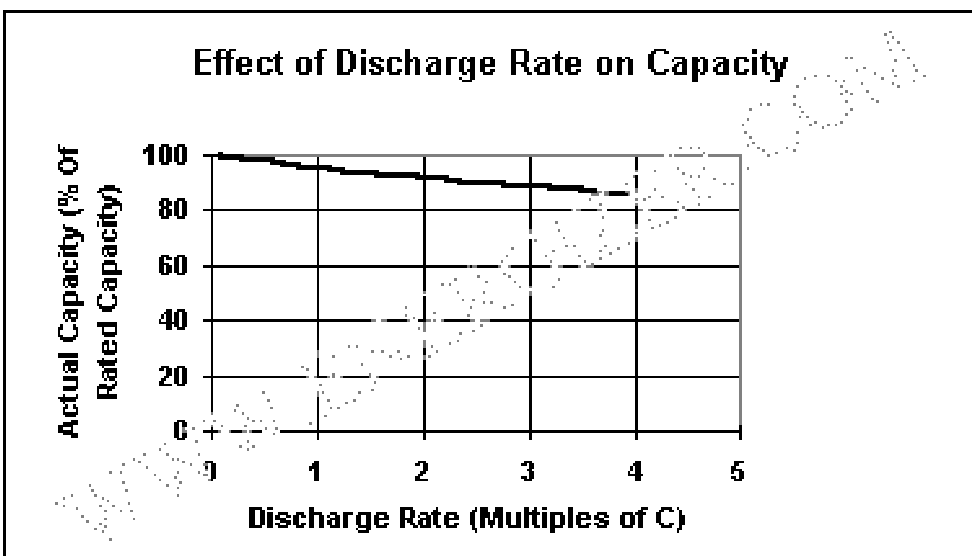


Figure 4: Capacity vs discharge rate

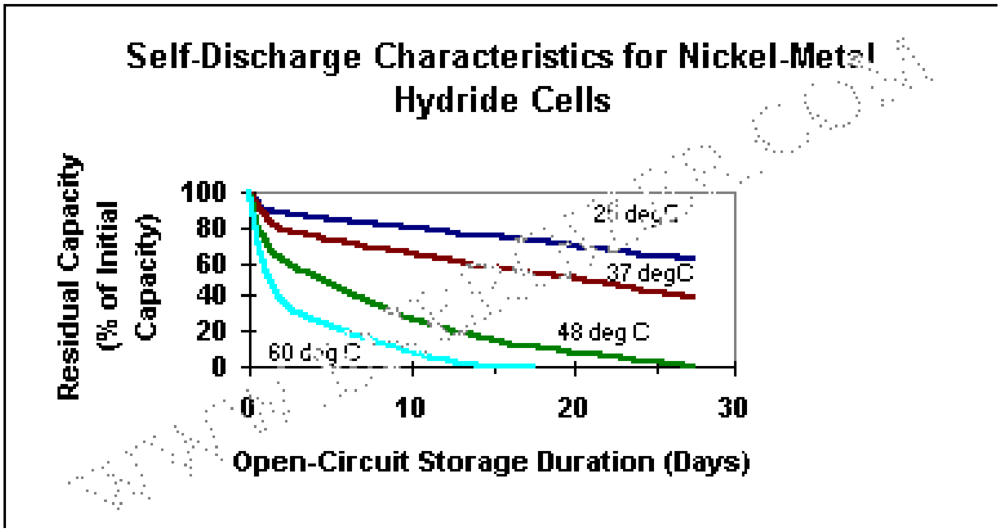


Figure 5: Self discharge profile of NiMH

A major downfall of NiMH is that it suffers from high self discharge. Figure 5 illustrates the effect of temperature on self discharge rate. At room temp (25 degrees C) the cell will lose approximately 25% after 20 days of open circuit operation. As mentioned before, a trickle current is needed to maintain the cell's full charge.

Capable of high discharge rates, but heavy load reduces life. Requires regular full discharge to prevent crystalline formation once every 3 months.
http://www.batteryuniversity.com/partone-4.htm

Summary of NiMH
Pros:
At lower depths of discharge, for example at 4 % DOD, more than 350.000 cycles can be expected.
Robust - NiMH batteries also tolerate over charge and over discharge conditions and this simplifies the battery management requirements.
Flat discharge characteristic (but falls off rapidly at the end of the cycle)

Cons:
Nearly 10 times the self-discharge rate of Lithium-Ion.
Suffers from memory effect.
Must "recondition" to get rid of memory effect. (Multiple charge and discharge cycles).
Might have a high capacity but it is not necessarily available all at once.
Discharge once per month to avoid memory effect.
http://www.mpoweruk.com/nimh.htm

Modeling of NiMH Batteries:

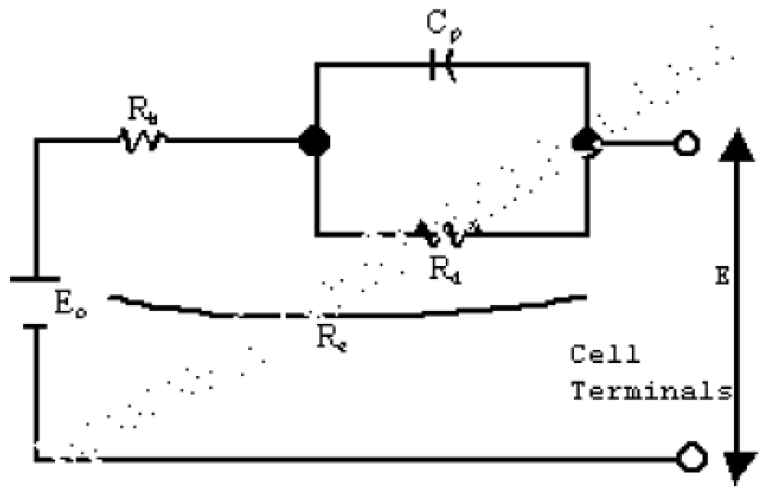


Figure 6: Electrical Model of NiMH cell

Figure 6 presents a typical NiMH battery model.   Re is the effective internal resistance of the battery, and Eo is the open circuit voltage of the cell. Unfortunately there is no NiMH model in VTB. Modeling this battery type may need to be electrically modeled in PSpice.

<u>LI –Ion Battery Research</u>:

Li-Ion has a number of advantages over some of the other battery topology. It is a fairly new system of storage and much more research has to still be done in order to minimize size and weight while maximizing energy density. Companies are still working on lowering manufacturing costs and improve cycle life. The Li-ion batteries come in a cylindrical and prismatic shape pattern.

Charging:

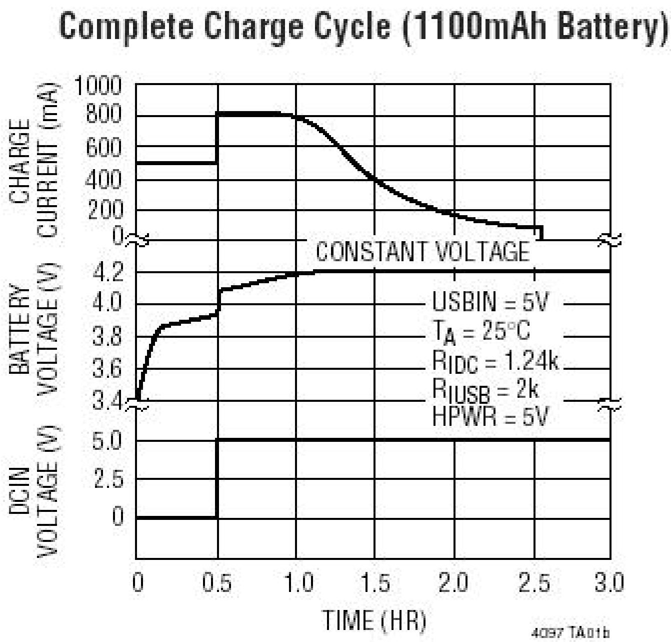


Figure 7a

The issue of charging the Li-ion batteries is not hard; the issue of doing it safely is a more difficult of a problem. The Li-ion batteries have a charge rate which can be seen in the figure 7a. It needs a steady current then a descending slope in order to fully charge the cells. This is a complex issue which only happens within the Li-ion cells. A charge timer is going to be needed in order to maintain and keep this charge to a safe standard. In a Li-ion Battery the current charges the battery up to a certain level, then the battery switches mode and holds a certain voltage. The battery then wait for the current to dissipate to 10% of the original value and then the battery is at max storage.

Source:
http://www.linear.com/pc/downloadDocument.do?navId=H0,C1,C1003,C1037,C1078,C1088,P37253,D19578

Discharging:

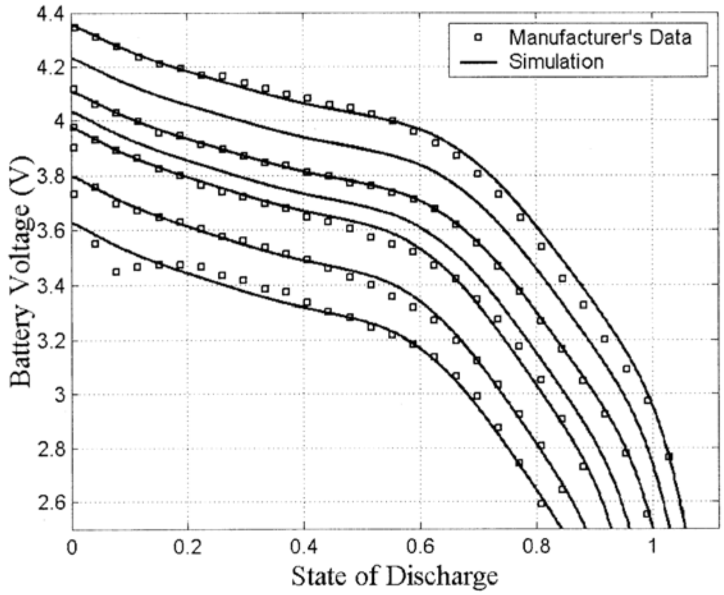


Figure 7b

Figure 7b displays the different charge rates versus the voltages of the cell due to a varying range of temperature. The top line starts at 45 deg C and the bottom line ends at 20 deg C. From this graph it is easy to seen how the batteries characteristics can change drastically depending on the type of environment.

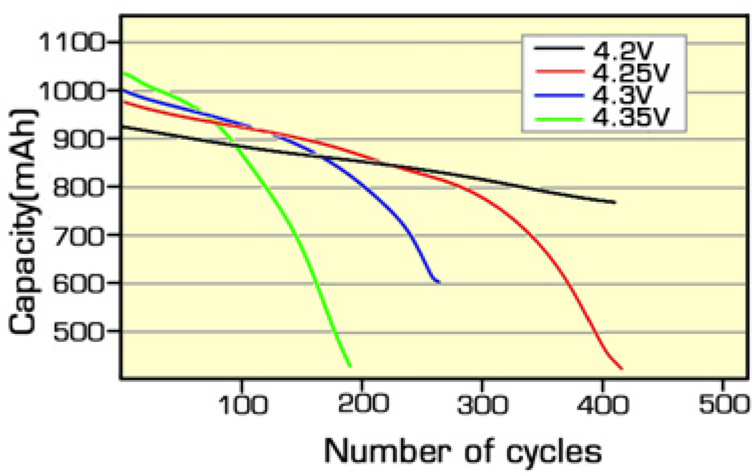


Figure 8

This Figure 8 compares the high voltage of the Li-ion per cell and shows that a high voltage leads to a high capacity. The higher voltage also decreases the number of life cycles drastically within each cell. It is noted that the Li ion cells prefers to operate not a full voltage potential but to operate between 80- 50% of its total capacitance. Fully charging should be avoided because it put an extra detrimental strain on the battery.

Source:
http://images.google.com/imgres?imgurl=http://www.batteryuniversity.com/images/parttwo-34.jpg&imgrefurl=http://www.batteryuniversity.com/parttwo-34.htm&usg=__G7-aWW11BtgrrkMk6IGRxs8fUsE=&h=308&w=487&sz=44&hl=en&start=13&um=1&tbnid=NV30GBs1GyPAUM:&tbnh=82&tbnw=129&prev=/images%3Fq%3Dli%2Bion%2Bcharge%2Brate%26um%3D1%26hl%3Den%26sa%3DN

Temperature	40% charge level (recommended storage charge level)	100% charge level (typical user charge level)
0°C	98% after 1 year	94% after 1 year
25°C	96% after 1 year	80% after 1 year
40°C	85% after 1 year	65% after 1 year
60°C	75% after 1 year	60% after 3 months

Figure 9

Figure 9 shows a comparison of the storage level that we can expect from the Li-ion batteries if they were to be unused. These batteries operate at a more efficient rate when they are at a cold temperature. The building and enclosure will be closely monitored in order to remain the batteries in an efficient comfort zone. High charge levels and high temperatures play an important part in the overall irreversible loss in battery capacity. The charge capacity of the typical Li-ion battery is approximately 20% every year.
Source :
http://images.google.com/imgres?imgurl=http://www.batteryuniversity.com/images/parttwo-34.jpg&imgrefurl=http://www.batteryuniversity.com/parttwo-34.htm&usg=__G7-aWW11BtgrrkMk6IGRxs8fUsE=&h=308&w=487&sz=44&hl=en&start=13&um=1&tbnid=NV30GBs1GyPAUM:&tbnh=82&tbnw=129&prev=/images%3Fq%3Dli%2Bion%2Bcharge%2Brate%26um%3D1%26hl%3Den%26sa%3DN

Li Model/Simulations

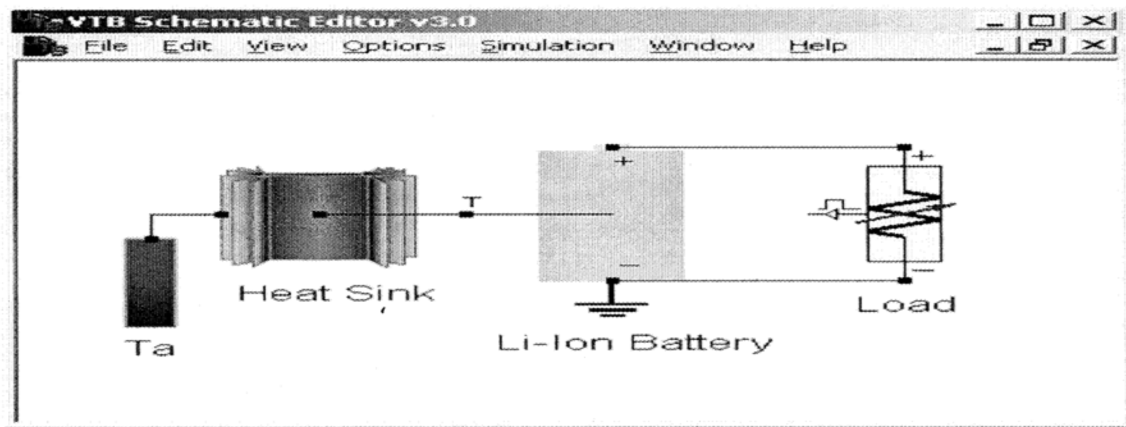


Figure10

The Li-ion Battery can be modeled within the VTB schematics like in Figure 10. In the schematic the battery is slowly going to discharge through the load that is given. Any excess heat generated will be dissipated by the heat sink.

Source: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=01159187

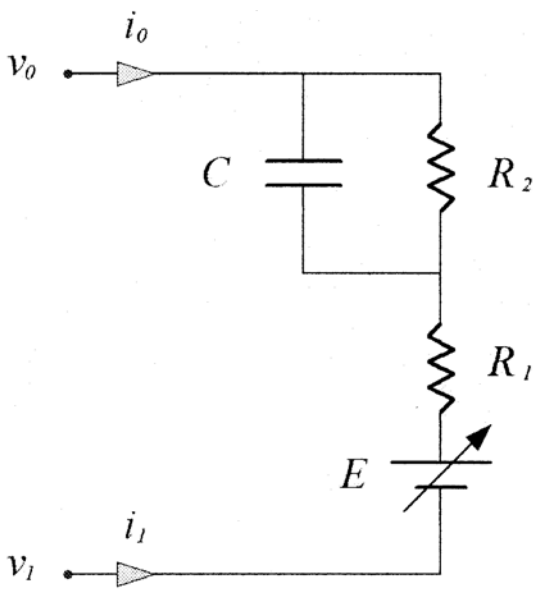


Figure 11

This is an equivalent circuit representation of the Li-ion battery. E is the open circuit voltage of the batter with R1 being the internal resistance. This model will be used for further reference in implementation in Pspice possibly.

Source: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=01159187

LI –Ion Summary”
Advantages-
No Memory, High Energy Density,
Operate at higher voltages than other battery cells
Low self discharge rate
Smaller and lighter than other batteries
Lose only 20% of Capacity per year

Disadvantages-
More expensive due to manufacturer costs
Limited/No availability in small standard cell sizes
Require sophisticated chargers
Custom chargers per battery – PCM-BMS-CMB
More volatile, higher likelihood to catch fire
Has difficulty charging in series
Need to charge below charge capacity
No fast charge
Need charge protection unit
Expensive

Source
www.batteryspace.com
www.greenbatteies.com
http://www.electronics-lab.com/articles/Li_Ion_reconstruct/
http://electronics.howstuffworks.com/lithium-ion-battery.htm

<u>LiFePo4 Battery Research</u>

LiFePo4 is an evolving technology that is looking to replace the regular Li-ion cells in a number of years. This is a branch off the Li ion battery system but is substantially safer. It is also the most stable of the Li-Polymer batteries.

Charging:

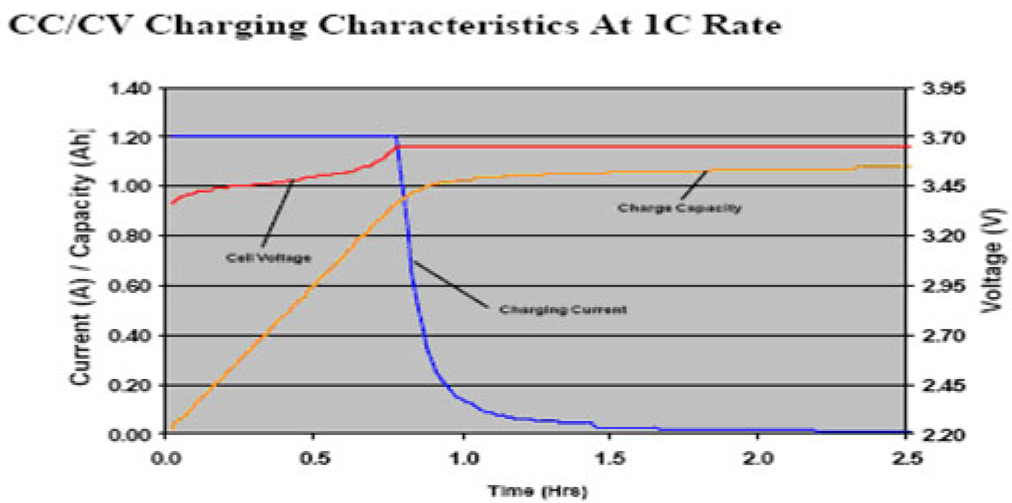


Figure 12

In Figure 12 shows the charging characteristic of a LiFePO4 battery in relation to cell voltage, capacity, and current. The charging happens at a constant rate until the cell reaches a certain level voltage. The cell is then charged at a constant voltage as the current decreasing steadily. Just like the Li-ion, when the current is at low level then the battery is at max capacity. This battery prefers to have a trickle charge method rather than a rapid charge in order to prolong battery life. This system has a very complex charging algorithm in order to prolong battery life.

Discharging:

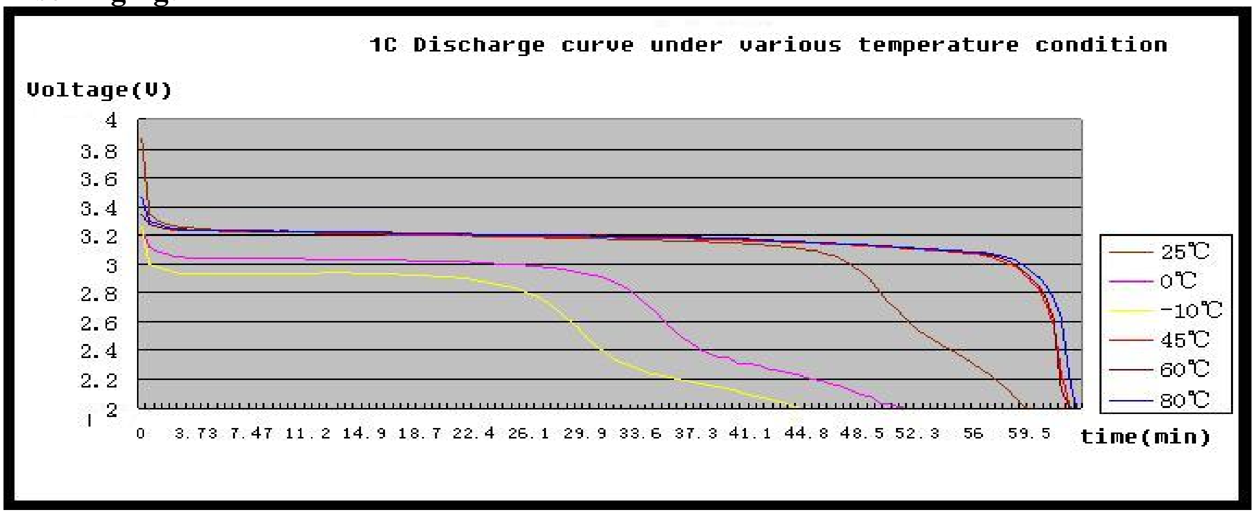


Figure 13

This battery likes to be discharged at a constant rate. This rate definitely is very temperature dependent. The battery has a low discharge rate and only loses approximately 5-10% of the charge a month.

Sources –
http://www.yesa.com.hk/pages.asp?id=19
www.batteryspace.com/prod-**specs**/HLCF18650PLi-ion.ppt

LiFePO4 Summary:

Advantages –
High cycle rate
High cost cycle/whr
Stores high energy amounts
Trickle charge is very good for lifespan
No memory affect
Very safe
Slower capacity loss rate than Li-ion
Low weight
Low self discharge rate
Low maintenance
High cost to energy ratio
Very durable

Disadvantages -
Can prematurely fail if deep cycled before 20 cycles
Rapid charge is very bad for lifespan
Lower nominal voltage, energy density than Li-ion
Need charge protection unit
Higher initial cost than Li-ion

Sources –
BatterySpace.com
http://www.yesa.com.hk/pages.asp?id=19

Flywheel Research

Flywheels store energy by rotating an object with a high moment of inertia. This energy is stored at rotational energy. Often they are built in vacuums with superconducting magnet bearing to reduce any energy loss due to friction.

Charging:

Charging a flywheel is done by spinning it. This can be done with a motor (electric or gas). Flywheels can be charged in a matter of minutes, which is much faster than batteries. It is important to avoid overcharging, as this will cause mechanical failure of the flywheel. The flywheel will explode, transmitting all its stored energy into flying pieces of itself.

Discharging:

When energy is needed out of a flywheel, it is slowed down. Its shaft can engage a generator which in turn produces electricity from the flywheel's rotation. A fly wheel can be discharged very rapidly. A flywheel's life is not adversely affected by a 100% discharge like chemical batteries.

Pros:

Can charge and discharge rapidly.
Little performance impact from temperature changes.
Lower maintenance when compared to batteries.
Very long life span (20yrs or more).
Faster charge and discharge rates than batteries.
Low environmental impact.

Cons:

Power loss is faster than that of batteries.
Can explode from over charging

Sources:
http://en.wikipedia.org/wiki/Flywheel_energy_storage
http://www.eere.energy.gov/de/flywheels.html

Super Capacitor Research:

This type of capacitor has an energy density on the order of 100 times the energy density of typical capacitors. These are typically used for short back up times or energy smoothing applications. They can charge up much faster than batteries, absorbing quick energy transients, and then discharging that energy later into a slower charging battery. They can also discharge much faster than batteries, making them favorable for relieving batteries from power surges. The capacitor will help provide power to a load that needs a large instantaneous amount of power.

Pros

High power density.
Fast charge and discharge rates.
Millions of charge/discharge cycles.
High charge efficiency.

Cons

Used for short term backup.
Not suitable for long term power such as our system.
Compared to batteries of the same storage capacity, super caps are very large in size.

Sources:
http://en.wikipedia.org/wiki/Supercapacitor
http://www.eere.energy.gov/de/supercapacitors.html

Battery Suppliers:

NiMH:
http://www.batteryjunction.com/24vpk.html
http://www.greenbatteries.com/

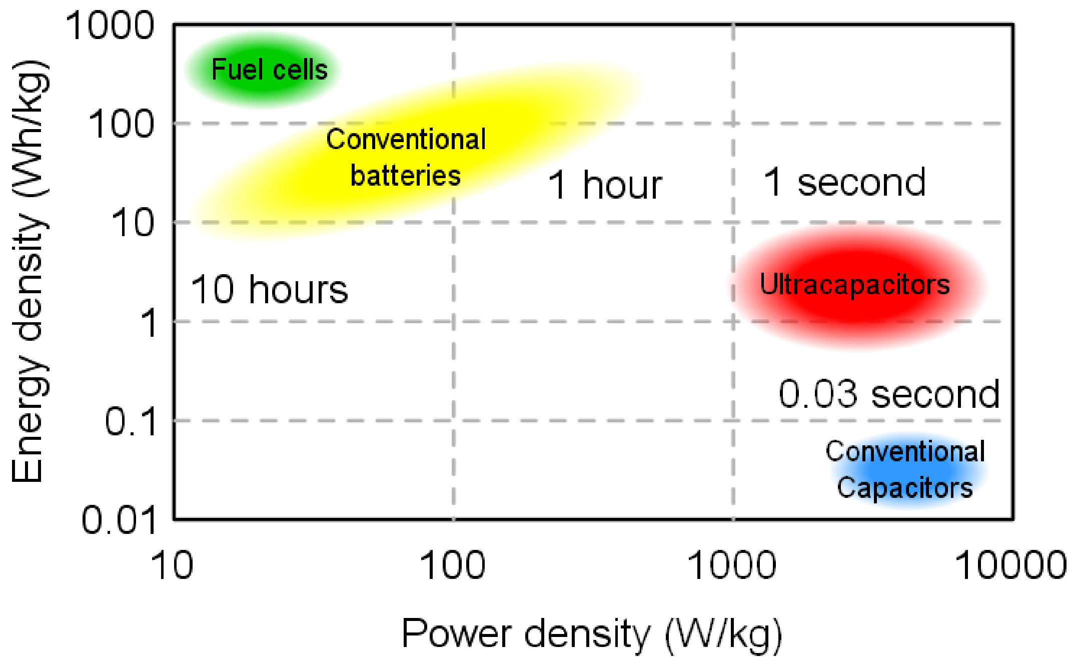
Li-Ion:
http://www.greenbatteries.com/
http://www.batteryspace.com/index.asp?PageAction=VIEWCATS&Category=894

LiFePo4:
http://www.evpower.com.au/-Lithium-Ion-LiFePO4-Batteries-.html
http://www.pingbattery.com/servlet/the-36V-LiFePO4-Battery-Packs/Categories

SuperCaps:
http://www.nesscap.com/products_lineup.htm

Flywheels:
http://www.beaconpower.com/products/EnergyStorageSystems/ProductOverview.htm

Energy Storage Comparison



From the power density picture above, capacitors are not ideal for long term storage. Batteries seem to be the best long term storage device for our application. In the table below, there is a summary of multiple energy storage technologies, including a breakdown of different chemical batteries. NiMH and LiFePO4 are the best battery solutions due to their robustness to overcharging. The other Li Ion handle overcharging poorly and are a serious safety issue.