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"Thinking Outside the Four-Wheeled Box"

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Introduction to Battery Types

The battery pack is one of the defining aspects of any PEV project; by and large it determines the weight, range, and cost of the vehicle. For these reasons a solid understanding of the various battery types is more than a little useful.

While there are a lot of chemical combinations that can and have been made into useful batteries, in practice there are only four rechargeable types readily available in sizes suitable for ebikes. Therse are Lead Acid (PbA), Nickel Metal Hydride (NiMH), Nickel Cadimium (NiCad), and Lithium-ion or Lithium Polymer.

For a long time, lead acid has been the defacto standard for EV's. The cost is low and the chemistry well understood: Always charge up the lead acid battery whenever you can, never leave it in a flat state, expect only 60-70% of the rated amp-hours, and be glad if you get 200 cycles in a deep discharge environment. Probably 95% of all ebikes sold around the world still use lead acid battery packs, but their days are limited. The weight of lead needed to propel a biycle for a decent 40-50km range is simply too much for a bicycle to easily handle.

Nickle Cadmium was the old standard for rechargeable consumer cells in the familar AA, C, 9V series. They are known for robust characteristics, a good cycle life, and high discharge capabilities. They are still widely used in cordless power tools, R/C toys and similar applications that demand large currents, but for nearly everything else NiCad's have been replaced by NiMH and lithiums.

Nickle Metal Hydride is quite similar to Nickle Cadmium, but with a higher energy density and a safer environmental record when disposed of in landfills. This is the dominant rechargeable battery type in digital cameras and other consumer products that offer user replaceable cells.

Almost all consumer electronics that have a plug-in charger these days are powered with lithium batteries because they can store about 3 times more energy than NiMH. Small devices like cell phones, mp3 players, and other gadgets typically have lithium-polymer packs, as these can be formed in conveniently shaped thin rectangular pouches. Larger devices like laptops and the new lithium cordless powertools generally use cylindrical Lithium-ion cells of a size smaller than a 'C' but bigger than a 'AA'. These are spot welded in series/parallel combination to give an appropriate voltage and capacity for the job.

Battery Basics and Terminology

Voltage

Battery packs are made up of individual cells connected together. Each cell has a more or less constant voltage dependent on its chemistry. For NiCad/NiMH, this is about 1.2V, for lead acid it is 2.0V, and for lithium cells it is on the order of 3.7V. Typical ebikes and scooters are designed to run on 24, 36, or 48 Volts, so a number of cells have to be series connected into a 'battery' that has the desired net voltage. A nominal 36V pack could be made from 10 lithium cells, 18 lead acid cells, or 30 NiMH cells.

<show picture of cells in opened packs>

Amp-Hours

As you draw current from a battery pack, the voltage will very slowly decrease until the cells start to go flat and then the voltage will plummet. The time that the battery lasts for is directly related to its capacity, measured in amp-hours (Ah). A pack that can deliver 1 amp for 1 hour has a capacity of 1 Ah. Most ebike batteries are on the order of 10 amp-hours. Suppose your bike uses 15 amps on average and has a 10Ah pack, then you would expect it to last for - quick, mental calculation... - 40 minutes.

In general, the size and cost of a cell will scale directly with its amp-hour capacity. To a first order, twice the amp-hours would mean twice the size, twice the weight, and twice the cost. In practice this deviates a little due to different packing densities and production scales, but it's usually pretty close. For instance, the familiar 'AA' NiMH has about 2 Ah, a 'C' cell has 4 Ah, a 'D' cell is about 8Ah, and the large 'F' cells are 12-13 Ah.

<Show above data in organized table form>

Watt Hours

The figure that matters most when comparing how far a given battery pack will take you is not the amp-hour capacity but the total energy stored watt-hours. To make things more familiar, one watt-hour is one-thousandth of a kWh, the unit of energy used to measure household electrical usage. The watt-hours stored in a battery pack is approximated by taking the actual amp-hours and multiplying it by the pack voltage.

A higher voltage setup therefor needs fewer amp-hours to deliver the same range. So a 24V 8Ah battery can deliver 192 watt-hours, while a 48V 4Ah pack also has 192 watt-hours. Assuming that both batteries are of the same chemistry, then you could expect they would weight the same, cost the same, and provide the same performance on appropriately designed ebikes (ie, one designed for 24V and the other for 48V).

192 watt-hours is about the smallest battery size you would want for an ebike. Many of the store-bought ebikes have about this much capacity since it keeps the battery cost down. For people who want to actually commute reasonable distances of 40-50km, then I would recommend on the order of 400 watt-hours. While it can vary a lot with usage habits, an energy consumption of 9-10 watt-hrs / km is typical.

Energy Density

When comparing between battery chemistries, one of the most relevent metrics is the Energy Density in watt-hrs / kg. This figure says how heavy a battery pack will have to be to achieve a certain range. For Lead Acid it is 20-30 whrs/kg, for nicad it is 35-40 whrs/kg, NiMH is 50-60 whrs/kg, Li-ion is ~110 whrs/kg, and Li-Polymer is up to 160 whrs / kg. Knowing these values makes it easy to project the weight of a pack without having to look up data from the manufacturer.

<table showing these values, as well as approximate weight for 400 w-hrs of battery>

C Rate

One term you will frequently come across is the 'C' rate of a battery pack. This is a way of normalizing the performance characteristics so that batteries of different capacity are compared on equal terms. Suppose you have an 8 amp-hour pack. Then 1C would be is 8 amps, 2C would be 16 amps, 0.25C would be 2 amps etc. A higher 'C' rate of discharge is more demanding on the cells, and often requires specialty high rate batteries.

For example, suppose you see a 24V 4Ah NiMH battery pack on ebay, that is rated for 1C continuous and 2C max for short times. You might want to get two of these to make a 48V 4Ah battery for your ebike. You calculate that the range will be more than adequate for your short commute to work and back. The problem is that 1C is just 4 amps, while your ebike will probably draw 10-20 amps. If these cells are subject to such discharge rates, then the voltage will sag considerably, leading to slower performance, and the cycle life of the packs will be greatly reduced.

Most inexpensive NiMH packs are not really designed for discharges greater than 1C. That means that if your ebike draws 15 amps on average, you would want a pack that has a capacity on the order of 15 amp-hours more.

How do I choose a pack?

The process of selecting a battery pack typically goes through the following process:

Step 1: Determine your voltage. In many situations, especially if you are replacing a battery pack on and existing setup, the voltage is defined by the controller electronics and cannot be readily changed. Otherwise, the voltage determines the maximum speed at which your vehicle will travel, and you have a degree of freedom in selecting the voltage to meet your performance expectations. If you know the volts/rpm for the motor, then it is straightforwards to calculate how fast it will go for a given voltage. Select a value that gives an unloaded speed of about 20% greater than your desired cruising speed for best performance.

While it it possible to build packs with any number of cells for just about any voltage, most have standardized in 12V increments, with 24V, 36V, and 48V being most common, and 72V used on occasion. Battery chargers are usually only stocked for these voltages as well.

Step 2: Determine your minimum capacity. With the voltage known, the next item to figure out is how many amp-hours will be required to achieve your desired trip distance without the battery running flat. This depends of course on how much pedaling you contribute to the effort, how fast you are traveling, and the terrain you are on. The table below was produced as a guideline based on my own experiments and those of others who have used the DrainBrain and provided me feedback:

<table of watt-hours/km, with functions of speed and pedal effort>

Now take your trip distance, multiply it by the appropriate watt-hours/km from the table above, and you'll get the total minimum watt-hours required for the trip. Take the watt-hours you've estimated and divide it by the voltage, and you now have an estimate on the minimum amp-hours you'll need from the pack.

Step 3: Choose your chemistry. Now you have the required specs on the pack, namely its voltage and capacity, so it's a matter of finding one that meets your budgetary and weight restrictions. To a first order, for a given voltage and capacity, NiMH will cost twice as much as lead acid but come in at half the weight, and lithium will be twice the cost of NiMH and a further half the weight again.
Pay attention

Details in Depth

NiMH / NiCad

The Nickle Metal Hydride (NiMH) battery has largely replaced the Nickle Cadmium (NiCad) cell as the stock rechargeable cell for consumer applications. They are less of an environmnental hazard, have up to 50% more energy density, and are not much more in price. The only drawback is that they have a finite shelf life of just a few years and the lack the large (1000+) cycle life of NiCad. Their charging and discharging characteristics are nearly identical

Charging Characteristics

Like all batteries, in order to properly charge a NiMH cell you want to add current until the charging reaction has finished and then stop. For the first 85% or so, NiMH behaves very much like other batteries in that the voltage steadily rises as the charge progresses. Then several side reactions begin to take place inside the cell, asbsorbing some of the charge current and causing a temperature increase. This temperature rise actually causes the cell voltage to fall, even though it is still charging.

Insert NiMH Charge Profiles

What makes charging NiMH difficult is that you cannot simply connect it to a power supply and charge it until it reaches a certain voltage. If you set the voltage too low, it will only get the pack ~80% charged. If it is much higher, then the pack will never hit that level because of the voltage drops as it overcharges. This causes a runaway phenomenon, as a lower pack voltage typically means more current from the charger which leads to even faster overcharging and the possibly catastrophic venting of the cells.

Discharging

The figure below shows a typical discharge curve for a NiMH cell at various discharge rates. Notice how you get nearly the same capacity regardless of the discharge current, but the voltage is less at higher amps. From this graph you can readily get a first order estimate of the internal resistance of the cells. R = DeltaV/DeltaI. High rate cells such as those made for RC and power tools will have substantially lower voltage drops, and hence can handle larger currents without suffering internal damage. However, they are not typically available in larger than 3 or 4Ah SubC sizes

Both NiMH cells and NiCad cells can be drained fully flat, all the way to zero volts, with no consequence. In fact many sources recommend periodically deep discharging to this point in order to 'recondition' the electrodes. This is in sharp contrast to lead acid and lithium batteries which should rarely and never be drained flat.

Capacity Matching

When cells are connected in series to make a battery pack, it is important that they are all matched with nearly the same amp-hour capacity. The discharge curve of the assembled pack should then resemble that of an individual cell just with a larger voltage scale. But if some cells have a lower capacity than others, they will drop to zero volts while the rest of the pack still has ample power remaining. This one cell then experiences a reverse voltage as current continues to be forced through it even though it is drained. The cell will heat up and suffer internal degradation and possibly vent, especially if the current is large as is usually the case in electric vehicles.

Insert Picture of Unmatched Pack

The above graph shows a particularly bad example of this from what was nominally a 36V 13Ah NiMH battery pack. You can see that at 10.5 Ahrs, there is a sudden 1.2V drop and then the discharge continues previously. Then at 11 Ahrs another cell drops out, and finally the pack as a whole begins to go flat. In use, you wouldn't notice the 1.2V drop and by the time the battery finally begins to feel flat, this one cell has already suffered a lot. You can see how it becomes a bit of a runnaway problem, since damage will reduce the capacity of this one cell even further.

Reputed companies that build the battery packs will use cells that have been individually selected to have identical capacity. Then all cells in the pack will go flat together and there is little risk of cell reversal. We have found that almost all companies claim that cells in each pack are matched within 2 to 3 %, but our own testing has shown that a significant percentage (sometimes over half) of packs have at least one cell that is will outside of this specification. In some cases, after a few cycles the under performing cell recovers and eventually shows the same capacity .

. If you are assembling your own pack from individual cells, then it is unlikely you will have any guarantee of well matched cells. The best solution in this case is simply not discharge the pack to the point where it even begins feels flat.

NiMH Discharge Rate Limitations

Asides from poor cell balancing, another frequent problem with NiMH setups is that the cells are not designed to handle the loads they experience. This is especially true with the abundant and inexpensive NiMH coming out of China which aren't designed for more than 1C of continuous discharge. A popular battery pack is 36V 8Ah made from 30 standard'D' cells. A typical ebike motor controller can draw 20 amps, which corresponds to a 2.5C discharge. At 2.5C, the voltage of the pack can easily drop by more than 20%, which leads to underwhelming performance. And frequent use at these currents will drastically shorten the cycle life of the battery. However, a similar pack built from higher-end D cells which are rated for 3-5C discharges will have no problem.

Leakage Currents

NiMH and NiCad batteries will both discharge slowly on their own even when no load is connected. For a pack that was just topped up, it may loose up to 10% of its charge in the first couple days, and then gradually over a few months it will loose much of its remaining charge. This is really of no consequence in an EV, as you typiclaly charge overnight and ride it the next day.

Conditioning and Balancing

NiMH and NiCad are both blessed with shuttle reactions that allow small amounts of current to continue to flow both during overcharge and over-discharge. Battery packs that have been sitting in storage for some time will often wind up with some cells more charged than others. This happens because the internal leakage currents are not necessarily the same from one cell to the next. When the pack is charged for the first time, some of the cells will be top up before others, and the shuttle reaction allows charge current to continue flowing through the pack untill all the cells are topped up, without damaging those cells that got overcharged.

NiMH packs that have been on the shelf for a year or more will usually not give near their full capacity on the first discharge. It takes several cycles before the battery will reach its optimum performance, a process known as conditioning. The graph below illustrates the situation with a NiMH laptop battery purchased at a surplus store. The first discharge yielded 1.1 Ahrs, then second 1.6, and by the fourth cycle the pack had stabilized at about 1.8 Ahrs. You don't need to do anything special to condition the pack, simply be aware that it might improve during the first few usages.

Insert Picture of Cell Conditioning

Marketing the Memory Effect

The so called 'Memory Effect' is one of the most misunderstood and overstated problems with rechargeable batteries. Essentially, if you only partly discharge NiCad batteries to the same point over and over, then when you finally do discharge it completely, there will be a small detent in the voltage when it goes past the partial discharge point. It is not true that the capacity is either permanently or temporarily reduced by this process, and therefor is of really no consequence in an EV application.

The problem is that NiCad was the standard rechargeable consumer battery for quite a while, and many people became familiar with the instructions recommending to periodically deeply drain the cells to avoid this 'memory effect'. When NiMH came out, they started advertizing it as having "No Memory Effect!" as a selling point over NiCads, and this marketting phrase lives on to this day even though it is a totally moot point, since the memory effect was never really a problem to begin with.

Making packs from individual cells

It is quite possible if you are up for the challenge to build your own NiMH or NiCad battery pack from cells rather than buying them pre-assembled. This approach gives you complete flexibility in the geometry of the pack as well as the ability to produce non-standard voltages. Many people in the R/C community already do this, and you can often get reasonably good deals when buying cells in bulk. There are a few things to know:

Unless you have a spot-welder, you should buy tabbed cells so that they can be readily soldered to one another. In consumer electronics, the cells do not have tabs and the connections are made via spring-loaded contacts. When you have 20 amps flowing like in an ebike, this approach is totally inadequate. A pressure connnection will heat up and corrode, possibly damage the cells and/or enclosure, and lead to unreliable performance. Trying to solder directly to large untabbed cells will also damage them.

The issue of balancing has already been mentioned. Since you don't get to pick and choose which cells will go in the pack, there will likely be one or two cells with lower capacity that will experience cell reversal before the pack as a whole feels dead.

Try to get cells that have your desired Ah rating instead of putting smaller cells in parallel. While the mass-produced AA NiMH and NiCads often have the lowest cost per watt-hour, there are complications involved when you connect these types in parallel. Not only is it more work, but if the temperature is not evenly distributed during charging, then some of the parallel cells will experience the voltage drop before others, and hog all of the charging current, so that they get overcharged while the neighboring cells never fully top-up.

Be careful with any metal tools when you are building the pack. It is easy to accidentally short various live connections together with sissors, wire cuttors, soldering irons etc. and the consequence can be pretty devestating. 100's of amps will arc through the tool, puncture holes through the walls of the cell, and leave you pretty startled.

Don't forget to embed a thermistor somewhere inside the pack, a thermal fuse on the charge wire, a regular fuse on the discharge wire.

Charging Details

NiMH Charging, T, dv/dt, dT/dt, parallel string charging NiMH 3 levels of charge protection NiCad with NiMH Charger NiMH with Lead Acid Charger

Li-ion / Li-Polymer

A few years ago, all cell phones and laptops ran off NiMH batteries. Now you would be hard pressed to find one, everything runs off Li-ion or lithium-polymer.

Charging

Cell Balancing

Battery Management

Discharge Characteristics

Cautionary Tales