BATTERY TECHNOLOGY

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INTRODUCTION

Electric vehicles, hybrids, and renewable energy have one thing in common: if they are ever going to be widely used, representing the majority of cars on the road or a large share of electricity supply, batteries need to get significantly better. Most e-cars cannot travel further than 62 miles or 100 kilometers before needing a battery recharge. Prices can run as much as $13,000 or €10,000 higher than one with a conventional internal combustion engine.

The next evolution will be combining battery power with solar energy and letting solar Photo Voltaic (PV) be the charger rather than the local utility company. Solar PV is becoming a peal and stick application. Melding the solar panel into the entire vehicle would turn it into its own charging station. Parking lots would become charging stations and the vehicles themselves would be charging themselves during the days when the sun is shining.

Batteries will need to store more energy, deliver it faster and more reliably, and ultimately, cost far less than existing batteries. The specific ways batteries need to improve vary by the application, but in all these areas, researchers have been making significant headway.

Figure 1. Lithium ion battery pack.

Figure 2. Electrical car battery recharging station.

Figure 3. Conceptual design of electrical car battery recharging using solar Photo-Voltaics, PVs.

There are a number of parameters on which battery technologies are compared, with the key parameters being specific energy and specific power.

The specific energy is a measure of the amount of energy that can be stored by a battery in comparison to its weight.

$$\text{Specific energy}=\frac{\text{Energy stored in battery}}{\text{Battery weight}}\left[\frac{Joule}{kg}\right] \quad (1)$$

The specific power compares the rate at which energy is delivered relative to the weight of the battery, which is related to the acceleration and top speed of a particular vehicle.

$$\text{Specific power}=\frac{\text{Power delivered by battery}}{\text{Battery weight}}\left[\frac{Watt}{kg}\right] \tag{2}$$

The faster the delivery of energy, the quicker a vehicle can get to top speed.

The energy density figure of merit is a measure of the amount of energy that can be stored per unit volume of the battery.

$$\text{Energy density}=\frac{\text{Energy stored in battery}}{\text{Battery volume}}\left[\frac{Joule}{m^3}\right] \tag{3}$$

HISTORICAL BATTERIES

A clay pot uncovered in Iraq suggests a battery use for metal electroplating using acid electrolytes such as vinegar or acetic acid and copper electrodes.

Figure 4. Sumerian clay "Baghdad Battery."

SILVER BATTERIES

Alessandro Volta invented the first battery using silver and zinc as the electrodes at the beginning of the 19th century. Silver batteries were not developed until military requirements for high energy density batteries emerged in the 1940s. Silver batteries are now used in a wide range of applications in everyday life all over the world, such as watches, calculators, electronics, and photography.

Japan is one of the world's biggest battery producers, with silver batteries accounting for over 20 percent of all primary battery sales in Japan in 2013.

SILVER OXIDE-ZINC PRIMARY BATTERIES

Silver oxide-zinc system batteries, or simply 'silver-oxide' batteries, first commercialized in the 1960s, are a major contributor to miniature power sources. A silver-oxide battery, which uses silver oxide as the positive electrode and zinc as the negative electrode, is a primary cell with a very high energy to weight ratio. Silver-oxide batteries can take the form of small-sized button cells which are used in hearing aids, photographic applications, toys, medical instruments, watches and other low power devices; or large cells for military applications, including missiles, torpedoes and submarines.

Notably, traditional silver-oxide batteries are non-rechargeable and as silver prices increased in recent years, they have been substituted by other batteries in many areas.

SILVER-ZINC SECONDARY BATTERIES

A second type of silver-containing battery, silver-zinc batteries, also has a wide range of applications. Silver-zinc batteries are rechargeable secondary batteries which share most of the characteristics of the silver-oxide batteries. These cells are able to deliver one of the highest specific energies of all presently known electrochemical power sources, making it widely used in high energy density applications.

However, the cost of large capacity silver-zinc batteries is extremely high because of the silver content and therefore they are mostly used in aerospace and military applications where the superior performance of the battery outweighs the cost of manufacture, typically in spaceships, satellites and rockets.

The cost of silver-zinc batteries to decline in the coming years which could help to slow down thrifting and substitution effects; and boost demand. In order to target mainstream markets, silver-zinc batteries have developed into smaller units applicable to applications where lithium-ion technology cannot be accommodated. Compared with lithium-ion batteries, silver-zinc batteries can store about 30-40% more energy in the same volume and are much safer and environment-friendly.

Recently, a new type of portable batteries, particularly designed for hearing aids and wearable electronic devices, were developed. Their aim is to provide at least 50 percent of all rechargeable hearing-aid batteries globally in the coming five to ten years.

At present, most portable electronic devices, such as smart phones, tablets, and laptops use lithium ion batteries and face the problem of power endurance, as their battery lives shorten with frequent recharges. Although silver-zinc batteries are more expensive than lithium ion ones, they are fully recyclable so that initial high costs can be mitigated. However, silver-zinc batteries also have relatively short cycle lives, typically less than 100 cycles per battery. Once scientists break through this technology bottleneck, silver-zinc batteries are expected to replace lithium ion batteries in many expensive electronic devices. As yet, the technology remains unproven on a commercial scale.

ZPower, a company based in the USA, was the first to develop rechargeable silver-zinc batteries which have already been used in hearing products and they remain bullish about the commercialization of this battery technology and are backed by Intel. Silver-zinc batteries used for military purposes tend to be one-time use, as they are impossible to recycle.

NICKEL METAL HYDRIDE, NiMH BATTERY

The most successful battery technology today is the Nickel Metal Hydride, NiMH battery that was used in the 2002 Toyota RAV4 Electric Vehicle, EV.

It is fully recyclable and with decade-old battery technology can get over 100 miles per charge. The RAV4 EVs, still in operation, accumulated over 100,000 miles of use and still get over 100 miles per charge.

LITHIUM ION BATTERY

Lithium batteries are the powerhouse behind the mobile gadget revolution from i-pods to i-pads to i-phones and laptop computers. They are reliable and they do not suffer from a serious multiple-cycle “memory effect” like the Ni-Cad (Nickel-Cadmium) batteries do.

They can be fashioned into a variety of different of shapes, and they are good a providing significant amounts of charge. However they are far from perfect: they present a fire hazard. This is because they are actually sophisticated inside, and the electrolyte the lithium is dissolved in is toxic as well as flammable.

Figure 5. Different shapes of Li batteries.

Two main lithium battery types are in use:

1. Primary, non-rechargeable

Including coin or cylindrical batteries used in calculators and digital cameras. The lithium battery has a higher energy density compared to alkaline batteries as well as a low weight and long shelf and operating life.

2. Secondary, rechargeable

The main applications are powering cell phones, laptops and other hand-held electronic equipment.

As with the primary battery, the lithium secondary battery has a higher energy density and lighter weight compared with NiCd and NiMH batteries.

AQUEOUS LITHIUM ION BATTERIES

Aqueous Li ion batteries work as efficiently as Li ion batteries, and in the future these power cells may take up some of the load of normal Li ion batteries.

The advantage of aqueous Li ion cells are that they are water-based, and thus potentially less toxic and prone to explosive behavior. The technology has been in existence for a while, but never seen mainstream adoption due to the short lifespan of the design. It is typical to see the capacity of an aqueous unit fall to less than 50 percent of charge after just a thousand cycles.

By optimizing the oxygen content in a Li sulphate/water electrolyte, the cells retained up to 90 percent of their capacity after a thousand cycles, closer to the performance of more normal Li cells.

A few drawbacks do remain: the power retention of the devices is reduced. The developers see that the system could have uses in situations where its safety is desirable though, such as for hybrid-engine city buses, or where wind turbines or other alternative power generators are producing spare electrical capacity that needs to be stored.

LI BATTERIES FOR AUTOMOTIVE POWER

In 2008, the Li-ion battery market was the second largest consumer of Li and accounted for 20 percent of Li consumption.

The emerging application of Li for batteries used as the power source for Hybrid Electric Vehicles, HEVs, Plug-in Hybrid Electric Vehicles, PHEVs and Electric Vehicles EVs.

Figure 6. Toyota Prius Hybrid Electric Vehicle, HEV power controls.

1. Hybrid Electric Vehicles, HEVs

In this case, the vehicle's power-train is a combination of electric power and a conventional gasoline engine. They come in two variants:
a) The mild HEV uses a battery pack to supplement the gasoline engine either during acceleration, when the vehicle is at rest or low speed driving.
b) The full HEV allows the car to be propelled in full electric mode and the batteries are recharged by regenerative braking.

HEVs use approximately 0.5 kg of Li per vehicle.

2. Plug-in Hybrid Electric Vehicles, PHEVs

These allow the batteries to be recharged by plugging the vehicle into the electric mains system.

PHEVs use about 1.8-4.2 kg of Li per vehicle.

3. Electric Vehicles, EVs

Fully electric vehicles are whose main propulsion mode is electric, but which may also have a small gasoline engine to either assist in recharging the batteries or provide power to the engine if the battery charge is depleted.

EVs use approximately 10 kg Li per vehicle.

With the increasing political and consumer focus on climate change, car producers are looking for ways to lower both carbon emissions and fuel consumption in transport applications.

HEVs have been on the market for a number of years, with annual sales in the USA increasing from approximately 20,000 in the year 2000 to almost 350,000 in 2007.

Most mass produced HEVs have incorporated Nickel Metal H (NiMH) batteries, although many automobile manufacturers are starting to develop EVs incorporating the lithium-ion battery as the electrical power source for their vehicles.

Lithium-ion batteries are optimized for high specific energy and energy density and are the only battery technology that can achieve the energy storage capacity required to match the performance of traditional fuel vehicles, without excessive weight compromising vehicle performance.

The demand for lithium is expected to increase as vehicle electrification moves toward full EVs from HEVs and PHEVs.

NEW BATTERY STORAGE TECHNOLOGY

Nano Li ion batteries using carbon fibers with at least 5 times the capacity of existing ones are in the development stage. High-power Li ion batteries would be useful for hybrid vehicles or for stabilizing the electrical grid. These batteries accept and deliver charge rapidly.

In hybrid vehicles, the goal is to supplement the gasoline engine, allowing it to run at its most efficient regime. The battery drives the car at low speeds for short distances and boosts its acceleration, lowering demand on the engine. It also captures energy from braking that would otherwise be lost as frictional heat.

For the electricity grid, such batteries could buffer changes in supply and demand of electricity which is becoming more important as more variable sources of electricity are introduced, such as wind and solar power.

A battery electrode, based on specially treated carbon nano-tubes that last for thousands of cycles without any loss in performance are under development. Batteries made from these electrodes could deliver enough power to propel large utility vehicles such as delivery vans without the batteries being too heavy to be practical.

The thickness of the electrodes needs to be increased for them to be practical in these applications. Companies such as A123 Systems, based in Watertown, MA, have very high power Li ion batteries.

ULTRA CAPACITORS

Academic groups and startups are developing carbon nano-tube ultra-capacitors, which store energy using a different mechanism than batteries that is particularly useful for high power and long life.

While the new electrodes could eventually be useful for hybrids, and for stabilizing the grid, they are not particularly good for other applications such as all-electric vehicles. For all-electric vehicles, the total amount of energy that batteries store is more important than how fast that energy can be delivered, since it is the total amount that determines the cruising range and how far these cars can travel between charges.

LITHIUM AIR BATTERY

A different type of battery to store large amounts of energy is called a Li air battery, where one of a battery's two electrodes is replaced by an interface with the air.

In theory, such batteries could store three times as much energy as the conventional lithium ion batteries.

The design has a number of problems that make it hard to commercialize. Among them is the vulnerability of its active materials to moisture: the Li metal it uses can catch fire if it gets wet. The batteries have a tendency to stop working after being recharged just a few times.

TECHNOLOGICAL HURDLES

Other potential high energy battery technologies face a number of hurdles, which could help explain why hybrid vehicles with their high-power rather than high-energy batteries have been more successful than electric vehicles.

Many of the most promising battery chemistries are too difficult to manufacture at a large scale. They fall apart after a few cycles or are too expensive.

According to the USA Department Of Energy (DOE), complete battery packs today cost between $800 and $1,200/kW.hr, and store about 100 to 120 Watt.hrs/kg.

To make electric vehicles practical and affordable, the DOE would like to see costs drop to $250/kW.hr and increase storage capacity to over 200 W.hr/kg.

Reaching these goals will require even higher storage capacities for the individual battery cells that make up battery packs to about 400 W.hr/kg.

WIND AND SOLAR APPLICATIONS

While improving batteries for hybrids and electric vehicles is difficult, one of the biggest long-term challenges for battery researchers is making batteries that can cheaply store vast amounts of energy generated by solar panels and wind turbines, so that electricity from these sources is available when the sun is not shining or the wind is not blowing.

Such batteries are not needed at this time since there is enough power from the conventional sources to take up the slack. If solar and wind are ever to provide the majority of electricity, storage will be needed, and batteries today are far too expensive.

The DOE goal for such batteries is less than $100/KW.hr, less than half its goal for electric vehicles.

It is still cheaper today to build a natural gas power plant as a backup source of power, or to store energy by pumped water storage, where it can later flow downhill to spin a generator.

An experimental approach to such low-cost batteries is a "liquid battery," which uses inexpensive battery materials that assemble themselves.

COMMERCIALIZATION HURDLES

Even if problems with batteries are overcome in the laboratory, these technologies face obstacles to being commercialized. To drive down costs, battery makers are turning to applications other than electric vehicles and the grid to get new technologies off the ground.

These applications include microelectronics, power tools, and race cars. Plug-in hybrid vehicles can serve as a bridge to electric vehicles. Plug-in vehicles use backup gas-powered generators to help extend their range, allowing automakers to use smaller, less expensive battery packs than they would need for electric vehicles.

Automakers such as GM, with its Chevrolet Volt design, are following this approach. The electric vehicles on sale now, and that will be going on sale in the next few years, are either expensive sports cars and luxury vehicles, where costs can be high, or their upfront costs are being decreased using creative financing, such as leasing battery packs or offering per-mile plans something like the per-minute plans offered by cell phone companies.

RECENT ADVANCES

An Arizona State University spinoff company: Fluidic Liquids, announced that it overcame dendrite formation in their ionic liquid battery, with a claim of 11 times the energy density of the best Li-ion batteries. Several liquids are under consideration which can be mass produced at the same price as liquid soap detergent. The only metal the battery needed was zinc. Cost was projected at about the same cost as a car starting battery, except with more energy density that even what the DOE is targeting.

Some new technology is under development using Mg in batteries.

REFERENCE

1. Kevin Bullis, “A Guide to Recent Battery Advances,” Technology Review, June 29, 2010.