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Battery Technology

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Introduction

Progress in battery technology has been key to the creation of mobile computing, cell phones and electric cars. These applications have driven a competitive race to improve battery technology. As battery performance has improved new applications have opened up in a virtuous cycle of product improvement and market expansion.

This research note reviews the current state of play and where this technology might go.

Batteries come in two basic sorts. Rechargeable batteries store electrical energy and release it on demand. Nonrechargeable batteries generate electricity from stored chemical reactants.

The familiar form of batteries package up the chemical constituents into a sealed package. An individual battery, or cell, is a fairly small package. Multiple cells are wired together to create large scale batteries. An emerging type of battery is the flow battery. Here the chemical reactants are stored as fluids in external tanks and the fluids are pumped through a reaction chamber for the electrical flow to occur. In this type of battery the cell concept does not really apply.

Basic Science

The science which deals with batteries is known as electrochemistry. The fundamental electrochemistry is entirely understood. A rechargeable battery works on the principle of a sponge. Placed in a bath of higher electrical potential, electricity flows into the matrix of the battery and is stored. Removed to a lower potential the electricity flows out. It takes work to create the high potential, so the battery stores this energy as well. As the electricity flows out the energy is liberated to do work. Thus one could look at the battery as an energy storage device just as well as regarding it as an electrical storage device. For nonrechargeable batteries the chemical reactants coexist stably together when no electrical flow is possible. But once flow is permitted the chemicals react to produce the flow.

What is less understood and what leads to the possibility of technical advance is the material science side of the problem. Selecting the right chemistry; preparing the materials properly; fabricating the units; adding trace dopants – all these details matter. As the research tools to understand materials on a molecular scale have become available, the homely battery has transformed into a high tech artifact.

Design Criteria and Applications

There are several different design goals for a battery. Specific energy refers to the stored energy per kilogram. Closely related is the energy density which refers to the stored energy per liter volume. Cycles is the number of times the battery may be charged and discharged. Cycle time is how long it takes to charge the battery. Efficiency is the ratio of output power to input power. Finally there are safety issues. It is desirable that the battery not be subject to thermal run-away and bursting into flame. It is desirable that the battery not be made of materials which are toxic or hard to recycle. It is desirable that the materials be available at low cost from multiple commercial sources in stable countries.

No battery is perfect along every dimension. Different applications weight the design criteria differently and so different batteries are the best match for each application.

For mobile computing and cell phones good specific energy is important. Cycles need to be long enough to match the life of the powered device. But fairly rapid obsolesce means very high cycle times are not needed. The battery is not usually a large part of the device cost, so lowest cost also is not important.

For electric vehicles, the battery must store large amounts of energy and both specific energy and energy density are important. Cost also is important as the battery is a meaningful part of vehicle cost.

Again cycles must match vehicle lifetime. Cycle time also is important.

Stationary Power Needs

The stationary power need is significantly different from the mobility and transportation applications. Accordingly it deserves a full subsection for its explication.

In any electrical grid there are multiple demand patterns. Industrial demand tends to be a fairly constant load. Agricultural demand primarily reflects seasonally varying irrigation needs. Commercial demand is strong during weekday business hours and less on weekends and nighttime. Residential demand peaks in early morning and evening hours. Air conditioning load at residential and commercial users drives a summertime peak, while heating demand causes a secondary winter time peak. Electricity demand from heating and cooling is minimal in spring and autumn. Grid operators need to match supply to demand to avoid frequency drift, brown outs or even grid shutdown. This leads to a demand for dispatchable power which can be called on at need. Generator assets are dispatchable on different response times. Idling generator capacity (spinning reserve) may be dispatched within a minute. Gas peaker plants are designed to be dispatchable on a half hour horizon. Hydropower can be throttled at a similar rate. Combined cycle gas utilities can be throttled up or down in the space of a half day. Nuclear facilities may be taken offline during seasons of low demand. Traditional grids utilize a mix of generating assets to balance supply and demand. Long line high voltage DC interties may loosely link grids to supply dispatchable reserve, particularly between grids with different patterns of imbalance in supply and demand.

Wind and solar generating assets change the basic picture. Solar production is a pretty good match to air conditioning load. But solar production is low to nonexistent from late afternoon through early morning. This creates both a diurnal and seasonal pattern in solar generation. Wind production is very low in summer day light hours and highest in nonsummer nightime hours. So it has a diurnal and seasonal rhythm which is negatively correlated to both solar and to demand. Both solar and wind can suffer week long decreases in production due to local weather.

Long line transmission could potentially shift some Western US solar production to the Eastern grid to meet early evening demand. Transmission can also move Midwestern wind power to the coastal grids.

Finally long line transmission can offset local weather disturbances. Existing lines, however, only support these patterns of use to a very modest degree.

There is also the issue of excess power. Limitations on throttling of solar, wind, nuclear and hydropower generators may result in power being produced in excess of demand. This excess power has zero value. It is thus, theoretically, available to charge storage facilities at very low cost.

When solar and wind generators are first added to a grid, they shift the pattern of supply/demand imbalance. But the shift is within the envelope of dispatchable reserve provided by gas fired utilities. Completing the green transition means phasing out gas fired generators and replacing them with less throttable renewable generators. As a result utilities face an emerging need to add dispatchable power to a renewable based generator base. This need can be subdivided into four time horizons. Grid stabilization services require power which is dispatchable in minute or subminute times to smooth random variation in grid balance. Diurnal dispatch is needed to address the daily imbalance cycle. Long duration dispatch addresses imbalances extending between 8 and 100 hours. Finally seasonal dispatch is needed to address the summer time peak usage.

It is estimated that a decarbonized grid serving a population of 1,000,000 in an advanced economy requires 20 GWh of dispatchable energy in a year with a maximum power of 2 GW. This figure was derived from a study in Australia. Applying it to the US we would estimate that a fully decarbonized grid will require dispatchable power/energy of 660 GW/6.6TWh. To put these numbers in perspective we should note that the nameplate figures for our largest hydropower facility (Hoover dam) are 2GW/10.3 TWh. Normal dispatch from the facility are about 20% of nameplate. The implication is that hydropower facilities can provide much of the energy storage need, but they alone cannot meet the dispatchable power need. Basically faster cycle storage facilities will need to be charged, either by trickle charging from hydrofacilities or by capturing excess power generated from renewables. In particular midday solar and late night wind production will routinely be in excess of demand.

We should also put in perspective the economic challenge of energy storage. Currently pumped hydro facilities store energy at a cost of less than $200 per MWh. A 20 GWh requirement is met at a cost of $4m. This works out to a per capita storage expense of $4. Although energy storage is expensive, it is not going to hold up the green energy transition.

For short cycle supply batteries are proving a competitive storage provider. They are suitable for both grid stabilization and for diurnal cycling. In the later role they are currently displacing gas peaker plants. For the long cycle need batteries are in contention with combined cycle gas utilities and with thermal storage. Currently the best developed thermal storage is plants which liquify air to store power and which regassify it to spin gas turbines and generate power. These plants are sometimes referred to as cryobatteries.

The economics of storage are controlled by two factors: capital cost and efficiency. The capital cost is a one time expense which is recaptured over the design life of the project and which is financed at a blended cost of capital of about 9%. For a 25 year design life this results in a 13% combined interest and amortization rate, whereas for a 40 year project the combined rate is 11.5%. This rate is spread across the number of cycles in a year. If the facility cycles daily the total capital cost per cycle is only 0.03%-0.035%. If the facility cycles weekly then the cost is 0.22%-0.25% per cycle. These capital costs would potentially come down by 20% in a lower rate environment. Operating costs are low, typically only 10% of capital costs. Efficiency determines the raw markup on power cost. For instance an efficiency of 50% marks cost up 2x, whereas an efficiency of 90% marks cost up 1.1x. If the stored power is excess power then the purchased power cost is zero and efficiency does not matter. If the power which is being stored was generated for that purpose, however, then the cost matters.

Let us give some basic figures. A 1 MWh lithium battery will cost about $400,000 but the total capital expenditure on a battery storage system could be $1,000,000 to $1,400,000 depending on project specific details. Typically one would assume a 15 year life, daily cycles and power output for 4 hours. This results in a combined rate of 15.6% or a cycle cost of 0.04%. That works out to a capital expense of $400 per cycle or $0.40 per kWh delivered. If sourced with waste power that is the full cost. Assumed efficiency will be 85%, resulting in a markup of 1.18x on purchased power price. Cheapest unsubsidized solar power is about $29 per MWh so the purchased power cost comes to about $0.034 per kilowatt hour, resulting in a kWh being dispatched at a cost of $0.434. For comparison, the cheapest cost of power from a new gas combined cycle generator is about $45 per MWh, or $0.045 per kWh. However, the battery is dispatchable over seconds whereas the combined cycle plant is only dispatchable over hours.

For the cryobattery the capital cost is about $1,300,000 per MWh. The amortization period is 45 years and with daily cycles that results in a per cycle capital cost of $390 per cycle. Efficiency for a standalone facility is about 60% and that rises to 75% when colocated with an industrial source of waste heat. Sited near sources of waste cooling efficiency might rise to 100%. These efficiencies result in power markups of 1.66x, 1.33x and 1.0x respectively. If power is purchased at the lowest solar rate, then delivered power costs $0.034-$0.048 per kWh. The cryogenic solution has a slight edge for the waste power case, whereas the battery has a slight edge in the typical purchased power case.

Unfortunately the cost of stored power is nearly 10x the cost of dispatchable gas fired power. The implication is that fully moving the grid off fossil fuels will be expensive and minimizing the need for power storage will be an important part of that cost control. Optimal mixes of generation technologies, power transmission across time zones and passive measures to reduce air conditioning loads (e. g. by planting shade trees) can all play a part in controlling this cost. Even so, tens of gigawatts of power storage are expected to be required. With such vast demand and high price incentives, we expect this to be an area of substantial technology development. As market forces are not driving this development, government policy choices will play a key role.

For the stationary power application, specific energy and energy density are not important. But capital cost is critical which implies the need for long lived reliable assets. Safety issues are also important as very high power and energies are involved. Efficiency may or may not be important depending on the source of charging power. The stationary power application is almost the opposite of the transportation application in terms of the technical demands it makes.

Current and Emerging Technologies

The Lithium Ion battery was developed for the mobile computing application and perfecting of the technology has made it the price-performance leader for many applications. Its characteristics are

Chemistry	
...cathode	Lithium Cobalt Oxide
...anode	graphite
...electrolyte	polymer gel
Specific Energy (Wh/kg)	100-265
Energy Density (Wh/L)	250-693
Specific Power (W/kg)	250-340
Cycles	400-1200
Efficiency (%)	80-90
Cost ($/kWh)	132
Safety Issues	thermal runaway+fire cobalt toxic few cobalt sources recycling requires care

Its good performance characteristics have made it the dominant technology and thus the benchmark for what an emergent technology must beat. Its safety issues are considerable however.

For automobile applications the current dominant technology is a variant, the NMC battery, which uses a Lithium Nickel-Manganese-Cobalt Oxide as the cathode instead of Lithium Cobalt oxide. Alternately Lithium Nickel Cobalt Aluminium Oxide and Lithium Iron Phosphate cathodes are used. In general specific energy and energy density are similar to Lithium Cobalt Oxide, but the number of cycles can be twice as high which reduces life time cost by about half. Also use of Cobalt is reduced. With the Lithium Iron Phosphate battery risk of thermal run away and fire is reduced. Also Cobalt is entirely eliminated. But these gains come at the cost of somewhat lower specific energy. Currently these batteries are preferred for buses and stationary power applications.

Several technologies are under development which could further improve the performance of Lithium batteries. So called solid state batteries replace the polymer gel electrolyte with a solid material. This results in better energy density and specific energy. It is also allows faster charging and cycles are claimed to be up to 7x higher. Currently solid state batteries are limited to critical applications like pacemakers. But Toyota is planning on using the batteries in cars commencing with the the 2026 model year.

The Lithium Sulfur battery is currently the shiny new toy on the test bench. It has specific energy of 450 Wh/kg and energy density of 550 Wh/L – figures which outperform current batteries by 2-3x. Sulfur is cheap, readily available and relatively nontoxic. Thermal run away and fire seem not to be problems. What is keeping these batteries in the lab and not yet deployed, however, is their limited life. Best claimed values are 1000 cycles. But in general these batteries are still finicky creatures which require careful handing. Making the battery more robust and longer lived is necessary for them to displace the current lithium batteries.

Getting rid of lithium is an attractive goal. Lithium is mostly sourced from desert salt pans and the extraction method uses lots of water which is in scarce supply in deserts. The Sodium ion battery replaces Lithium with Sodium, which is easily sourced from sea water. This battery technology could ultimately deliver lower cost safer batteries than lithium batteries. Current specific energy is in the range of 70 Wh/kg, however. So considerable improvement is required to close the performance gap against the emerging lithium batteries.

In the power storage application lithium batteries have made initial headway, but it looks as if they will be displaced from this role by flow batteries. For a long time vanadium flow batteries looked to be the best contender here, but it now appears that iron flow batteries will actually be the ultimate winner.

For the power storage application iron flow based batteries have strong features: safe, nontoxic, easily sourced materials, long life and low cost. Their key limitation is low energy density , which is less important in this application. ESS is currently shipping an iron flow battery which stores 1 MWh in a shipping container size package (20 foot x 9 foot x 9 foot.) As there is no fire risk, many such modules can be stacked and close packed to provide higher storage capacity. The battery is designed to deliver 145 kW for 8 hours at 880 volt DC. They are rated to unlimited cycles over a 25 year design life. Capital costs are claimed to be as low as $20,000 per MWh. Efficiency of about 70% is expected. These figures suggest the technology is competitive with gas fired power in the waste power case and less than twice as expensive in the purchased power case.

Metal air batteries use an elemental metal in the anode, an electrolyte that is either an aqueous solution or organic solvent and air as the cathode. Aluminum air batteries have demonstrated specific energy of 1300 Wh/kg with a theoretical upper limit of 4300 Wh/kg. However the battery is not rechargeable. The iron-air battery uses an iron anode salted with various catalysts. These batteries have theoretical specific energy of 1431 Wh/kg and are rechargeable. To date, however, they have efficiencies of less than 50%, rather than the 90% typical of Lithium batteries. The first prototypes at grid scale are currently coming online. Design studies for 1GW facilities designed to deliver 10MW for 100 hours have been drawn up.

For truly massive energy storage, however, the cryobattery still looks to be dominant. Highview Power is currently building a 50 MW/300MWh energy storage facility in the UK at cost of $1.31 per watt hour. Design studies for multiple GW scale plants are underway. The technology is proven, reliable and ready for mass roll out. It may end up dominating the waste energy application in which its lower efficiency is less important.

While not yet demonstrated at scale the combination of pumped hydro and battery is easily envisioned. In this design, the battery absorbs large amounts of power quickly which it then feeds more slowly to the pumping facility to build up a large reservoir of stored energy. In discharge mode the reservoir is slowly tapped to charge the battery. The battery can then be discharged quickly to provide high rapidly dispatchable power. For instance a battery discharged over a 4 hour interval joined to a hydro facility which charges the battery over a 20 hour window effectively acts as a power multiplier of 5x on the hydro facility's power rating. The downside of a two stage process is lower combined efficiency – here about 65%.

Market Impacts

Presently the largest market for batteries is electric vehicles, and particularly electric cars. To get a feel for the potential impact of battery improvements we compare the Tesla Model 3 sedan with the Ford Explorer light SUV. The Tesla is priced at $40,000 and in normal driving has an annual operating cost of $600. The Ford is priced at $39,000, but its annual operating cost of $3,700 makes it 75% more expensive over a ten year life. The Tesla's power plant delivers 257 horsepower, while the Ford's 2.3 liter 4 cylinder engine is rated at 300 horsepower. However, the 0 to 60 time of the two cars is nearly identical. In short, these are functionally comparable vehicles. The Tesla's power plant consists of a 471 kg battery and a 81kg motor. The battery constitutes more than half the $18,000 estimated part cost of the vehicle. The Ford's engine weighs only 141 kg and costs about $5,000. But the mechanical package also includes a fuel system, a coolant system, and the power train. These components add about $8,000 in cost, which brings the Ford's total system cost up to the same level as the Teslas. At this point the Ford mechanicals have had a century of engineering refinement and significant improvement in the cost-performance curve is going to be at best incremental. For existing Lithium-metal oxide batteries it looks as if near term improvements of 20% in energy density are possible, while the Lithium-Sulfur battery could deliver cost reduction and energy density improvements of 2-3x over the midterm. These figures suggest the competitive advantage moving towards the Tesla by about $2000 over a two year horizon and by $6000 over a five year horizon. Thus, battery improvement could make the electric vehicle even more competitive against the gas powered vehicle in this price range.

An interesting question is whether batteries can improve enough to make other forms of transportation viable for battery driven vehicles. Light trucks, ferries and various specialized industrial vehicles are already being tried out in this form. In the air, battery powered drones have made a distinct mark in the military sphere. The combination of solar cells and Lithium-Sulfur battery has been demonstrated in the high endurance light airplane. Such systems may compete with satellites in the earth observation and microwave relay roles. However, we think the battery driven airship may prove the better application of battery power in the air. Such vehicles are under construction for tourism purposes and potentially could provide air lift capability to remote regions without landing strips. For moment we do not see batteries competitive in high power applications such as heavy trucks, heavy construction equipment, large marine vessels or passenger airliners. Here we think the future lies immediately with biofuels and carbon offsets.

Battery power storage is another large market which will experience excellent growth driven by adoption of renewable energy. Lithium battery power storage is currently cost competitive against gas peaker power plants. Iron Flow and Iron Air batteries in conjunction with solar and wind may be able to deliver steady power at a price point that retires most fossil fueled power plants. The initial prototype facilities will be looked at carefully to see if they deliver on the claimed reliability and cost factors.

In power systems, solar and batteries both operate in DC mode whereas electrical distribution runs in AC. Adoption of solar and batteries therefore stimulates demand for power conditioning equipment. Such equipment is a meaningful chunk of total system cost and another target for technical improvement.

Country Differences

The solar cell and lithium battery were both invented in the US, but the hostility of Republican administrations to green energy allowed Japan and China to capture these essential technologies. China, with its vast internal market, is now the technology leader in solar cells, lithium batteries and long line power transmission. Transition to new battery chemistries may allow the US to recover some of its ceded technical leadership. The US's federal structure is hobbling its efforts in power transmission and grid modernization.

Europe is the region which has moved most strongly into green energy. So far it has not developed leading positions in many technologies, but it may have a better grasp of system integration issues than its competitors. Some of its design studies are notably ambitious – as reflects the strong role of its universities and think tanks in policy making. The UK seems to be the leader in cryogenic energy storage.

Conclusions

In summary, the pace of battery improvement is likely to drive numerous market developments in capital goods, industry and manufacturing. It is a technology well worth keeping an eye on. In terms of the green energy transition, solar and wind have both progressed to the point where technical improvements, while ongoing, are now incremental rather than revolutionary. Batteries, by contrast, still have the potential for delivering 2x-10x improvements. As such, developments here could significantly effect the green energy transition.