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Developments In Battery Technology - The Solution To Our Energy Problems?

Modern life would be extremely different if batteries were not part of the picture. If we did not have batteries, all electrical appliances would need to be plugged into a socket to run. You probably remember needing to press a button on the television to change the channel, or only being able to use a phone plugged into the wall. Batteries provide engineers with a portable source of electrical energy necessary to most technologies designed today.

In recent years batteries have become of even greater importance to engineers. The threat of climate change has meant energy production is moving from the traditional combustion of fossil fuels to sustainable sources such as wind, solar or tidal. The problem with these sources is that they are unreliable. This means they may produce a lot of energy when little is needed or produce little energy when much is needed. This means solar powered vehicles would be very impractical because you could only use them when the sun is shining. Batteries can solve both of these problems since they work by converting stored chemical energy into electrical energy and engineers are developing them to be powerful enough for use in this way.

The significance of batteries to modern civilisation is demonstrated by the British government's £246 million investment into battery technology development[1]. However this issue is not only important to richer western countries. Innovation in battery technology would improve the lives of poorer developing nations with no access to electricity. In 2014 only 8% of Chad's population had access to electricity, and Nigeria only 57.7%[2]. These countries have extremely sunny climates, and if batteries could store the energy produced from the sun cheaply, their electricity problems would be solved. If engineers succeed with battery technology it would benefit the rich and poor alike.

The invention of the electrical battery came from an accidental scientific discovery by an Italian physician called Luigi Galvani. Galvani conducted experiments at the University of Bologna with dead animals and electricity to see the effects one caused on the other. In one of these experiments, Galvani connected a metal wire to the nerves of a dead frog and pointing the wire towards the sky in a thunderstorm. With each flash of lightening the frog's legs jumped — an observation which would inspire Mary Shelley to write the novel *Frankenstein*. Galvani labelled this animal electricity.

This prompted Alessandro Volta, a professor of experimental physics at Pavia University, to hypothesize it was a chemical reaction causing the convulsions rather than energy stored in the muscles. His theory would be right and, in 1799, after delays caused by the French revolution, Volta would go on to produce the first electrical battery called the voltaic pile. This was a stack of

[1] https://eandt.theiet.org/content/articles/2017/07/government-to-create-battery-institute-for-energy-storage-technologies/
[2] https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS

zinc, copper and brine soaked cardboard discs. The voltaic pile produced a continuous electrical current when a wire was connected to either end of it, but how does sandwiching zinc, copper and sodium chloride solution create electricity?

Figure 1 shows a simple voltaic cell which uses the same principles as Alessandro Volta's voltaic pile. It consists of two different metals suspended in solution called the electrolyte. In the voltaic pile the two metals were zinc and copper and the electrolyte was sodium chloride solution (brine). Because the metals are separated, two half reactions take place. When the wire is connected between the zinc and copper, the zinc atoms lose two electrons forming ions. This is called an oxidation reaction and is shown in the half equation below.

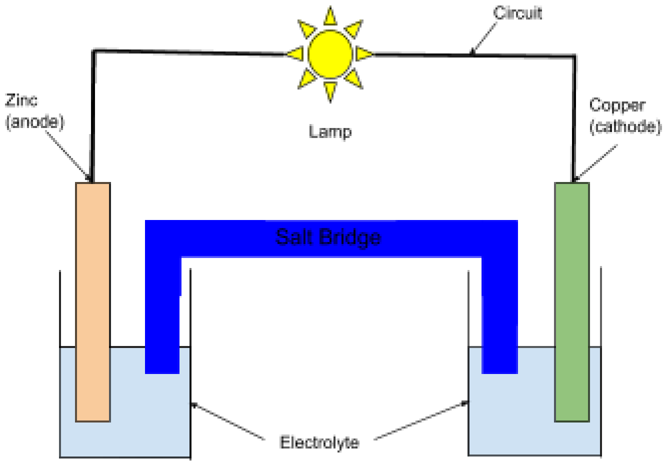

Figure 1: A voltaic cell

$$Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$$

The electrons from zinc atoms flow through the wire to the copper electrode. They travel down the electrode and into the electrolyte solution where there are copper ions. These accept the electrons forming copper atoms and a copper sludge is deposited at the bottom of the beaker. This is called a reduction reaction and is shown in the half equation below.

$$Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$$

The electrons will continue to flow through the wire in this manner, being lost by zinc atoms and gained by copper atoms. This means an electrical current will flow and a potential difference is induced.

Alessandro Volta had invented the first battery and he wrote to the Royal Society in 1799 to share his discovery. The redox reactions involved in his voltaic cell underlie all batteries that have since been developed. Why, however, is this cell not the solution to our energy problems? The main problem is that the reactions are spontaneous. This means you cannot reverse the process so eventually the flow of electrons will stop and the cell will cease to work.

This type of cell is called a primary battery because it is non-rechargeable and can be used only once. Other types of primary batteries are the standard zinc-carbon batteries and alkaline batteries found in supermarkets. Due to their nature of only being used once, these batteries pose great environmental risk. The resources that make batteries are taken from the earth, including energy, but the earth's resources are finite — one day they will be used up. It is unsustainable to continually be taking materials. Primary batteries can be recycled but this uses a lot of energy. Furthermore, batteries that are thrown away are sent to landfill which is an eyesore, leaking toxic chemicals into the earth and consuming valuable land. Engineers must design products that use another type of battery. One that can be recharged and not thrown away. Consequently, the voltaic cell or other primary batteries are not the solution to our energy problems.

Secondary batteries involve chemical reactions that are not spontaneous. This means they can be recharged and reused so are a sustainable solution. There are many examples of secondary batteries, but modern appliances and electric cars mainly use the lithium-ion battery.

A lithium-ion battery contains a negative electrode made of graphite coated in lithium metal and a positive electrode typically made from CoO_2. When the battery is discharging, lithium atoms lose electrons to form ions and the electrons travel around the circuit. At the same time, lithium ions travel from the negative electrode to the positive electrode. Therefore, the chemical equation of the reaction at the negative electrode is shown below.

$$\mathbf{Li \rightleftharpoons Li^+ + e^-}$$

At the positive electrode, a process called intercalation occurs. This is when lithium ions slot into nanoscale gaps of the electrode, gaining an electron and forming a compound. The reaction at the positive electrode is shown below.

$$\mathbf{Li^+ + CoO_2\ e^- \rightleftharpoons LiCoO_2}$$

When the battery is charging, the reverse process occurs and electrons are returned to their starting position at the positive electrode.

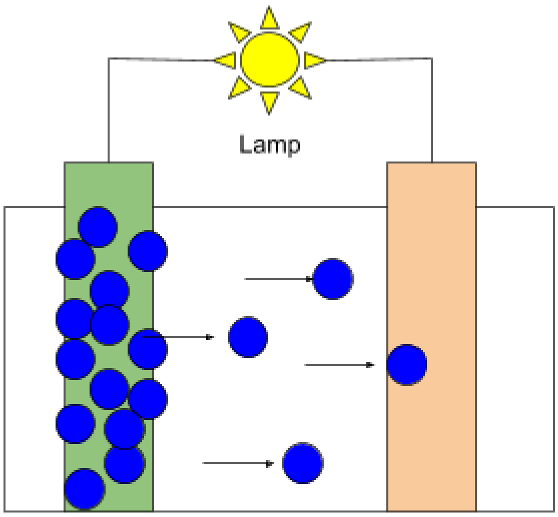

Figure 2: The movement of lithium ions in a lithium-ion cell.

The disadvantage of this type of battery is that they are highly flammable because lithium is a very reactive alkali metal. The South Korean firm Samsung lost heavily in 2016 when they had to recall 2.5 million phones due to the lithium-ion batteries exploding and it cost them $5.3 billion[3]. However, due to lithium being lightweight, lithium-ion batteries have a very high energy density as there are more charge-carrying ions. This makes them extremely popular, shown by the investors showering money into lithium mining shares. The global market of lithium-ion batteries is expected to reach $77.42 billion in 2024, this is an increase of 11.6% from 2016[4].

At the moment, lithium-ion batteries are the unbeaten battery used in electric cars. Engineering visionaries like Elon Musk are paving the way forward with inventions such as the Model S electric car designed by Tesla Motors. It can go from zero to 95 kilometers an hour in 3.1 seconds and can travel about 430 kilometers on a single charge[5]. The problems associated with greenhouse gas emission and sustainability from ordinary petrol or diesel engines will be eradicated when the world switches to electric cars as long as the electricity is generated by a renewable source.

[3] http://www.bbc.co.uk/news/business-38714461
[4] https://www.prnewswire.com/news-releases/lithium-demand-is-growing-as-electric-and-hybrid-vehicles-increase-in-popularity-675985693.html
[5] https://www.newscientist.com/article/mg22730312-200-total-recharge-better-batteries-will-help-us-all/

Slowly, society will adopt this new technology and all cars will be powered by a lithium-ion battery.

Flow batteries are another example of a rechargeable battery. They consist of two electrolyte solutions held in separate containers, two electrodes, and a partially permeable membrane which allows for the exchange of ions and electrons between the solutions. Often the electrolytes are solutions of vanadium ions because vanadium can form many different charged ions. However vanadium is expensive so zinc-bromine solutions are being more commonly used.

The main difference between flow batteries and electrolytic ones such as the lithium-ion battery is that energy is stored as the electrolyte rather than the electrode material. This means they have the potential to store more energy than conventional batteries because they can be bigger. For example, the containers holding the electrolyte solution can be as big as shipping containers. This means flow batteries have the potential to store spare power produced by unreliable sources of energy such as solar, wind or biomass. When the energy produced is not needed, the battery is charged, and when energy supply is in demand the process is reversed and the battery can supply energy to farms, homes or even neighbourhoods.

Harvard School of Engineering and Applied Sciences have developed flow batteries that use organic compounds such as the micronutrient riboflavin (vitamin B2) and quinones. The benefit of using organic solutions is that they are more readily available than metallic solutions traditionally required. In addition, quinones undergo two-electron redox reactions meaning a greater negative voltage can be induced.The quinone rhein (1,8-dihydroxy-3-carboxy-anthraquinone) is obtained from rhubarb, so in the future energy may be stored in rhubarb or vitamin powered batteries!

Currently, engineers have not developed any vehicles for commercial use that operate with a flow battery. Since the main advantage of the flow battery is its ability to store huge amounts of energy, engineers propose to use this battery for grid level storage. The batteries are safe, and can store variable amounts of energy depending on the fluctuating amounts produced by sustainable sources. However, there are limitations as they are expensive to setup and use expensive materials. The quinone electrolyte alternative is cheaper, but it does not have the same performance as the vanadium system. They are very durable, but the the pumps and tubes are difficult to maintain making long term use difficult. These problems all contribute to why flow batteries are not yet used at grid level.

Professor Donald Sadoway and a team of engineers at the Massachusetts Institute of Technology have developed the liquid-metal battery to overcome these problems. This battery uses liquid metal electrodes and a molten salt electrolyte inspired by the process used to extract aluminium. These consist of three layers: the top layer is a light metal, in the middle is the electrolyte and at the bottom is a dense metal. The layers can stay separated due to their relative densities. Figure 3 shows the structure of the battery.

When a wire is connected across the battery, magnesium atoms lose two electrons to become a magnesium ion. The magnesium ion travels across the electrolyte to the liquid antimony, it accepts two electrons here and bonds to antimony to become an alloy. The electrons flow through the wire from the liquid magnesium to the liquid antimony producing an electric current.

$$Mg \rightleftharpoons Mg^{2+} + 2e^-$$

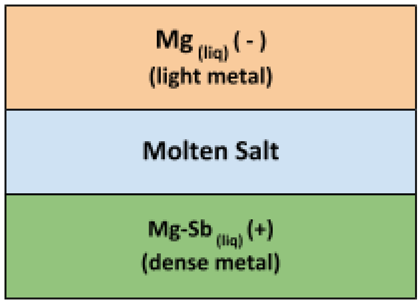

Figure 3: The magnesium-antimony liquid-metal battery.

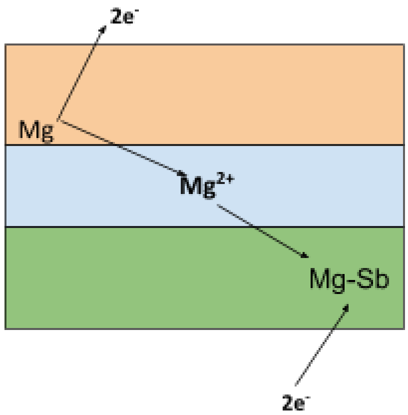

Figure 4: The movement of ions and electrons when discharging.

Sadoway understood from the flow battery that the problem preventing batteries being used for grid level storage was their expense. To reduce costs, he picked two metals that are abundant on earth; they also needed to be highly reactive and have different relative densities. The two metals which fit these conditions used in the liquid-metal battery are magnesium (the light metal on top) and antimony (the heavier metal underneath). The current through the battery generates enough heat to keep it at the right temperature hence minimising running costs. Ambri, the company developing the battery for commercial use, are still researching a seal that will stop air leaking from each individual cell, thus enabling years of high temperature operation. Once that is complete, the battery will be primed for national grid storage systems.

In conclusion, the best solution to storing large amounts of energy necessary for the grid is the liquid-metal battery. It is more suitable than the flow battery because it is cost effective and easy to maintain. The liquid-metal battery will mean we can power electrical appliances using energy derived from the sun even when the sun is not shining. Lithium-ion batteries are already being used in electric cars because of their high energy density. In the future, many more cars will be electrically powered by lithium-ion batteries and perhaps other modes of transport as well. Engineers have been crucial to their development and more importantly all future engineers will design with the purpose of zero greenhouse gas emission and sustainability. Batteries are important to reduce the effect of climate change and the consumption of finite fuels thereby solving the current energy problems faced by society today. However, society must catch on and integrate this new technology to reap the rewards.

Word count:2170

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