

Storage of Electrical Energy*

Batteries and Supercapacitors

Trilochan Bagarti and Arun M Jayannavar

In this article, we will focus on the development of electrical energy storage systems, their working principle, and their fascinating history. Since the early days of electricity, people have tried various methods to store electricity. One of the earliest devices was the Leyden jar which is a simple electrostatic capacitor that could store less than a micro Joule of energy. The battery has been the most popular in storing electricity as it has higher energy density. In this article, we will describe and compare the working of various kinds of batteries and capacitors. We will review the recent technological breakthrough in electrical energy storage devices.

Introduction

Electricity was known to many cultures as a mysterious force of Nature since ancient times. The first scientific study was published in 1600 by William Gilbert in *De Magnete*, and until the beginning of the nineteenth century, no useful application of electricity existed. Today, we are all surrounded by various devices that use electrical energy to function. Energy is stored in the chemical bonds of the materials that are cleverly chosen to make the batteries of these devices. However, more than a hundred years ago, when people were just beginning to understand the nature of electricity with their intriguing experiments, mostly on static electricity, a very simple and useful device was invented—the Leyden jar. It was the first device that could store electrical energy. It consisted of a glass jar with a conducting foil coated on the inner and outer surfaces, and a metal electrode connecting the inner foil that projects through the stopper at the mouth



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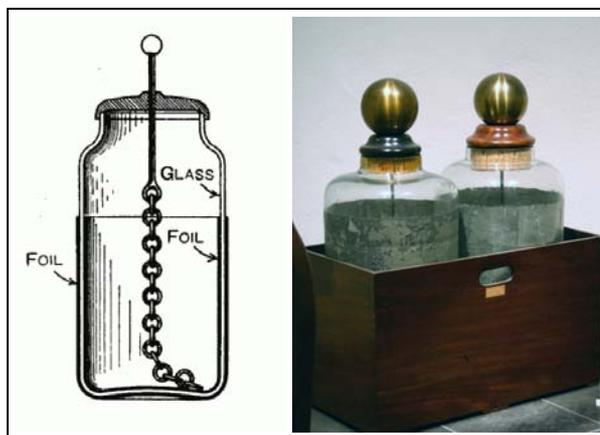
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Keywords

Battery, supercapacitor, pseudo-capacitor, graphene, electrical energy.

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Figure 1. The Leyden jar: Invented by Ewald Georg von Kleist and Pieter van Musschenbroek in 1745–46. (Image Source: wikipedia.org)



The voltaic pile was used immediately to split water.

Figure 1. The capacitors that are manufactured today have fundamentally the same design except that they have become more efficient in storing energy. Today a capacitor can store billions of times larger energy than that of a Leyden jar. How this has been achieved in the course of the past several decades is most fascinating. In the following sections, we shall discuss about batteries and capacitors, and their uses in electrical energy storage. We will see how nanotechnology has enabled the production of supercapacitors. With the recent breakthrough in nanotechnology, it appears that the specific energy of supercapacitors may be comparable to that of certain batteries.

1. Electrochemical Batteries

Although the term ‘battery’ is today used for an electrochemical cell that converts chemical energy to electrical energy, it was actually used for a combination of Leyden jars by Benjamin Franklin. The first battery consisted of zinc and copper disks separated by paper soaked in a salt solution. It was invented by Alessandro Volta, a professor at University of Pavia, Italy in the year 1800. A stack of several disks arranged alternately provided a large potential difference. Unlike a Leyden jar, it was a source of continuous electrical current. It was also used to electrolyse water to obtain hydrogen and oxygen. The voltaic pile is also some-

times called the Galvani cell after its inventor Luigi Galvani who used it to contract frog's leg. He named it 'animal electricity'. Volta, however, believed that electricity arises from the contact of metal electrodes! It was only after 34 years when Michel Faraday showed that electricity arises from the contact at the electrode surface due to the oxidation and reduction reactions. In *Figure 4 (a)* is shown a replication of the voltaic pile. A simplified electrochemical process is shown in the schematic *Figure 4(b)*. Electrons from the zinc anode moves through the external wire and arrive at the copper cathodes, thus, lighting the bulb. In our day to day life, we come across two different kinds of batteries, (1) primary battery, and (2) secondary battery. The primary battery is a one-time use battery. The electrochemical reaction in a primary battery is not reversible. Examples are alkaline and dry cell batteries. The secondary battery is a rechargeable battery and can be used multiple times. The electrochemical reactions in these are reversible. Examples of secondary batteries are lead-acid battery, lithium-ion battery, etc.

Did You Know?

The energy consumption per capita in 2014 was 3.12 kW which is around thrice that in 1970 (*Figure 2*). It simply means that every year the energy consumption increases by 44 Wh per person! As oil and coal reserves continue to deplete and climate change becomes more severe in the future, we will be forced to use more renewable energy. In the next decade, more people will be using electricity than fossil fuel. Future technologies will give us more freedom to use electrical energy as the cost of electricity will reduce.

It reminds us of Michael Faraday who when questioned in 1859 by William Gladstone, British Chancellor of the Exchequer, on the usefulness of electricity, replied, "One day, Sir, you may tax it."

In the following section we will see how the battery works and



Figure 2. World electricity consumption per capita (Image source: www.iea.org)

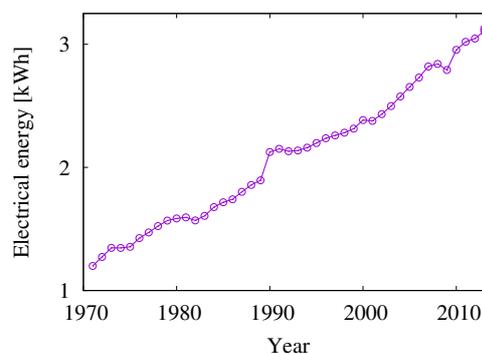
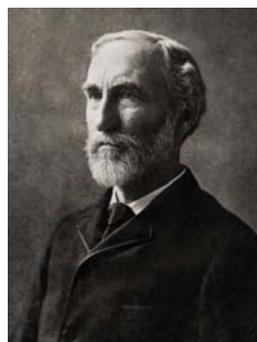


Figure 3. Josiah Willard Gibbs (1839–1903), American theoretical physicist, one of the founders of statistical mechanics, introduced the concept of chemical potential. For a mixture of N different species, Gibbs gave a general expression for the change in energy $dE = TdS - pdV + \sum_i^N \mu_i dN_i$. The chemical potential $\mu_i = \partial E / \partial N_i$ at constant entropy S , volume V , and particles N_i . In any open system undergoing a spontaneous process, Gibbs potential $G = H - TS$ attains a minimum. (Image courtesy: www.wikipedia.org)



try to understand the basic principles involved.

2. Spontaneity and Gibbs Free Energy

Natural spontaneous processes are easy to witness. Water flowing down a stream, smoke rising from a chimney, and the freezing of a lake during winter in cold countries are some examples of spontaneous processes. Have you ever wondered how a spoonful of sugar added to a cup of water spontaneously dissolves and vanishes into the water in a few minutes? It dissolves because by doing so the system goes to a lower free energy state. The second law of thermodynamics demands that the entropy of an isolated system always increases. Here, in this particular example, the Gibbs free energy of the system decreases. In all spontaneous processes that we observe, Nature somehow tries to remain in the lowest free energy state.

Consider a jar filled with white marbles upto say one third from the bottom and on top of it are filled up to the same height, black marbels. So we have black marbles on top of white marbles—a very ordered state. Now shaking the jar well for some time will mix the marbels, and we get a completely disordered state. In going from an ordered state to a disordered state we have just increased the entropy, i.e., the change in entropy $\Delta S > 0$. At the molecular level, for the sugar molecules, the shaking is done by the thermal energy. The Gibb's free energy change of the system in this example is $\Delta G = -T\Delta S$ where T is the temperature. In general, Gibbs free energy change $\Delta G = \Delta H - T\Delta S$, where ΔH is the enthalpy or the heat absorbed at constant pressure. However, in a closed thermodynamic system, i.e., a system at constant volume and temperature, one defines the Helmholtz free energy, $F = U - TS$. Note that instead of enthalpy, here we have the internal energy U . A spontaneous process in general is given by a positive entropy change as demanded by the second law. From processes at constant temperature and at constant volume/pressure a spontaneous process may be defined by the Helmholtz and Gibbs free energy change:

$$\Delta F < 0, \quad (\text{at constant volume, temperature}), \quad (1)$$

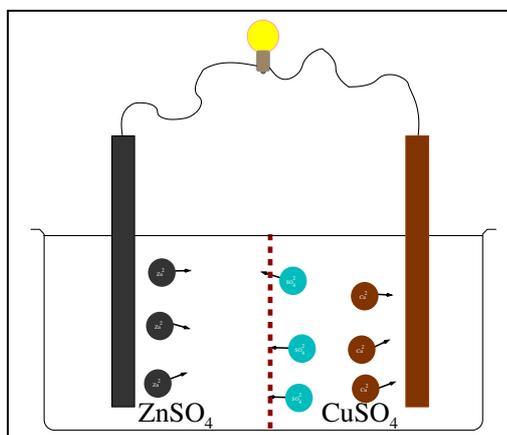
$$\Delta G < 0, \quad (\text{at constant pressure, temperature}). \quad (2)$$

At equilibrium, the free energies attains a minima, hence $\Delta F = 0$ and $\Delta G = 0$, and there is positive free energy change for a non-spontaneous process.

Before the invention of his voltaic pile, Volta performed hundreds of experiments with different pairs of metals and found that when two dissimilar metal pieces are brought in contact with each other, they acquire opposite charges. Although at that time, it was not known that it was the electron that moves from one metal to the other creating a charge imbalance. Note that we can see great similarities between our marbles in the jar example and the electrons in the metals. The only difference here is that unlike marbles, electrons cannot be distinguished with colors, and they possess a negative charge.

In all spontaneous processes that we observe, Nature somehow tries to remain in the lowest free energy state.

Figure 4. What goes on in a voltaic pile? : (a) Replication of a voltaic pile (Image courtesy: www.wikipedia.org), (b) Simplified electrochemical cell: Copper has a higher electron affinity as compared to that of zinc. Electrons rush through the wire from zinc to copper. An electric field is produced inside the media which drives the positive ions towards copper and negative ions towards zinc. This results in the formation of zinc sulfate in the left half cell and deposition of copper on the electrode in the right half cell. The semi-permeable membrane allows the passage of sulfate ions from the right to the left half cell.



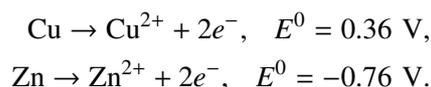
3. How Batteries Work?

Consider the zinc and copper electrodes in a voltaic pile. Copper has a free electron density of $n_{Cu} = 8.59 \times 10^{28}/m^3$ and that in zinc is $n_{Zn} = 1.31 \times 10^{29}/m^3$. It is easy to find these densities simply by considering the unit cells of zinc and copper and the number of electrons in it that can contribute to an electrical current. If the electrons had no charge, the electrons would simply move from zinc to copper, and there would be an equilibrium density of 1.08×10^{29} electrons in each of the metal pieces. Due to the charge transfer, there develops a potential difference across the contact surfaces called the ‘contact potential’ or the Volta potential. Let us assume that n electrons move from the zinc plate to the copper plate. The free energy change is given by $\Delta G = \Delta E + \sum_i \mu_i \Delta N_i$. The first term is the change in the internal energy due to the contact potential, and the second term is that due to the change in the number of particles. At equilibrium we have $\Delta G = 0$. Here, we just have one species, hence we should have, $0 = -en(\phi_{Cu} - \phi_{Zn}) + \mu_{Cu}n + \mu_{Zn}(-n)$. Note that ΔN is positive for copper and negative for zinc. Rearranging the terms gives us $\mu_{Cu} - e\phi_{Cu} = \mu_{Zn} - e\phi_{Zn}$. In general, the following quantity may be constant across a contact surface

$$\mu_0 + q\phi = \text{const}, \quad (3)$$

where μ_0 is the intrinsic chemical potential.

In the voltaic pile, there are two contact surfaces—the contact between the copper plate and the wet paper soaked in salt solution and the contact between the zinc plate and the wet paper. We know that a salt solution does not conduct electricity by the free movement of electrons. Instead, it conducts by the movement of oppositely charged ions. To understand how this happens, we have a simplified Voltaic cell in *Figure 4 (b)*. It consists of a zinc and copper electrode in zinc sulfate and copper sulfate solution which is separated by a semi-permeable membrane in the middle. The semi-permeable membrane allows the passage of sulfate ions only. As we saw earlier, zinc loses electrons through the wire and acquires a positive charge while the copper electrode accepts those electrons and becomes negatively charged. Hence zinc is oxidized by the loss of electrons, and copper is reduced by the gain of electrons. We call the zinc plate the ‘anode’ and the copper plate the ‘cathode’. The cell potential is given by the difference in the standard reduction potential of the cathode and the anode, i.e., $E_{\text{cell}} = E_{\text{cathode}}^0 - E_{\text{anode}}^0$. The standard reduction potential is measured with respect to the standard hydrogen electrode at 25°C with unit activity of all the ions species involved in the reaction. [3] From *Figure 4(b)*, the left and the right half cells can be written as follows:



The negatively charged copper electrodes attract Cu^{2+} in the copper electrode, and the SO_4^{2-} sulfate ions get attracted to the positively charged zinc electrode. As a result, zinc sulfate (ZnSO_4) is formed in the left half cell, and Cu is deposited on the right electrode. Of course, there has to be a movement of a sulfate ion through the membrane to balance the total charge to zero. In this process, zinc is oxidized by losing two electrons, and copper is reduced by gaining the same number of electrons. This is called a ‘redox reaction’. The potential difference can be obtained from the standard electrode potentials E^0 of zinc and copper, i.e., from the half-reaction described above, we have $E_{\text{cell}} =$

$E_{\text{cathode}}^0 - E_{\text{anode}}^0 = 0.34 - (-0.76) = 1.10\text{V}$. The change in free energy $\Delta G = -nFE_{\text{cell}}$, where $n = 2$ is the number of moles of electrons transferred, $F = 98654$ Coulombs charge in a unit mole of electrons is the Faraday constant. So the amount of energy stored in a battery with anode and cathode weighing 65 g and 1 molar concentration solution of the salts will be 2.17×10^5 J.

Lead-acid battery was the first rechargeable battery.

The Voltaic cell was a milestone in technological advancement. It started a whole new branch of study called 'electrochemistry'. Within months of the invention of the voltaic pile, several discoveries were made, such as the splitting of water into hydrogen and oxygen, and the isolation of various alkali metals. The Voltaic cell converts chemical energy spontaneously into electricity and is a primary battery. We will next look at the working of rechargeable or secondary batteries.

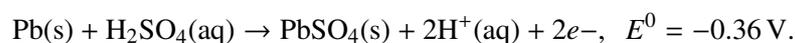
4. The Rechargeable Battery

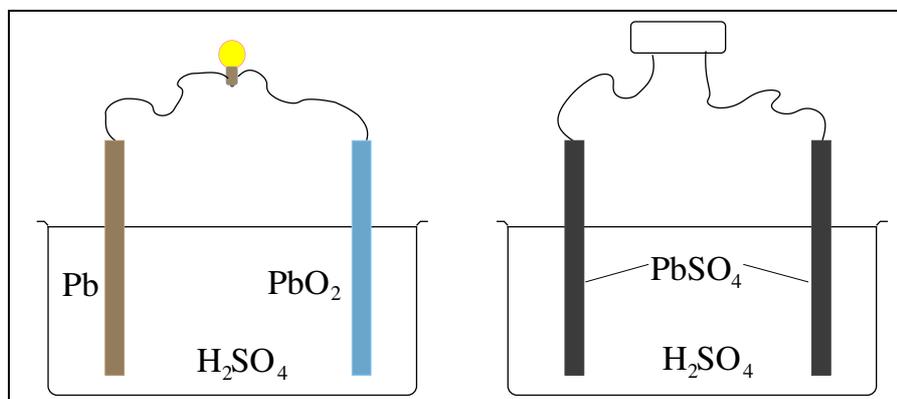
The Voltaic cell is a one-time use battery because as the zinc electrode is consumed its potential drops to zero. In 1859, the French physicist Gaston Planté invented the first rechargeable battery, the lead-acid battery. The battery consists of a lead anode and a lead dioxide cathode in the charged state. During the discharging process, the electrodes are converted to lead(II) sulfate electrodes. After the battery is fully discharged, the battery can be recharged by applying a voltage with the opposite polarity. To understand the working of a lead-acid battery, we need to look at the redox reaction that takes place on the electrode surfaces during the charging and recharging process. During the discharging process, we have [4]

Cathode:



Anode:





The net cell reaction is given by



The working of a lead-acid battery is shown in *Figure 5*. Note that during the discharging process, the lead-acid battery acts just as a Voltaic cell where lead is oxidized at the anode, and lead oxide is reduced at the cathode to form lead sulfate. During the recharging process, the opposite reaction takes place, and the lead sulfate converts back to lead and lead oxide electrodes. From the standard electrode potential, we obtain a cell potential of $E_{\text{cell}} = 2.05 \text{ V}$. In reality, the voltage of a lead-acid cell may range from 1.8–2.1 V. Recently, in a very interesting paper, it was shown that lead being a heavy element, out the 2.1 V in a cell, 1.7–1.8 V arises due to relativity! [5] The lead-acid battery brought a revolution in electrical storage devices.

Today there are various other rechargeable batteries in use. The lithium-ion battery is the most advanced with the highest energy density. Although its development dates back to the seventies, the first commercial battery was introduced in 1991 by Sony and Asahi Kasei [11]. There are several types of lithium-ion batteries such as lithium cobalt oxide (LiCO_2), lithium manganese oxide (LiMn_2O_4 , Li_2MnO_3), lithium nickel cobalt manganese oxide (LiNiMnCoO_2), lithium iron phosphate (LiFePO_4), etc. The specific energy varies from 100–265 Wh/kg. In lithium-ion batteries,

Figure 5. Working of a lead-acid battery. (a) Discharging cycle, and (b) Charging cycle.

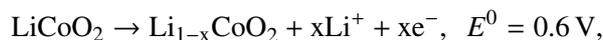
Relativity makes the lead-acid battery work!

the lithium ions move from the cathode to the anode and vice versa during the charging and discharging cycles in a reversible process. Due to this mechanism of the lithium ions moving back and forth, it is called a ‘rocking chair’ battery. In general, we can represent the overall process by



where Li_xA is a compound that can readily accept and exchange lithium ions and B is another lithium accepting compound [13]. Here, the process going from left to right represents discharging, and the reverse process represents the charging cycle. As an example, we consider the lithium intercalation reaction of LiCoO_2 and graphite [5].

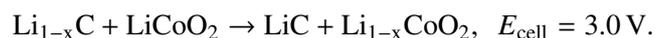
Cathode:



Anode:



Here the cobalt reaction is reversible when $x < 0.5$. The net reaction can be written as



There are various other rechargeable batteries with varied specific energies. Lithium-ion has one of the highest specific energies in electrical energy storage system. [6, 7, 8]

Did You Know?

The nickel-iron (NiFe) battery was invented by Thomas Edison in 1901, and it could last for one hundred years! Although it has a lower operating voltage of 1.2 V, it has a very simple design and uses aqueous potassium hydroxide electrolyte which is very commonly available. The battery was used as a power source for the electric vehicle made by Detroit Electric and Baker Electric [12].



5. What are Supercapacitors?

Supercapacitors, as the name suggests, are capacitors with extremely high capacitance. A typical supercapacitor may have a capacity of 100–1000 farad (F). The capacitance arises from an extremely high surface area electrode material such as charcoal, graphene, carbon nanotubes, etc. A large number of ions get adsorbed on the surface during the charging process. Unlike the electrostatic capacitor, it consists of a positive and negative electrode separated by a porous membrane with an electrolyte in between. There are three different types of supercapacitors: (1) electric double-layer capacitor, (2) pseudocapacitor, and (3) hybrid capacitor. The electric double-layer capacitor charged ions are separated in a Helmholtz layer that lies at the interface of the electrode and the electrolyte. The process of charging and discharging is purely non-Faradaic. A pseudocapacitor consists of an electric double-layer capacitor and a Faradaic redox reaction. It is achieved by the use of transition metal oxides such as MnO_2 , RuO_2 , etc. The hybrid capacitor is a type of supercapacitor that utilizes both electric double-layer mechanism and intercalation of ions.

Now, before we proceed further, it is important to first understand how large is a farad? Let us construct a capacitor with an aluminium foil of area $10 \times 10\text{cm}^2$ as electrodes separated by a piece of paper. If we connect the electrodes to a battery, a charge (Q) will be accumulated on the foils which is equal to the capacitance (C) times the applied potential difference (V). The capacitance of this capacitor is $C = \epsilon_r \epsilon_0 A/d$ where A is the area of the foil, d is thickness of the paper, ϵ_r is the dielectric constant and $\epsilon_0 = 8.85 \times 10^{-12} \text{F/m}^2$. Assuming that the paper has a dielectric constant $\epsilon_r = 2.5$ and thickness $d = 0.01\text{mm}$, the capacitance can be computed to be $C = 2.2 \times 10^{-9}$ farad or $C = 2.2$ nano farad (nF). This is the capacitance of a typical Leyden jar! Charging it with a $V = 12$ Volt battery will, therefore, store energy $E = CV^2/2 = 0.16 \times 10^{-6}$ joules of energy. Note that the energy stored in a capacitor is propor-



¹ 1 Pascal = 1 Newton/meter².

tional to the square of the potential difference. Now to understand how big or small 0.16×10^{-6} J is let us consider the rubber band of length $l = 10$ cm and see how much energy is required to stretch it by 10 cm. The spring constant can be obtained using the Hooke's law which says that stress (σ) is equal to the Young's modulus (Y) times the strain (ϵ) in a material, i.e., $\sigma = Y\epsilon$. Let us assume that the rubber band has a diameter $d = 1$ mm and we have $Y = 0.0015$ giga Pascal¹, then the spring constant $k = YA/l = 0.0015 \times 10^6 \pi d^2 / l = 0.015\pi$ Newton/meter. The energy stored in a spring which is stretched by an amount of x in length is $E = kx^2/2$. So if we stretch the rubber band by $x = 1$ cm we require energy $E = 0.015\pi(10^{-2})^2/2 = 0.23 \times 10^{-5}$ joules. This is around ten times more energy than that can be stored in the Leyden jar. In other words, we will need ten Leyden jars to stretch the rubber band by one centimeter!

Our comparison of the energy stored in a capacitor with that of a battery shows that to use capacitors for electrical storage, we need huge capacitance. The capacitance can be increased in two ways, one by increasing the area of the electrodes and two by increasing the dielectric constant. In recent years, there has been so much excitement and hope in utilizing the former by the use of advanced materials such as graphene. We shall come back to it later but first, let us see how a supercapacitor works. In 1957, H. Becker registered the first patent of an electrolytic supercapacitor that was constructed by the use of porous carbon electrodes and an electrolyte. It had a capacitance of around 6 farads, but he had no idea what gave rise to such a huge capacitance [1]. It was, of course, due to the large surface area of the electrodes that was responsible for the rise in capacitance. However, the working of a supercapacitor is slightly different from that of an electrostatic capacitor. In *Figure 6* we have a simple design of a supercapacitor. It consists of two electrodes with large surface areas usually made of carbon-based materials such as activated charcoal, graphene, carbon nanotubes, or a combination of the three. In between the electrodes, there is an electrolyte and a porous membrane that allows the passage of ions. The porous electrode is in

Around ten Leyden jars can stretch as a rubber band by one centimeter.



contact with a current collector—usually metallic—that has high electrical conductivity. When the electrodes of the capacitor are connected to an external source, positive and negative ions in the electrolyte move in the opposite directions. They are accumulated on an electric double-layer on the porous electrodes. The double-layer consists of electrons and holes on the porous carbon and oppositely charged ions on the surface separated by a thin layer of the solvent molecules. Now as we discussed earlier, the capacitance C is inversely proportional to the distance d between the electrodes, i.e. $C = \epsilon_r \epsilon_0 A/d$. In a supercapacitor, the separation between oppositely charged ions in the double layer is a few nanometers. Hence, we may say that d is of the order of nanometers. This gives rise to a huge capacitance! This kind of capacitor is called the electric double-layer capacitor.

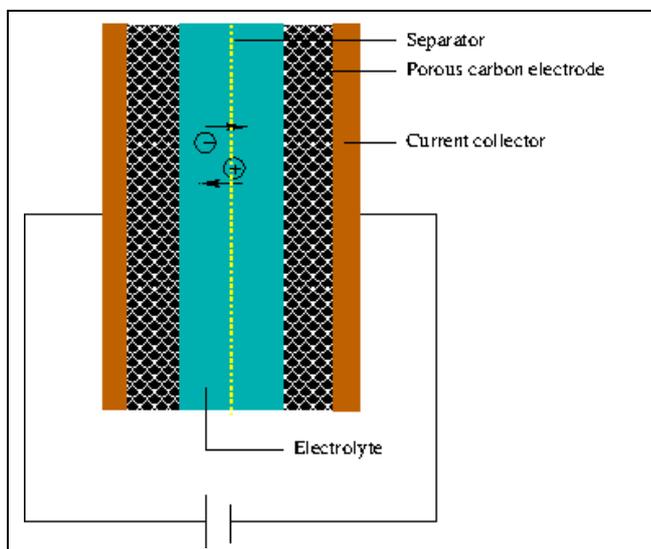
Unlike batteries that can be charged and discharged about 1000–500 times, the supercapacitors practically lasts forever since it has a charge-discharge cycle of 10^6 . The power density of a capacitor is also enormous due to very low equivalent series resistance which remains constant during discharge. Such a large cycle is not possible in batteries since the electrodes degrade due to the redox reactions with every charge-discharge cycle. Although the electric double-layer capacitor stores energy by a completely non-Faradaic process, there are, however, other kinds of capacitors called the pseudocapacitors that utilize a Faradaic charge transfer by the use of transition metal oxides such as RuO_2 , IrO_2 , FeO_4 , MnO_2 , and titanium sulfides (TiS_2). The specific capacitance of pseudocapacitors is larger than that of the electric double-layer capacitors, but they have a lower specific power density. A list of commercially available supercapacitors may be found in [14].

6. Graphene in Supercapacitors

In the last couple of decades, there has been tremendous progress in our understanding of the microscopic world. Graphene is an atomically thin two-dimensional sheet of carbon. It was discovered by Andre Geim and Konstantin Novoselov at the University



Figure 6. Construction of a supercapacitor.



of Manchester (UK), in 2004 [9]. It consists of sp^2 bonded carbon atoms in a hexagonal lattice structure. It has exquisite electrical, thermal, and mechanical properties. The surface area of one gram of graphene is 2630 m^2 and has excellent electrical conductivity. Theoretically, the capacitance of a graphene-based supercapacitor is 550 F/g . Almost all the supercapacitors available in the market use some form of carbon-based electrode with a large surface area. Research is under progress to achieve higher specific energy using graphene-based supercapacitors [10].

7. Present Status of Electrical Storage Devices

In *Figure 7*, we have a comparison of various kinds of electrical storage devices. The lithium-ion batteries have the highest specific energy of around $100\text{--}250 \text{ Wh/kg}$ with a cycle life of around 1000 cycles. The lead-acid battery that remains in use has a specific energy of $30\text{--}40 \text{ Wh/kg}$ ($1 \text{ Wh} = 3600 \text{ J}$) and has one of the highest power density. Of all the batteries sold today, the lead-acid battery comprises around one half due to its cheaper raw materials and simpler technology. Recently, the specific energy of supercapacitors appears to have reached an equivalent of



the lead-acid battery. Although, supercapacitors have a relatively low energy density as compared to batteries its power density is extremely high. In various countries buses equipped with large supercapacitors called *capabus* are being used. The supercapacitor can hold an amount of energy that can run the *capabus* for a few kilometers before getting discharged. However, since the supercapacitors can be charged extremely fast it get recharged every time it stops at a bus-stop on its route. This energy is sufficient to run a few miles till it reaches the next bus stop. This technology has been used in Switzerland, Germany, the UK, the US, and China. The technology is remarkable, not only because it is greener but also its uses almost half the energy required the capacitors have made the bus lighter.

If we look at rechargeable batteries that were used a decade ago, we can recall that they took an awful lot of time to recharge. Today, the rechargeable batteries are equipped with supercapacitors that enable it to charge in a few minutes. These are called the hybrid batteries—use a battery coupled to a supercapacitor. Interestingly, one of the earliest batteries that used this technique is the hybrid lead-acid battery, developed by CSIRO, Australia in 2007. In China, the CSR Zhuzhou Electric Locomotive has built the prototype of a light metro train that uses supercapacitors to run and uses no other power supply [15].

8. Technologies to Come in Future

The future of electrical storage devices is not very coherent at present. Several promising ideas are currently being pursued by researchers around the world. Even at present, the Li-ion battery is many-fold expensive compared to other alternatives. We may see a more powerful lithium battery in the near future. In this direction, the technology that could soon become a reality is the lithium-sulfur battery which has a specific energy density as high as 500 Wh/kg. Recently, researchers at the University of Alberta, Canada, have developed a silicon and graphene-based lithium cell that has a tenfold higher capacity than the currently



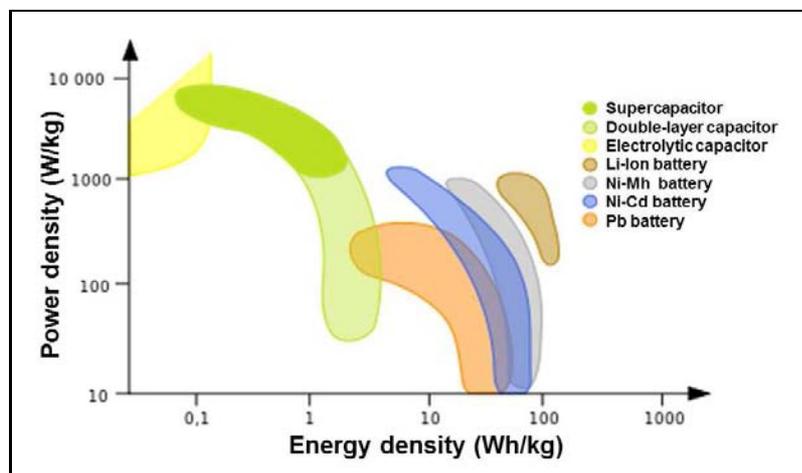


Figure 7. Ragone plot: Comparison of energy storage devices. (Image courtesy: wikipedia.org)

available lithium batteries [16]. It is essential to develop technologies that are not only advanced but are affordable as well. The sodium-ion battery looks very promising as it has a large cycle life of 2000 cycles although the specific energy is low.

Supercapacitors, on the other hand, will make possible technologies in the areas of wearable electronics, energy scavenging, energy storage for microscopic machines, and fast charging hybrid battery systems. In a recent paper [17] structural composites using reinforced carbon nanotubes electric double layer capacitor were proposed which has multiple functionalities. Similarly, supercapacitors that can charge itself with the sunlight has been reported which uses graphene silver 3D foam electrodes [18].

Although the above speculations look very attractive, there are several technological bottlenecks in realizing them. To increase the specific energy of supercapacitors, one needs to design extremely porous and highly conducting electrodes. Furthermore, one should utilize pseudocapacitance by the incorporation of transition metal oxides. Currently, we have in the market batteries that have an inbuilt supercapacitor. These supercapacitors allow fast recharging of the battery

Did You Know?

The bacteria present in the soil can be used to produce electricity. In 1911, M. C. Potter, a professor in botany at the University of Durham, used *S. cerevisiae* a kind of yeast used in winemaking to generate electricity. In 1931, B. Cohen constructed a microbial half cell that could generate 35 V with a very small current of 2 milliamperes [19]. Recently, scientists at the Wageningen University and the Wageningen Research foundation had designed a plant microbial fuel cell called plant-e that produces electricity from plants [20]. The fuel cell works using the mutual cooperation of bacteria present in the soil and the plants (*Figure 8*).

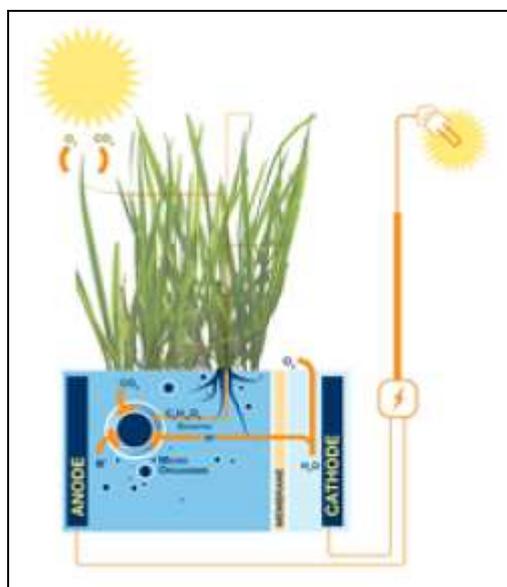


Figure 8. Plant microbial fuel cell (Image courtesy: John Wiley & Sons.)

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Suggested Reading

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