

## Chapter 7

# Power Storage Devices

(Batteries, Capacitors, and Super-capacitors)

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## Li batteries and Li ion batteries

Two types of Li batteries:

- 1) Li electrode (old)
- 2) Li<sup>+</sup> insertion

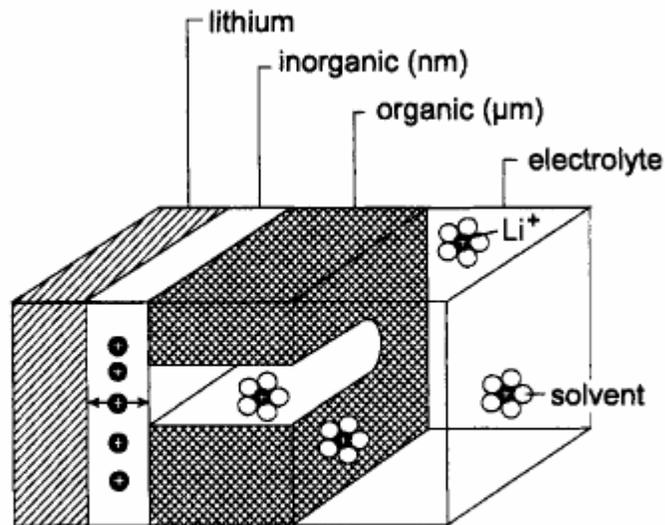
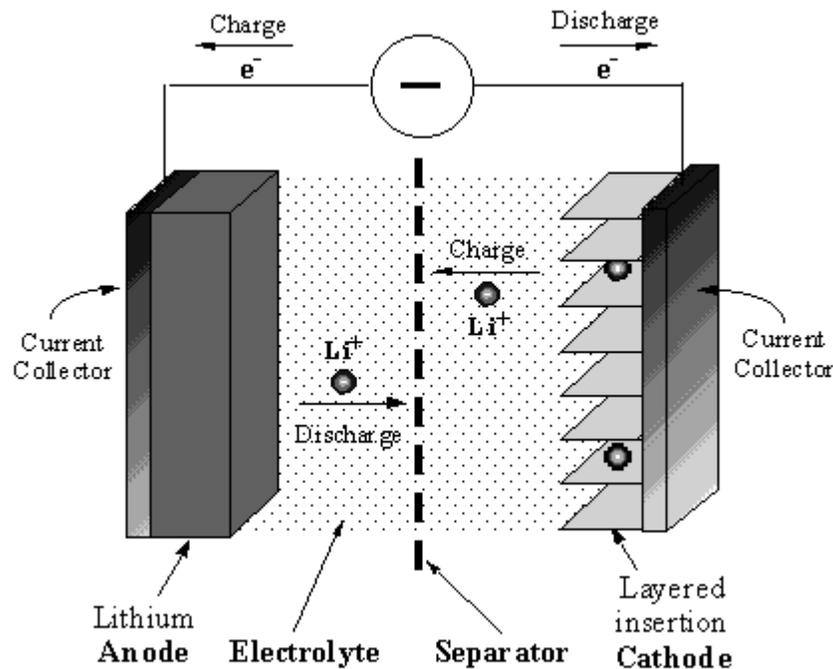


Fig. 1: Schematic representation of protection of lithium in organic solvent-based electrolytes, from (ref. 18).



**Figure (1) Lithium Insertion Battery**

Lithium batteries work by shuttling lithium ions between the anode and cathode of the battery. The anode, source of the ions and electrons, is elemental lithium (or a lithium-containing compound) and the cathode, receptor of the ions and electrons, is a material capable of accepting lithium ions into its structure. When a battery is discharged, lithium ions flow from the anode to the cathode, accompanied by electrons. This flow of electrons is electrical current and can be used to power portable devices such as laptop computers. The battery can be charged by supplying an external electric current, which drives the lithium ions back to the anode. This charging process "resets" the anode and cathode so that the battery can once again power your laptop through a hectic day.

#### Types of Batteries:

**Non-rechargeable batteries (Primary batteries):** to be used until discharged and then discarded (hopefully recycled); Both conventional (Zinc and graphite) and alkaline batteries belong to this class.

**Rechargeable (secondary) batteries:** are a breed apart. We buy them to last and we want them to be ready anytime after recharge. Two main types of rechargeable batteries dominate the market right now: **Lead-acid** and **Nickel-Cadmium** batteries.

**Lead** batteries have been hiding in our cars for many decades. The electricity they provide is only used for starting, lighting and ignition (SLI), **Disadvantage: Low energy per unit weight.**

**Nickel-Cadmium** batteries (NiCad) were adopted for feeding small appliances such as videocameras, and portable phones and computers. **Disadvantages:** 1) they run out of charge too quickly, even when not in use and they have a tricky "memory effect" that causes a loss of capacity. 2) **highly toxic**, especially **lead and cadmium.**

And yet, the market demand for rechargeable batteries will keep growing in the short run. Research on lighter batteries with increased energy densities for the consumer market is urgently driven by the electronics industries. **We need small batteries.**

**Electric vehicles will emerge.** Most demanded part of electric car.

Very clean and environmentally friendly.

**Example of new candidate batteries are: Sodium/Sulfur, Zinc/Air, Metal Hydride/Nickel Oxide and Lithium batteries.** All of them have specific advantages and drawbacks but for the consumer market most experts agree that **lithium batteries**, together perhaps with **metal hydride** are the ones with a stronger potential. Metal hydride technology has been developed earlier, but lithium technology is catching up quickly with market demands.

Why is Li ion battery good??

1) Li element is very light metal, little weight only. (Figure (2)).

Carga específica para distintos ánodos

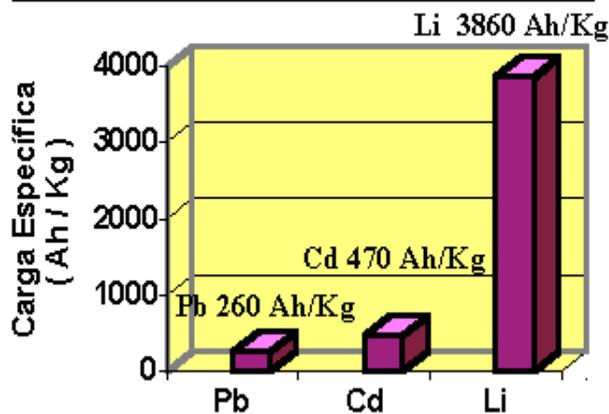


Figure 1. Specific charge for lead (Pb), cadmium (Cd) and lithium (Li) anodes.

Masa necesaria para producir 1 Amperio durante 1 hora

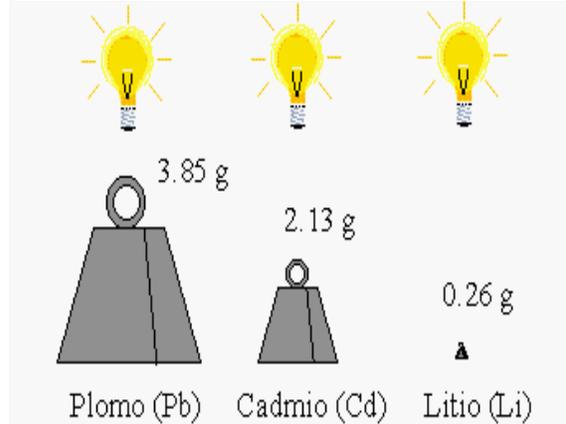


Figure 2. Mass needed to produce 1 Amp for 1 hour

2) Another advantage of lithium ion batteries is that their individual cells provide higher voltages than those of lead or cadmium and this gives you a greater energy density.

- 3) Not harmful to environment.
- 4) Safe
- 5) Highly reversible charge/discharge and long life
- 6) Becoming lower price with more R&D and large production scale.
- 7) Has no memory effect (that occurs in Ni-Cd batteries)

## Lithium-ion batteries and the chemistry behind them.

**The Li battery (Li electrode):** The first laboratory prototypes of **lithium** batteries had positive electrodes (cathodes) composed of metal oxides or sulfides with the ability to **intercalate** and **deintercalate lithium** ions reversibly during the processes of battery discharge and charge. **The negative electrode (anode) in these old lithium batteries was always made of metallic lithium** which would get dissolved during discharged and plated back as metal upon recharging. **But as a metal, lithium is very reactive, represents a potential explosion hazard and that slowed down the development of lithium batteries.**

**The alternative Li ion insertion:** The problem was solved in a most satisfactory way thanks to the introduction of **lithium-ion** technology. In these systems the negative electrode is not made of **lithium metal** but of other safer materials such as graphite or other carbons able to intercalate **lithium** ions.

**Unlike the Li metal, ( $\text{Li}^+$ ) is very stable and unreactive.**

**When intercalated in the negative electrode, its potential is much lower than when in the positive electrode (this difference of potential is in fact the source of the energy in every battery) but explosive reactivity is absolutely eliminated.**

The battery works with **lithium** ions shuttling from one electrode to the other through an electrolyte solution. They move spontaneously from the negative to the positive electrode during discharge giving up the energy stored.

During the recharge process we spend energy in relocating those ions back in the place where they don't like to be (the negative electrode). The following animation shows this working mechanism at the atomic level.

**DURING DISCHARGE:** Lithium ions (yellow) spontaneously shuttle from the negative insertion electrode (black) into the electrolyte (blue) and from the electrolyte into the positive insertion electrode (red). **The electrolyte allows the diffusion of ions but prevents electrons flow.** At the same time electrons spontaneously flow through the only way we let them free from the negative to the positive electrode: through the load. As discharge proceeds the potential (E) of each electrode shifts resulting in a decreasing difference between them ( $\Delta E$ ) and thus to a decreasing voltage as we get charge (Q) out of the battery.

**DURING CHARGE:** **Lithium ions are forced out of the positive into the electrolyte and into the negative electrode.** Electrons are injected into the negative and taken from the positive electrode. In doing so we get the negative potential more negative and the positive more positive thus increasing the difference of potential which can be equated to the voltage.

**NOTE:** We always put more energy into charging than we get back in the discharge (((Explain using thermodynamics))). That is Nature's way. One of our goals is to minimize that difference ((lost energy)).

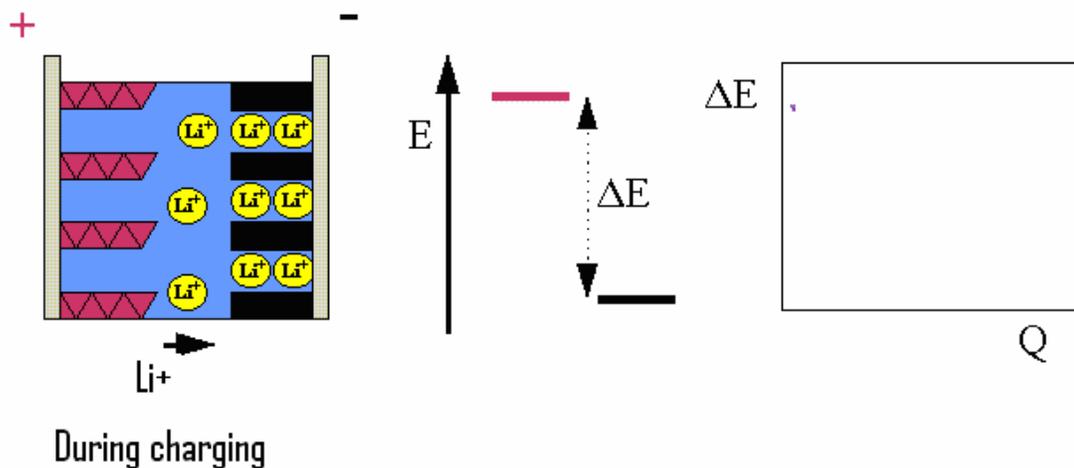
Li ion batteries are in the market.

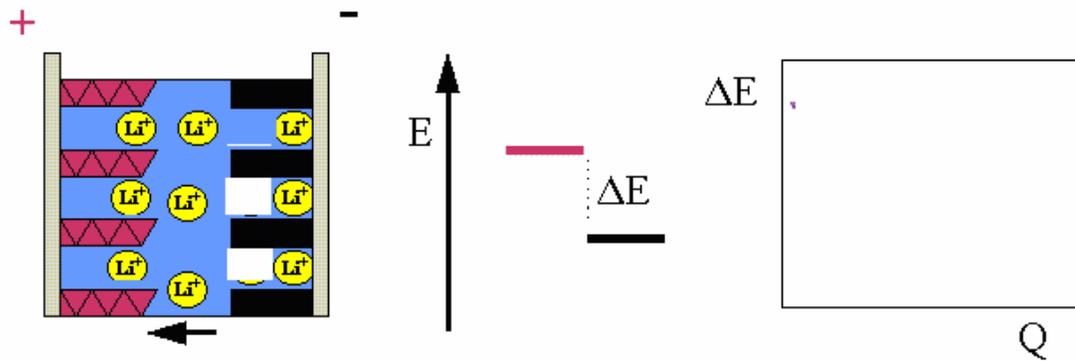
R& D is ongoing to improve and optimize the electrodes. ((Sometimes we see pull from the market)).

Currently: The negative electrode is made of Graphite

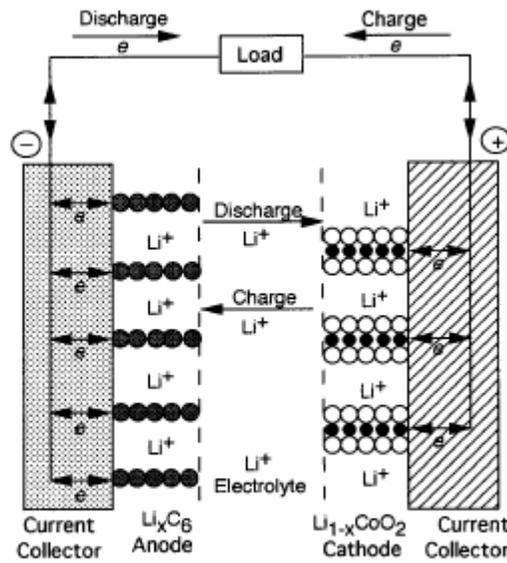
The positive electrode is made of  $\text{LiCoO}_2$ .

We will need more research for electric vehicles.



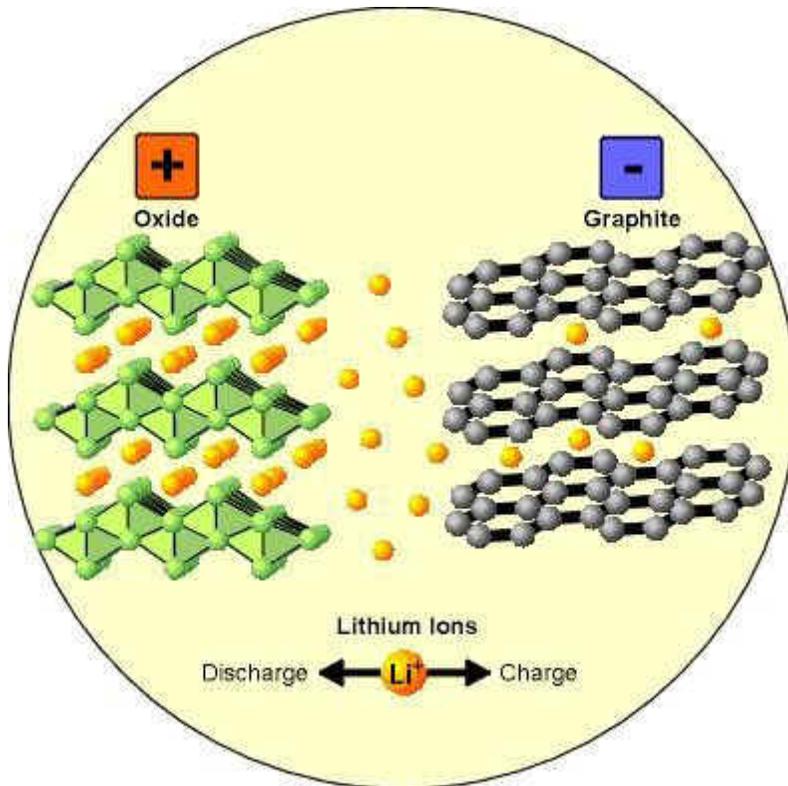


During discharging

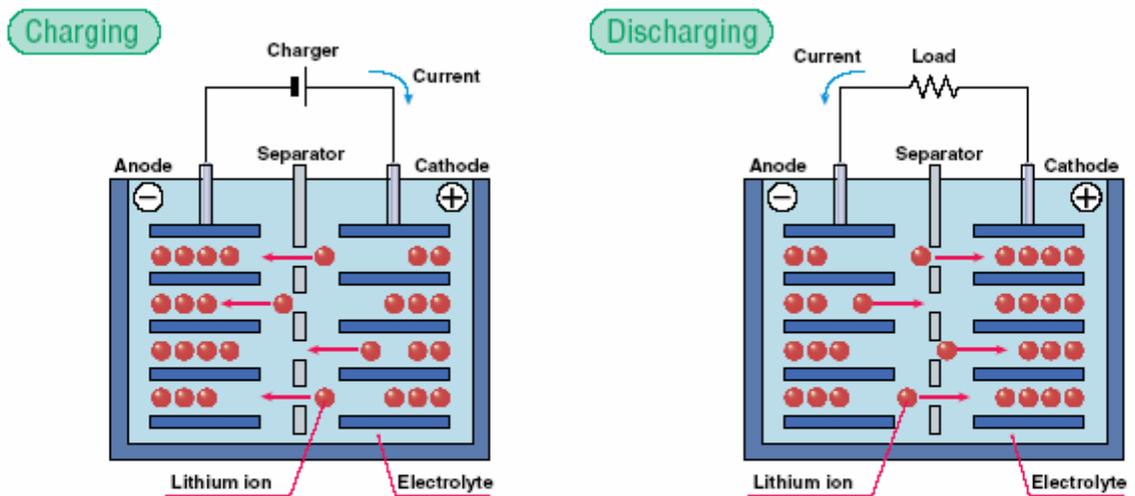


**Figure 6.** Schematic illustration of the discharge and charge processes in a rechargeable lithium ion battery. In the  $\text{Li}_x\text{CoO}_2$  cathode, the solid and open circles refer, respectively, to Co and O atoms (adapted from ref 14).

Taken from A. Manthiram & J. Kim - "Low Temperature Synthesis of Insertion Oxides for Lithium Batteries", *Chem. Mater.* **10**, 2895-2909 (1998).



## Operating principles of lithium ion rechargeable battery



The operating principle of a lithium ion rechargeable battery is shown in the figure above. When the battery is charged, lithium ions in the cathode material move in between the layers of the anode, which is carbon material, thus charging the battery. During discharging, the lithium ions move from the anode to the cathode, and a discharge current flows. In this way, the lithium ion rechargeable battery is charged and discharged only through the movement of lithium ions.

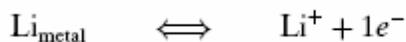
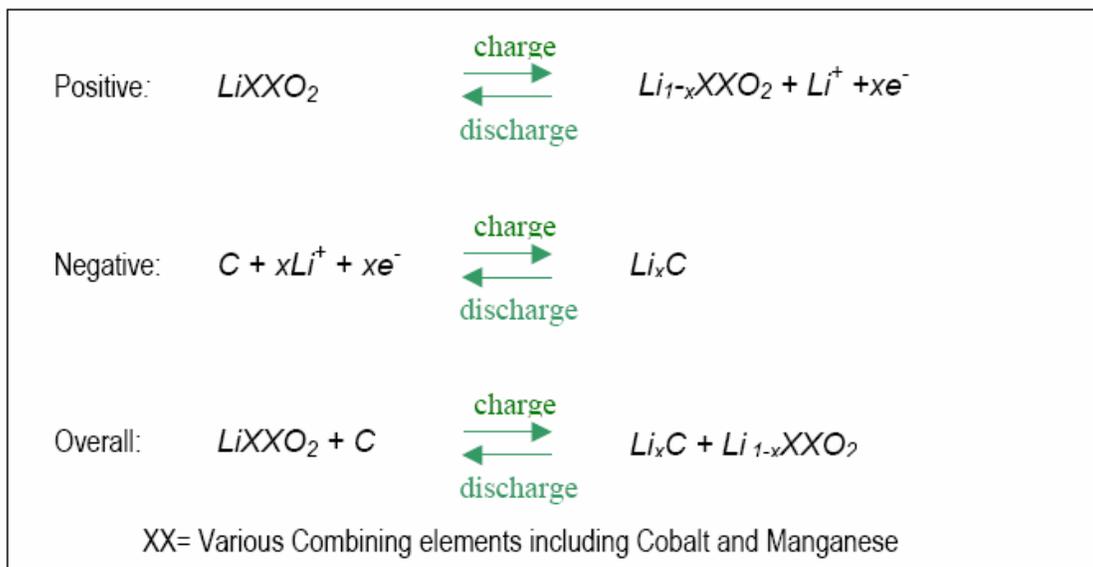
### Li-Ion Principles of Operation

The lithium ion battery employs a metal oxide material (such as lithium cobalt oxide  $\text{LiCoO}_2$ ), or a material with a tunneled structure (such as lithium manganese oxide  $\text{LiMn}_2\text{O}_4$ ) as its positive electrode. The negative electrode is typically a graphitic carbon. During the charge and discharge processes, lithium ions are inserted or extracted from interstitial space between atomic layers within the active material of the battery.

### Charge/Discharge Chemical Reaction

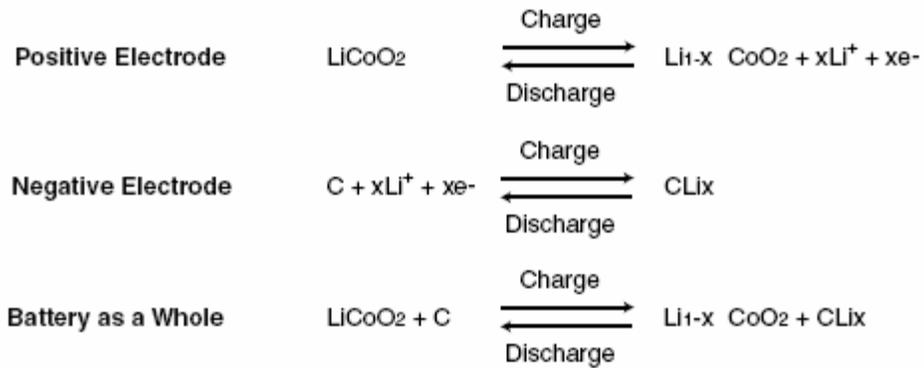
During charge, the positive material is oxidized and the negative material is reduced. In this process, lithium ions are de-intercalated from the positive material and intercalated into the negative material. (Intercalated – a reaction where lithium ions are reversibly removed or inserted into a host without a significant structural change to the host) The reverse process is present during a discharge cycle.

**Figure 5.2.1:** Charge/Discharge Chemical Reactions



The total equation is thus:





Current areas of research:

- 1) Use solid electrolytes, conductive polymer with no solvent.
- 2) Increase energy density
- 3) Smaller sizes.
- 4) New electrode materials; Nanoparticles for the electrodes.

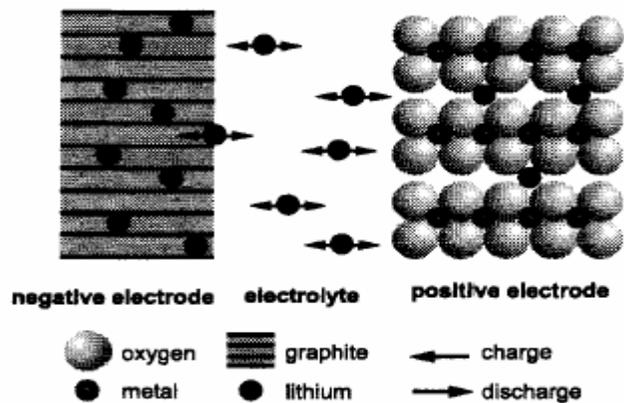


Fig. 3: Operating principle of a rechargeable lithium cell based on  $\text{Li}^+$  insertion materials for the positive and negative electrode (lithium-ion cell), from

(ref. 24).

**During charge** the positive electrode ( $\text{Li}_x\text{MO}_2$ ) provides  $\text{Li}^+$  cations, the negative electrode (graphite) serves for the acceptance of delivered  $\text{Li}^+$  in its interlayer gaps and forms a lithium/graphite insertion compound  $\text{Li}_x\text{C}_6$ .

**During discharge** the  $\text{Li}^+$  cations move back into the layered oxide host matrix. Ref: ((Jurgen Otto Besenhard and Martin Winter , *Pure & Appl. Chem.*, Vol. 70, No. 3, pp. 603-608, 1998. Printed in Great Britain. © 1998 IUPAC

### Polymer electrolyte systems:

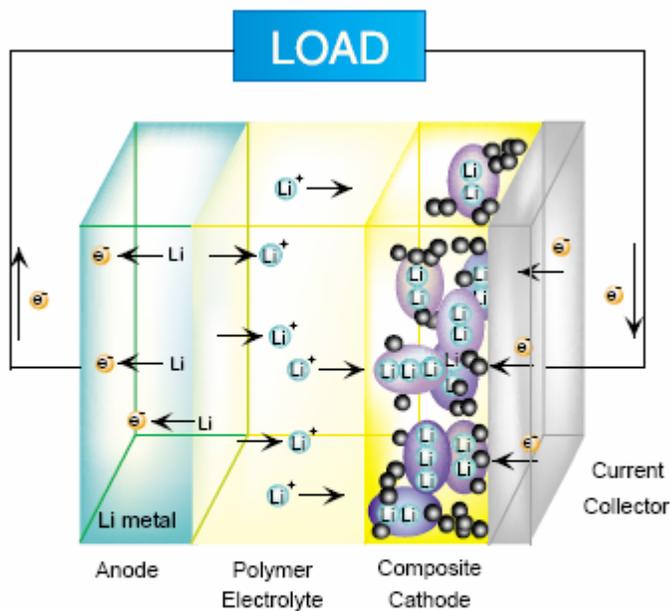
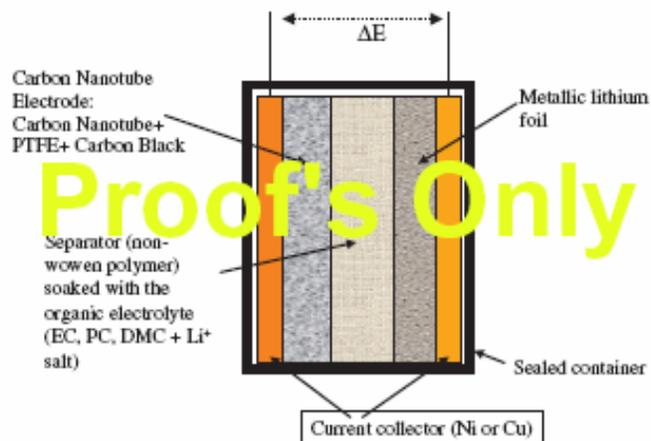


Fig.1 Conceptual structure of lithium polymer electrolyte battery.

### Carbon nano-tube techniques



**Figure 7.** Schematic representation of an electrochemical cell used for characterizing the redox reactions between  $\text{Li}^+$  and the electrode which contains the active carbon (i.e., graphite, CNTs, etc.).

# Applications of lithium ion rechargeable battery

Lithium ion rechargeable battery used as the main power supply for mobile devices mean smaller size, reduced weight, and a longer operating time.

## Communications devices



Cellular phones



Transceivers

Cellular phones, radio devices, transceivers

## Information devices



Notebook PCs



PDA's



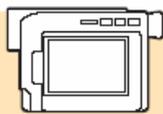
Handy terminals



Printers

Notebook PCs, PDA's, portable photocopiers, hand-held data terminals, digital book players, printers

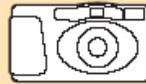
## Audio and video devices



Camcorders



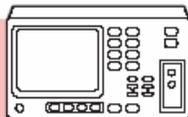
MP3 players



Digital still cameras

Camcorders, MP3 players, digital still cameras, LCDTV's, compact cameras

## Others



Measuring equipment



Portable video games



Blue tooth

Portable measuring equipment, wireless conferencing systems, portable video games, Blue tooth, other new applications

Tips on using Li ion insertion batteries:

- 1) Do not leave at or above 55°C.
- 2) Do not leave un-charged for long time.
- 3) Do not punctures or heat

# CAPACITORS

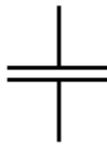
<http://electronics.howstuffworks.com/capacitor1.htm>

## CAPACITORS

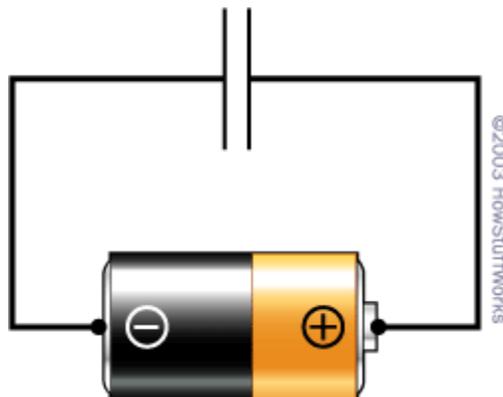
### The Basics

Like a battery, a capacitor has two terminals. Inside the capacitor, the terminals connect to two metal **plates** separated by a **dielectric**. The dielectric can be air, paper, plastic or anything else that does not conduct electricity and keeps the plates from touching each other. You can easily make a capacitor from two pieces of aluminum foil and a piece of paper. It won't be a particularly good capacitor in terms of its storage capacity, but it will work.

In an **electronic circuit**, a capacitor is shown like this:



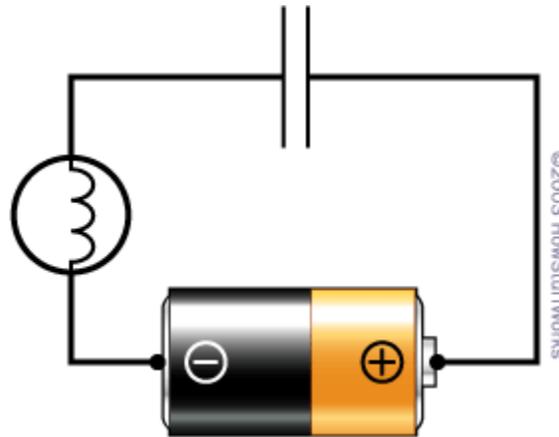
When you **connect a capacitor to a battery**, here's what happens:



- The plate on the capacitor that attaches to the negative terminal of the battery accepts electrons that the battery is producing.
- The plate on the capacitor that attaches to the positive terminal of the battery loses electrons to the battery.

Once it's charged, the capacitor has the same [voltage](#) as the battery (1.5 volts on the battery means 1.5 volts on the capacitor). For a small capacitor, the capacity is small. But large capacitors can hold quite a bit of charge. You can find capacitors as big as soda cans, for example, that hold enough charge to light a flashlight bulb for a minute or more. When you see [lightning](#) in the sky, what you are seeing is a huge capacitor where one plate is the cloud and the other plate is the ground, and the lightning is the charge releasing between these two "plates." Obviously, in a capacitor that large, you can hold a huge amount of charge!

Let's say you hook up a capacitor like this:



Here you have a battery, a [light bulb](#) and a capacitor. If the capacitor is pretty big, what you would notice is that, when you connected the battery, the light bulb would light up as current flows from the battery to the capacitor to charge it up. The bulb would get progressively dimmer and finally go out once the capacitor reached its capacity. Then you could remove the battery and replace it with a wire. Current would flow from one plate of the capacitor to the other. The light bulb would light and then get dimmer and dimmer, finally going out once the capacitor had completely discharged (the same number of electrons on both plates).

### Like a Water Tower

One way to visualize the action of a capacitor is to imagine it as a [water tower](#) hooked to a pipe. A water tower "stores" water pressure -- when the water system pumps produce more water than a town needs, the excess is stored in the water tower. Then, at times of high demand, the excess water flows out of the tower to keep the pressure up. A capacitor stores electrons in the same way, and can then release them later.

<http://electronics.howstuffworks.com/capacitor2.htm>

## Farads

The unit of capacitance is a **farad**. A 1-farad capacitor can store one coulomb (coo-lomb) of charge at 1 volt. A coulomb is  $6.25 \times 10^{18}$  (6.25 billion billion) electrons. One **amp** represents a rate of electron flow of 1 coulomb of electrons per second, so a 1-farad capacitor can hold 1 amp-second of electrons at 1 volt.

A 1-farad capacitor would typically be pretty big. It might be as big as a can of tuna or a 1-liter soda bottle, depending on the voltage it can handle. So you typically see capacitors measured in microfarads (millionths of a farad).

To get some perspective on how big a farad is, think about this:

- A typical alkaline AA [battery](#) holds about 2.8 amp-hours.
- That means that a AA battery can produce 2.8 amps for an hour at 1.5 volts (about 4.2 watt-hours -- a AA battery can light a 4-watt bulb for a little more than an hour).
- Let's call it 1 volt to make the math easier. To store one AA battery's energy in a capacitor, you would need  $3,600 \times 2.8 = 10,080$  farads to hold it, because an amp-hour is 3,600 amp-seconds.

If it takes something the size of a can of tuna to hold a farad, then 10,080 farads is going to take up a LOT more space than a single AA battery! Obviously, it is impractical to use capacitors to store any significant amount of power unless you do it at a high voltage.

<http://electronics.howstuffworks.com/capacitor3.htm>

## Applications

The difference between a capacitor and a battery is that a capacitor can dump its entire charge in a tiny fraction of a second, where a battery would take minutes to completely discharge itself. That's why the electronic flash on a [camera](#) uses a capacitor -- the battery charges up the flash's capacitor over several seconds, and then the capacitor dumps the full charge into the flash tube almost instantly. This can make a large, charged capacitor extremely dangerous -- flash units and [TVs](#) have warnings about opening them up for this reason. They contain big capacitors that can, potentially, kill you with the charge they contain.

Capacitors are used in several different ways in electronic circuits:

- Sometimes, capacitors are used to **store charge for high-speed use**. That's what a flash does. Big [lasers](#) use this technique as well to get very bright, instantaneous flashes.

- Capacitors can also **eliminate ripples**. If a line carrying DC voltage has ripples or spikes in it, a big capacitor can even out the voltage by absorbing the peaks and filling in the valleys.
- A capacitor can **block DC voltage**. If you hook a small capacitor to a battery, then no current will flow between the poles of the battery once the capacitor charges (which is instantaneous if the capacitor is small). However, any alternating current (AC) signal flows through a capacitor unimpeded. That's because the capacitor will charge and discharge as the alternating current fluctuates, making it appear that the alternating current is flowing.

One big use of capacitors is to team them up with [inductors](#) to create **oscillators**. See [How Oscillators Work](#) for details.

For more information on capacitors and related topics, check out the links on the next page.

## How Oscillators Work

by [Marshall Brain](#)

Oscillators are important in many different types of electronic equipment. For example, a [quartz watch](#) uses a quartz oscillator to keep track of what time it is. **An AM radio transmitter uses an oscillator to create the carrier wave for the station, and an AM radio receiver uses a special form of oscillator called a resonator to tune in a station.** There are oscillators in [computers](#), [metal detectors](#) and even [stun guns](#).



To understand how electronic oscillators work, it is helpful to look at examples from the physical world. In this article, you'll learn the basic idea behind oscillators and how they're used in electronics.

### The Basics

One of the most commonly used oscillators is the [pendulum](#) of a clock. If you push on a pendulum to start it swinging, it will oscillate at some **frequency** -- it will swing back and forth a certain number of times per second. The length of the pendulum is the main thing that controls the frequency.

For something to oscillate, energy needs to move back and forth between two forms. For example, in a pendulum, energy moves between **potential energy** and **kinetic energy**. When the pendulum is at one end of its travel, its energy is all potential energy and it is ready to fall. When the pendulum is in the middle of its cycle, all of its potential energy turns into kinetic energy and the pendulum is moving as fast as it can. As the pendulum moves toward

the other end of its swing, all the kinetic energy turns back into potential energy. This movement of energy between the two forms is what causes the oscillation.

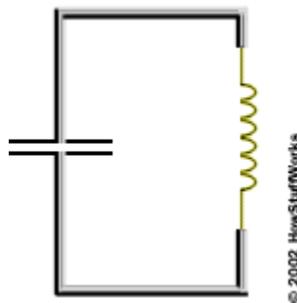
Eventually, any physical oscillator stops moving because of **friction**. To keep it going, you have to add a little bit of energy on each cycle. In a pendulum clock, the energy that keeps the pendulum moving comes from the spring. The pendulum gets a little push on each stroke to make up for the energy it loses to friction. See [How Pendulum Clocks Work](#) for details.

An electronic oscillator works on the same principle.

## Electronic Oscillators

Energy needs to move back and forth from one form to another for an oscillator to work. You can make a very simple oscillator by connecting a [capacitor](#) and an [inductor](#) together. If you've read [How Capacitors Work](#) and [How Inductors Work](#), you know that both capacitors and inductors **store energy**. A capacitor stores energy in the form of an electrostatic field, while an inductor uses a magnetic field.

Imagine the following circuit:



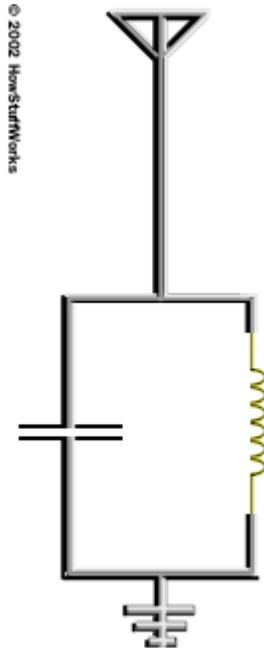
If you charge up the capacitor with a [battery](#) and then insert the inductor into the circuit, here's what will happen:

- The capacitor will start to discharge through the inductor. As it does, the inductor will create a magnetic field.
- Once the capacitor discharges, the inductor will try to keep the current in the circuit moving, so it will charge up the other plate of the capacitor.
- Once the inductor's field collapses, the capacitor has been recharged (but with the opposite polarity), so it discharges again through the inductor.

This oscillation will continue until the circuit runs out of energy due to **resistance** in the wire. It will oscillate at a frequency that depends on the size of the inductor and the capacitor.

## Resonators

In a simple crystal radio (see [How Radio Works](#) for details), a capacitor/inductor oscillator acts as the **tuner** for the radio. It is connected to an antenna and ground like this:



Thousands of **sine waves** from different radio stations hit the antenna. The capacitor and inductor want to resonate at one particular frequency. The sine wave that matches that particular frequency will get **amplified** by the resonator, and all of the other frequencies will be ignored.

In a radio, either the capacitor or the inductor in the resonator is **adjustable**. When you turn the tuner knob on the radio, you are adjusting, for example, a variable capacitor. Varying the capacitor changes the resonant frequency of the resonator and therefore changes the frequency of the sine wave that the resonator amplifies. This is how you "tune in" different stations on the radio!

For more information, check out the links on the next page.

<http://en.wikipedia.org/wiki/Capacitor>

# CAPACITORS

A **capacitor** is an [electrical](#) device that can store [energy](#) in the [electric field](#) between a pair of closely-spaced [conductors](#) (called 'plates'). When voltage is applied to the capacitor, electric [charges](#) of equal magnitude, but opposite polarity, build up on each plate.

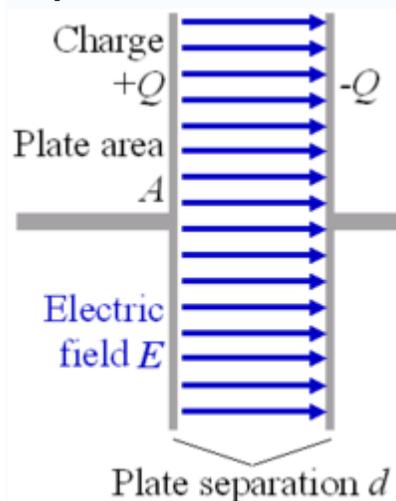
Capacitors are used in electrical circuits as [energy-storage](#) devices. They can also be used to differentiate between high-frequency and low-frequency signals and this makes them useful in [electronic filters](#).

Capacitors are occasionally referred to as **condensers**. This is now considered an antiquated term.

## Physics

A capacitor consists of two conductive [electrodes](#), or plates, separated by an [insulator](#).

### Capacitance



When electric charge accumulates on the plates, an [electric field](#) is created in the region between the plates that is proportional to the amount of accumulated charge. This electric field creates a potential difference  $V = E \cdot d$  between the plates of this simple parallel-plate capacitor.

The capacitor's [capacitance](#) ( $C$ ) is a measure of the amount of [charge](#) ( $Q$ ) stored on each plate for a given [potential difference](#) or *voltage* ( $V$ ) which appears between the plates:

$$C = \frac{Q}{V}$$

In [SI](#) units, a capacitor has a capacitance of one [farad](#) when one [coulomb](#) of charge is stored due to one [volt](#) applied potential difference across the plates. Since the farad is a very large unit, values of capacitors are usually expressed in microfarads ( $\mu\text{F}$ ), nanofarads (nF), or picofarads (pF).

The **capacitance** is proportional to the surface area of the conducting plate and inversely proportional to the distance between the plates. It is also proportional to the [permittivity](#) of the [dielectric](#) (that is, non-[conducting](#)) substance that separates the plates.

The capacitance of a parallel-plate capacitor is given by:

$$C \approx \frac{\epsilon A}{d}; A \gg d^2 \quad \square$$

where  $\epsilon$  is the [permittivity](#) of the dielectric (see [Dielectric constant](#)),  $A$  is the area of the plates and  $d$  is the spacing between them.

In the diagram, the rotated molecules create an opposing electric field that partially cancels the field created by the plates, a process called [dielectric polarization](#).

# Permittivity

From Wikipedia, the free encyclopedia

Jump to: [navigation](#), [search](#)

**Permittivity** is a [physical quantity](#) that describes how an [electric field](#) affects and is affected by a [dielectric](#) medium, and is determined by the ability of a material to [polarize](#) in response to the field, and thereby reduce the field inside the material. Thus, permittivity relates to a material's ability to transmit (or "permit") an electric field.

It is directly related to [electric susceptibility](#). For example, in a [capacitor](#), an increased permittivity allows the same [charge](#) to be stored with a smaller electric field (and thus a smaller [voltage](#)), leading to an increased [capacitance](#).

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## Explanation

In [electromagnetism](#), the [electric displacement field](#) **D** represents how an electric field **E** influences the organization of electrical charges in a given medium, including charge migration and electric [dipole](#) reorientation. Its relation to permittivity is

$$\mathbf{D} = \boldsymbol{\varepsilon} \cdot \mathbf{E}$$

where the permittivity  $\boldsymbol{\varepsilon}$  is a [scalar](#) if the medium is [isotropic](#) or a second rank [tensor](#) for an anisotropic linear medium.

In general, permittivity is not a constant, as it can vary with the position in the medium, the frequency of the field applied, humidity, temperature, and other parameters. In a [nonlinear medium](#), the permittivity can depend on the strength of the electric field. Permittivity as a function of frequency can take on real or complex values.

In [SI](#) units, permittivity is measured in [farads](#) per [metre](#) (F/m). The displacement field **D** is measured in units of [coulombs](#) per [square metre](#) (C/m<sup>2</sup>), while the electric field **E** is measured in [volts](#) per [metre](#) (V/m). **D** and **E** represent the same phenomenon, namely, the interaction between charged objects. **D** is related to the *charge densities* associated with this interaction, while **E** is related to the *forces* and *potential differences*.

## Vacuum permittivity

*Main article:* [electric susceptibility](#)

Vacuum permittivity  $\epsilon_0$  (also called **permittivity of free space** or the **electric constant**) is the ratio **D/E** in vacuum.

$$\epsilon_0 = \frac{1}{c^2 \mu_0} \approx 8.8541878176 \times 10^{-12} \text{ F/m (or } \text{C}^2/(\text{N m}^2)\text{),}$$

where

$c$  is the [speed of light](#)  
 $\mu_0$  is the [permeability](#) of vacuum.

All three of these constants are exactly defined in [SI](#) units.

Vacuum permittivity also appears in [Coulomb's law](#) as a part of the [Coulomb force constant](#),  $\frac{1}{4\pi\epsilon_0}$ , which expresses the force between two unit charges separated by unit distance in vacuum.

The permittivity of a material is usually given relative to that of vacuum, as a relative permittivity  $\epsilon_r$  (also called [dielectric constant](#)). The actual permittivity is then calculated by multiplying the relative permittivity by  $\epsilon_0$ :

$$\epsilon = \epsilon_r \epsilon_0 = (1 + \chi_e) \epsilon_0$$

where

$\chi_e$  is the [electric susceptibility](#) of the material.

## Permittivity in media

In the common case of [isotropic](#) media,  $\mathbf{D}$  and  $\mathbf{E}$  are parallel [vectors](#) and  $\epsilon$  is a [scalar](#), but in general [anisotropic](#) media this is not the case and  $\epsilon$  is a rank-2 [tensor](#) (causing [birefringence](#)). The permittivity  $\epsilon$  and [magnetic permeability](#)  $\mu$  of a medium together determine the [phase velocity](#)  $v$  of [electromagnetic radiation](#) through that medium:

$$\epsilon\mu = \frac{1}{v^2}$$

When an external electric field is applied to a real medium, a [current](#) flows. The *total current* flowing within the medium consists of two parts: a [conduction](#) and a [displacement current](#). The displacement current can be thought of as the elastic response of the material to the applied electric field. As the magnitude of the externally applied electric field is increased, an increasing amount of energy is stored in the electric displacement field within the material. If the electric field is subsequently decreased, the material will release the stored electrostatic energy. The displacement current reflects the resulting change in [electrostatic](#) energy stored within the material. The electric displacement can be separated into a vacuum contribution and one arising from the material by

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P} = \epsilon_0 \mathbf{E} + \epsilon_0 \chi \mathbf{E} = \epsilon_0 \mathbf{E} (1 + \chi),$$

where

$\mathbf{P}$  is the [polarization](#) of the medium  
 $\chi$  its [electric susceptibility](#).

It follows that the relative permittivity and susceptibility of a sample are related,  
 $\epsilon_r = \chi + 1$ .

## Dielectric constant

From Wikipedia, the free encyclopedia

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**Dielectric constants of some materials at [room temperature](#) (except where indicated otherwise)**

Material	Dielectric constant
<a href="#">Vacuum</a>	1 (by definition)
<a href="#">Air</a>	1.00054
<a href="#">Teflon™</a>	2.1
<a href="#">Polyethylene</a>	2.25

<a href="#">Concrete</a>	4.5
<a href="#">Pyrex (glass)</a>	4.7 (3.7–10)
<a href="#">Rubber</a>	7
<a href="#">Diamond</a>	5.5–10
<a href="#">Salt</a>	3–15
<a href="#">Graphite</a>	10–15
<a href="#">Silicon</a>	11.68
<a href="#">Methanol</a>	30
<a href="#">Furfural</a>	42.0
<a href="#">Glycerol</a>	47–68
<a href="#">Water</a>	88–80.1–55.3–34.5 (0–20–100–200 °C)
<a href="#">Hydrofluoric acid</a>	83.6 (0 °C)
<a href="#">Formamide</a>	84.0 (20 °C)
<a href="#">Sulfuric acid</a>	84–100 (20–25 °C)
<a href="#">Hydrogen peroxide</a>	128 <a href="#">aq</a> –60 (–30–25 °C)
<a href="#">Hydrocyanic acid</a>	158.0–2.3 (0–21 °C)
<a href="#">Titanium dioxide</a>	86–173
<a href="#">Strontium titanate</a>	310
Barium strontium titanate	15 <a href="#">nc</a> –500
<a href="#">Barium titanate</a>	90 <a href="#">nc</a> –1250–10,000 (20–120 °C)
<a href="#">(La,Nb):(Zr,Ti)PbO<sub>3</sub></a>	500-6000

The **relative dielectric constant** of a material under given conditions is a measure of the extent to which it concentrates [electrostatic](#) lines of flux. It is the ratio of the amount of stored electrical energy when a potential is applied, relative to the permittivity of a vacuum. It is also called **relative [permittivity](#)**.

The dielectric constant is represented as  $\epsilon_r$  or sometimes  $\kappa$  or  $K$  or  $D_k$ . It is defined as

$$\epsilon_r = \frac{\epsilon_s}{\epsilon_0}$$

permittivity is derived from [Maxwell's equations](#) by relating the [electric field intensity](#)  $\mathbf{E}$  to the [electric flux density](#)  $\mathbf{D}$ . In vacuum ([free space](#)), the permittivity  $\epsilon$  is just  $\epsilon_0$ , so the dielectric constant is 1.

The relative permittivity of a medium is related to its [electric susceptibility](#),  $\chi_e$  by

$$\epsilon_r = 1 + \chi_e.$$

## Measurement

The relative dielectric constant  $\epsilon_r$  can be measured for static [electric fields](#) as follows: first the [capacitance](#) of a test capacitor  $C_0$  is measured with vacuum between its plates. Then, using the same capacitor and distance between its plates the capacitance  $C_x$  with a dielectric between the plates is measured. The relative dielectric constant can be then calculated as

$$\epsilon_r = \frac{C_x}{C_0}.$$

For time-varying [electromagnetic fields](#), the dielectric constant of materials becomes [frequency](#) dependent and in general is called [permittivity](#).

## Stored energy

As opposite charges accumulate on the plates of a capacitor due to the separation of charge, a voltage develops across the capacitor owing to the electric field of these charges. Ever-increasing work must be done against this ever-increasing electric field as more charge is separated. The [energy](#) (measured in [joules](#), in [SI](#)) stored in a capacitor is equal to the amount of work required to establish the voltage across the capacitor, and therefore the electric field. The energy stored is given by:

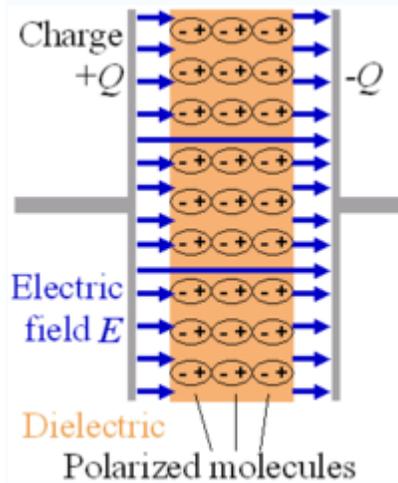
$$E_{\text{stored}} = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}VQ$$

where  $V$  is the voltage across the capacitor.

The maximum energy that can be (safely) stored in a particular capacitor is limited by the maximum electric field that the dielectric can withstand before it breaks down. Therefore, all capacitors made with the same dielectric have about the same maximum energy density (joules of energy per cubic meter).

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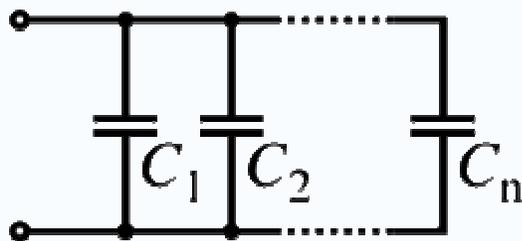
## Electrical circuits



The electrons within dielectric molecules are influenced by the electric field, causing the molecules to rotate slightly from their equilibrium positions. The air gap is shown for clarity; in a real capacitor, the dielectric is in direct contact with the plates. Capacitors also allow AC current to flow and block DC current.

Main article: [Series and parallel circuits](#)

Capacitors in a [parallel](#) configuration each have the same potential difference (voltage). Their total capacitance ( $C_{eq}$ ) is given by:



$$C_{eq} = C_1 + C_2 + \dots + C_n$$

The reason for putting capacitors in parallel is to increase the total amount of charge stored. In other words, increasing the capacitance also increases the amount of energy that can be stored. Its expression is:

$$E_{\text{stored}} = \frac{1}{2}CV^2.$$

The current through capacitors in [series](#) stays the same, but the voltage across each capacitor can be different. The sum of the potential differences (voltage) is equal to the total voltage. Their total capacitance is given by:



$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n}$$

In parallel the effective area of the combined capacitor has increased, increasing the overall capacitance. While in series, the distance between the plates has effectively been increased, reducing the overall capacitance.

In practice capacitors will be placed in series as a means of economically obtaining very high voltage capacitors, for example for smoothing ripples in a high voltage power supply. Three "600 volt maximum" capacitors in series, will increase their overall working voltage to 1800 volts. This is of course offset by the capacitance obtained being only one third of the value of the capacitors used. This can be countered by connecting 3 of these series set-ups in parallel, resulting in a 3x3 matrix of capacitors with the same overall capacitance as an individual capacitor but operable under three times the voltage. In this application, a large [resistor](#) would be connected across each capacitor to ensure that the total voltage is divided equally across each capacitor and also to discharge the capacitors for safety when the equipment is not in use.

Another application is for use of polarized capacitors in alternating current circuits; the capacitors are connected in series, in reverse polarity, so that at any given time one of the capacitors is not conducting...

## Capacitor/inductor duality

In mathematical terms, the ideal capacitor can be considered as an inverse of the ideal [inductor](#), because the voltage-current equations of the two devices can be transformed into one another by exchanging the voltage and current terms. Just as two or more inductors can be magnetically coupled to make a [transformer](#), two or more charged conductors can be electrostatically coupled to make a capacitor. The *mutual capacitance* of two conductors is defined as the current that flows in one when the voltage across the other changes by unit voltage in unit time. There is a symmetry breakdown here as well: There is no perfect analog to the magnetic transformer in the electrostatic world. Ceramic transformers have to have physically moving elements in order to work. One can excite a transformer with AC and derive a higher potential across the secondary if there are more turns on the secondary than the primary, and it is not overloaded. No non-linear mechanism is necessary for this to occur. In order to obtain this effect from a circuit

using capacitors for energy storage, there needs to be an active element such as a transistor acting as switch used. Radio broadcasting is an extreme case of a magnetic transformer. The transmit antenna is the primary, the receive antenna is the secondary. If there weren't a symmetry breakdown here, there would be an alternative form of radio based on charge effects available to man.

## Capacitor types

Listed by di-electric material.

- **Vacuum** : Two metal, usually copper, electrodes are separated by a vacuum. The insulating envelope is usually glass or ceramic. Typically of low capacitance - 10 - 1000 pF and high voltage, up to tens of kilovolts, they are most often used in radio transmitters and other high voltage power devices. Both fixed and variable types are available. Variable vacuum capacitors can have a minimum to maximum capacitance ratio of up to 100, allowing any tuned circuit to cover a full decade of frequency. Vacuum is the most perfect of dielectrics with a zero loss tangent. This allows very high powers to be transmitted without significant loss and consequent heating.
- **Air** : Air dielectric capacitors consist of metal plates separated by an air gap. The metal plates, of which there may be many interleaved, are most often made of aluminium or silver-plated brass. Nearly all air dielectric capacitors are variable and are used in radio tuning circuits.
- **Metal film**: Made from high quality polymer film and metal foil (usually [polycarbonate](#), [polystyrene](#), [polypropylene](#), [polyester \(Mylar\)](#), and for high quality capacitors [polysulfone](#)), with a layer of metal deposited on surface. They have good quality and stability, and are suitable for timer circuits. Suitable for high frequencies.
- **Mica**: Similar to metal film. Often high voltage. Suitable for high frequencies. Expensive. Excellent tolerance.
- **Paper**: Used for relatively high voltages. Now obsolete.
- **Glass**: Used for high voltages. Expensive. Stable temperature coefficient in a wide range of temperatures.
- **Ceramic**: Chips of alternating layers of metal and ceramic. Depending on their dielectric, whether [Class 1](#) or [Class 2](#), their degree of temperature/capacity dependence varies. They often have (especially the class 2) high [dissipation factor](#), high frequency coefficient of dissipation, their capacity depends on applied voltage, and their capacity changes with aging. However they find massive use in common low-precision coupling and filtering applications. Suitable for high frequencies.
- **Aluminum electrolytic**: Polarized. Constructionally similar to metal film, but the electrodes are made of etched aluminium to acquire much larger surfaces. The dielectric is soaked with liquid electrolyte. They can achieve high capacities but suffer from poor tolerances, high instability, gradual loss of capacity especially when subjected to heat, and high leakage. Tend to lose capacity in low temperatures. Bad frequency characteristics make them unsuited for high-

frequency applications. Special types with low [equivalent series resistance](#) are available.

- [Tantalum electrolytic](#): Similar to the aluminum electrolytic capacitor but with better frequency and temperature characteristics. High dielectric absorption. High leakage. Has much better performance in low temperatures.
- [Supercapacitors](#): Made from carbon [aerogel](#), carbon nanotubes, or highly porous electrode materials. Extremely high capacity. Can be used in some applications instead of [rechargeable batteries](#).

## Applications

### Energy storage

A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary [battery](#). Capacitors are commonly used in electronic devices to maintain power supply while batteries are being changed. (This prevents loss of information in volatile memory.)

Capacitors are used in [power supplies](#) where they smooth the output of a full or half wave [rectifier](#). They can also be used in [charge pump](#) circuits as the energy storage element in the generation of higher voltages than the input voltage.

Capacitors are connected in parallel with the power circuits of most electronic devices and larger systems (such as factories) to shunt away and conceal current fluctuations from the primary power source to provide a "clean" power supply for signal or control circuits. Audio equipment, for example, uses several capacitors in this way, to shunt away power line hum before it gets into the signal circuitry. The capacitors act as a local reserve for the DC power source, and bypass AC currents from the power supply. This is used in [car audio](#) applications, when a [stiffening capacitor](#) compensates for the inductance and resistance of the leads to the [lead-acid car battery](#).

### Other applications

#### Sensing

Most capacitors are designed to maintain a fixed physical structure. However, various things can change the structure of the capacitor — the resulting change in capacitance can be used to [sense](#) those things.

Changing the dielectric: the effects of varying the physical and/or electrical characteristics of the **dielectric** can also be of use. Capacitors with an exposed and porous dielectric can be used to measure humidity in air.

Changing the distance between the plates: Capacitors are used to accurately measure the fuel level in [airplanes](#). Capacitors with a flexible plate can be used to measure strain or pressure. Capacitors are used as the [sensor](#) in [condenser microphones](#), where one plate is

moved by air pressure, relative to the fixed position of the other plate. Some [accelerometers](#) use [MEMS](#) capacitors etched on a chip to measure the magnitude and direction of the acceleration vector. They are used to detect changes in acceleration, eg. as tilt sensors or to detect free fall, as sensors triggering [airbag](#) deployment, and in many other applications. Also some [fingerprint sensors](#).

Changing the effective area of the plates: capacitive touch switches [\[1\]](#) [\[2\]](#) [\[3\]](#).

### **Pulsed power and weapons**

Groups of large, specially constructed, low-[inductance](#) high-voltage capacitors (*capacitor banks*) are used to supply huge pulses of current for many [pulsed power](#) applications. These include [electromagnetic forming](#), [Marx generators](#), pulsed [lasers](#) (especially [TEA lasers](#)), [pulse forming networks](#), [radar](#), [fusion research](#), and [particle accelerators](#).

Large capacitor banks are used as energy sources for the [exploding-bridgewire detonators](#) or [slapper detonators](#) in [nuclear weapons](#) and other specialty weapons. Experimental work is under way using banks of capacitors as power sources for electromagnetic [armour](#) and electromagnetic [railguns](#) or [coilguns](#).

See also [Explosively pumped flux compression generator](#).

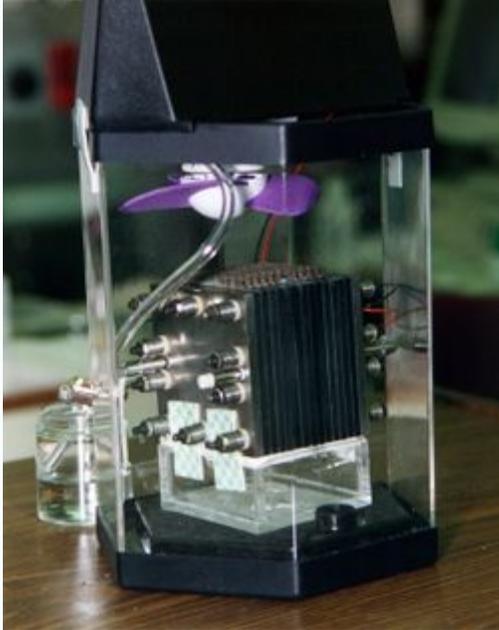
### **Future**

Capacitor development continues, as new means are discovered to increase surface area, reduce the distance between either plates or microwhiskers, and improve the dielectric. For example, in April, 2006, EESor patented a device which they claim will be able to recharge in five minutes and allow a car to travel "500 miles on about \$9 worth of electricity."([CNN Money article](#))

[http://en.wikipedia.org/wiki/Fuel\\_cell](http://en.wikipedia.org/wiki/Fuel_cell)

## Fuel cells

Jump to: [navigation](#), [search](#)



 Methanol fuel cell. The actual fuel cell stack is the layered cubic structure in the center of the image

A **fuel cell** is an [electrochemical](#) energy conversion device. It produces electricity from external supplies of fuel (on the [anode](#) side) and oxidant (on the [cathode](#) side). These react in the presence of an [electrolyte](#). Generally, the reactants flow in and reaction products flow out while the electrolyte remains in the cell. Fuel cells can operate virtually continuously as long as the necessary flows are maintained.

*Fuel Cell Technology Showcase*

### How Fuel Cells Work

A fuel cell is an electrochemical device that produces electricity by separating the fuel (generally hydrogen gas) via a catalyst. The protons flow through a membrane and combine with oxygen to form water - again with the help of a catalyst. The electrons flow from the anode to the cathode to create electricity. As long as the reactants - pure hydrogen and oxygen - are supplied to the fuel cell, it will produce electrical energy.

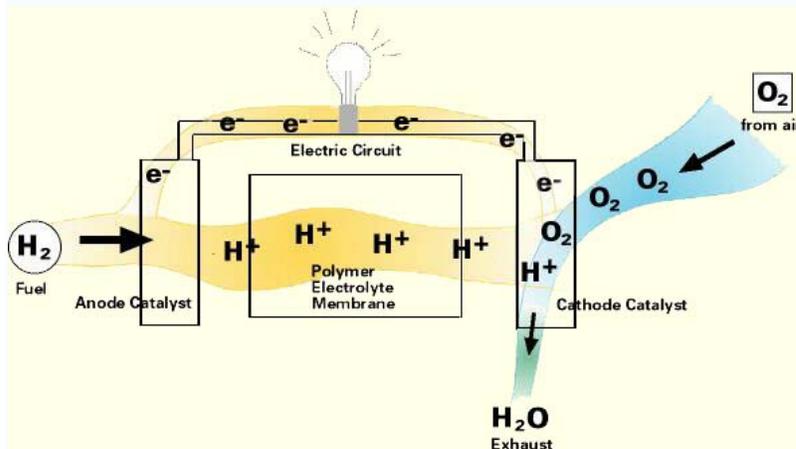
A single fuel cell is basically a piece of plastic between a couple of pieces of carbon plates that are sandwiched between two end plates acting as electrodes. These plates have channels that distribute the fuel and oxygen.

A factor that draws interest to the fuel cell is that it can operate at efficiencies two to three times that of the internal combustion engine, and it requires no moving parts. Since it converts the fuel, hydrogen, and oxygen directly to electrical energy, the only by-products are heat and water. Without combustion, fuel cells are virtually pollution free.

Although hydrogen is the most common fuel used to power a fuel cell, research is being done on a new type of fuel cell that operates using methanol (without using a reformer to convert it to hydrogen) and oxygen. However, this type of fuel cell remains in the early stages of development.

Fuel cells differ from [batteries](#) in that they consume reactants, which must be replenished, while batteries store electrical energy chemically in a closed system. Additionally, while the electrodes within a battery react and change as a battery is charged or discharged, a fuel cell's electrodes are [catalytic](#) and relatively stable.

Many combinations of fuel and oxidant are possible. A hydrogen cell uses [hydrogen](#) as fuel and [oxygen](#) as oxidant. Other fuels include [hydrocarbons](#) and [alcohols](#). Other oxidants include air, [chlorine](#) and [chlorine dioxide](#).<sup>[1]</sup>



## History

The principle of the fuel cell was discovered by German scientist [Christian Friedrich Schönbein](#) in 1838 and published in the January 1839 edition of the "Philosophical Magazine".<sup>[5]</sup> Based on this work, the first fuel cell was developed by Welsh scientist Sir [William Robert Grove](#) in 1843. The fuel cell he made used similar materials to today's

[phosphoric-acid fuel cell](#). It wasn't until 1959 that British engineer [Francis Thomas Bacon](#) successfully developed a 5 kW stationary fuel cell. In 1959, a team led by Harry Ihrig built a 15 kW fuel cell tractor for Allis-Chalmers which was demonstrated across the US at state fairs. This system used potassium hydroxide as the electrolyte and compressed hydrogen and oxygen as the reactants. Later in 1959, Bacon and his colleagues demonstrated a practical five-kilowatt unit capable of powering a welding machine. In the 1960s, Pratt and Whitney licensed Bacon's U.S. patents for use in the U.S. space program to supply electricity and drinking water (hydrogen and oxygen being readily available from the spacecraft tanks).

[UTC's](#) Power subsidiary was the first company to manufacture and commercialize a large, stationary fuel cell system for use as a [co-generation](#) power plant in hospitals, universities and large office buildings. UTC Power continues to market this fuel cell as the PureCell 200, a 200 kW system.<sup>[6]</sup> UTC Power continues to be the sole supplier of fuel cells to NASA for use in space vehicles, having supplied the [Apollo missions](#) and currently the [Space Shuttle program](#), and is developing fuel cells for automobiles, buses, and cell phone towers; the company has demonstrated the first fuel cell capable of starting under freezing conditions with its [proton exchange membrane](#) automotive fuel cell.

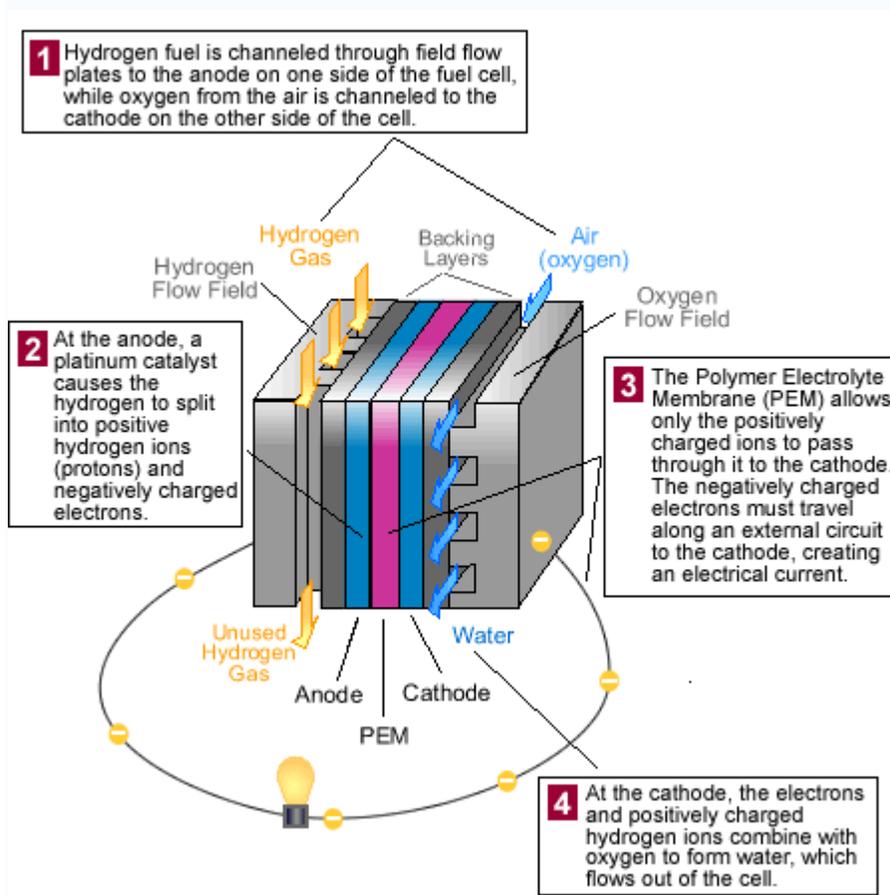
In 2006 [Staxon](#) introduced an inexpensive OEM fuel cell module for system integration. In 2006 [Angstrom Power](#), a British Columbia based company, began commercial sales of portable devices using proprietary hydrogen fuel cell technology, trademarked as "micro hydrogen."<sup>[citation needed]</sup>

## Fuel cell design

In the archetypal example of a hydrogen/oxygen [proton exchange membrane fuel cell](#) (PEMFC), which used to be called solid polymer electrolyte fuel (SPEFC) around 1970 and now is polymer electrolyte membrane fuel cell (PEFC or PEMFC, same as the short writing of proton exchange membrane) while the proton exchange mechanism was doubted, a [proton](#)-conducting polymer membrane, (the [electrolyte](#)), separates the anode and cathode sides.

On the anode side, hydrogen diffuses to the anode catalyst where it later dissociates into protons and [electrons](#). The protons are conducted through the membrane to the cathode, but the electrons are forced to travel in an external [circuit](#) (supplying power) because the membrane is electrically insulating. On the cathode catalyst, oxygen [molecules](#) react with the electrons (which have traveled through the external circuit) and protons to form water. In this example, the only waste product is [water vapor](#) and/or liquid [water](#).

In addition to pure hydrogen, there are [hydrocarbon](#) fuels for fuel cells, including [diesel](#), [methanol](#) (see: [direct-methanol fuel cells](#)) and chemical hydrides. The waste products with these types of fuel are [carbon dioxide](#) and water.



The construction of the Low temperature fuel cell [PEMFC](#): Bipolar plate as [electrode](#) with in-milled gas channel structure, fabricated from conductive plastics (enhanced with carbon nanotubes for more conductivity); Porous carbon papers; Reactive layer, usually on the [polymer](#) membrane applied; polymer membrane.

The materials used in fuel cells differ by type. The electrode/[bipolar](#) plates are usually made of [metal](#), [nickel](#) or [carbon nanotubes](#), and are coated with a [catalyst](#) (like [platinum](#), [nano iron powders](#) or [palladium](#)) for higher efficiency. [Carbon paper](#) separates them from the electrolyte. The electrolyte could be [ceramic](#) or a [membrane](#).

A typical fuel cell produces about 0.86 volt. To create enough [voltage](#), the cells are layered and combined in [series and parallel circuits](#) to form a *fuel cell stack*. The number of cells used is usually greater than 45 but varies with design.

## Fuel cell design issues

- Costs. In 2002, typical cells had a catalyst content of US\$1000 per kilowatt of electric power output. The goal is to reduce the cost in order to compete with current market technologies including gasoline internal combustion engines. Many companies are working on techniques to reduce cost in a variety of ways including reducing the amount of platinum needed in each individual cell. [Ballard Power Systems](#) have experiments with a catalyst enhanced with [carbon silk](#) which allows a 30% reduction (1 mg/cm<sup>2</sup> to 0.7 mg/cm<sup>2</sup>) in platinum usage without reduction in performance.<sup>[2]</sup>
- The production costs of the PEM (proton exchange membrane). The [Nafion](#)® membrane currently costs €400/m<sup>2</sup>. This, and the [Toyota](#) PEM and [3M](#) PEM membrane can be replaced with the [ITM Power](#) membrane (a hydrocarbon polymer), resulting in a price of ~€4/m<sup>2</sup>. In 2005 Ballard Power Systems announced that its fuel cell will use Solupor®, a porous [polyethylene](#) film patented by [DSM](#),<sup>[3]</sup> in its fuel cells.<sup>[4]</sup>
- Water management (in PEMFCs). In this type of fuel cell, the membrane must be hydrated, requiring water to be evaporated at precisely the same rate that it is produced. If water is evaporated too quickly, the membrane dries, resistance across it increases, and eventually it will crack, creating a gas "short circuit" where hydrogen and oxygen combine directly, generating heat that will damage the fuel cell. If the water is evaporated too slowly, the electrodes will flood, preventing the reactants from reaching the catalyst and stopping the reaction. Methods to manage water in cells are being developed by fuel cell companies and [academic research labs](#).
- Flow control. Just as in a combustion engine, a steady ratio between the reactant and oxygen is necessary to keep the fuel cell operating efficiently.
- Temperature management. The same temperature must be maintained throughout the cell in order to prevent destruction of the cell through [thermal](#) loading.
- Durability, [service life](#), and special requirements for some type of cells. Stationary applications typically require more than 40,000 hours of reliable operation at a temperature of -35 °C to 40 °C, while

automotive fuel cells require a 5,000 hour lifespan (the equivalent of 150,000 miles) under extreme temperatures. Automotive engines must also be able to start reliably at -30 °C and have a high power to volume ratio (typically 2.5 kW per liter).

- Limited [carbon monoxide](#) tolerance of the anode.

## Types of fuel cells

Fuel Cell Name	Electrolyte	Qualified Power (W)	Working Temperature (°C)	Electrical efficiency	Status
<a href="#">Metal hydride fuel cell</a>	<a href="#">Aqueous alkaline</a> solution (e.g. <a href="#">potassium hydroxide</a> )	?	above -20 50%P <sub>peak</sub> @ 0	?	<a href="#">Commercial/Research</a>
<a href="#">Electro-galvanic fuel cell</a>	Aqueous alkaline solution (e.g., potassium hydroxide)	?	under 40	?	Commercial/Research
<a href="#">Direct formic acid fuel cell (DFAFC)</a>	Polymer membrane (ionomer)	to 50 W	under 40	?	Commercial/Research
<a href="#">Zinc-air battery</a>	Aqueous alkaline solution (e.g., potassium hydroxide)	?	under 40	?	<a href="#">Mass production</a>
<a href="#">Microbial fuel cell</a>	Polymer membrane or <a href="#">humic acid</a>	?	under 40	?	Research

<b><u>Upflow microbial fuel cell (UMFC)</u></b>		?	under 40	?	Research
<b><u>Reversible fuel cell</u></b>	Polymer membrane (ionomer)	?	under 50	?	Commercial/Research
<b><u>Direct borohydride fuel cell</u></b>	Aqueous alkaline solution (e.g., sodium hydroxide)	?	70	?	Commercial
<b><u>Alkaline fuel cell</u></b>	Aqueous alkaline solution (e.g., potassium hydroxide)	10 kW to 100 kW	under 80	Cell: 60–70% System: 62%	Commercial/Research
<b><u>Direct methanol fuel cell</u></b>	Polymer membrane (ionomer)	100 kW to 1mW	90–120	Cell: 20–30% System: 10–20%	Commercial/Research
<b><u>Reformed methanol fuel cell</u></b>	Polymer membrane (ionomer)	5W to 100 kW	(Reformer) <sup>2</sup> 50–300 (PBI) <sup>125–200</sup>	Cell: 50–60% System: 25–40%	Commercial/Research
<b><u>Direct-ethanol fuel cell</u></b>	Polymer membrane (ionomer)	up to 140 mW/cm <sup>2</sup>	above 25 ? 90–120	?	Research
<b><u>Formic acid fuel cell</u></b>	Polymer membrane (ionomer)	?	90–120	?	Research

<a href="#"><u>Proton exchange membrane fuel cell</u></a>	Polymer membrane (ionomer) (e.g., <a href="#"><u>Nafion®</u></a> or <a href="#"><u>Polybenzimidazole fiber</u></a> )	100W to 500 kW	(Nafion)70–120 (PBI)125–220	Cell: 50–70% System: 30–50%	Commercial/Research
<a href="#"><u>RFC - Redox</u></a>	Liquid electrolytes with <a href="#"><u>redox</u></a> shuttle & polymer membrane (Ionomer)	1 kW to 10MW	?	?	Research
<a href="#"><u>Phosphoric acid fuel cell</u></a>	Molten <a href="#"><u>phosphoric acid</u></a> (H <sub>3</sub> PO <sub>4</sub> )	up to 10MW	150-200	Cell: 55% System: 40% Co-Gen: 90%	Commercial/Research
<a href="#"><u>Molten carbonate fuel cell</u></a>	Molten alkaline <a href="#"><u>carbonate</u></a> (e.g., <a href="#"><u>sodium bicarbonate</u></a> NaHCO <sub>3</sub> )	100MW	600-650	Cell: 55% System: 47%	Commercial/Research
<a href="#"><u>Tubular solid oxide fuel cell (TSOFC)</u></a>			600-650		Research
<a href="#"><u>Protonic ceramic fuel cell</u></a>	H <sup>+</sup> -conducting ceramic oxide	?	700	?	Research
<a href="#"><u>Direct carbon</u></a>	Several different	?	700-850	Cell: 80% System:	Commercial/Research

<b><u>fuel cell</u></b>				70%	
<b><u>Solid oxide fuel cell</u></b>	O <sup>2-</sup> -conducting ceramic <u>oxide</u> (e.g., <u>zirconium dioxide</u> , ZrO <sub>2</sub> )	up to 100MW	700–1000	Cell: 60–65% System: 55–60%	Commercial/Research

A variant of fuel cell, the unitized regenerative fuel cell (URFC), has been developed by Lawrence Livermore National Laboratory and AeroVironment of Monrovia, California. The URFC integrates fuel cell and electrolyzer functions into a single unit. By reversing the direction of operation, water and electricity are converted into hydrogen and oxygen; when operating normally, hydrogen and oxygen are converted into electricity and water just as in a conventional fuel cell.

Currently Ovonic offers a version of the URFC that does not regenerate hydrogen and oxygen, but instead stores energy in the fuel cell stack.

Proton Energy Systems also markets a regenerative fuel cell (RFC) system, UNIGEN, for backup power systems, as well as aerospace and military applications.

References: [\[1\]](#), [\[2\]](#), [\[3\]](#), [\[4\]](#) and [\[5\]](#), [\[6\]](#)

## Efficiency

### Energy cell efficiency

Energy cells are not constrained by the maximum Carnot cycle efficiency as combustion engines are, because they do not operate with a thermal cycle. At times, this is misrepresented when fuel cells are stated to be exempt from the laws of thermodynamics. Instead, it can be described that the "limitations imposed by the second law of thermodynamics on the operation of fuel cells are much less severe than the limitations imposed on conventional energy conversion systems".<sup>[7]</sup> Consequently, they can have very high efficiencies in converting chemical energy to electrical energy, especially when they are operated at low power density, and using pure hydrogen and oxygen as reactants.

The efficiency of a fuel is very dependent on the current through the fuel cell: as a general rule, the more current drawn, the lower the efficiency. A cell running at 0.6V has an efficiency of about 50%, meaning that 50% of the *available* energy content of the hydrogen is converted into electrical energy; the remaining 50% will be converted into heat. For a hydrogen cell the second law efficiency is equal to cell voltage divided by 1.23, when operating at standard conditions. This voltage varies with fuel used, and quality and temperature of the cell. The difference between the reaction's enthalpy and

[Gibbs free energy](#) (that cannot be recovered in any case) will also appear as heat, along with any losses in electrical conversion efficiency.

## In practice

For a fuel cell operated on air (rather than bottled oxygen), losses due to the air supply system must also be taken into account. This refers to the pressurization of the air and adding moisture to it. This reduces the efficiency significantly and brings it near to the efficiency of a compression ignition engine. Furthermore fuel cells have lower efficiencies at higher loads. It is also important to take losses due to production, transportation, and storage into account. Fuel cell vehicles running on compressed hydrogen may have a power-plant-to-wheel efficiency of 22% if the hydrogen is stored as high-pressure gas, and 17% if it is stored as [liquid hydrogen](#).<sup>[8]</sup>

Fuel cells cannot store energy like a battery, but in some applications, such as stand-alone power plants based on discontinuous sources such as [solar](#) or [wind power](#), they are combined with [electrolyzers](#) and storage systems to form an energy storage system. The overall efficiency (electricity to hydrogen and back to electricity) of such plants (known as *round-trip efficiency*) is between 30 and 50%, depending on conditions.<sup>[9]</sup> While a much cheaper [lead-acid battery](#) might return about 90%, the electrolyzer/fuel cell system can store indefinite quantities of hydrogen, and is therefore better suited for long-term storage.

Solid-oxide fuel cells produce exothermic heat from the recombination of the oxygen and hydrogen. The ceramic can run as hot as 800 degrees Celsius. This heat can be captured and used to heat water in a combined heat and power (CHP) application. When the heat is captured, total efficiency can reach 80-90%. CHP units are being developed today for the European home market.

## Fuel cell applications

Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks, rural locations, and in certain military applications. A fuel cell system running on hydrogen can be compact, lightweight and has no major moving parts. Because fuel cells have no moving parts, and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability.<sup>[10]</sup> This equates to less than one minute of down time in a six year period.

A new application is [micro combined heat and power](#), which is [cogeneration](#) for family homes, office buildings and factories. This type of system generates constant electric power (selling excess power back to the grid when it is not consumed), and at the same time produce hot air and water from the waste heat. A lower fuel-to-electricity conversion efficiency is tolerated (typically 15-20%), because most of the energy not converted into electricity is utilized as heat. Some heat is lost with the exhaust gas just as in a normal [furnace](#), so the combined heat and power efficiency is still lower than 100%, typically around 80%. In terms of [exergy](#) however, the process is inefficient, and one could do

better by maximizing the electricity generated and then using the electricity to drive a [heat pump](#). [Phosphoric-acid fuel cells](#) (PAFC) comprise the largest segment of existing CHP products worldwide and can provide combined efficiencies close to 80% (45-50% electric + remainder as thermal). UTC Power is currently the world's largest manufacturer of PAFC fuel cells. [Molten-carbonate fuel cells](#) have also been installed in these applications, and [solid-oxide fuel cell](#) prototypes exist.

However, since electrolyzer systems do not store fuel in themselves, but rather rely on external storage units, they can be successfully applied in large-scale energy storage, rural areas being one example. In this application, batteries would have to be largely oversized to meet the storage demand, but fuel cells only need a larger storage unit (typically cheaper than an electrochemical device).

One such pilot program is operating on Stuart Island in Washington State. There the Stuart Island Energy Initiative [7] has built a complete, closed-loop system: Solar panels power an electrolyzer which makes hydrogen. The hydrogen is stored in a 500 gallon tank at 200 PSI, and runs a ReliOn fuel cell to provide full electric back-up to the off-the-grid residence. The SIEI website gives extensive technical details.

### **Suggested applications**

- [Base load power plants](#)
- [Electric](#) and [hybrid vehicles](#).
- [Auxiliary power](#)
- Off-[grid](#) power supply
- [Notebook computers](#) for applications where [AC](#) charging may not be available for weeks at a time.
- Portable charging docks for small electronics (e.g. a belt clip that charges your [cell phone](#) or [PDA](#)).

### **Hydrogen transportation and refuelling**



[Toyota FCHV PEM FC](#) fuel cell vehicle

*For more details on this topic, see [Hydrogen station](#).*

The first public hydrogen refuelling station was opened in [Reykjavík, Iceland](#) in April 2003. This station serves three buses built by [DaimlerChrysler](#) that are in service in the [public transport](#) net of Reykjavík. The station produces the hydrogen it needs by itself, with an electrolyzing unit (produced by [Norsk Hydro](#)), and does not need refilling: all that enters is electricity and water. [Royal Dutch Shell](#) is also a partner in the project. The station has no roof, in order to allow any leaked hydrogen to escape to the atmosphere.

*For more details on this topic, see [Hydrogen highway](#).*

The GM 1966 Electrovan was the automotive industry's first attempt at an automobile powered by a hydrogen fuel cell. The Electrovan, which weighed more than twice as much as a normal van, could travel up to 70 miles an hour.<sup>[11]</sup>

The 2001 [Chrysler Natrium](#) used its own on-board hydrogen processor. It produces hydrogen for the fuel cell by reacting sodium borohydride fuel with [Borox](#), both of which Chrysler claimed was naturally occurring in great quantity in the United States.<sup>[8]</sup> The hydrogen produces electric power in the fuel cell for near-silent operation and a range of 300 miles without impinging on passenger space. [Chrysler](#) also developed vehicles which separated hydrogen from gasoline in the vehicle, the purpose being to reduce emissions without relying on a nonexistent hydrogen infrastructure and to avoid large storage tanks.<sup>[12]</sup>

In 2005 the British firm Intelligent Energy produced the first ever working hydrogen run [motorcycle](#) called the [ENV](#) (Emission Neutral Vehicle). The motorcycle holds enough fuel to run for four hours, and to travel 100 miles in an urban area. Its top speed is 50 miles per hour.<sup>[13]</sup> [Honda](#) is also going to offer [fuel-cell motorcycles](#).<sup>[14][15]</sup>

There are numerous prototype or production cars and buses based on fuel cell technology being researched or manufactured. Research is ongoing at a variety of motor car manufacturers. [Honda](#) has announced the release of a [hydrogen vehicle](#) in 2008.<sup>[16]</sup>

Currently, a team of college students called [Energy-Quest](#) is planning to take a hydrogen fuel cell powered boat around the world (as well as other projects using efficient or renewable fuels). Their venture is called the *Triton*.<sup>[citation needed]</sup>

[Type 212 submarines](#) use fuel cells to remain submerged for weeks without the need to surface.

[Boeing](#) researchers and industry partners throughout Europe are planning to conduct experimental flight tests in 2007 of a manned [airplane](#) powered only by a fuel cell and lightweight [batteries](#). The Fuel Cell Demonstrator Airplane research project was completed recently and thorough systems integration testing is now under way in

preparation for upcoming ground and flight testing. The Boeing demonstrator uses a Proton Exchange Membrane (PEM) fuel cell/[lithium-ion battery](#) hybrid system to power an electric motor, which is coupled to a conventional propeller.

## Hydrogen economy

*Main article: [Hydrogen economy](#)*

[Electrochemical](#) extraction of energy from hydrogen via fuel cells is an especially clean and efficient method of meeting our power needs, and introduces the need for establishing the infrastructure for a hydrogen economy. It must however be noted that regarding the concept of the [hydrogen vehicle](#), burning/[combustion](#) of hydrogen in an [internal combustion engine](#) (IC/ICE) is oftentimes confused with the electrochemical process of generating electricity via fuel cells (FC) in which there is no combustion (though there is a small byproduct of heat in the reaction). Both processes require the establishment of a hydrogen economy before they may be considered commercially viable. Hydrogen combustion is similar to petroleum combustion (minus the emissions) and is thus limited by the Carnot efficiency, but is completely different from the hydrogen fuel cell's chemical conversion process of hydrogen to electricity and water without combustion. Hydrogen fuel cells emit only water, while direct [methane](#) or [natural gas](#) conversions (whether IC or FC) generate carbon dioxide emissions.

Hydrogen is typically thought of as an [energy carrier](#), and not generally as an energy source, because it is usually produced from other energy sources via petroleum combustion, [wind power](#), or [solar photovoltaic cells](#). Nevertheless, hydrogen may be considered an energy source when extracted from subsurface reservoirs of hydrogen gas, methane and natural gas ([steam reforming](#) and [water gas shift reaction](#)), [coal](#) ([coal gasification](#)) or [shale oil](#) ([oil shale gasification](#)). Electrolysis, which requires [electricity](#), and [high-temperature electrolysis/thermochemical production](#), which requires high temperatures (ideal for [nuclear reactors](#)), are two primary methods for the extraction of hydrogen from water.

As of 2005, 49.7% of the electricity produced in the [United States](#) comes from [coal](#), 19.3% comes from [nuclear](#), 18.7% comes from [natural gas](#), 6.5% from [hydroelectricity](#), 3% from [petroleum](#) and the remaining 2.8% mostly coming from [geothermal](#), [solar](#) and [biomass](#). [9] When hydrogen is produced through electrolysis, the energy comes from these sources. Though the fuel cell itself will only emit heat and water as waste, pollution is oftentimes produced to make the hydrogen that it runs on; unless it is either mined, or generated by solar, wind or other clean power sources. If [fusion power](#) were to become a viable energy source then this would provide a clean method of producing abundant electricity. Hydrogen production is only clean as the energy sources used to produce it. A holistic approach has to take into consideration the impacts of an extended hydrogen scenario. This refers to the production, the use and the disposal of infrastructure and energy converters.

Nowadays low temperature fuel cell stacks [proton exchange membrane fuel cell](#) (PEMFC), [direct methanol fuel cell](#) (DMFC) and [phosphoric acid fuel cell](#) (PAFC) make extensive use of [catalysts](#). Impurities poison or foul the catalysts (reducing activity and efficiency), thus higher catalyst densities are required.<sup>[17]</sup> Limited reserves of [platinum](#) quicken the synthesis of an inorganic complex very similar to the catalytic iron-sulfur core of bacterial hydrogenase to step in.<sup>[18]</sup> Although platinum is seen by some as one of the major "showstoppers" to mass market fuel cell commercialization companies, most predictions of platinum running out and/or platinum prices soaring do not take into account effects of thrifting (reduction in catalyst loading) and recycling. Recent research at [Brookhaven National Laboratory](#) could lead to the replacement of platinum by a [gold-palladium](#) coating which may be less susceptible to poisoning and thereby improve fuel cell lifetime considerably.<sup>[19]</sup> Current targets for a transport PEM fuel cells are 0.2 g/kW Pt – which is a factor of 5 decrease over current loadings – and recent comments from major [original equipment manufacturers](#) (OEMs) indicate that this is possible. Also it is fully anticipated that [recycling](#) of fuel cells components, including platinum, will kick-in. One company, NedStack, is already stating that its units are 98% recyclable.<sup>[citation needed]</sup>

## Research and development

- **August 2005:** [Georgia Institute of Technology](#) researchers use [triazole](#) to raise the operating temperature of PEM fuel cells from below 100 °C to over 120 °C, claiming this will require less carbon-monoxide purification of the hydrogen fuel.<sup>[20]</sup>
- **September 2005:** [Technical University of Denmark](#) (DTU) scientists announced in September 2005 a method of storing hydrogen in the form of [ammonia](#) saturated into a salt tablet. They claim it will be an inexpensive and safe storage method.<sup>[21]</sup>
- **January 2006:** Virent Energy Systems is working on developing a low cost method<sup>[22]</sup> for producing hydrogen on demand - from certain sugar/water mixtures (using one of [glycerol](#), [sorbitol](#), or hydrogenated glucose derivatives). Such a technology, if successful would solve many of the infrastructure ([hydrogen storage](#)) issues associated with the hydrogen economy.<sup>[23]</sup>
- **May 2007:** [Purdue University](#) researchers have developed a method that uses aluminum and [gallium](#) alloy to extract hydrogen from water. They state that "the hydrogen is generated on demand, so you only produce as much as you need when you need it."<sup>[24]</sup>

[http://www.nrel.gov/learning/eds\\_supercapacitors.html](http://www.nrel.gov/learning/eds_supercapacitors.html)

## Supercapacitors

Supercapacitors are electrochemical storage devices that work like large versions of common electrical capacitors. They are also known as ultracapacitors or electrochemical double-layer capacitors. Unlike batteries, supercapacitors store their energy in an electrostatic field rather than in chemical form. **A supercapacitor or ultracapacitor is**

**an electrochemical capacitor that has an unusually high energy density when compared to common capacitors.** *They are of particular interest in automotive applications for hybrid vehicles and as supplementary storage for battery electric vehicles*

Batteries are charged when they undergo an internal chemical reaction. They discharge, delivering the absorbed energy, when they reverse the chemical reaction. **In contrast, when a supercapacitor is charged, there is no chemical reaction. Instead, the energy is stored as a charge or concentration of electrons on the surface of a material.**

Supercapacitors are capable of very fast charges and discharges, and can typically be recharged hundreds of thousands of times, unlike conventional batteries which last for only a few hundred or thousand recharge cycles. But their power is available only for a very short duration, and their self-discharge rate is much higher than with batteries. Common applications include starting diesel trucks and railroad locomotives, and in electric/hybrid-electric vehicles for transient load leveling and capturing the energy used in braking. In power systems, they are most likely to be used as bridging power sources in uninterruptible power supplies, much like flywheels.

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<http://en.wikipedia.org/wiki/Supercapacitor>



MC and BC series supercapacitors (up to 3000 farad capacitance) produced by [Maxwell Technologies](#)

## History

The first supercapacitor based on a double layer mechanism was developed in 1957 by [General Electric](#) using a [porous carbon electrode](#)<sup>[1]</sup>. **It was believed that the energy was stored in the carbon pores and it exhibited "exceptionally high capacitance"**, although the mechanism was unknown at that time. It was the [Standard Oil Company](#),

Cleveland (SOHIO) in 1966 that patented a device that stored energy in the double layer interface.<sup>[21]</sup>

## Current state

- One of the earliest commercial-grade electronic devices powered by a single SuperCapacitor (a high-quality Audio mixer) was described in the milestone article "Single capacitor powers audio mixer" authored by Alexander Bell (EDN, March 14, 1997) [1]. (1) **capable of running for more than 2 hours on a single charge.** (2) **It also demonstrated the ability to be charged very fast (in about ten seconds) compared to the hours required for traditional rechargeable batteries.** (3) Due to the capacitor's high number of charge-discharge cycles (millions or more compared to 200–1000 for most commercially available rechargeable batteries) there were no disposable parts during the whole operating life of the device, which made the device very environmentally friendly. Compared with rechargeable batteries, supercapacitors (4) **are extremely low internal resistance or ESR,** (5) **high efficiency (up to 97-98%),** (6) **high output power,** (7) **extremely low level of heating,** and (8) **improved safety and Low toxicity of materials used .** (8) **Good reversibility** (9) **High cycle efficiency (95% or more)** (10) **Very high rates of charge and discharge** (11) **Little degradation over hundreds of thousands of cycles.**

According to ITS (Institute of Transportation Studies, Davis, CA) test results the specific power of supercapacitors can exceed 6 kW/kg at 95% efficiency.

The idea of replacing batteries with capacitors in conjunction with novel alternative energy sources became a conceptual umbrella of Green Electricity (GEL) Initiative [2], [3], introduced by Dr. Alexander Bell. One particular successful implementation of the GEL Initiative concept was introduced in the article: "Muscle power drives battery-free electronics" (Alexander Bell, EDN, 11/21/2005)[4], describing muscle-driven autonomous, environmentally-friendly solution, which employs a multi-Farad supercapacitor (hecto- and kilofarad range capacitors are now widely available) as **intermediate energy storage to power the variety of portable electrical and electronic devices such as MP3 players, AM/FM radios, flashlights, cell phones, and emergency kits.**

**As the energy density of supercapacitors is bridging the gap with batteries, it could be expected that in the near future the automotive industry will deploy ultracapacitors as a replacement for chemical batteries.**

The first trials of supercapacitors in industrial applications were carried out for supporting the energy supply to robots. [5]

In [2005](#) aerospace systems and controls company [Diehl Luftfahrt Elektronik GmbH](#) chose ultracapacitors Boostcap of [Maxwell Technologies](#) to power emergency actuation systems for doors and [evacuation slides](#) in passenger aircraft, including the new [Airbus 380](#) jumbo jet. [\[6\]](#)

In [2006](#), Joel Schindall and his team at [MIT](#) began working on a "super battery", using nanotube technology to improve upon capacitors. They hope to have a prototype within the next few months and put them on the market within five years. [\[7\]\[8\]](#)

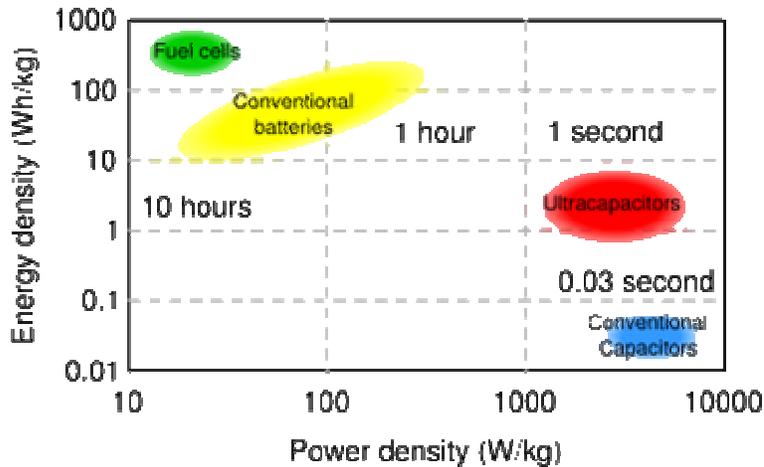
## Applications in public transport

[China](#) is experimenting with a new form of [electric bus](#) that runs without powerlines using power stored in large onboard supercapacitors, which are quickly recharged whenever the electric bus stops at any bus stop, and get fully charged in the terminus. A few prototypes were being tested in Shanghai in early [2005](#). In [2006](#), two commercial bus routes began to use supercapacitor buses; one of them is route 11 in [Shanghai](#). [\[9\]](#)

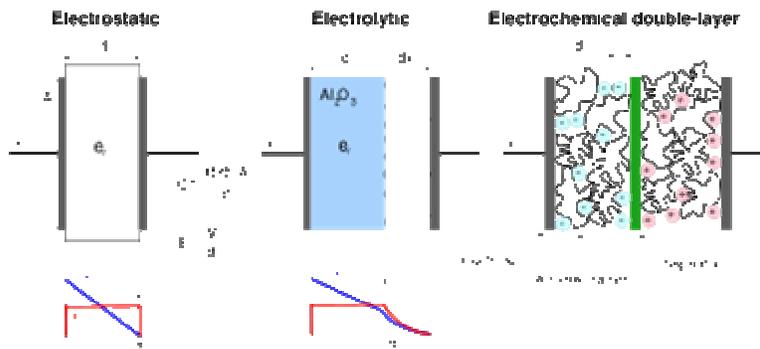
[Siemens AG](#) is developing a mobile energy storage based on double-layer capacitors called Sibac Energy Storage [\[13\]](#). The company Cegelec is also developing a supercapacitor-based energy storage system [\[citation needed\]](#).

## Disadvantages:

- The amount of energy stored per unit weight is considerably lower than that of an electrochemical battery ([3-5 Wh/kg for an ultracapacitor compared to 30-40 Wh/kg for a battery](#)). It is also only about 1/10,000th the volumetric energy density of gasoline.
- [The voltage varies with the energy stored](#). To effectively store and recover energy requires sophisticated electronic control and switching equipment.
- Has the highest [dielectric](#) absorption of all types of capacitors.



Ragone plot showing [energy density](#) vs. [power density](#) for various energy-storage devices



Comparison of construction diagrams of three capacitors. Left: "normal" [capacitor](#), middle: [electrolytic](#), right: supercapacitor

## Technology

[Carbon nanotubes](#) and certain [conductive polymers](#), or [carbon aerogels](#), are practical for [supercapacitors](#). Carbon nanotubes have excellent nanoporosity properties, allowing tiny spaces for the polymer to sit in the tube and act as a dielectric. Some polymers (eg. [polyacenes](#)) have a [redox](#) (reduction-oxidation) storage mechanism along with a high surface area. MIT's [Laboratory of Electromagnetic and Electronic Systems \(LEES\)](#) is researching using [carbon nanotubes](#)<sup>[3]</sup>.

Supercapacitors are also being made of carbon aerogel. Carbon aerogel is a unique material providing extremely high surface area of about 400-1000 m<sup>2</sup>/g. Small aerogel supercapacitors are being used as backup batteries in microelectronics, but applications for [electric vehicles](#) are expected<sup>[4]</sup>.

The electrodes of aerogel supercapacitors are usually made of non-woven paper made from [carbon fibers](#) and coated with organic aerogel, which then undergoes [pyrolysis](#). The

paper is a [composite material](#) where the carbon fibers provide structural integrity and the aerogel provides the required large surface.

The capacitance of a single cell of an ultracapacitor can be as high as 3000 F (see photo at the beginning).

### Supercapacitor Materials:

- 1) Carbon Nano-tubes
- 2) Likewise, nanoscale spinel structures ( $MgAl_2O_4$ ) and carbon nanotubes are considered as electrode material in supercapacitors, which, however, are still too expensive for competitive applications. Companies such as Panasonic, Maxwell or Ness already offer supercapacitors commercially, whereby performance characteristics do not correspond yet to those of a postulated "nanocap", which is to be realized approximately by 2005.
- 3) Conductive polymers
- 4) A novel composite of  $Co(OH)_2$  and  $TiO_2$  nanotubes was synthesized by a chemical precipitation method. A maximum specific capacitance of 229 F/g was obtained for the composite..

### Comparison Chart

The following table gives a brief summary of some critical properties of each technology. Because there are so many types with widely different properties, battery values are shown as a range.

Property	CAP-XX Supercapacitors	Capacitors	Micro-Fuel Cells	Batteries
Charge/Discharge Time	Milliseconds to Seconds	Picoseconds ( $10^{-12}$ ) to Milliseconds	Typically 10 to 300 hrs. Instant charge (refuel).	1 to 10 hrs
Operating Temperature	-40 to +85 °C	-20 to +100 °C	+25 to +90 °C	-20 to +65 °C
Operating Voltage	2.5 V / cell	6 to 800 V	0.6 V / cell	1.25 to 4.2 V / cell
Capacitance	100 mF to > 2F	10 pF to 2.2 mF	N/A	N/A
Life	30,000+ hrs average	>100,000 cycles	1500 to 10,000 hrs	150 to 1500 cycles
Weight	1 g to 2 g	1 g to 10 kg	20 g to over 5 kg	1 g to over 10 kg
Power Density	10 to 100 kW/kg	0.25 to 10,000 kW/kg	0.001 to 0.1 kW/kg	0.005 to 0.4 kW/kg
Energy Density	1 to 5 Wh/kg	0.01 to 0.05 Wh/kg	300 to 3000 Wh/kg	8 to 600 Wh/kg
Pulse Load	Up to 100 A	Up to 1000 A	Up to 150 mA / $cm^2$	Up to 5 A

