TIME TO CHANGE THE BULB

The incandescent light bulb is being phased out, but what will replace it? **Stefano Tonzani** investigates the technologies that are vying for our sockets.

OWAKI-KULLA/CORBIS

The Centennial Light, which hangs in a fire station in Livermore, California, is the oldest working light bulb on Earth. The four-watt night-light was switched on in 1901 and has been shining almost non-stop ever since, consuming roughly 3,500 kilowatt-hours of energy in total. As the picture opposite shows, the bulb also looks surprisingly familiar: the technology of incandescent lights has changed very little over its lifetime. Inside the bulb is a filament — carbon in this case, tungsten in today's models — that is heated by the flow of electricity until it glows white and lights up the room. The design is simple, versatile and cheap, just as it was when Thomas Edison first made it a commercial success in the 1880s.

Nonetheless, that technology is now on the way out. In today's energy-hungry world, the devices are too wasteful: some 98% of the energy input ends up as heat instead of light. Halogen lamps, which look more high-tech, are not any better. Multiply that waste by the number of incandescent bulbs in residential, industrial and commercial settings — an estimated 4 billion standard light sockets in the United States alone — and it is clear why several countries are seeking to eliminate the bulbs entirely as a way to control carbon dioxide emissions. In 2007, for example, Australia became the first country to ban incandescent bulbs entirely; the phase-out is scheduled to be completed by 2012. The member states of the European Union agreed to a similar ban in 2008. And the United States has pledged to eliminate most incandescents by 2014.

"The lighting field is a fairly conservative one, so these government mandates are putting on some welcome pressure to evolve," says Karl Leo, an optoelectronics specialist and a founder of Novaled, a company in Dresden, Germany, that develops organic light-emitting diodes (OLEDs).

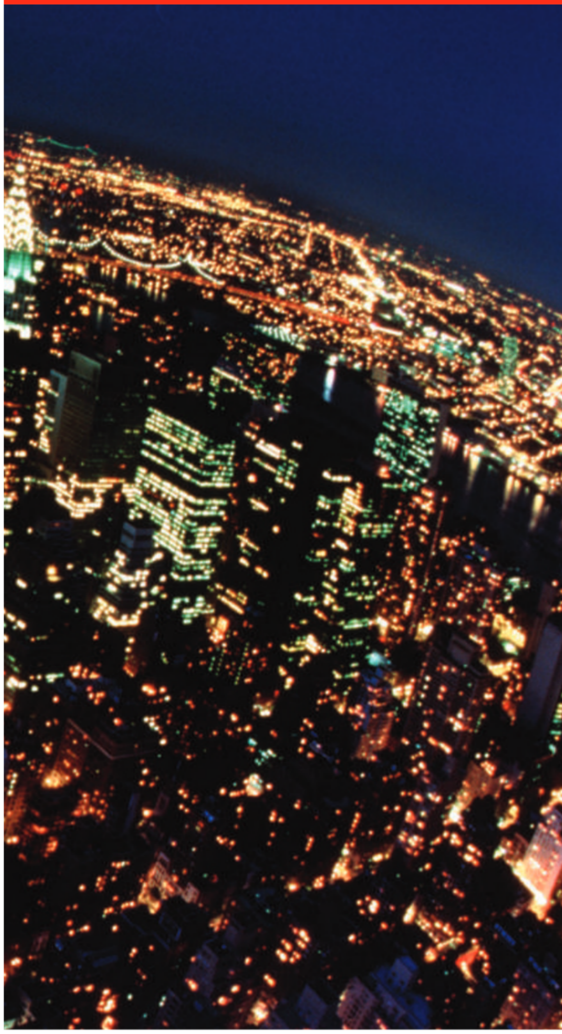
> "Government mandates are putting welcome pressure on the field to evolve."
> — Karl Leo

But evolve into what? Although getting rid of incandescent bulbs makes environmental and economic sense, the race for a long-term replacement is wide open.

At present, the only technology that is mature enough to take over from the conventional light bulb is fluorescent lighting, which can turn 10–15% of the input energy into light. Fluorescent technology has improved substantially since the days when it was synonymous with being harsh and funny-coloured, and has come to dominate in industrial and commercial settings, where energy efficiency and long life are prime concerns. In recent years, compact fluorescent bulbs that can be screwed into standard sockets have brought it ever farther into the home.

But fluorescent lighting has a number of drawbacks. For example, fluorescent lamps do not work well in cold temperatures, and their lifespan can be significantly shortened if they are turned on and off frequently. Perhaps worst of all, each lamp contains a small amount of mercury, which is toxic. This presents consumers with a disposal problem at the end of the lamp's life.

Some people also still complain about the colour rendering of fluorescent lights — the way the lamps make objects look compared with their appearance in natural sunlight. Despite the substantial progress, domestic users in particular tend to prefer the warmer, slightly red-tinged tones of incandescent lights — although that preference is highly individual, says Charles Hunt, an electrical engineer



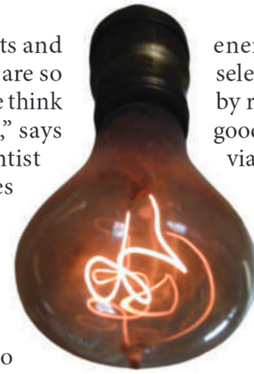
at the University of California, Davis. "The subjective fondness for particular light shades depends on gender (women tend to prefer less harsh, warmer-coloured lights) and origin of the person (people from northern European countries prefer warmer lights whereas southern Europeans prefer colder, more blue-tinged ones)." Another issue is that fluorescent lights require special circuitry to work with a dimming switch. And dimmable is desirable: "Fifty per cent of home lights in the United States are dimmable," says Hunt.

These problems may be overcome — but they seem serious enough to encourage innovators to search out successor technology.

Heavy investment

Perhaps the most widely anticipated of the technologies vying for centre stage is the light-emitting diode (LED), which consists of two types of semiconductors in contact. When a voltage is applied, positive charges coming from one side flow towards the junction and meet negative charges coming from the other side. As these charges combine, they release their energy in the form of light, usually as one particular colour.

LEDs are long-lived, robust and roughly twice as efficient as fluorescents. Indeed, they are already widely used for computers, television sets and other consumer electronics, and are becoming a market leader for outdoor applications such as traffic lights and indicator lights on cars. "There are so many advantages to LEDs that we think there lies the future of lighting," says Hans van Sprang, a senior scientist at Philips Research Laboratories in Eindhoven, the Netherlands. Philips and other big industry players are investing heavily in the technology, supporting materials-science research that has helped LED technology to evolve rapidly.



D. JONES

Going strong 108 years on.

Despite this, LEDs have not yet been adopted on a large scale for general lighting applications. One problem is that an LED light powerful enough for room lighting has a very high initial cost compared with an equivalent incandescent bulb. This can be a large psychological barrier for consumers, even though the cost of energy and maintenance is considerably lower. Another problem is that an LED's lifetime can reduce dramatically if it is operated at a high temperature. This makes heat dissipation an important issue, especially for powerful lamps, and complicates efforts to reduce costs. Making the LED semiconductors from substrates other than sapphire would be cheaper, and the alternatives, including silicon-based substrates, might improve heat management.

Another challenge is how to generate white light from LEDs. The preferred technique for commercially available devices is to coat a blue or ultraviolet LED with a phosphorescent material that will absorb the monochromatic emissions, and then re-emit the energy as a broad-spectrum white light. Another, potentially more energy-efficient, way of generating white light is to mix the light of red, blue and green LEDs. But both of these methods have issues with colour rendering. And the latter method has the added problem that the lifespans of the three different LED types are not the same, so the light will change in colour as the lamp ages. Gain in one dimension and you can lose in another — devices that have very good colour rendering tend to have poor energy efficiency.

One potential solution is now under development by Sandra Rosenthal, a chemist at Vanderbilt University in Nashville, Tennessee. Her idea is to use an ultraviolet-emitting LED to energize the electrons in cadmium selenide nanocrystals, which respond by re-emitting a white light with very good colour rendering. "This could be a viable alternative if we could substantially improve their efficiency," says Rosenthal.

Organic compounds, which have already been looked at as a possible alternative to silicon in solar cells, are being investigated for use in LEDs. OLEDs produce light in much the same way that ordinary LEDs do, except that the positive and negative charges originate in organic compounds rather than in crystalline semiconductors. Typically, these organic compounds are attached to a fixed polymer sheet. The advantage of organic materials is that, at least in theory, they can be produced comparatively cheaply with the same roll-to-roll technology used to handle other types of plastic films.

The main problem with OLEDs is that the organic materials are degradable by water and oxygen, which tends to give the devices a short lifespan. This can be solved, to some extent, by encapsulating the organic compounds in an inert, transparent polymer such as epoxy resin. But the compounds degrade intrinsically anyway, especially the blue OLEDs that are required for mixing with red and green to generate white light.

The outsiders

Farther out of the mainstream — in the sense that the technologies are being developed by smaller start-up companies — are induction lamps and cathodoluminescence.

Induction lamps, also known as electrodeless lamps, have been around since the 1890s, when Nikola Tesla invented a fluorescent light powered by currents oscillating in a coil of wires on the outside of the tube, rather than by electrodes on the inside. But some people think that these lamps are finally ready for

OSRAM

Mixing light-emitting diodes of a few basic colours can produce a wide colour palette.

J. GOLLINGS/ARCAID/CORBIS

Light-emitting diodes, such as these in Craigieburn, Australia, can be combined to create huge displays.

prime time. The newest devices feature an electrodeless bulb that is filled with argon gas plus a small amount of metal halide salts. A microwave generator, much like the ones in microwave ovens, produces a wave that is channelled through a waveguide and concentrated on to the container, where it ionizes the gas to form a plasma and vaporizes the salts. The plasma and vapour together generate a broad-spectrum white light with an efficiency similar to that of LEDs. The devices are also very bright, which means they are likely to find their initial applications where intense light is required, such as in car headlights or industrial illumination.

"It will take LEDs a long, long time to catch up with the intensity of illumination possible with induction lamps," says Robin Devonshire, chief scientist of Ceravision, a company in Milton Keynes, UK, that is one of several developing this technology. As these lamps do not place electrodes in contact with the harsh plasma environment, they can potentially last for decades.

Cathodoluminescence works like the cathode-ray tubes found in old-fashioned television sets. It uses a source of electrons to bombard a phosphorescent material coated on the inside of a glass bulb, causing the material to emit light. An electrical field, high temperature or photoelectric effect is used to make a metal surface emit the electrons. Such a light source can be quite efficient, comparable to compact fluorescent sources. It renders colours well, and the lamps can be shaped to look like incandescent bulbs. Initial applications will be geared towards home usage.

> "It will take LEDs a long time to catch up with the light intensity of induction lamps."
> — Robin Devonshire

However, both induction lamps and cathodoluminescence lamps have a perception problem. "There is scepticism in industry with respect to these technologies that are not solid state," says Bruce Pelton, director of engineering of the University of California, Davis, California Lighting Technology Center. This is partly because solid-state devices such as LEDs — which generate light through processes in solid material, having no moving parts or bulbs that can break — are thought to have major advantages in the long run when it comes to ruggedness and long life. But it is also because a previous incarnation of the induction lamp, based on sulphur, failed to gain a foothold in the market. The sulphur lamp was efficient and bright, but was large and required air cooling to stop parts melting in the high temperatures reached by the sulphur plasma.

Blazing competition

The competition to replace incandescent light bulbs is likely to be fierce. But consumer acceptance is far from guaranteed for any of the rival technologies. One problem is the confusion generated by the sheer number of alternatives. Another is that each of these devices has several parts, so that the lifespans and energy efficiencies reported for basic technology do not correspond to those of the whole device, which are, as yet, not that far ahead of incandescent bulbs. In LED lamps, for example, the electronics or the phosphors are likely to degrade much earlier than the solid-state device itself. US Department of Energy data published in 2008 found that commercially available LEDs were about half as efficient as compact fluorescent lights. And, although development since then has been fast, the problems remain.

Meanwhile, because widespread acceptance of these technologies is crucial to changing the habits of consumers — and ultimately, to saving substantial amounts of energy — governments are keen to avoid the errors made with previous technologies, such as the early fluorescent lamps, which many end-users hated. If a technology is initially viewed negatively by the public, this can mar its subsequent evolution — a good reason not to mandate a technology before it is market-tested and ready. Comments on websites mentioning the planned phase-outs of incandescent lights have highlighted that many people's opinions of fluorescent lights have not changed much over time. Cost, colour rendering, flicker and the presence of mercury are only a few of the issues mentioned. Fluorescent lights are still a small percentage of the market compared with more energy-intensive lamps.

For all these reasons, the general-purpose incandescent light bulb might not be replaced by a single new source, but by a range of technologies, each suited to a particular use. For example, if OLED lighting can economically be produced in continuous sheets by industrial roll-to-roll techniques, it will be a natural candidate for flat panels that generate a diffuse glow for area lighting. That would make OLEDs a natural complement to the bright, directional light coming from semiconductor LEDs, which could instead be used for more light-intensive tasks such as reading. Such combinations could lead to new concepts of lighting design, so that architects could help save energy by not wasting light where it is not needed. ■

Stefano Tonzani is an associate editor at *Nature*.