Solar Energy Resources

Solar radiation, often called the solar resource, is a general term for the electromagnetic radiation emitted by the sun. Solar radiation can be captured and turned into useful forms of energy, such as heat and electricity, using a variety of technologies. However, the technical feasibility and economical operation of these technologies at a specific location depends on the available solar resource.

Basic Principles

Every location on Earth receives sunlight at least part of the year. The amount of solar radiation that reaches any one spot on the Earth's surface varies according to:

Geographic location
Time of day
Season
Local landscape
Local weather.

Because the Earth is round, the sun strikes the surface at different angles, ranging from 0° (just above the horizon) to 90° (directly overhead). When the sun's rays are vertical, the Earth's surface gets all the energy possible. The more slanted the sun's rays are, the longer they travel through the atmosphere, becoming more scattered and diffuse. Because the Earth is round, the frigid polar regions never get a high sun, and because of the tilted axis of rotation, these areas receive no sun at all during part of the year.

The Earth revolves around the sun in an elliptical orbit and is closer to the sun during part of the year. When the sun is nearer the Earth, the Earth's surface receives a little more solar energy. The Earth is nearer the sun when it is summer in the southern hemisphere and winter in the northern hemisphere. However, the presence of vast oceans moderates the hotter summers and colder winters one would expect to see in the southern hemisphere as a result of this difference.

The 23.5° tilt in the Earth's axis of rotation is a more significant factor in determining the amount of sunlight striking the Earth at a particular location. Tilting results in longer days in the northern hemisphere from the spring (vernal) equinox to the fall (autumnal) equinox and longer days in the southern hemisphere during the other 6 months. Days and nights are both exactly 12 hours long on the equinoxes, which occur each year on or around March 23 and September 22.

Countries such as the United States, which lie in the middle latitudes, receive more solar energy in the summer not only because days are longer, but also because the sun is nearly overhead. The sun's rays are far more slanted during the shorter days of the winter months. Cities such as Denver, Colorado, (near 40° latitude) receive nearly three times more solar energy in June than they do in December.

The rotation of the Earth is also responsible for hourly variations in sunlight. In the early morning and late afternoon, the sun is low in the sky. Its rays travel further through the atmosphere than at noon, when the sun is at its highest point. On a clear day, the greatest amount of solar energy reaches a solar collector around solar noon.

Diffuse and Direct Solar Radiation

As sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected by:

Air molecules
Water vapor
Clouds
Dust
Pollutants
Forest fires
Volcanoes.

This is called *diffuse solar radiation*. The solar radiation that reaches the Earth's surface without being diffused is called *direct beam solar radiation*. The sum of the diffuse and direct solar radiation is called *global solar radiation*. Atmospheric conditions can reduce direct beam radiation by 10% on clear, dry days and by 100% during thick, cloudy days.

Measurement

Scientists measure the amount of sunlight falling on specific locations at different times of the year. They then estimate the amount of sunlight falling on regions at the same latitude with similar climates. Measurements of solar energy are typically expressed as total radiation on a horizontal surface,or as total radiation on a surface tracking the sun.

Radiation data for solar electric (photovoltaic) systems are often represented as kilowatt-hours per square meter (kWh/m^2). Direct estimates of solar energy may also be expressed as watts per square meter (W/m^2).

Radiation data for solar water heating and space heating systems are usually represented in British thermal units per square foot (Btu/ft^2).

Distribution

The solar resource across the United States is ample for photovoltaic (PV) systems because they use both direct and scattered sunlight. Other technologies may be more limited. However, the amount of power generated by any solar technology at a particular site depends on how much of the sun's energy reaches it. Thus, solar technologies function most efficiently in the southwestern United States, which receives the greatest amount of solar energy.

Photovoltaics

Photovoltaic (PV) materials and devices convert sunlight into electrical energy, and PV cells are commonly known as solar cells. Photovoltaics can literally be translated as light-electricity.
First used in about 1890, "photovoltaic" has two parts: *photo*, derived from the Greek word for light, and*volt*, relating to electricity pioneer Alessandro Volta. And this is what photovoltaic materials and devices do—they convert light energy into electrical energy, as French physicist Edmond Becquerel discovered as early as 1839.
Becquerel discovered the process of using sunlight to produce an electric current in a solid material. But it took more than another century to truly understand this process. Scientists eventually learned that the photoelectric or photovoltaic effect caused certain materials to convert light energy into electrical energy at the atomic level.
PV systems are already an important part of our daily lives. Simple PV systems provide power for small consumer items such as calculators and wristwatches. More complicated systems provide power for communications satellites, water pumps, and the lights, appliances, and machines in some homes and workplaces. Many road and traffic signs also are now powered by PV. In many cases, PV power is the least expensive form of electricity for these tasks.

Photovoltaic Cells

Photovoltaic (PV) cells, or solar cells, take advantage of the photoelectric effect to produce electricity. PV cells are the building blocks of all PV systems because they are the devices that convert sunlight to electricity.
Commonly known as solar cells, individual PV cells are electricity-producing devices made of semiconductor materials. PV cells come in many sizes and shapes, from smaller than a postage stamp to several inches across. They are often connected together to form PV modules that may be up to several feet long and a few feet wide.
Modules, in turn, can be combined and connected to form PV arrays of different sizes and power output. The modules of the array make up the major part of a PV system, which can also include electrical connections, mounting hardware, power-conditioning equipment, and batteries that store solar energy for use when the sun is not shining.
When light shines on a PV cell, it may be reflected, absorbed, or pass right through. But only the absorbed light generates electricity. The energy of the absorbed light is transferred to electrons in the atoms of the PV cell semiconductor material. With their newfound energy, these electrons escape from their normal positions in the atoms and become part of the electrical flow, or current, in an electrical circuit. A special electrical property of the PV cell—what is called a "built-in electric field"—provides the force, or voltage, needed to drive the current through an external load, such as a light bulb.

Crystalline Silicon Cells

Crystalline silicon PV cells are the most common photovoltaic cells in use today. They are also the earliest successful PV devices. Therefore, crystalline silicon solar cells provide a good example of typical PV cell functionality. Learn more about crystalline silicon cells and how these solar cells work with semiconductors and the built-in electric field.

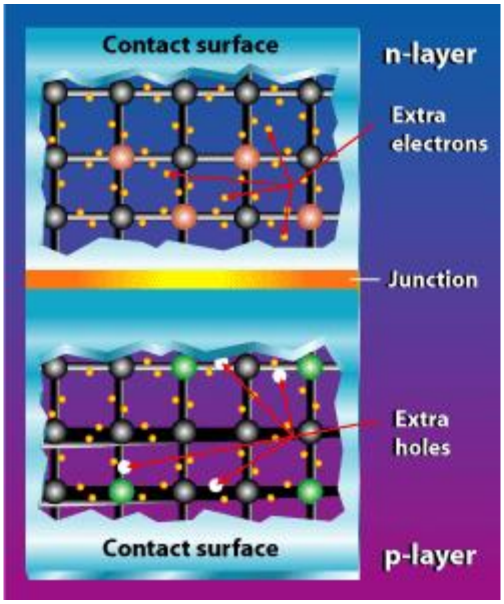
Photovoltaic Systems

A photovoltaic (PV), or solar electric system, is made up of several photovoltaic solar cells. An individual PV cell is usually small, typically producing about 1 or 2 watts of power. To boost the power output of PV cells, they are connected together to form larger units called modules. Modules, in turn, can be connected to form even larger units called arrays, which can be interconnected to produce more power, and so on. In this way, PV systems can be built to meet almost any electric power need, small or large.
The basic PV or solar cell produces only a small amount of power. To produce more power, cells can be interconnected to form modules, which can in turn be connected into arrays to produce yet more power. Because of this modularity, PV systems can be designed to meet any electrical requirement, no matter how large or how small.
By themselves, modules or arrays do not represent an entire PV system. Systems also include structures that point them toward the sun and components that take the direct-current electricity produced by modules and "condition" that electricity, usually by converting it to alternate-current electricity. PV systems may also include batteries. These items are referred to as the balance of system (BOS) components.
Combining modules with BOS components creates an entire PV system. This system is usually everything needed to meet a particular energy demand, such as powering a water pump, the appliances and lights in a home, or—if the PV system is large enough—all the electrical requirements of a community.

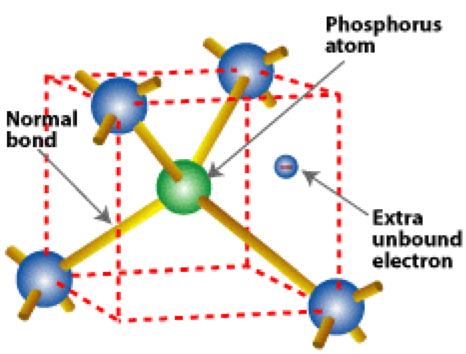
Semiconductors and the Built-In Electric Field for Crystalline Silicon Photovoltaic Cells

To separate electrical charges, crystalline silicon cells must have a built-in electric field. Light shining on crystalline silicon may free electrons within the crystal lattice, but for these electrons to do useful work—such as provide electricity to a light bulb—they must be separated and directed into an electrical circuit.

PV Semiconductors



Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a p/n junction at their interface, thereby creating an electric field.



Substituting a phosphorus atom (with five valence electrons) for a silicon atom in a silicon crystal leaves an extra, unbonded electron that is relatively free to move around the crystal.

To create an electric field within a crystalline silicon photovoltaic (PV) cell, two silicon semiconductor layers are sandwiched together. P-type (or positive) semiconductors have an abundance of positively charged holes, and n-type (or negative) semiconductors have an abundance of negatively charged electrons. When n- and p-type silicon layers contact, excess electrons move from the n-type side to the p-type side. The result is a buildup of positive charge along the n-type side of the interface and a buildup of negative charge along the p-type side.

Because of the flow of electrons and holes, the two semiconductors behave like a battery, creating an electric field at the surface where they meet"what is called the *p/n junction*. The electrical field causes the electrons to move from the semiconductor toward the negative surface, making them available for the electrical circuit. At the same time, the holes move in the opposite direction, toward the positive surface, where they await incoming electrons.

Creating P-Type and N-Type Semiconductors

In a crystalline silicon PV cell, p-type silicon must contact n-type silicon to create the built-in electrical field. The process of *doping*, which is used to create these materials, introduces an atom of another element into silicon crystal to alter its electrical properties. The *dopant*, which is the introduced element, has either three or five valence electrons—which is one less or one more than silicon's four.

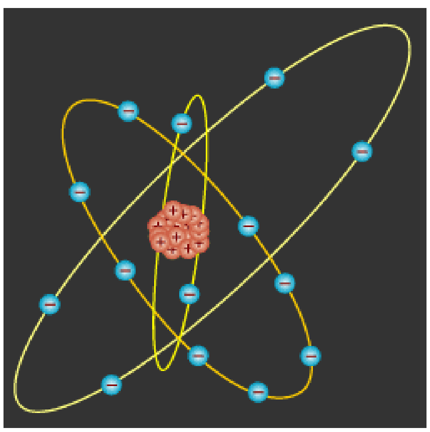
Phosphorus atoms, which have five valence electrons, are used to dope n-type silicon because phosphorus provides its fifth free electron. A phosphorus atom occupies the same place in the crystal lattice formerly occupied by the silicon atom it replaced. Four of its valence electrons take over the bonding responsibilities of the four silicon valence electrons that they replaced. But the fifth valence electron remains free, having no bonding responsibilities. When phosphorus atoms are substituted for silicon in a crystal, many free electrons become available.

The most common method of doping is to coat a layer of silicon material with phosphorus and then heat the surface. This allows the phosphorus atoms to diffuse into the silicon. The temperature is then reduced so the rate of diffusion drops to zero. Other methods of introducing phosphorus into silicon include gaseous diffusion, a liquid dopant spray-on process, and a technique in which phosphorus ions are precisely driven into the surface of the silicon.
But the n-type silicon cannot form an electric field by itself. It also needs p-type silicon. Boron, which has only three valence electrons, is used for doping p-type silicon. Boron is introduced during silicon processing when the silicon is purified for use in photovoltaic devices. When a boron atom takes a position in the crystal lattice formerly occupied by a silicon atom, a bond will be missing an electron.
In other words, there is an extra positively charged hole.

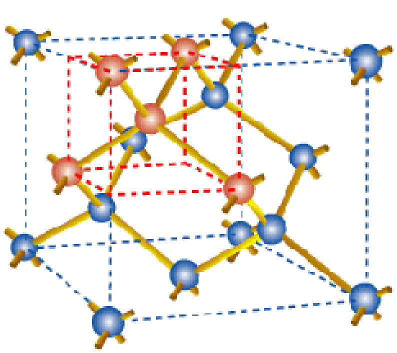
P-Layer Design
In a PV cell, photons are absorbed in the p-layer. It is therefore important that this layer be "tuned" to the properties of incoming photons so it can absorb as many as possible and, thus, free up as many electrons as possible. The design of the p-layer must also keep the electrons from meeting up with holes and recombining with them before they can escape from the PV cell. To accomplish these goals, p-layers are designed to free electrons as close to the junction as possible, so that the electric field can help send the free electrons through the conduction layer (the n-layer) and out into the electrical circuit.
By optimizing these characteristics, the PV cell's conversion efficiency (how much light energy is converted into electrical energy) is improved.

Crystalline Silicon Photovoltaic Cells
Crystalline silicon cells are made of silicon atoms connected to one another to form a crystal lattice. This lattice comprises the solid material that forms the photovoltaic (PV) cell's semiconductors. This section describes the atomic structure and bandgap energy of these cells.

Atomic Structure
All matter is composed of atoms, which are made up of positively charged protons, negatively charged electrons, and neutral neutrons. Protons and neutrons, which are about the same size, are in the close-packed, central nucleus of the atom. The much lighter electrons orbit the nucleus. Although atoms are built of oppositely charged particles, their overall charge is neutral because they contain an equal number of positive protons and negative electrons, whose charges offset each other.



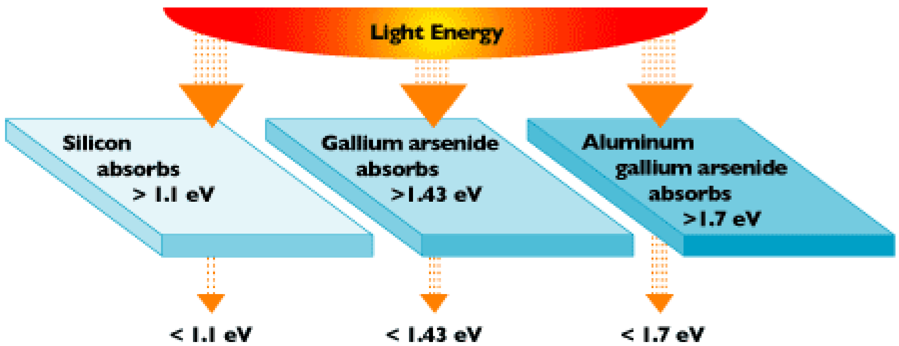
As depicted in this simplified diagram, silicon has 14 electrons. The four electrons that orbit the nucleus in the outermost "valence" energy level are given to, accepted from, or shared with other atoms.



In the basic unit of a crystalline silicon solid, a silicon atom shares each of its four valence electrons with each of four neighboring atoms.

Electrons orbit at different distances from the nucleus, depending on their energy level. Electrons with less energy orbit close to the nucleus, and electrons with more energy orbit farther away. The higher-energy electrons farthest from the nucleus are the ones that interact with neighboring atoms to form solid structures.
A silicon atom has 14 electrons, but their natural orbital arrangement allows only the outermost four electrons to be given to, accepted from, or shared with other atoms. These four electrons, called *valence* electrons, play an important role in the photoelectric effect.
Large numbers of silicon atoms bond with one another by means of their valence electrons to form a crystal. In a crystalline solid, each silicon atom normally shares one of its four valence electrons in a covalent bond with each of four neighboring silicon atoms. The solid thus consists of basic units of five silicon atoms: the original atom plus the four atoms with which it shares valence electrons.
The solid silicon crystal is thus made up of a regular series of units of five silicon atoms. This regular, fixed arrangement of silicon atoms is known as the *crystal lattice*.

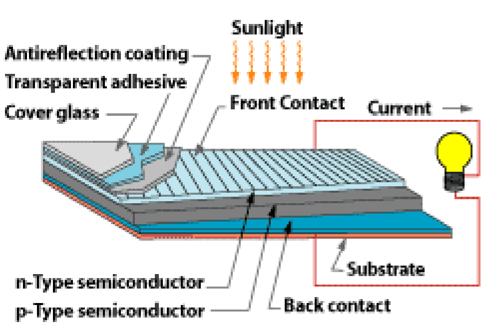
Bandgap Energy
Bandgap energy is the amount of energy required to dislodge an electron from its covalent bond and allow it to become part of an electrical circuit. When light shines on crystalline silicon, electrons within its crystal lattice may be freed. But not all photons—as packets of light energy are called—are created equal.
To free an electron, the energy of a photon must be at least as great as the bandgap energy. However, photons with more energy than the bandgap energy will expend the extra as heat when freeing electrons. So it is important for a photovoltaic (PV) cell to be "tuned"—through slight modifications to the silicon's molecular structure—to optimize the photon energy.
Crystalline silicon has a bandgap energy of 1.1 electron-volts (eV). (An electron-volt is equal to the energy gained by an electron when it passes through a potential of 1 volt in a vacuum.) The bandgap energies of other effective PV semiconductors range from 1.0 to 1.6 eV. In this range, electrons can be freed without creating extra heat.
The photon energy of light varies according to the wavelengths of the light. The entire spectrum of sunlight, from infrared to ultraviolet, covers a range of about 0.5 eV to about 2.9 eV. For example, red light has an energy of about 1.7 eV, and blue light has an energy of about 2.7 eV. Most PV cells cannot use about 55% of the energy of sunlight because this energy is either below the bandgap of the material used or carries excess energy.



Different PV materials have different energy band gaps. Photons with energy equal to the band gap energy are absorbed to create free electrons. Photons with less energy than the band gap energy pass through the material.

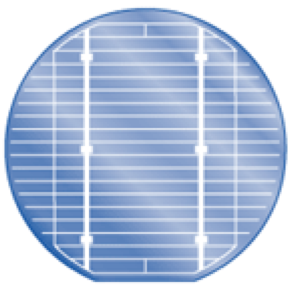
Photovoltaic Electrical Contacts and Cell Coatings
The outermost layers of photovoltaic (PV) cell, or solar cell, are the electrical contacts and anti-reflective coating. These layers provide essential functions to the cell's operation.

Electrical Contacts
Electrical contacts are essential to PV cells because they bridge the connection between thesemiconductor material and the external electrical load, such as a light bulb.



A typical solar cell consists of a glass or plastic cover, an antireflective coating, a front contact to allow electrons to enter a circuit, a back contact to allow them to complete the circuit, and the semiconductor layers where the electrons begin and complete their journey.
The back contact of a cell—the side away from the incoming sunlight—is relatively simple. It usually consists of a layer of aluminum or molybdenum metal.
But the front contact—the side facing the sun—is more complicated. When sunlight shines on a PV cell, a current of electrons flows over the surface. To collect the most current, contacts must be placed across the surface of the cell. This is normally done with a grid of metal strips or "fingers." However, placing a large grid, which is opaque, on top of the cell shades active parts of the cell from the sun and reduces the cell's conversion efficiency. To improve conversion efficiency, shading effects must be minimized.

Another challenge in cell design is to minimize the electrical resistance losses when applying grid contacts to the solar cell material. These losses are related to the solar cell material's property of opposing the flow of an electric current, which results in heating the material. Therefore, shading effects must be balanced against electrical resistance losses. The usual approach is to design grids with many thin, conductive fingers that spread to every part of the cell's surface. The fingers of the grid must be thick enough to conduct well (with low resistance) but thin enough not to block too much incoming light.



Grid contacts on the top surface of a typical cell are designed to have many thin, conductive fingers spreading to every part of the cell's surface.
Grids can be expensive to make and can affect the cell's reliability. To make top-surface grids, metallic vapors are deposited on a cell through a mask or painted on via a screen-printing method. An alternative to metallic grid contacts is a transparent conducting oxide (TCO) layer made of, for example, tin oxide (SnO_2). The advantages o TCOs are that they are nearly invisible to incoming light and they form a good bridge from the semiconductor material to the external electrical circuit. TCOs are very useful in manufacturing processes involving a glass superstrate, which is the covering on the sun-facing side of a PV module. In this process, the TCO is generally deposited as a thin film on the glass superstrate before the semiconducting layers are deposited. The semiconducting layers are then followed by a metallic contact that is actually the bottom of the cell. The cell is therefore constructed "upside down," from the top to the bottom.
The sheet resistance of the semiconductor is also an important consideration in grid design. In crystalline silicon, for example, the semiconductor carries electrons well enough to reach a finger of a metallic grid. Because the metal conducts electricity better than a TCO, shading losses are less than losses associated with a TCO. Other semiconductors, such as amorphous silicon, conduct very poorly in the horizontal direction. Therefore, they benefit from having a TCO over the entire surface.

Cell Coatings
Silicon is a shiny gray material that can act as a mirror by reflecting more than 30% of the light that shines on it. To improve the conversion efficiency of a solar cell, the amount of light reflected must be minimized.
Two techniques are commonly used to reduce reflection. The first technique is to coat the top surface with a thin layer of silicon monoxide (SiO). A single layer reduces surface reflection to about 10%, and a second layer can lower the reflection to less than 4%. The second technique is to texture the top surface. Chemical etching creates a pattern of cones and pyramids, which captures light rays that might otherwise be deflected away from the cell. Reflected light is redirected into the cell, where it has another chance to be absorbed.

Photovoltaic Cell Materials
Although crystalline silicon cells are the most common type, photovoltaic (PV), or solar cells, can be made of many semiconductor materials. Each material has unique strengths and characteristics that influence its suitability for specific applications. For example, PV cell materials may differ based on their crystallinity, bandgap, absorbtion, and manufacturing complexity.

Solar cell materials:

Silicon (Si)—including single-crystalline Si, multicrystalline Si, and amorphous Si

Polycrystalline Thin Films—including copper indium diselenide (CIS), cadmium telluride (CdTe), and thin-film silicon

Single-Crystalline Thin Films—including high-efficiency material such as gallium arsenide (GaAs).

Crystallinity
The crystallinity of a material indicates how perfectly ordered the atoms are in the crystal structure. Silicon, as well as other solar cell semiconductor materials, comes in various forms, including single-crystalline, multicrystalline, polycrystalline, and amorphous. In a single-crystal material, the atoms that make up the framework of the crystal are repeated in a very regular, orderly manner from layer to layer. In contrast, in a material composed of numerous smaller crystals, the orderly arrangement is disrupted moving from one crystal to another.

Bandgap
The bandgap of a semiconductor material is the minimum energy needed to move an electron from its bound state within an atom to a free state. This free state is where the electron can be involved in conduction. The lower energy level of a semiconductor is called the *valence band*, and the higher energy level where an electron is free to roam is called the *conduction band*. The bandgap (often symbolized by Eg) is the energy difference between the conduction and valence bands.

Absorption
The absorption coefficient of a material indicates how far light with a specific wavelength (or energy) can penetrate the material before being absorbed. A small absorption coefficient means that light is not readily absorbed by the material.
The absorption coefficient of a solar cell depends on two factors: the material of the cell and the wavelength or energy of the light being absorbed. Solar cell material has an abrupt edge in its absorption coefficient because light with energy below the material's bandgap cannot free an electron.

Manufacturing Complexity
The most important parts of a solar cell are the semiconductor layers because this is where electrons are freed and electric current is created. Several semiconductor materials can be used to make the layers in solar cells, and each material has its benefits and drawbacks. The cost and complexity of manufacturing varies across materials and device structures based on many factors, including deposition in a vacuum environment, amount and type of material used, number of steps involved, and the need to move cells into different deposition chambers.

Photovoltaic Cell Structures
The actual structural design of a photovoltaic (PV), or solar cell, depends on the limitations of the material used in the PV cell. The four basic device designs are:

Homojunction Devices
Crystalline silicon is the primary example of this kind of cell. A single material—crystalline silicon—is altered so that one side is p-type, dominated by positive holes, and the other side is n-type, dominated by negative electrons. The p/n junction is located so that the maximum light is absorbed near it. The free electrons and holes generated by light deep in the silicon diffuse to the p/n junction and then separate to produce a current if the silicon is of sufficiently high quality.
In this homojunction design, these aspects of the cell may be varied to increase conversion efficiency:

- Depth of the p/n junction below the cell's surface
- Amount and distribution of dopant atoms on either side of the p/n junction
- Crystallinity and purity of the silicon.

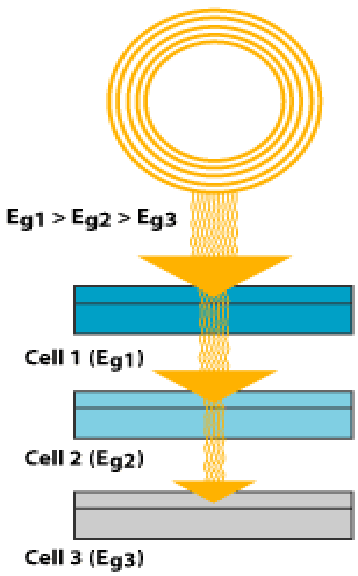
Some homojunction cells have also been designed with the positive and negative electrical contacts on the back of the cell. This geometry eliminates the shadowing caused by the electrical grid on top of the cell. A disadvantage is that the charge carriers, which are mostly generated near the top surface of the cell, must travel farther—all the way to the back of the cell—to reach an electrical contact. To be able to do this, the silicon must be of very high quality, without crystal defects that cause electrons and holes to recombine.

Heterojunction Devices
An example of this type of device structure is a copper indium diselenide cell, in which the junction is formed by contacting different semiconductors—cadmium sulfide and copper indium diselenide. This structure is often chosen to produce cells made of thin-film materials that absorb light better than silicon.
The top and bottom layers in a heterojunction device have different roles. The top layer, or *window layer*, is a material with a high bandgap selected for its transparency to light. The window allows almost all incident light to reach the bottom layer, which is a material with low bandgap that readily absorbs light. This light then generates electrons and holes very near the junction, which helps to effectively separate the electrons and holes before they can recombine.
Heterojunction devices have an inherent advantage over homojunction devices, which require materials that can be doped both p- and n-type. Many PV materials can be doped either p-type or n-type but not both. Again, because heterojunctions do not have this constraint, many promising PV materials can be investigated to produce optimal cells.
Also, a high-bandgap window layer reduces the cell's series resistance. The window material can be made highly conductive, and the thickness can be increased without reducing the transmittance of light. As a result, light-generated electrons can easily flow laterally in the window layer to reach an electrical contact.

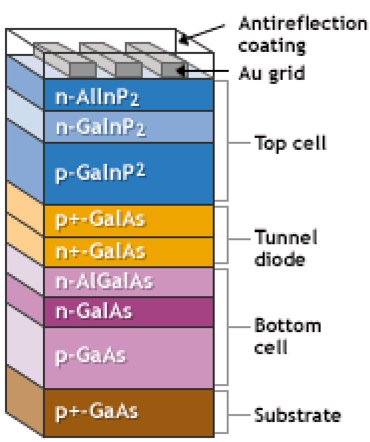
p-i-n and n-i-p Devices

Typically, amorphous silicon thin-film cells use a p-i-n structure, whereas cadmium telluride (CdTe) cells use an n-i-p structure. The basic scenario is as follows: A three-layer sandwich is created, with a middle intrinsic (i-type or undoped) layer between an n-type layer and a p-type layer. This geometry sets up an electric field between the p- and n-type regions that stretches across the middle intrinsic resistive region. Light generates free electrons and holes in the intrinsic region, which are then separated by the electric field.

In the p-i-n amorphous silicon (a-Si) cell, the top layer is p-type a-Si, the middle layer is intrinsic silicon, and the bottom layer is n-type a-Si. Amorphous silicon has many atomic-level electrical defects when it is highly conductive, so very little current would flow if an a-Si cell had to depend on diffusion. However, in a p-i-n cell, current flows because the free electrons and holes are generated *within* the influence of an electric field rather than having to move toward the field.



A multijunction device is a stack of individual single-junction cells in descending order of bandgap (Eg). The top cell captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-bandgap cells.



This multijunction device has a top cell of gallium indium phosphide, a tunnel junction to allow the flow of electrons between the cells, and a bottom cell of gallium arsenide.

In a CdTe cell, the device structure is similar to the a-Si cell, except the order of layers is flipped upside down. Specifically, in a typical CdTe cell, the top layer is p-type cadmium sulfide (CdS), the middle layer is intrinsic CdTe, and the bottom layer is n-type zinc telluride (ZnTe).

Multijunction Devices

This structure, also called a cascade or tandem cell, can achieve a higher total conversion efficiency by capturing a larger portion of the solar spectrum. In the typical multijunction cell, individual cells with different bandgaps are stacked on top of one another. The individual cells are stacked in such a way that sunlight falls first on the material having the largest bandgap. Photons not absorbed in the first cell are transmitted to the second cell, which then absorbs the higher-energy portion of the remaining solar radiation while remaining transparent to the lower-energy photons. These selective absorption processes continue through to the final cell, which has the smallest bandgap.

A multijunction cell can be made two ways. In the mechanical stack approach, two individual solar cells are made independently, one with a high bandgap and one with a lower bandgap. Then the two cells are mechanically stacked, one on top of the other. In the monolithic approach, one complete solar cell is made first, and then the layers for the second cell are grown or deposited directly on the first.

Much of today's research in multijunction cells focuses on gallium arsenide as one (or all) of the component cells. These cells have efficiencies of more than 35% under concentrated sunlight, which is high for PV devices. Other materials studied for multijunction devices are amorphous silicon and copper indium diselenide.

Photovoltaic Cell Performance

Photovoltaic (PV), or solar cells use the energy in sunlight to produce electricity. However, the amount of electricity produced depends on the quality of the light available and the performance of the PV cell.

Researchers make measurements of conversion efficiency and quantum efficiency to characterize the performance of PV cells. Based on these results, researchers may redesign aspects of the cell—e.g., material compositions or thicknesses of layers—to improve performance.

Lighting

There are many different types of artificial lights, all of which have different applications and uses. Types of lighting include:

- Fluorescent Lighting
- High-intensity Discharge Lighting
- Incandescent Lighting
- LED Lighting
- Low-pressure Sodium Lighting.

Lighting Type	Efficacy (lumens/watt)	Lifetime (hours)	Color Rendition Index (CRI)	Color Temperature (K)	Indoors/Outdoors
Fluorescent					
Straight Tube	30–110	7000–24,000	50–90 (fair to good)	2700–6500 (warm to cold)	Indoors/outdoors
Compact Fluorescent	50–70	10,000	65–88 (good)	2700–6500 (warm to cold)	Indoors/outdoors
Circline	40–50	12,000			Indoors
High-Intensity Discharge					
Mercury Vapor	25–60	16,000–24,000	50 (poor to fair)	3,200–7,000 (warm to cold)	Outdoors
Metal Halide	70–115	5,000–20,000	70 (fair)	3,700 (cold)	Indoors/outdoors
High-Pressure Sodium	50–140	16,000–24,000	25 (poor)	2,100 (warm)	Outdoors
Incandescent					
Standard "A"	10–17	750–2,500	98–100 (excellent)	2,700–2,800 (warm)	Indoors/outdoors
Tungsten Halogen	12–22	2,000–4,000	98–100 (excellent)	2,900–3,200 (warm to neutral)	Indoors/outdoors
Reflector	12–19	2,000–3,000	98–100 (excellent)	2,800 (warm)	Indoors/outdoors
Light-Emitting Diodes					
Cool White LEDs	60–92	35,000–50,000	70–90 (fair to good)	5000 (cold)	Indoors/ outdoors
Warm White LEDs	27–54	35,000–50,000	70–90 (fair to good)	3300 (neutral)	Indoors/ outdoors
Low-Pressure Sodium	60–150	12,000–18,000	-44 (very poor)		Outdoors

Fluorescent Lighting

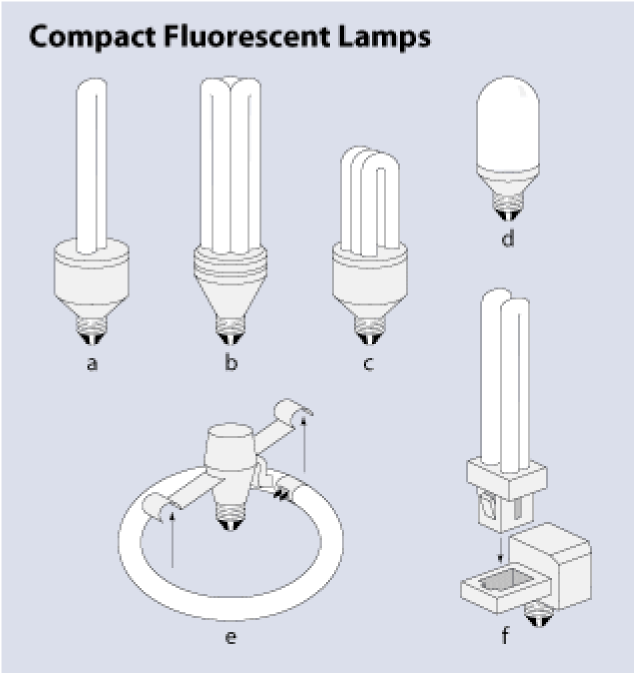
Fluorescent lamps use 25%-35% of the energy used by incandescent lamps to provide the same amount of illumination (efficacy of 30-110 lumens per watt). They also last about 10 times longer (7,000-24,000 hours).

The light produced by a fluorescent tube is caused by an electric current conducted through mercury and inert gases. Fluorescent lamps require a ballast to regulate operating current and provide a high start-up voltage. Electronic ballasts outperform standard and improved electromagnetic ballasts by operating at a very high frequency that eliminates flicker and noise. Electronic ballasts also are more energy-efficient. Special ballasts are needed to allow dimming of fluorescent lamps.

The two general types of fluorescent lamps are:

- Compact fluorescent lamps
- Fluorescent tube and circline lamps

Compact Fluorescent Lamps:



CFLs come in a variety of sizes and shapes, including (a) twin-tube integral, (b and c) triple-tube integral, (d) integral model with casing that reduces glare, (e) modular circline and ballast, and (f) modular quad-tube and ballast varieties.
Compact fluorescent lamps (CFLs) combine the energy efficiency of fluorescent lighting with the convenience and popularity ofincandescent fixtures.

CFLs can replace incandescents that are roughly 3-4 times their wattage, saving up to 75% of the initial lighting energy. Although CFLs cost 3-10 times more than comparable incandescent bulbs, they last 6-15 times as long (6,000-15,000 hours).

CFLs work much like standard fluorescent lamps. They consist of two parts: a gas-filled tube and a magnetic or electronic ballast. The gas in the tube glows with ultraviolet light when electricity from the ballast flows through it. This, in turn, excites a white phosphor coating on the inside of the tube, which emits visible light throughout the surface of the tube.

CFLs with magnetic ballasts flicker slightly when they start. They are also heavier than those with electronic ballasts. This may make them too heavy for some light fixtures. Electronic ballasts are more expensive but light immediately (especially at low temperatures). They are also more efficient than magnetic ballasts. The tubes will last about 10,000 hours and the ballast about 50,000 hours. Most currently available CFLs have electronic ballasts.

CFLs are designed to operate within a specific temperature range. Temperatures below the range cause reduced output. Most are for indoor use, but there are models available for outdoor use. A CFL's temperature range is usually listed on its package.

CFLs are most cost-effective and efficient in areas where lights are on for long periods of time. Because CFLs do not need to be changed often, they are ideal for hard-to-reach areas.

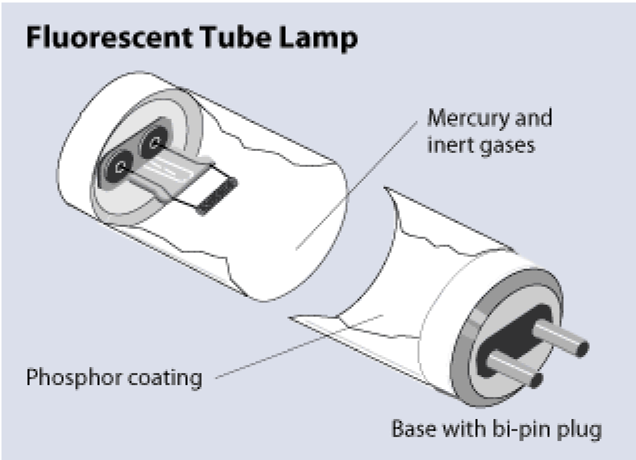
Types of Compact Fluorescent Lamps

CFLs are available in a variety of styles and shapes. They may have two, four, or six tubes or circular or spiral-shaped tubes. The size or total surface area of the tube(s) determines how much light is produced.

In some CFLs, the tubes and ballast are permanently connected. Other CFLs have separate tubes and ballasts. This allows the tubes to be changed without changing the ballast. There are also types enclosed in a glass globe. These look somewhat similar to conventional incandescent light bulbs, except they are larger.

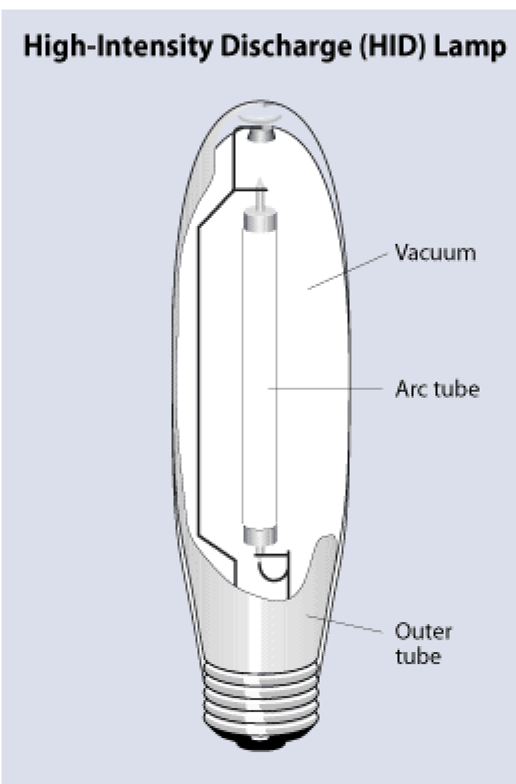
Sub-CFLs fit most fixtures designed for incandescent lamps. Although most CFLs fit into existing three-way light sockets, only a few special CFL models can be dimmed.

Fluorescent Tube and Circline Lamps



In fluorescent tubes, a very small amount of mercury mixes with inert gases to conduct electrical current. This allows the phosphor coating on the glass tube to emit light.
Fluorescent tube lamps—the second most popular type of lamps—are more energy efficient than the more popular A-typestandard incandescent lamps.
The traditional tube-type fluorescent lamps are usually identified as T12 or T8 (twelve-eighths or eight-eighths of an inch tube diameter, respectively). They are installed in a dedicated fixture with a built-in ballast. The two most common types are 40-watt, 4-foot (1.2-meter) lamps and 75-watt, 8-foot (2.4-meter) lamps.
Tubular fluorescent fixtures and lamps are preferred for ambient lighting in large indoor areas. In these areas, their low brightness creates less direct glare than incandescent bulbs.
Circular tube-type fluorescent lamps are called*circline lamps*. They are commonly used for portable task lighting.

High-Intensity Discharge Lighting



In a high-intensity discharge lamp, electricity arcs between two electrodes, creating an intensely bright light. Mercury, sodium, or metal halide gas actS as the conductor.
High-intensity discharge (HID) lighting provides the highest efficacy and longest service life of any lighting type. It can save 75%-90% of lighting energy when it replaces incandescent lighting.

HID lamps use an electric arc to produce intense light. Like fluorescent lamps, they require ballasts. They also take up to 10 minutes to produce light when first turned on because the ballast needs time to establish the electric arc. Because of the intense light they produce at a high efficacy, HID lamps are commonly used for outdoor lighting and in large indoor arenas. Because the lamps take awhile to establish, they are most suitable for applications in which they stay on for hours at a time. They are not suitable for use with motion detectors.
The three most common types of high-intensity discharge lamps are:

- Mercury vapor lamps
- Metal halide lamps
- High-pressure sodium lamps

Mercury Vapor Lamps

Mercury vapor lamps—the oldest types of high-intensity discharge lighting—are used primarily for street lighting.
Mercury vapor lamps provide about 50 lumens per watt. They cast a very cool blue/green white light. Most indoor mercury vapor lamps in arenas and gymnasiums have been replaced by metal halide lamps. Metal halide lamps have better color rendering and a higher efficacy. However, like high-pressure sodium lamps, mercury vapor lamps have longer lifetimes (16,000-24,000 hours) than metal halide lamps.
Significant energy savings are also possible by replacing old mercury vapor lamps with newer high-pressure sodium lamps.

Metal Halide Lamps

Metal halide lamps produce a bright, white light with the best color rendition among high-intensity lighting types. They are used to light large indoor areas, such as gymnasiums and sports arenas, and outdoor areas, such as car lots.
Metal halide lamps are similar in construction and appearance to mercury vapor lamps. The addition of metal halide gases to mercury gas within the lamp results in higher light output, more lumens per watt, and better color rendition than from mercury gas alone.
Metal halide lamps have shorter lifetimes (5,000-20,000 hours) than mercury vapor and high-pressure sodium lamps.

High-Pressure Sodium Lamps

High-pressure sodium lighting—a type of high-intensity discharge lighting—is becoming the most common type of outdoor lighting.
High-pressure sodium lamps have an efficacy of 50-140 lumens per watt—an efficiency exceeded only by low-pressure sodium lamps. They produce a warm white light.
Like mercury vapor lamps, high-pressure sodium lamps have poorer color rendition than metal halide lamps but longer lifetimes (16,000-24,000 hours).

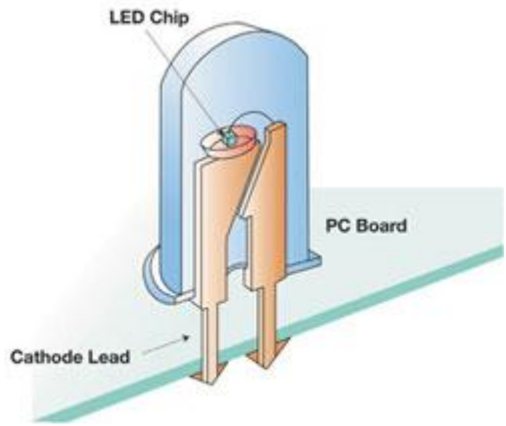
Low-pressure sodium lighting provides more energy-efficient outdoor lighting than high-intensity discharge lighting, but it has very poor color rendition. Typical applications include highway and security lighting, where color is not important.
Low-pressure sodium lamps work somewhat like fluorescent lamps. Like high-intensity discharge lighting, low-pressure sodium lamps require up to 10 minutes to start and have to cool before they can restart. Therefore, they are most suitable for applications in which they stay on for hours at a time. They are not suitable for use with motion detectors.
The chart below compares low-pressure sodium lamps and high-intensity discharge lamps.

Lighting Type	Efficacy (lumens/watt)	Lifetime (hours)	Color Rendition Index (CRI)	Color Temperature (K)	Indoors/Outdoors
High-Intensity Discharge					
Mercury vapor	25–60	16,000–24,000	50 (poor to fair)	3200–7000 (warm to cold)	Outdoors
Metal halide	70–115	5000–20,000	70 (fair)	3700 (cold)	Indoors/outdoors
High-pressure sodium	50–140	16,000–24,000	25 (poor)	2100 (warm)	Outdoors
Low-Pressure Sodium	60–150	12,000–18,000	-44 (very poor)		Outdoors

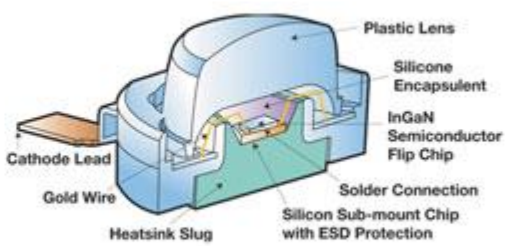
Reference Materials:
U.S. Department of ENERGY
Energy Efficiency & Renewable Energy
http://www.eere.energy.gov/

LED Lighting
Light-emitting diodes (LEDs) are light sources that differ from more traditional sources of light in that they are semiconductor devices that produce light when an electrical current is applied. Applying electrical current causes electrons to flow from the positive side of a diode to the negative side. Then, at the positive/negative junction of the diode, the electrons slow down to orbit at a lower energy level. The electrons emit the excess energy as photons of light.
LEDs are often used as small indicator lights on various electronic devices. Because of their long life, durability, and efficiency, LEDs are becoming more common in residential, commercial, and outdoor area lighting applications.

Common LED Types and Packages



Structure of a 5mm type LED.
Source: Lumileds™

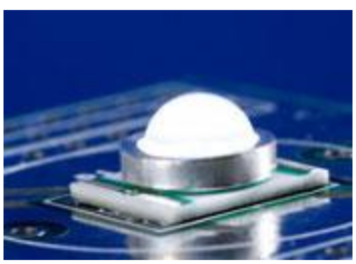
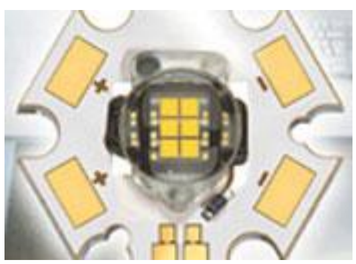


Structure of a high-brightness LED.
Source: Lumileds™

LEDs come in two basic categories:

Low power LEDs commonly come in 5 mm size, although they are also available in 3 mm and 8 mm sizes. These are fractional wattage devices, typically 0.1 watt, operate at low current (~20 milliamps) and low voltage (3.2 volts DC), and produce a small amount of light, perhaps 2 to 4 lumens.

High power LEDs come in 1-3 watt packages. They are driven at much higher current, typically 350, 700, or 1000 mA, and—with current technology—can produce 40-80 lumens per 1-watt package.
High power LEDs come in many different shapes and sizes. Some current products from the leading LED manufacturers are shown below.

 Cree® XLamp 7090	 Philips Lumileds Luxeon® K2 Emitter	 Osram® OSTAR Lighting

Glossary of LED Terms

Solid-state lighting (SSL) technology uses semi-conducting materials to convert electricity into light. SSL is an umbrella term encompassing both light-emitting diodes (LEDs) and organic light emitting diodes (OLEDs).
Light-emitting diodes (LEDs) are based on inorganic (non-carbon based) materials. An LED is a semi-conducting device that produces light when an electrical current flows through it. LEDs were first developed in the 1960s but were used only in indicator applications until recently.

Organic light-emitting diodes (OLEDs) are based on organic (carbon based) materials. In contrast to LEDs, which are small point sources, OLEDs are made in sheets which provide a diffuse area light source. OLED technology is developing rapidly and is increasingly used in display applications such as cell phones and PDA screens. However, OLEDs are still some years away from becoming a practical general illumination source. Additional advancements are needed in light output, color, efficiency, cost, and lifetime.

General illumination is a term used to distinguish between lighting that illuminates tasks, spaces, or objects from lighting used in indicator or purely decorative applications. In most cases, general illumination is provided by white light sources, including incandescent, fluorescent, high-intensity discharge sources, and white LEDs. Lighting used for indication or decoration is often monochromatic, as in traffic lights, exit signs, vehicle brake lights, signage, and holiday lights.

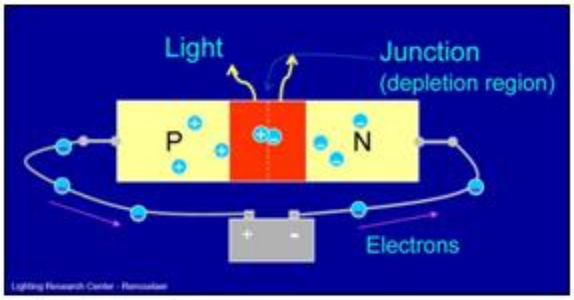
Luminous efficacy is the most commonly used measure of the energy efficiency of a light source. It is stated in lumens per watt (lm/W), indicating the amount of light a light source produces for each watt of electricity consumed. For white high-brightness LEDs, luminous efficacy published by LED manufacturers typically refers to the LED chip only, and doesn't include driver losses. See more information in the Energy Efficiency section.

Correlated color temperature (CCT) is the measure used to describe the relative color appearance of a white light source. CCT indicates whether a light source appears more yellow/gold/orange or more blue, in terms of the range of available shades of "white." CCT is given in kelvins (unit of absolute temperature). See more information in the Color Quality section.

Color rendering index (CRI) indicates how well a light source renders colors of people and objects, compared to a reference source. See more information in theColor Quality section.

RGB stands for red, green, and blue, the three primary colors of light. When the primaries are mixed, the resulting light appears white to the human eye. Mixing the light from red, green, and blue LEDs is one way to produce white light. The other approach is known as phosphor conversion [see below]. See more information in the Color Quality section.

Phosphor conversion is a method used to generate white light with LEDs. A blue or near-ultraviolet LED is coated with a yellow or multichromatic phosphor, resulting in white light. See more information in the Color Quality section.



LEDs differ from traditional light sources in the way they produce light. In an incandescent lamp, a tungsten filament is heated by electric current until it glows or emits light. In a fluorescent lamp, an electric arc excites mercury atoms, which emit ultraviolet (UV) radiation. After striking the phosphor coating on the inside of glass tubes, the UV radiation is converted and emitted as visible light.

An LED, in contrast, is a semiconductor diode. It consists of a chip of semiconducting material treated to create a structure called a p-n (positive-negative) junction. When connected to a power source, current flows from the p-side or anode to the n-side, or cathode, but not in the reverse direction. Charge-carriers (electrons and electron holes) flow into the junction from electrodes. When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon (light).

The specific wavelength or color emitted by the LED depends on the materials used to make the diode.
Red LEDs are based on aluminum gallium arsenide (AlGaAs). Blue LEDs are made from indium gallium nitride (InGaN) and green from aluminum gallium phosphide (AlGaP). "White" light is created by combining the light from red, green, and blue (RGB) LEDs or by coating a blue LED with yellow phosphor. See "Color Quality" section for more information.

Energy Efficiency of White LEDs

The energy efficiency of LEDs is expected to rival the most efficient white light sources by 2010. But how energy efficient are LEDs right now? This section discusses various aspects of lighting energy efficiency and the rapidly evolving status of white LEDs. Click on the topics below for more information.

Luminous Efficacy
Comparing LEDs to Traditional Light Sources
Application Efficiency

Luminous Efficacy

Energy efficiency of light sources is typically measured in lumens per watt (lm/W), meaning the amount of light produced for each watt of electricity consumed by the light source. This is known as luminous efficacy. DOE's long-term research and development goal calls for white-light LEDs producing 160 lm/W in cost-effective, market-ready systems by 2025. In the meantime, how does the luminous efficacy of today's white LEDs compare to traditional light sources? Currently, the most efficacious white LEDs can perform similarly to fluorescent lamps. However, there are several important caveats, as explained below.

Color Quality

The most efficacious LEDs have very high correlated color temperatures (CCTs), often above 5000K, producing a "cold" bluish light. However, warm white LEDs (2600K to 3500K) have improved significantly, now approaching the efficacy of CFLs. In addition to warmer appearance, LED color rendering is also improving: leading warm white LEDs are now available with color rendering index (CRI) of 80, equivalent to CFLs.

Driver Losses

Fluorescent and high-intensity discharge (HID) light sources cannot function without a ballast, which provides a starting voltage and limits electrical current to the lamp. LEDs also require supplementary electronics, usually called drivers. The driver converts line power to the appropriate voltage (typically between 2 and 4 volts DC for high-brightness LEDs) and current (generally 200-1000 milliamps or mA), and may also include dimming and/or color correction controls.

Currently available LED drivers are typically about 85% efficient. So LED efficacy should be discounted by 15% to account for the driver. For a rough comparison, the range of luminous efficacies for traditional and LED sources, including ballast and driver losses as applicable, are shown below.

Light Source	Typical Luminous Efficacy Range in lm/W
	(varies depending on wattage and lamp type)
Incandescent (no ballast)	10-18
Halogen (no ballast)	15-20
Compact fluorescent (CFL) (incl. ballast)	35-60
Linear fluorescent (incl. ballast)	50-100
Metal halide (incl. ballast)	50-90
Cool white LED 5000K (incl. driver)	47-64*
Warm white LED 3300K (incl. driver)	25-44*

* As of October 2007.

Thermal Effects

The luminous flux figures cited by LED manufacturers are based on an LED junction temperature (Tj) of 25°C. LEDs are tested during manufacturing under conditions that differ from actual operation in a fixture or system. In general, luminous flux is measured under instantaneous operation (perhaps a 20 millisecond pulse) in open air. Tj will always be higher when operated under constant current in a fixture or system. LEDs in a well-designed luminaire with adequate heat sinking will produce 10%-15% less light than indicated by the "typical luminous flux" rating.

Terms

Efficiency or efficacy?

The term "efficacy" normally is used where the input and output units differ. For example in lighting, we are concerned with the amount of light (in lumens) produced by a certain amount of electricity (in watts). The term "efficiency" usually is dimensionless. For example, lighting fixture efficiency is characterized as a ratio of the total lumens exiting the fixture to the total lumens produced by the light source. "Efficiency" is also used to discuss the broader concept of using resources efficiently.

Lumen:
The SI unit of luminous flux. The total amount of light emitted by a light source, without regard to directionality, is given in lumens.

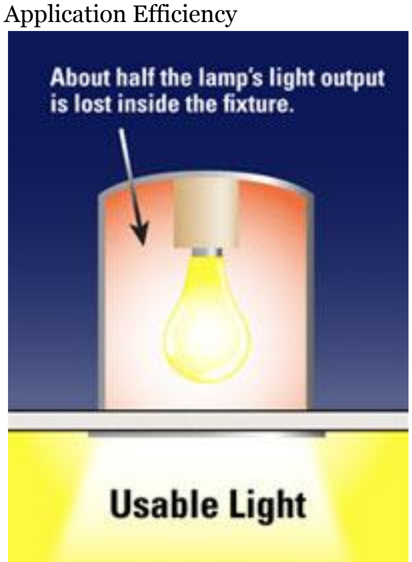
Luminous efficacy:
The total luminous flux emitted by the light source divided by the lamp wattage; expressed in lumens per watt (lm/W).

Luminaire efficacy:
The total luminous flux emitted by the luminaire divided by the total power input to the luminaire, expressed in lm/W.

Comparing LEDs to Traditional Light Sources
Energy efficiency proponents are accustomed to comparing light sources on the basis of luminous efficacy. To compare LED sources to CFLs, for example, the most basic analysis should compare lamp-ballast efficacy to LED+driver efficacy in lumens per watt. Data sheets for white LEDs from the leading manufacturers will generally provide "typical" luminous flux in lumens, test current (mA), forward voltage (V), and junction temperature (T_j), usually 25 degrees Celsius. To calculate lm/W, divide lumens by current times voltage. As an example, assume a device with typical flux of 45 lumens, operated at 350 mA and voltage of 3.42 V. The luminous efficacy of the LED source would be:
45 lumens/(.35 amps x 3.42 volts) = 38 lm/W

To include typical driver losses, multiply this figure by 85%, resulting in 32 lm/W. Because LED light output is sensitive to temperature, some manufacturers recommend de-rating luminous flux by 10% to account for thermal effects. In this example, accounting for this thermal factor would result in a system efficacy of approximately 29 lm/W. However, actual thermal performance depends on heat sink and fixture design, so this is only a very rough approximation. Accurate measurement can only be accomplished at the luminaire level.

Application Efficiency



The low-profile design of this undercabinet light takes advantage of LED directionality to deliver light where it is needed. Available in 3W (shown), 6W, and 9W models.

Photo credit: Finelite.

Luminous efficacy is an important indicator of energy efficiency, but it doesn't tell the whole story, particularly with regard to directional light sources.

Due to the directional nature of their light emission, LEDs potentially have higher application efficiency than other light sources in certain lighting applications. Fluorescent and standard "bulb" shaped incandescent lamps emit light in all directions. Much of the light produced by the lamp is lost within the fixture, reabsorbed by the lamp, or escapes from the fixture in a direction that is not useful for the intended application. For many fixture types, including recessed downlights, troffers, and under-cabinet fixtures, it is not uncommon for 40-50% of the total light output of the lamp(s) to be lost before it exits the fixture.

LEDs emit light in a specific direction, reducing the need for reflectors and diffusers that can trap light, so well-designed fixtures, like the undercabinet light shown below, can deliver light more efficiently to the intended location.

Application efficiency

While there is no standard definition of application efficiency, we use the term here to denote an important design consideration: that the desired illuminance level and lighting quality for a given application should be achieved with the lowest practicable energy input. Light source directionality and intensity may result in higher application efficiency even though luminous efficacy is lower relative to other light sources.

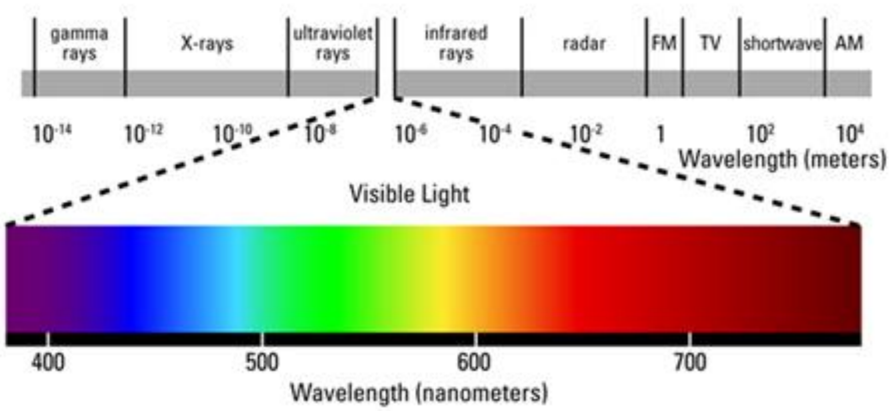
Color Quality of White LEDs

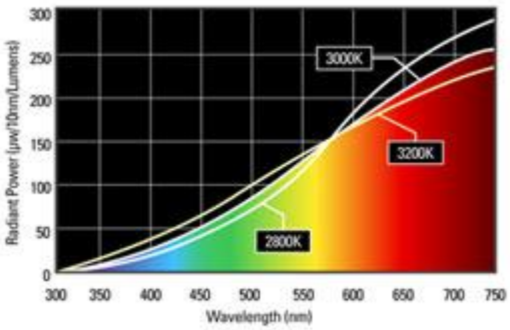
Color quality has been one of the key challenges facing white light-emitting diodes (LEDs) as a general light source. This section reviews the basics regarding light and color and summarizes the most important color issues related to white light LEDs, including recent advances. Click on the links below for more information.

Light and Color Basics
Correlated Color Temperature (CCT)
Color Rendering Index (CRI)
Making White Light with LEDs
Luminous Efficacy and Color Characteristics

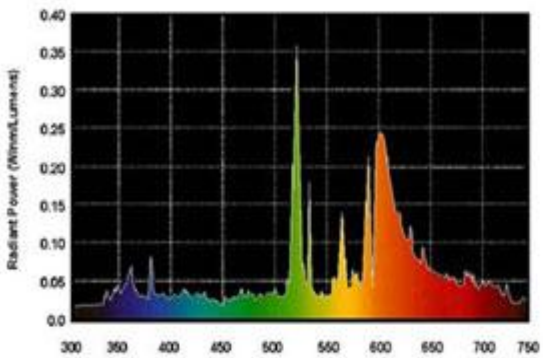
Light and Color Basics

Light-emitting diodes (LEDs) differ from other light sources, such as incandescent and fluorescent lamps, in the way they generate white light. We are accustomed to lamps that emit white light. But what does that really mean? What appears to our eyes as "white" is actually a mix of different wavelengths in the visible portion of the electromagnetic spectrum. The diagram below illustrates visible light as one small portion of the overall electromagnetic spectrum. Electromagnetic radiation in wavelengths from about 380 to 770 nanometers is visible to the human eye.

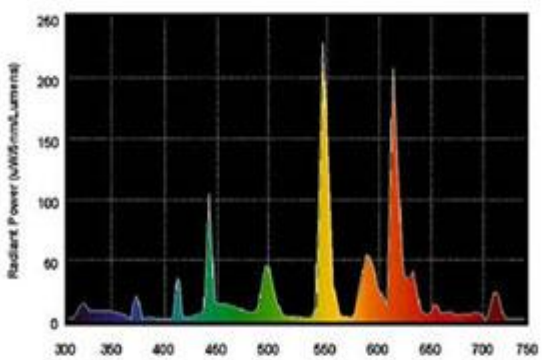




Example of a Typical Incandescent Spectral Power Distribution



SPX35 Tri-phosphor fluorescent. GE Lighting.



ConstantColor® Ceramic Metal Halide. GE Lighting.

Incandescent, fluorescent, and high-intensity discharge (HID) lamps radiate across the visible spectrum, but with varying intensity in the different wavelengths. The spectral power distribution (SPD) for a given light source shows the relative radiant power emitted by the light source at each wavelength. Incandescent sources have a continuous SPD, but relative power is low in the blue and green regions. The typically "warm" color appearance of incandescent lamps is due to the relatively high emissions in the orange and red regions of the spectrum.

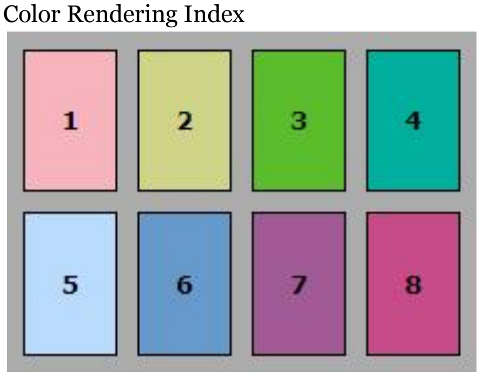
SPDs for fluorescent and HID sources are provided for comparison. These sources have "spikes" of relatively higher intensity at certain wavelengths, but still appear white to our eyes.

Unlike incandescent, fluorescent and HID sources, LEDs are near-monochromatic light sources. An individual LED chip emits light in a specific wavelength. This is why LEDs are comparatively so efficient for colored light applications. In traffic lights, for example, LEDs have largely replaced the old incandescent + colored filter systems. Using colored filters or lenses is actually a very inefficient way to achieve colored light. For example, a red filter on an incandescent lamp can block 90 percent of the visible light from the lamp. Red LEDs provide the same amount of light for about one-tenth the power (12 watts compared to 120+ watts) and last many times longer. However, to be used as a general light source, "white" light is needed. LEDs are not inherently white light sources.

Correlated Color Temperature

Correlated color temperature (CCT) describes the relative color appearance of a white light source, indicating whether it appears more yellow/gold or more blue, in terms of the range of available shades of white.
CCT is given in Kelvin (SI unit of absolute temperature) and refers to the appearance of a theoretical black body heated to high temperatures. As the black body gets hotter, it turns red, orange, yellow, white, and finally blue. The CCT of a light source is the temperature (in K) at which the heated black body matches the color of the light source in question.

Color Rendering Index



Eight standard color samples used in the test-color method for measuring and specifying the color rendering properties of light sources. Adapted from IESNA Handbook.
Reprinted courtesy of the Illuminating Engineering Society of North America.

Another important measure of color quality used by the lighting industry is the color rendering index (CRI). CRI indicates how well a light source renders colors, on a scale of 0 to 100, compared to a reference light source of similar color temperature.
The test procedure established by the International Commission on Illumination (CIE) involves measuring the extent to which a series of eight standardized color samples differ in appearance when illuminated under a given light source, relative to the reference source. The average "shift" in those eight color samples is reported as Ra or CRI. In addition to the eight color samples used by convention, some lighting manufacturers report an "R9" score, which indicates how well the light source renders a saturated deep red color.

Making White Light with LEDs
White light can be achieved with LEDs in two main ways: 1) phosphor conversion, in which a blue or near-ultraviolet (UV) chip is coated with phosphor(s) to emit white light; and 2) RGB systems, in which light from multiple monochromatic LEDs (red, green, and blue) is mixed, resulting in white light.
The phosphor conversion approach is most commonly based on a blue LED. When combined with a yellow phosphor (usually cerium-doped yttrium aluminum garnet or YAG:Ce), the light will appear white to the human eye. Research continues to improve the efficiency and color quality of phosphor conversion.
The RGB approach produces white light by mixing the three primary colors - red, green, and blue. The color quality of the resulting light can be enhanced by the addition of amber to "fill in" the yellow region of the spectrum.

Comparison of White Light LED Technologies

Each approach to producing white light with LEDs (described above) has certain advantages and disadvantages. The key trade-offs are among color quality, light output, luminous efficacy, and cost. The technology is changing rapidly due to intensive private and publicly funded research and development efforts in the U.S., Europe, and Asia. The primary pros and cons of each approach at the current level of technology development are outlined below.

	Advantages	Disadvantages
Phosphor conversion	Most mature technology High-volume manufacturing processes Relatively high luminous flux Relatively high efficacy Comparatively lower cost	High CCT (cool/blue appearance) Warmer CCT may be less available or more expensive May have color variability in beam
RGB	Color flexibility, both in multi-color displays and different shades of white	Individual colored LEDs respond differently to drive current, operating temperature, dimming, and operating time Controls needed for color consistency add expense Often have low CRI score, in spite of good color rendering

Most currently available white LED products are based on the blue LED + phosphor approach. A recent product (see photo) is based on violet LEDs with proprietary phosphors emphasizing color quality and consistency over time. Phosphor-converted chips are produced in large volumes and in various packages (light engines, arrays, etc.) that are integrated into lighting fixtures. RGB systems are more often custom designed for use in architectural settings.

Typical Luminous Efficacy and Color Characteristics of Current White LEDs

How do currently available white LEDs compare to traditional light sources in terms of color characteristics and luminous efficacy? Standard incandescent A-lamps provide about 15 lumens per watt (lm/W), with CCT of around 2700 K and CRI close to 100. ENERGY STAR-qualified compact fluorescent lamps (CFLs) produce about 50 lm/W at 2700-3000 K with a CRI of at least 80. Typical efficacies of currently available LED devices from the leading manufacturers are shown below. Improvements are announced by the industry regularly. Please note the efficacies listed below do not include driver or thermal losses.

CCT	CRI	70-79	80-89	90+
2600-3500 K		23-43 lm/W		25 lm/W
3500-5000 K		36-73 lm/W	36-54 lm/W	
> 5000 K		54-87 lm/W	38 lm/W	

Sources: Manufacturer datasheets including Cree XLamp XR-E,
Philips Lumileds Rebel, Philips Lumileds K2.

Lifetime of White LEDs

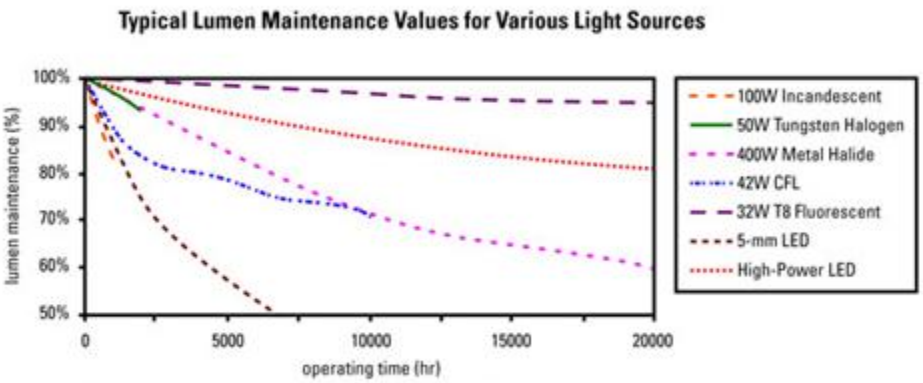
One of the main "selling points" of LEDs is their potentially very long life. Do they really last 50,000 hours or even 100,000 hours? It depends on LED quality, system design, operating environment, and other factors. This section provides information on lumen depreciation and life measurement for LEDs compared to other light sources.

Lumen Depreciation
Defining LED Useful Life
Measuring Light Source Life

Lumen Depreciation

All types of electric light sources experience lumen depreciation, defined as the decrease in lumen output that occurs as a lamp is operated. The causes of lumen depreciation in incandescent lamps are depletion of the filament over time and the accumulation of evaporated tungsten particles on the bulb wall. This typically results in 10% to 15% depreciation compared to initial lumen output over the 1,000 hour life of an incandescent lamp.

In fluorescent lamps, the causes of lumen depreciation are photochemical degradation of the phosphor coating and the glass tube, and the accumulation of light-absorbing deposits within the lamp over time. Specific lamp lumen depreciation curves are provided by the lamp manufacturers. Current high quality fluorescent lamps using rare earth phosphors will lose only 5-10% of initial lumens at 20,000 hours of operation. Compact fluorescent lamps (CFLs) experience higher lumen depreciation compared to linear sources, but higher quality models generally lose no more than 20% of initial lumens over their 10,000 hour life.



Source: Adapted from Bullough, JD. 2003. *Lighting Answers: LED Lighting Systems.* Troy, NY. National Lighting Product Information Program, Lighting Research Center, Rensselaer Polytechnic Institute.

Lumen depreciation in LEDs varies depending on package and system design. The primary cause of lumen depreciation is heat generated at the LED junction. LEDs do not emit heat as infrared radiation (IR) like other light sources, so the heat must be removed from the device by conduction or convection. If the LED system design has inadequate heat sinking or other means of removing the heat, the device temperature will rise, resulting in lower light output. Clouding of the epoxy encapsulant used to cover some LED chips also results in decreased lumens making it out of the device. Newer high-power LED devices use silicone as an encapsulant, which prevents this problem. LEDs continue to operate even after their light output has decreased to very low levels. This becomes the important factor in determining the effective useful life of the LED.

Defining LED Useful Life

To provide an appropriate measure of useful life of an LED, a level of acceptable lumen depreciation must be chosen. At what point is the light level no longer meeting the needs of the application? The answer may differ depending on the application of the product. For a common application such as general lighting in an office environment, research has shown that the majority of occupants in a space will accept light level reductions of up to 30% with little notice, particularly if the reduction is gradual. Therefore a level of 70% of initial light level could be considered an appropriate threshold of useful life for general lighting. Based on this research, the Alliance for Solid State Illumination Systems and Technologies (ASSIST), a group led by the Lighting Research Center (LRC), recommends defining useful life as the point at which light output has declined to 70% of initial lumens (abbreviated as L70) for general lighting and 50% (L50) for LEDs used for decorative purposes. For some applications, a level higher than 70% may be required.

Measuring Light Source Life

We've all heard the small "pop" as an incandescent lamp fails. It's the sound of the tungsten filament finally breaking as the electric current hits it. This makes it easy to recognize the end of life for an incandescent light source. With fluorescent lamps, end of life may involve flickering or the lamp may simply not activate when the switch is turned on. With LEDs, outright failure of the device is less likely, although it can happen due to component failure. Instead, the LED's light output slowly declines over time.

The lifetimes of traditional light sources are rated through established test procedures. The life testing procedure for compact fluorescent lamps, for example, is published by the Illuminating Engineering Society (IES) as LM-65. It calls for a statistically valid sample of lamps to be tested at an ambient temperature of 25 degrees Celsius using an operating cycle of 3 hours ON and 20 minutes OFF. The point at which half the lamps in the sample have failed is the rated average life for that lamp. For 10,000 hour lamps, this process takes about 15 months.

How are LED lifetimes rated? Life testing for LEDs is impractical due to the long expected lifetimes. Switching is not a determining factor in LED life, so there is no need for the on-off cycling used with other light sources. But even with 24/7 operation, testing an LED for 50,000 hours would take 5.7 years. Because the technology continues to develop and evolve so quickly, products would be obsolete by the time they finished life testing.

A life testing procedure for LEDs is currently under development by the Illuminating Engineering Society of North America (IESNA). The proposed method is based on the idea of "useful life," i.e., the operating time in hours at which the device's light output has declined to a level deemed to no longer meet the needs of the application. For example, for general ambient lighting, the level might be set at 70% of initial lumens. Useful life would be stated as the average number of hours that the LED would operate before depreciating to 70% of initial lumens.

The leading LED manufacturers have begun using the L70 language, stating that their white LEDs "are projected" to have lumen maintenance of greater than 70% on average after 50,000 hours when used in accordance with published guidelines.
Electrical and thermal design of the LED system or fixture determine how long LEDs will last and how much light they will provide. Driving the LED at higher than rated current will increase relative light output but decrease useful life. Operating the LED at higher than design temperature will also decrease useful life significantly.

How do the lifetime projections for LEDs compare to traditional light sources?

Light Source	Range of Typical Rated Life (hours)* (varies by specific lamp type)	Estimated Useful Life (L_{70})
Incandescent	750-2,000	
Halogen incandescent	3,000-4,000	
Compact fluorescent (CFL)	8,000-10,000	
Metal halide	7,500-20,000	
Linear fluorescent	20,000-30,000	
High-Power White LED		35,000-50,000

*Source: lamp manufacturer data.

Thermal Management of White LEDs
LEDs won't burn your hand like some light sources, but they do produce heat. In fact, thermal management is arguably the most important aspect of successful LED system design. This section reviews the role of heat in LED performance and methods for managing it.

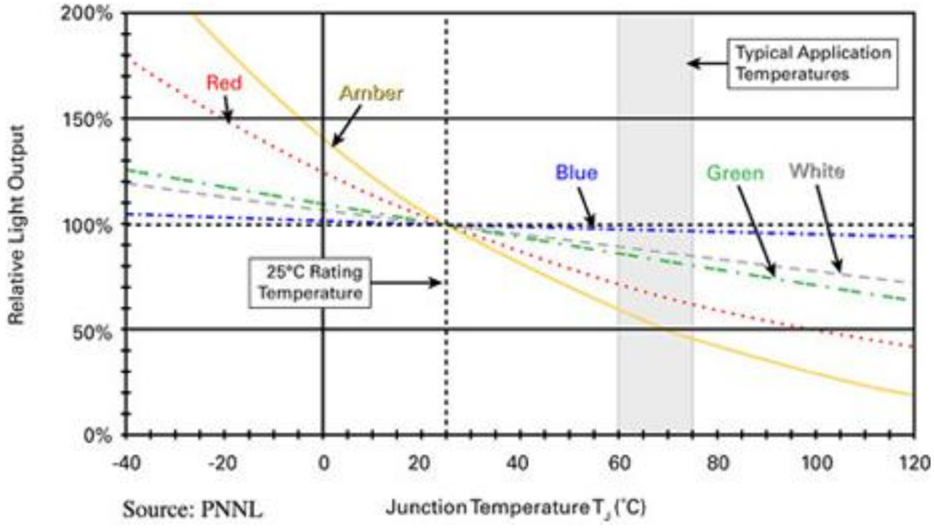
Comparison of Power Conversion of White Light Sources
All light sources convert electric power into radiant energy and heat in various proportions. Incandescent lamps emit primarily infrared (IR), with a small amount of visible light. Fluorescent and metal halide sources convert a higher proportion of the energy into visible light, but also emit IR, ultraviolet (UV), and heat. LEDs generate little or no IR or UV, but convert only 15%-25% of the power into visible light; the remainder is converted to heat that must be conducted from the LED die to the underlying circuit board and heat sinks, housings, or luminaire frame elements. The table below shows the approximate proportions in which each watt of input power is converted to heat and radiant energy (including visible light) for various white light sources.

Power Conversion for "White" Light Sources				
	Incandescent† (60W)	Fluorescent† (Typical linear CW)	Metal Halide‡	LED*
Visible Light	8%	21%	27%	15-25%
IR	73%	37%	17%	~0%
UV	0%	0%	19%	0%
Total Radiant Energy	81%	58%	63%	15-25%
Heat (Conduction + Convection)	19%	42%	37%	75-85%
Total	100%	100%	100%	100%

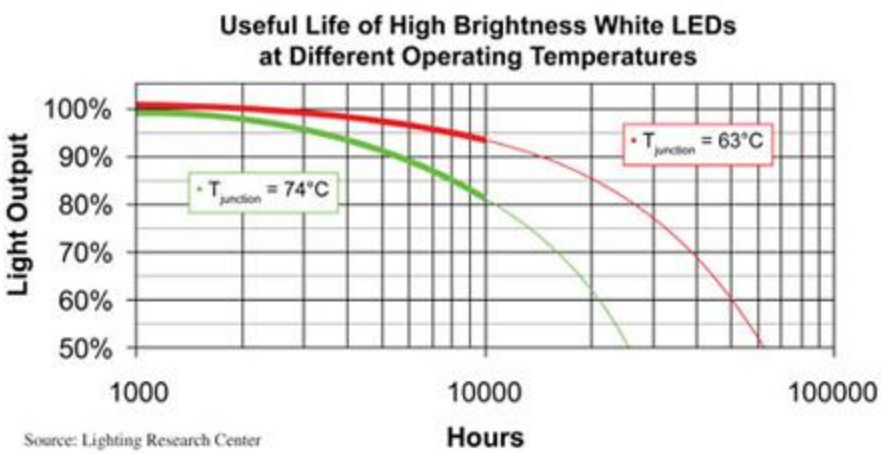
† IESNA Handbook ‡ Osram Sylvania
* Varies depending on LED efficacy. This range represents best currently available technology in color temperatures from warm to cool. DOE's SSL Multi-Year Program Plan (March 2006) calls for increasing extraction efficiency to more than 50% by 2012.

Why Does Thermal Management Matter?

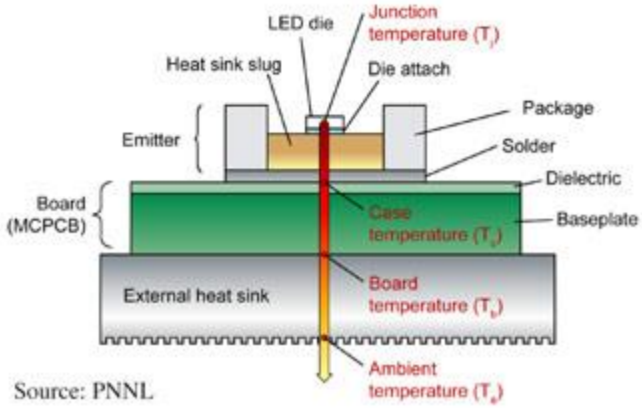
Excess heat directly affects both short-term and long-term LED performance. The short-term (reversible) effects are color shift and reduced light output while the long-term effect is accelerated lumen depreciation and thus shortened useful life.
The light output of different colored LEDs responds differently to temperature changes, with amber and red the most sensitive, and blue the least. (See graph below.) These unique temperature response rates can result in noticeable color shifts in RGB-based white light systems if operating T_j differs from the design parameters. LED manufacturers test and sort (or "bin") their products for luminous flux and color based on a 15-20 millisecond power pulse, at a fixed T_j of 25°C (77°F). Under constant current operation at room temperatures and with engineered heat mitigation mechanisms, T_j is typically 60°C or greater. Therefore white LEDs will provide at least 10% less light than the manufacturer's rating, and the reduction in light output for products with inadequate thermal design can be significantly higher.



Continuous operation at elevated temperature dramatically accelerates lumen depreciation resulting in shortened useful life. The chart below shows the light output over time (experimental data to 10,000 hours and extrapolation beyond) for two identical LEDs driven at the same current but with an 11°C difference in T_j. Estimated useful life (defined as 70% of initial lumen output) decreased from ~37,000 hours to ~16,000 hours, a 57% reduction, with the 11°C temperature increase.
However, the industry continues to improve the durability of LEDs at higher operating temperatures. The Luxeon K2, for example, claims 70% lumen maintenance for 50,000 hours at drive currents up to 1000 mA and T_j at or below 120°C. (Luxeon K2 Emitter Datasheet DS51, dated 5/06)



What Determines Junction Temperature?



Source: PNNL

Three things affect the junction temperature of an LED: drive current, thermal path, and ambient temperature. In general, the higher the drive current, the greater the heat generated at the die. Heat must be moved away from the die in order to maintain expected light output, life, and color. The amount of heat that can be removed depends upon the ambient temperature and the design of the thermal path from the die to the surroundings.

The typical high-flux LED system is comprised of an emitter, a metal-core printed circuit board (MCPCB), and some form of external heat sink. The emitter houses the die, optics, encapsulant, and heat sink slug (used to draw heat away from the die) and is soldered to the MCPCB. The MCPCB is a special form of circuit board with a dielectric layer (non-conductor of current) bonded to a metal substrate (usually aluminum). The MCPCB is then mechanically attached to an external heat sink which can be a dedicated device integrated into the design of the luminaire or, in some cases, the chassis of the luminaire itself. The size of the heat sink is dependent upon the amount of heat to be dissipated and the material's thermal properties.

Heat management and an awareness of the operating environment are critical considerations to the design and application of LED luminaires for general illumination. Successful products will use superior heat sink designs to dissipate heat, and minimize T_j. Keeping the T_j as low as possible and within manufacturer specifications is necessary in order to maximize the performance potential of LEDs.

LED Applications

The small size and inherent directionality of white LEDs make them a promising option for a number of general illumination applications. This section looks at the advantages and disadvantages of using LEDs in recessed downlights, kitchen undercabinet lighting, and portable desk/task light designs. It also includes discussions of using LEDs to their best advantage based on a number of unique characteristics, as well as issues surrounding dimming LEDs in residential applications.

Recessed Downlights
Kitchen Undercabinet Lighting
Portable Desk/Task Lighting
Outdoor Area Lighting
Using LEDs to Their Best Advantage
Dimming LEDs

Outdoor Area Lighting

LED technology is rapidly becoming competitive with high-intensity discharge light sources for outdoor area lighting. This section reviews the major design and specification concerns for outdoor area lighting, and discusses the potential for LED luminaires to save energy while providing high quality lighting for outdoor areas.

Overview of Outdoor Area Lighting
Energy Efficiency
Durability
Color
Life and Lumen Maintenance
Light Distribution and Glare
Cost
Checklist for Outdoor Area Lighting

Overview of Outdoor Area Lighting

Lighting of outdoor areas including streets, roadways, parking lots, and pedestrian areas is currently dominated by metal halide (MH) and high-pressure sodium (HPS) sources. These relatively energy-efficient light sources have been in use for many years and have well-understood performance characteristics. Recent advances in LED technology have resulted in a new option for outdoor area lighting, with several potential advantages over MH and HPS sources. Well-designed LED outdoor luminaires can provide the required surface illuminance using less energy and with improved uniformity, compared to HID sources. LED luminaires may also have significantly longer life (50,000 hours or more, compared to 15,000 to 35,000 hours) with better lumen maintenance. Other LED advantages include: they contain no mercury, lead, or other known disposal hazards; and they come on instantly without run-up time or restrike

delay. Further, while MH and HPS technologies continue to improve incrementally, LED technology is improving very rapidly in terms of luminous efficacy, color quality, optical design, thermal management, and cost.
Current LED product quality can vary significantly among manufacturers, so due diligence is required in their proper selection and use. LED performance is highly sensitive to thermal and electrical design weaknesses that can lead to rapid lumen depreciation or premature failure. Further, long-term performance data do not exist given the early stage of the technology's development. Interested users should continue to monitor available information sources on product performance and lifetime, such as CALiPER test results and GATEWAY demonstration program reports.

Design and Specification Considerations
Many issues enter into design and specification decisions for outdoor lighting. Energy efficiency is especially a priority in this application due to the long running hours and relatively high wattages typically involved. This section looks in detail at energy efficiency factors, as well as issues related to durability, color quality,life and lumen maintenance, light distribution and glare, and cost.

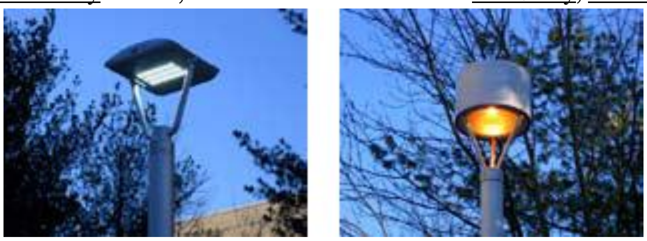
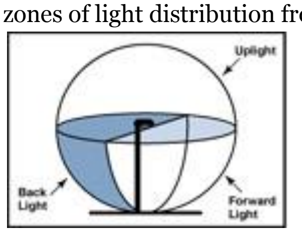


Figure 1. Several HPS fixtures (right) were replaced with LED pole-top mounted luminaires (left) to illuminate a pedestrian area at a Federal Aviation Administration facility in Atlantic City, NJ. A full reporton this installation is available.
Terms

LCS:
Luminaire classification system for outdoor luminaires, published as an IESNA technical memorandum, TM-15-07. Addresses three zones of light distribution from outdoor area luminaires: forward light (F), backlight (B), and uplight (U).



Glare:
Sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted causing annoyance, discomfort, or loss in visual performance and visibility.

Light trespass:
Effect of light that strays from the intended purpose and becomes an annoyance, a nuisance, or a determent to visual performance.

Sky glow:
The brightening of the night sky that results from the reflection of radiation (visible and non-visible), scattered from the constituents of the atmosphere (gaseous molecules, aerosols, and particulate matter), in the direction of the observer.

Energy Efficiency of Outdoor Area Lighting
Energy effectiveness encompasses luminous efficacy of the light source and appropriate power supply in lumens per watt (lm/W), optical efficiency of the luminaire (light fixture), and how well the luminaire delivers light to the target area without casting light in unintended directions. The goal is to provide the necessary illuminance in the target area, with appropriate lighting quality, for the lowest power density. One step in comparing different light source and luminaire options is to examine luminaire photometric files. Look for photometry in standard IES file format from qualified independent or qualified manufacturer-based laboratories.[1] The photometry should be based on an actual working product, not a prototype or computer model.

Table 1: Examples of Outdoor Area Luminaire Photometric Values

	150W HPS	150W CMH	LED
Luminaire (system) watts	183W	167W	153W
CCT	2000 K	3000 K	6000 K
CRI	22	80	75

Rated lamps lumens, initial	16000	11900	n/a
Downward luminaire efficiency	70%	81%	n/a
Downward luminaire lumens, initial	11200	9639	10200
Luminaire efficacy	61 lm/W	58 lm/W	67 lm/W

Sources. HPS and CMH: published luminaire photometric (.ies) files. LED: manufacturer data.
Table 1 provides photometric data for several outdoor area luminaires, to illustrate basic comparisons. Lumen output and efficacy vary greatly across different outdoor area luminaires, so these data should not be used to generalize the performance of all luminaires using the listed lamp types.

Luminaires differ in their optical precision. Photometric reports for outdoor area luminaires typically state downward fixture efficiency, and further differentiate downward lumens as "streetside" and "houseside." These correspond to forward light (F) and backlight (B), respectively, referenced in the Luminaire Classification System (LCS). How does luminaire photometry translate to site performance? The next step is to analyze illuminance levels provided to the target areas, both horizontal and vertical. This is done through lighting design software and actual site measurements.
Table 2 compares measured illuminance data from the recent installation of LED outdoor luminaires referenced in Figure 1, in which existing 70W HPS luminaires were replaced with new LED luminaires.[2] The LED luminaires installed used three arrays containing 20 LEDs each. An option using two arrays was also modeled in lighting software (see Table 2, last column). Note that in this installation, the uniformity was improved by more than a factor of two with the LED luminaires. The maximum illuminance decreased and the minimum illuminance was the same or slightly higher than the HID, which led to a lower uniformity ratio. These results cannot be generalized for LEDs, but indicate a potential benefit possible with well-designed LED luminaires for outdoor area lighting.

Table 2: Comparison of HPS and LED Outdoor Luminaires for Demonstration Site

	Existing 70W HPS	LED 3-array Luminaire	Optional LED 2-array Luminaire
Total power draw	97W	72W	48W
Average illuminance levels	3.54 fc	3.63 fc	2.42 fc
Maximum illuminance	7.55 fc	5.09 fc	3.40 fc
Minimum illuminance*	1.25 fc	1.90 fc	1.27 fc**
Max/Min Ratio (uniformity)	6.04:1	2.68:1	2.68:1
Energy consumption per luminaire***	425 kWh/yr	311 kWh/yr	210 kWh/yr
Energy savings per luminaire	--	114 kWh/yr **(26.8%)**	215 kWh/yr **(50.6%)**

** Lowest measured or modeled for each luminaire. IESNA guidelines call for at least 0.5 fc.*
*** Modeled results.*
**** Energy consumption for the HPS system is based on manufacturer-rated power levels for lamps and ballasts, multiplied by 4380 hours per year. Energy consumption for the 3-bar LED unit is based on laboratory power measurements multiplied by 4380 hours per year. Energy consumption for the 2-bar unit is based on manufacturer-rated power levels multiplied by 4380 hours per year.*

Since HID lamps are high-intensity near-point sources, the optical design for these luminaires causes the area directly below the luminaire to have a much higher illuminance than areas farther away from the luminaire. In contrast, the smaller, multiple point-source and directional characteristics of LEDs can allow better control of the distribution, with a resulting visible improvement in uniformity. This difference is evident in Figure 2, where "hot spots" are visible under the HPS luminaires. This overlighting represents wasted energy, and may decrease visibility since it forces adaptation of the eye when looking from brighter to darker areas.
[1] National Voluntary Laboratory Accreditation Program (NVLAP) accreditation for LED luminaire testing is not yet available, but is in development. In the meantime, DOE has pre-qualified several independent testing laboratories for LM-79 testing.
[2] Kinzey, BR and MA Myer. Demonstration Assessment of Light Emitting Diode (LED) Walkway Lighting at the Federal Aviation Administration William J. Hughes Technical Center, in Atlantic City, New Jersey, March 2008. PNNL-17407. Available for download fromhttp://www.eere.energy.gov/buildings/ssl/techdemos.htm.

Durability of Outdoor Area Lighting

Figure 2. Installation of LED parking lot lights (left) compared to HPS lights (right) shows the difference in color appearance and distribution. Photo credit: Beta Lighting.

Outdoor lights often become perches for birds and the debris that comes with them. The luminaire should not collect and retain dirt or water on the top side, and the optical chamber should remain clean for the LED luminaire to truly reduce maintenance. Ingress Protection (IP) ratings describe the luminaire's resistance to dust and moisture penetration. Look for an IP rating appropriate to the conditions in which the luminaire will be used. For example, a rating of 65 indicates "dust tight, and protected from water jets from any direction." Ask the manufacturer about the long-term reliability of gaskets and seals relative to the expected useful life of the LEDs, and make sure the manufacturer will replace the product if it fails before 5 years, similar to the warranty for an HID luminaire. A quick disconnect point between the light engine and the drivers will allow for field maintenance on the power supply. Keeping the maintenance contact points to this level reduces the opportunity for installation mishaps that create reliability issues during normal use.

Color

The most efficient white LEDs at this time emit light of 4500K to 6500K correlated color temperature (CCT). This makes them white to bluish-white in appearance. Some LED luminaire manufacturers mix LEDs of various color temperatures to reach a target CCT for the array or luminaire, balancing the highest efficacy sources with warmer LEDs. Color rendering varies according to the make, model, and CCT of the LEDs, but generally is better than HPS (usually around 22 CRI) and standard MH (around 65 CRI), but somewhat lower than ceramic MH (80 to 90 CRI). The nominal CRI for neutral (4000K to 4500K) and cool white (5000K or higher) LEDs is typically 70 to 75. In most street and area lighting applications, CRIs of 50 or higher are adequate for gross identification of color.
In addition to CCT and CRI, it is useful to see the spectral power distribution (SPD) for the light source, to evaluate relative output in each area of the visual spectrum. See Figure 3 below for a comparison of several sources, including the LED luminaire cited in Table 1.

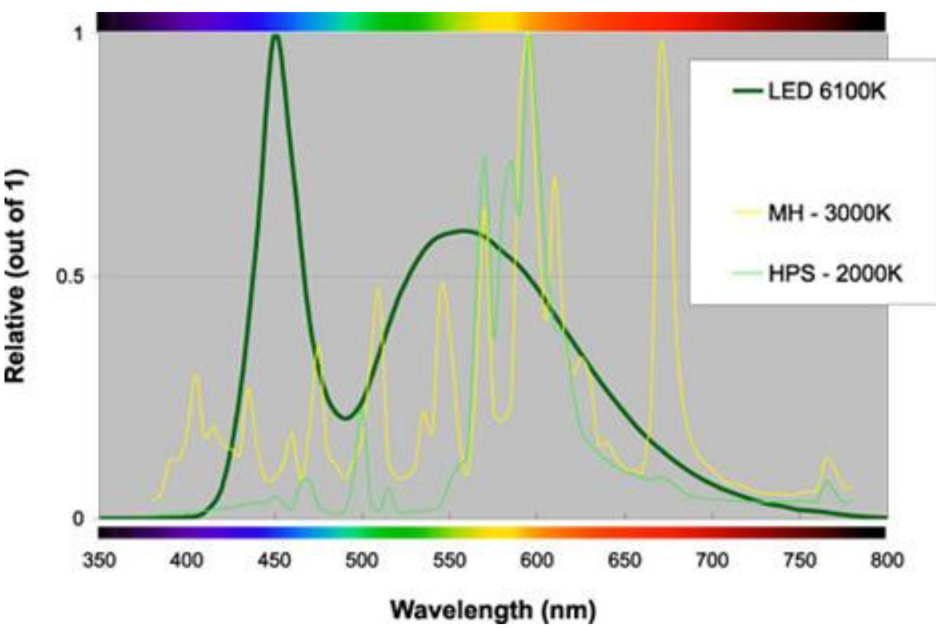


Figure 3. Comparative spectral power distributions for HPS, MH, and LED. Colors shown along top and bottom are approximations provided for reference.

Life and Lumen Maintenance

Estimating LED life is problematic because the long projected lifetimes make full life testing impractical, and because the technology continues to evolve quickly, superseding past test results. Most LED manufacturers define useful life based on the estimated time at which LED light output will depreciate to 70% of its initial rating; often the target is 50,000 hours for interior luminaires, but some outdoor luminaires are designed for much longer useful lives of 100,000 to 150,000 hours. Luminaire manufacturers typically determine the maximum drive current and LED junction temperature at which the LEDs will produce greater than 70% of initial lumens for at least the target useful life in hours. If the LEDs are driven at lower current and/or maintained at lower temperatures, useful life may be greatly increased. In general, LEDs in well-designed luminaires are less likely to fail catastrophically than to depreciate slowly over time, so it may be difficult for a utility or maintenance crew to identify when to replace the luminaire or LED arrays. In contrast, poorly-designed LED luminaires may experience rapid lumen depreciation or outright failure.

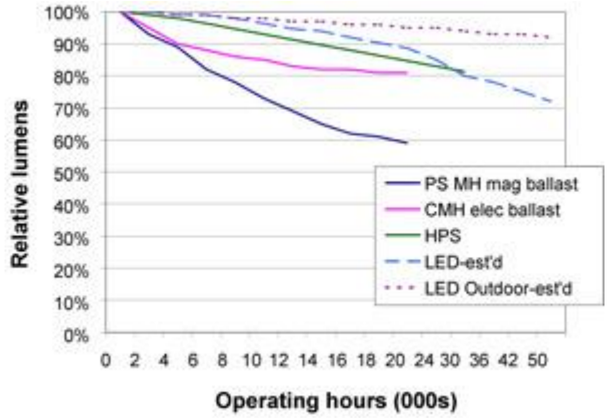


Figure 4. Typical lumen maintenance curves for HID sources, and estimated curves for LED.

Thermal management is critical to the long-term performance of the LED, since heat can degrade or destroy the longevity and light output of the LED. The temperature at the junction of the diode determines performance, so heat sinking and air flow must be designed to maintain an acceptable range of operating temperature for both the LEDs and the electronic power supply. Ask the luminaire manufacturer to provide operating temperature data at a verifiable temperature measurement point on the luminaire, and data explaining how that temperature relates to expected light output and lumen maintenance for the specific LEDs used.

All light sources experience a decrease in light output (lumen depreciation) over their operating life. To account for this, lighting designers use mean lumens, usually defined as luminous flux at 40% of rated life, instead of initial lumens. For HPS lamps, mean lumens are about 90% of initial lumens. Pulse-start MH mean lumens are about 75% of initial lumens, while ceramic MH lamps have slightly higher mean lumens, around 80% of initial lumens. See Figure 4 for typical lumen maintenance curves for these HID light sources and two example curves for LEDs: one designed for 50,000-hour useful life (LED example 1) and one designed for longer life (LED example 2).

Light Distribution and Glare

LED luminaires use different optics than MH or HPS lamps because each LED is, in effect, an individual point source. Effective luminaire design exploiting the directional nature of LED light emission can translate to lower optical losses, higher luminaire efficacy, more precise cutoff of backlight and uplight, and more uniform distribution of light across the target area. Better surface illuminance uniformity and higher levels of vertical illuminance are possible with LEDs and close-coupled optics, compared to HID luminaires.

Polar plots given in photometric reports depict the pattern of light emitted through the 90° (horizontal) plane and 0° (vertical) plane. In general, look for a reduction in luminous intensity in the 70° to 90° vertical angles to avoid glare and light trespass; zero to little intensity emitted between 90° and 100°, the angles which contribute most seriously to skyglow; and much reduced light between 100° and 180° (zenith) which also contribute to skyglow. Figures 5 and 6 illustrate the forward light and uplight angles referenced in the Luminaire Classification System (LCS). Luminaires for outdoor area lighting are classified in terms of the light patterns they provide on the ground plane. Figure 7 shows IESNA outdoor fixture types classifying the distributions for spacing luminaires.

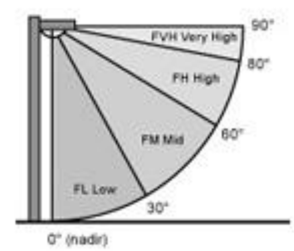


Figure 5. Section view for forward (F) solid angle. Light emmitted at high and very high angles can cause discomfort and disability glare for roadway users. Used with permission of IESNA.

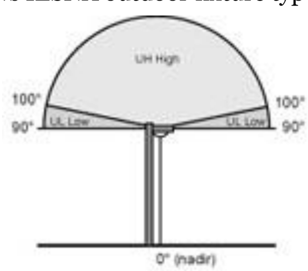


Figure 6. Section view for uplight (U) solid angle. Uplight contributes to light trespass and skyglow. Used with permission of IESNA.

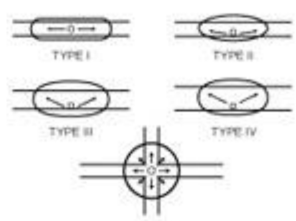


Figure 7. IESNA Outdoor lighting distribution types I - V. Used with permission of IESNA.

Follow IESNA recommendations for designing roadway and parking lot lighting rather than just designing for average illuminance on the paving surface. Illuminance alone does not consider the disabling glare that reduces visibility for the driver. For example, although an IES Type I or Type II distribution may provide the most uniform spread of illuminance with the widest pole spacing along a roadway, the angles of light that allow the very wide spacing are often the angles that subject the driver and pedestrian to disability and discomfort glare.

Using LEDs to Their Best Advantage

How do building owners, facility managers, and lighting specifiers choose lighting products? Purchase price and operating costs (energy and maintenance) are usually the top concerns but a host of other aspects may come into play, depending on the application. Here are some unique LED characteristics:
Directional light emission – directing light where it is needed.
Size advantage – can be very compact and low-profile.
Breakage resistance – no breakable glass or filaments.
Cold temperature operation – performance improves in the cold.
Instant on – require no "warm up" time.
Rapid cycling capability – lifetime not affected by frequent switching.
Controllability – compatible with electronic controls to change light levels and color characteristics.
No IR or UV emissions - LEDs intended for lighting do not emit infrared or ultraviolet radiation.

What makes LEDs different from other light sources?
LEDs are semiconductor devices, while incandescent, fluorescent, and high-intensity discharge (HID) lamps are all based on glass enclosures containing a filament or electrodes, with fill gases and coatings of various types.
LED lighting starts with a tiny chip (most commonly about 1 mm^2) comprising layers of semi-conducting material. LED packages may contain just one chip or multiple chips, mounted on heat-conducting material and usually enclosed in a lens or encapsulant. The resulting device, typically around 7 to 9 mm on a side, can produce 30 to 150 lumens each, and can be used separately or in arrays. LED devices are mounted on a circuit board and attached to a lighting fixture, architectural structure, or even a "light bulb" package.
General illumination applications that may most benefit from the LED attributes described in this section including the following:
Undercabinet lighting
In-cabinet accent lighting
Adjustable task lighting
Refrigerated case lighting
Outdoor area lighting
Elevator lighting
Recessed downlights
Accent lights
Step and path lighting
Cove lighting
Spaces with occupancy sensors
Food preparation areas
Retail display cases
Art display lighting

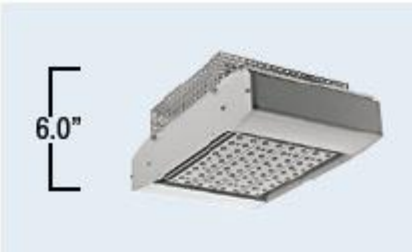
Directional Light Emission

Example of directional task lamp using LEDs.
Photo credit: Finelite.

Traditional light sources emit light in all directions. For many applications, this results in some portion of the light generated by the lamp being wasted. Special optics and reflectors can be used to make directional light sources, but they cause light losses. Because LEDs are mounted on a flat surface, they emit light hemispherically, rather than spherically. For task lighting and other directional applications, this reduces wasted light.

Low Profile/Compact Size
The small size and directional light emission of LEDs offer the potential for innovative, low-profile, compact lighting design. However, achieving a low-profile requires careful design. To produce illuminance levels equivalent to high output traditional luminaires requires grouping multiple LEDs, each of which increases the heat sinking needed to maintain light output and useful life. Even "large" LED fixtures producing thousands of lumens can be lower-profile than their HID counterparts.
The LED parking structure light shown here is only 6 inches high, compared to a common metal halide parking garage fixture almost 12 inches high. In parking garages with low ceilings, that six-inch difference can be valuable. For directed light applications with lower luminous flux requirements, the low profile benefit of LEDs can be exploited to a greater extent. Under-, over-, and in-cabinet LED

lighting can be very low-profile, in some cases little more than the LED devices on a circuit board attached unobtrusively to the cabinetry.



LED Fixture	
Dimensions	6" high by 17" long
Watts	118
Initial lumens	6,400
Photo credit: Beta Lighting	

Metal Halide Fixture	
Dimensions	11.5" high by 15" wide
Watts	175
Initial lumens	10,400
Photo credit: Lithonia	

Breakage Resistance

LEDs are largely impervious to vibration because they do not have filaments or glass enclosures. Standard incandescent and discharge lamps may be affected by vibration when operated in vehicular and industrial applications, and specialized vibration-resistant lamps are needed in applications with excessive vibration. LED's inherent vibration resistance may be beneficial in applications such as transportation (planes, trains, automobiles), lighting on and near industrial equipment, elevators and escalators, and ceiling fan light kits.

Photo credit: Sea Gull Lighting

Traditional light sources are all based on glass or quartz envelopes. Product breakage is a fact of life in electric lamp transport, storage, handling, and installation. LED devices usually do not use any glass. LED devices mounted on a circuit board are connected with soldered leads that may be vulnerable to direct impact, but no more so than cell phones and other electronic devices. LED light fixtures may be especially appropriate in applications with a high likelihood of lamp breakage, such as sports facilities or where vandalism is likely. LED durability may provide added value in applications where broken lamps present a hazard to occupants, such as children's rooms, assisted living facilities, or food preparation industries

Cold Temperature Operation

Photo credit: GE Lumination

Close up of refrigerated case lighting.
Photo credit: GE Lumination

Cold temperatures present a challenge for fluorescent lamps. At low temperatures, higher voltage is required to start fluorescent lamps, and luminous flux is decreased. A non-amalgam CFL, for example, will drop to 50% of full light output at 0°C. The use of amalgam (an alloy of mercury and other metals, used to stabilize and control mercury pressure in the lamp) in CFLs largely addresses this problem, allowing the CFL to maintain light output over a wide temperature range (-17°C to 65°C). The trade-off is that amalgam lamps have a noticeably longer "run-up" time to full brightness, compared to non-amalgam lamps. In contrast, LED performance inherently increases as operating temperatures drop. This makes LEDs a natural fit for grocery store refrigerated and freezer cases, cold storage facilities, and outdoor applications. In fact, DOE testing of an LED refrigerated case light measured 5% higher efficacy at -5°C, compared to operation at 25°C.

Instant On

Fluorescent lamps, especially those containing amalgam, do not provide full brightness immediately upon being turned on. Fluorescents using amalgam can take three minutes or more to reach their full light output. HID lamps have longer warm up times, from several minutes for metal halide to 10 minutes or more for sodium lamps. HID lamps also have a "re-strike" time delay; if turned off they must be allowed to cool down before turning on again, usually for 10-20 minutes. Newer pulse-start HID ballasts provide faster restrike times of 2-8 minutes. LEDs, in contrast, come on at full brightness almost instantly, with no re-strike delay. This characteristic of LEDs is notable in vehicle brake lights, where they come on 170 to 200 milliseconds faster than standard incandescent lamps, providing an estimated 19 feet of additional stopping distance at highway speeds (65 mph). In general illumination applications, instant on can be desirable for safety and convenience.

Rapid Cycling

Traditional light sources will burn out sooner if switched on and off frequently. In incandescent lamps, the tungsten filament degrades with each hour of operation, with the final break (causing the lamp to "burn out") usually occurring as the lamp is switched on and the electric current rushes through the weakened filament. In fluorescent and HID lamps, the high starting voltage erodes the emitter material coating the electrodes. In fact, linear fluorescent lamps are rated for different expected lifetimes, depending on the on-off frequency, achieving longer total operating hours on 12-hour starts (i.e., turned on and left on for 12 hours) compared to shorter cycles. HID lamps also have long warm up times and are unable to re-start until cooled off, so rapid cycling is not an option. LED life and lumen maintenance is unaffected by rapid cycling. In addition to flashing light displays, this rapid cycling capability makes LEDs well-suited to use with occupancy sensors or daylight sensors.

Controllability and Tunability

Traditional, efficient light sources (fluorescent and HID) present a number of challenges with regard to lighting controls. Dimming of commercial (specification)-grade fluorescent systems is readily available and effective, although at a substantial price premium. For CFLs used in residential applications, dimming is more problematic. Unlike incandescent lamps, which are universally dimmable with inexpensive controls, only CFLs with a dimming ballast may be operated on a dimming circuit. Further, CFLs usually do not have a continuous (1% to 100% light output) dimming range like incandescents. Often CFLs will dim down to about 30% of full light output. LEDs may offer potential benefits in terms of controlling light levels (dimming) and color appearance. However, not all LED devices are compatible with all dimmers, so manufacturer guidelines should be followed. As LED driver and control technology continues to evolve, this is expected to be an area of great innovation in lighting. Dimming, color control, and integration with occupancy and photoelectric controls offer potential for increased energy efficiency and user satisfaction.

No Infrared or Ultraviolet Emissions

Photo credit: Scott Rosenfeld

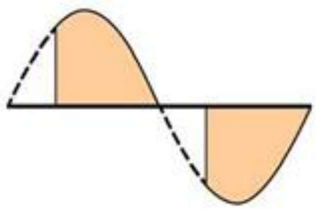
Incandescent lamps convert most of the power they draw into infrared (IR) or radiated heat; less than 10% of the power they use is actually converted to visible light. Fluorescent lamps convert a higher proportion of power into visible light, around 20%. HID lamps can emit significant ultraviolet radiation (UV), requiring special shielding and diffusing to avoid occupant exposure. LEDs emit virtually no IR or UV. Excessive heat (IR) from lighting presents a burn hazard to people and materials. UV is extremely damaging to artwork, artifacts, and fabrics, and can cause skin and eye burns in people exposed to unshielded sources.

Dimming LEDs

Lack of effective and affordable dimming has hampered the adoption of CFLs in the residential sector. LEDs are in theory fully dimmable, but are not compatible with all dimmer controls designed for incandescent lamps. What are the prospects for dimming LEDs in residential applications? Click on the links below for more information.

Dimming overview
Will LEDs solve the dimming problem?
Flicker and dimming
Changes in color and efficacy with dimming
Future developments

Standard Dimming Controls



Alternating current (AC) wave form, showing one complete cycle. AC cycles at 60 hertz, or 60 times per second. Typical household dimmers switch off the current twice per cycle, or 120 times per second.

Typical residential incandescent lamp dimmers are essentially electronic switches that toggle on and off 120 times per second. By delaying the beginning of each half-cycle of AC power (known as "phase control"), they regulate the amount of power to the lamp filament. Because this occurs so quickly, most people do not detect flicker, but see continuous dimming. Although the general operation of such electronic dimmers is the same, the specific electrical characteristics of residential dimmers can vary considerably. These variations are immaterial to incandescent lamps, but matter greatly when used with electronic devices such as compact fluorescent lamps (CFLs) and LEDs.

Dimming CFLs

Some screw-in (integral) CFLs can be dimmed using line-voltage incandescent dimmers but must be specifically designed to do so. They typically dim only to about 20% of maximum intensity, due to limitations of the low-cost ballast. More sophisticated electronic ballasts providing continuous dimming below 5% are available, but are simply not cost-effective for use in screw-in CFLs. Some fixtures (e.g., torchieres) successfully use pin-based CFLs in combination with on-board dimming controls. Four-pin CFLs using separate dimming ballasts can be dimmed via line voltage or 0-10 volt DC control, with dimming range as low as 1%, but more commonly 5% or 20%.

Terms

Line voltage

A voltage supplied by the electric grid. In US residential buildings, this refers to 120-volt alternating current (AC) power.

Low voltage

Some electrical devices are designed to work with voltage lower than that supplied by the electrical system. Such devices use a transformer or power supply to convert 120v AC power to the voltage and current needed by the device.

CCT

Correlated color temperature indicates the relative color appearance of a white light source, from yellowish-white or "warm" (2700-3000 K) to bluish-white or "cool" (5000+ K).

Luminous efficacy

Light output of a light source, divided by nominal wattage, given in lumens per watt (lm/W). Does not include driver, thermal, or luminaire optical losses.

Luminaire efficacy

Light output of a luminaire, divided by total wattage to the power supply, given in lumens per watt (lm/W). Luminaire efficacy accounts for all driver, thermal, and luminaire optical losses.

Will LEDs Solve the Dimming Problem?

Photo credit: Miro™ Dimmer photo courtesy of Watt Stopper/Legrand

LEDs face a dimming challenge similar to that of CFLs: their electronics are often incompatible with dimmers designed for incandescents. An LED driver connected directly to a line-voltage incandescent dimmer may not receive enough power to operate at lower dimming levels or it may be damaged by current spikes. Some LED products can be used with line-voltage incandescent dimmers, but the dimmer and the LED driver electronics must be carefully matched. Because of variability in installed dimmers, it is not possible to guarantee that a given LED fixture will work with all dimmers. Some LED light fixture manufacturers publish lists of specific dimmer products tested and approved for use with their fixtures.

More sophisticated LED dimmers use low-voltage controls (either variable resistors or 0-10 volt DC control) connected separately to the electronic driver. Full AC power is provided to the driver enabling the electronic controls to operate at all times, thus allowing LEDs to be uniformly dimmed (typically down to 5% or lower). However, they may require additional low-voltage wiring for retrofit applications.

Flicker and Dimming

Most LED drivers use pulse width modulation (PWM) to regulate the amount of power to the LEDs. This technique turns the LEDs on and off at high frequency, varying the total on time to achieve perceived dimming. Driver output frequency should be at least 120 Hertz (Hz) to avoid perceptible flicker under typical circumstances.

LED light fixtures may appear to flicker at the lowest settings, but only when the dimmer control is moved. This is due to the finite "resolution" of the digital electronics. Good-quality electronic drivers feature 12-bit or greater resolution to obtain flicker-free operation throughout their dimming range.

Changes in Color and Efficacy With Dimming

When an incandescent lamp is dimmed, the filament temperature decreases, causing the emitted light to appear "warmer," changing from white to yellow to orange/red. The luminous efficacy of the lamp also decreases: a 15 lm/W lamp at full power will be 10 lm/W at 50% dimmed.

CFL color temperature does not change with dimming as dramatically as with incandescents, running counter to our expectation of significantly warmer color at low light levels. Luminous efficacy of fluorescent sources stays approximately constant with dimming until about 40%-50%; thereafter it decreases, but not as steeply as with incandescent lamps.

Most "white" LEDs are actually blue LEDs with a phosphor coating that generates warm or cool white light. Their light does not shift to red when dimmed; some may actually appear bluer with dimming. White light can also be made by mixing red, green, and blue (RGB) LEDs, allowing a full range of color mixing and color temperature adjustment. Overall LED luminaire efficacy decreases with dimming due to reduced driver efficiency at low dimming levels.

LED Measurement

New measurement protocols and test procedures are currently being developed for LEDs. Methods to measure total luminous flux, luminous intensity, color temperature, color rendering, lumen depreciation, and electrical characteristics are all under development or revision to accommodate specific attributes of LEDs that differ from other lighting technologies. The LED Measurement Series explores these topics.

Solid State Lighting Standards — an overview and listing of industry standards and test procedures relevant to LED products

Color Rendering Index and LEDs — explains why CRI is not necessarily a reliable indicator of LED color rendering ability

Luminaire Efficacy — describes the preferred energy efficiency metric for LED lighting

Luminaire Reliability — outlines the issues and provides suggestions for understanding and interpreting LED product life claims

Solid-State Lighting Standards

Like traditional lighting products, LED-based luminaires sold in the US are subject to industry standards governing safety and performance. To accommodate LEDs, some existing standards and test procedures are being modified, while in other cases, new standards have been developed. This section lists the key performance and safety standards applicable to LED-based lighting products.

Product Performance and Measurement Standards

Safety, Installation, and Other Requirements

Color Rendering Index and LEDs

The color rendering index (CRI) has been used to compare fluorescent and HID lamps for over 40 years, but the International Commission on Illumination (CIE) does not recommend its use with white light LEDs. A new metric is under development. In the meantime how should we use CRI when it comes to LEDs?

Overview of CRI and LEDs
How is CRI Measured?
"Tuning" the Spectrum for High CRI
Recommendations

Overview of Luminaire Efficacy

Lighting energy efficiency is a function of both the light source (the light "bulb" or lamp) and the fixture, including necessary controls, power supplies and other electronics, and optical elements. The complete unit is known as a luminaire.

Traditionally, lighting energy efficiency is characterized in terms of lamp ratings and fixture efficiency. The lamp rating indicates how much light (in lumens) the lamp will produce when operated at standard room/ambient temperature (25 degrees C). The luminous efficacy of a light source is typically given as the rated lamp lumens divided by the nominal wattage of the lamp, abbreviated lm/W. The fixture efficiency indicates the proportion of rated lamp lumens actually emitted by the fixture; it is given as a percentage. Fixture efficiency is an appropriate measure for fixtures that have interchangeable lamps for which reliable lamp lumen ratings are available.

Currently, lamp rating and fixture efficiency measures have limited usefulness for LED lighting, for two important reasons:

There is no industry standard test procedure for rating the performance of LED devices or packages.

The luminaire design and the manner in which the LEDs are integrated into the luminaire have a material impact on the performance of the LEDs. This makes it difficult to compare LEDs to other types of lighting.

Terms

Photometry

The measurement of quantities associated with light, including luminance, luminous intensity, luminous flux, and illuminance.

Integrating sphere

A device that enables geometrically total luminous flux to be determined by a single measurement. The usual type is the Ulbricht sphere with associated photometric equipment for measuring the indirect illuminance of the inner surface of the sphere.

Goniophotometer

An apparatus for measuring the directional light distribution characteristics of light sources, luminaires, media, and surfaces. Goniophotometry can be used to obtain total luminaire flux (lumens) and efficacy (lumens/watt), but not the color metrics (chromaticity, CCT, and CRI).

Spectroradiometer

An instrument for measuring radiant flux (visible and non-visible) as a function of wavelength. Visible radiation measurements can be converted into luminous intensity (candela) and flux (lumens).

Lamp or light source

A generic term for a device created to produce optical radiation.

Luminaire

A complete lighting unit consisting of a lamp or lamps and ballast(s) (when applicable) together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.

Comparison of LEDs to Traditional Light Sources

Standard methods for rating lamps and fixture efficiency are inappropriate when comparing LEDs for two important reasons:

There is no industry standard test procedure for rating the performance of LED devices or packages.

The luminaire design and the manner in which the LEDs are integrated into the luminaire have a material impact on the performance of the LEDs.

Given these limitations, how can LED luminaires be compared to traditional lighting technologies? As an example, the table below compares two recessed downlight fixtures, one using a 13-watt CFL and the other using an array of LEDs. The table differentiates data related to the light source and data resulting from actual luminaire measurements. Luminaire photometry shows that in this case the LED fixture has input wattage and light output similar to the CFL fixture, and matches the CFL product's luminaire efficacy. This example is based on a currently available, residential-grade, six-inch diameter downlight. LED downlight performance continues to improve rapidly, with some LED retrofit products surpassing CFL downlights in luminaire efficacy.

Example: Comparison of CFL and LED Downlight Luminaires		
	CFL	LED
Light Source		
Lamp lumen rating	860 lm	
Light source wattage	13 W	1 W
LED manufacturer declared "typical luminous flux"		*≈100 lm per LED**
Number of lamps/LEDs per fixture	1	12
Luminaire Measurements		
Luminaire lumens	514 lm	589 lm
Measured luminaire wattage	12 W	14 W
Fixture efficiency	60%	
Luminaire efficacy	42 lm/W	42 lm/W

Items in *italics* are not based on industry standard test procedures.
*Depends on specific LED used. Estimate is based on "typical luminous flux" declared by LED manufacturer on the product datasheet, which assumes 25°C LED junction temperature.

The Impact of LED Luminaire Design
For all light sources, there is a difference between rated luminous flux of the lamp and actual performance in a luminaire. However, traditional light sources installed in luminaires operate relatively predictably because the performance of traditional light sources in a wide range of luminaire types, applications, and use conditions is well documented and understood. LED technology is at a far earlier stage of development, so experience and documentation of performance within luminaires is lacking. The efficiency of LEDs is very sensitive to heat and optical design, which increases the relative importance of luminaire design.
Ensuring necessary light output and life of LEDs requires careful thermal management, typically requiring the use of the fixture housing as a heat sink or at least as an element in the heat removal design. Luminaires therefore have a fundamental and typically large effect on the luminous flux produced by the LEDs, and on the rate of lumen depreciation over time. LED "drop-in" replacement lamps, such as Edison-based reflector lamps or MR-16 replacements, are in theory designed to provide the necessary heat sinking for the LEDs, but given their installation in fixtures not specifically designed for LEDs, good heat management will be a challenge.

Why a New Testing Standard Is Needed for LEDs
Traditional light sources (incandescent, fluorescent, and high-intensity discharge) are rated for luminous flux according to established test procedures. In contrast, there is no standard procedure for rating the luminous flux of LED devices. LED light output estimates (as reported on manufacturer datasheets) are typically based on a short (<1 second) pulse of power applied to the LED chip, with junction temperature held at 25 degrees C. This is because LED chips must be binned for luminious flux and color during the manufacturing process. To run them longer without a heat sink would damage them. LED manufacturers usually list "minimum" and "typical" luminous flux on their product datasheets. There is no standardization of the test conditions, or the meaning of "typical." Further, there is no standard test procedure for measuring the luminous flux of LED arrays, such as multiple LEDs mounted on a circuit board.
In summary, luminous flux—and by extension, luminous efficacy—must be measured at the luminaire level for two primary reasons: 1) no standard procedures are available for rating LED devices on their own, and 2) the amount of light emitted by a fixture cannot be predicted reliably based on available information about LED devices and fixtures. The lighting industry has adopted luminaire efficacy as the preferred measure of LED performance, as evident in the development of a new test procedure based on this approach.

Concentrating Solar Power

This solar concentrator has a fixed-focus faceted dish with a concentration of about 250 suns. This system can be used for large fields connected to the utility grid, hydrogen generation, or water pumping.
Credit: Science Applications International Corporation / PIX 13464

Concentrating solar power (CSP) technologies use mirrors to reflect and concentrate sunlight onto receivers that collect solar energy and convert it to heat. This thermal energy can then be used to produce electricity via a steam turbine or heat engine that drives a generator.

Concentrating solar power offers a utility-scale, firm, dispatchable renewable energy option that can help meet our nation's demand for electricity. CSP plants produce power by first using mirrors to focus sunlight to heat a working fluid. Ultimately, this high-temperature fluid is used to spin a turbine or power an engine that drives a generator. The final product is electricity.

Smaller CSP systems can be located directly where power is needed. For example, single dish/engine systems can produce 3 to 25 kilowatts of power and are well suited for distributed applications.

There are several varieties of CSP systems. Learn more about:

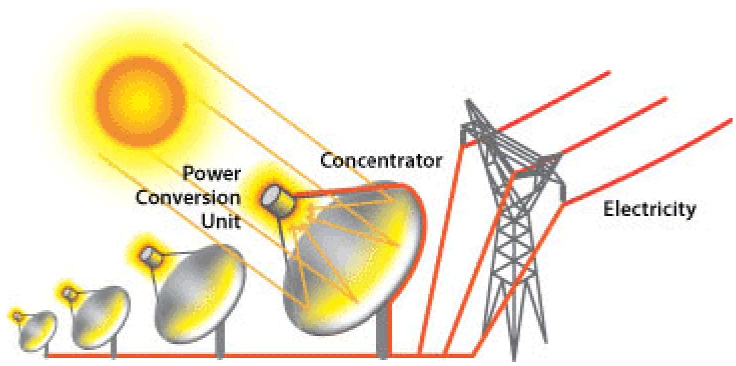
Linear Concentrator Systems
Dish/Engine Systems
Power Tower Systems
Thermal Storage Systems.

Energy 101: Concentrating Solar Power Basics

From towers to dishes to linear mirrors to troughs, concentrating solar power (CSP) technologies reflect and collect solar heat to generate electricity. A single CSP plant can generate enough power for about 90,000 homes. This video explains what CSP is, how it works, and how systems like parabolic troughs produce renewable power.

Dish/Engine Systems for Concentrating Solar Power

The dish/engine system is a concentrating solar power (CSP) technology that produces relatively small amounts of electricity compared to other CSP technologies—typically in the range of 3 to 25 kilowatts. Dish/engine systems use a parabolic dish of mirrors to direct and concentrate sunlight onto a central engine that produces electricity. The two major parts of the system are the solar concentrator and the power conversion unit.



A dish/engine power plant.

Solar Concentrator

The solar concentrator, or dish, gathers the solar energy coming directly from the sun. The resulting beam of concentrated sunlight is reflected onto a thermal receiver that collects the solar heat. The dish is mounted on a structure that tracks the sun continuously throughout the day to reflect the highest percentage of sunlight possible onto the thermal receiver.

Power Conversion Unit

The power conversion unit includes the thermal receiver and the engine/generator. The thermal receiver is the interface between the dish and the engine/generator. It absorbs the concentrated beams of solar energy, converts them to heat, and transfers the heat to the engine/generator. A thermal receiver can be a bank of tubes with a cooling fluid—usually hydrogen or helium—that typically is the heat-transfer medium and also the working fluid for an engine. Alternate thermal receivers are heat pipes, where the boiling and condensing of an intermediate fluid transfers the heat to the engine.

The engine/generator system is the subsystem that takes the heat from the thermal receiver and uses it to produce electricity. The most common type of heat engine used in dish/engine systems is the Stirling engine. A Stirling engine uses the heated fluid to move pistons and create mechanical power. The mechanical work, in the form of the rotation of the engine's crankshaft, drives a generator and produces electrical power.

Linear Concentrator Systems for Concentrating Solar Power

The Solar Electric Generating Station IV power plant in California consists of many parallel rows of parabolic trough collectors that track the sun. The cooling towers can be seen with the water plume rising into the air, and white water tanks are in the background. *Credit: Sandia National Laboratory / PIX 14955*

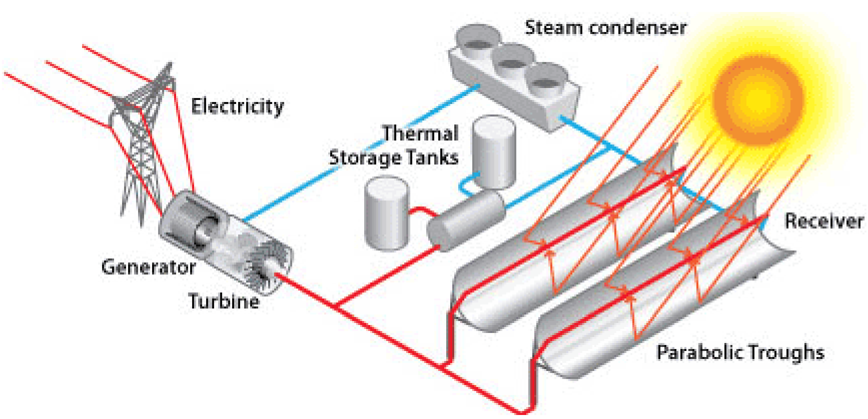
Linear concentrating solar power (CSP) collectors capture the sun's energy with large mirrors that reflect and focus the sunlight onto a linear receiver tube. The receiver contains a fluid that is heated by the sunlight and then used to create superheated steam that spins a turbine that drives a generator to produce electricity. Alternatively, steam can be generated directly in the solar field, which eliminates the need for costly heat exchangers.

Linear concentrating collector fields consist of a large number of collectors in parallel rows that are typically aligned in a north-south orientation to maximize annual and summer energy collection. With a single-axis sun-tracking system, this configuration enables the mirrors to track the sun from east to west during the day, which ensures that the sun reflects continuously onto the receiver tubes.

Parabolic Trough Systems

The most common CSP system in the United States is a linear concentrator that uses parabolic trough collectors. In such a system, the receiver tube is positioned along the focal line of each parabola-shaped reflector. The tube is fixed to the mirror structure, and the heated fluid—either a heat-transfer fluid or water/steam—flows through and out of the field of solar mirrors to where it is used to create steam (or, in the case of a water/steam receiver, it is sent directly to the turbine).

The largest individual trough systems generate 80 megawatts of electricity. However, individual systems being developed will generate 250 megawatts. In addition, individual systems can be co-located in power parks. Their capacity would be constrained only by the transmission capacity of nearby power lines and the availability of contiguous land.

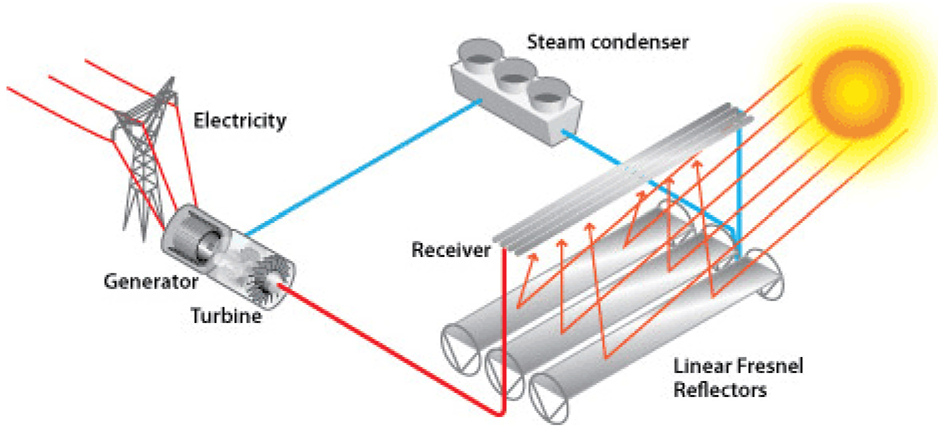


A linear concentrator power plant using parabolic trough collectors.

Trough designs may incorporate thermal storage. In these systems, the collector field is oversized to heat a storage system during the day that can be used in the evening or during cloudy weather to generate additional steam to produce electricity. Parabolic trough plants can also be designed as hybrids, meaning that they use fossil fuel to supplement the solar output during periods of low solar radiation. In such a design, a natural gas-fired heater or gas-steam boiler/reheater is used. In the future, troughs may be integrated with existing or new combined-cycle natural-gas- and coal-fired plants.

Linear Fresnel Reflector Systems

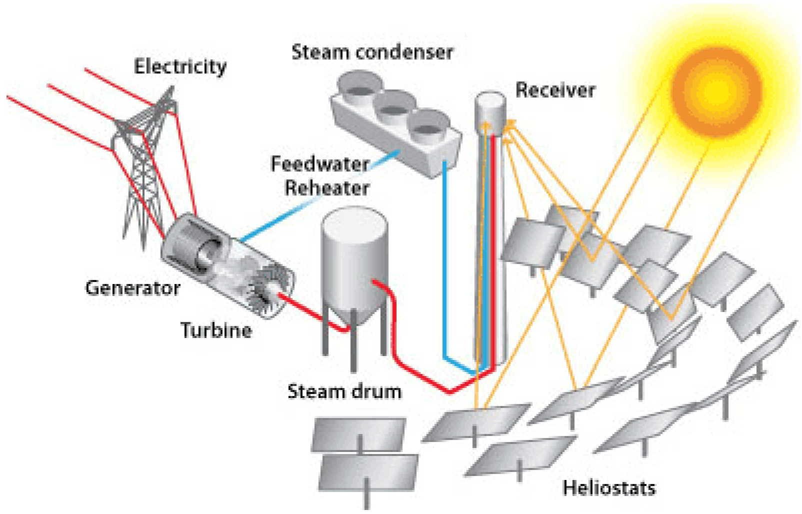
A second linear concentrator technology is the linear Fresnel reflector system. Flat or slightly curved mirrors mounted on trackers on the ground are configured to reflect sunlight onto a receiver tube fixed in space above the mirrors. A small parabolic mirror is sometimes added atop the receiver to further focus the sunlight.



A linear Fresnel reflector power plant.

Power Tower Systems for Concentrating Solar Power

In power tower concentrating solar power systems, numerous large, flat, sun-tracking mirrors, known as*heliostats*, focus sunlight onto a receiver at the top of a tall tower. A heat-transfer fluid heated in the receiver is used to generate steam, which, in turn, is used in a conventional turbine generator to produce electricity. Some power towers use water/steam as the heat-transfer fluid. Other advanced designs are experimenting with molten nitrate salt because of its superior heat-transfer and energy-storage capabilities. Individual commercial plants can be sized to produce up to 200 megawatts of electricity.



A power tower power plant.

Two large-scale power tower demonstration projects have been deployed in the United States. During its operation from 1982 to 1988, the 10-megawatt Solar One plant near Barstow, California, demonstrated the viability of power towers by producing more than 38 million kilowatt-hours of electricity.

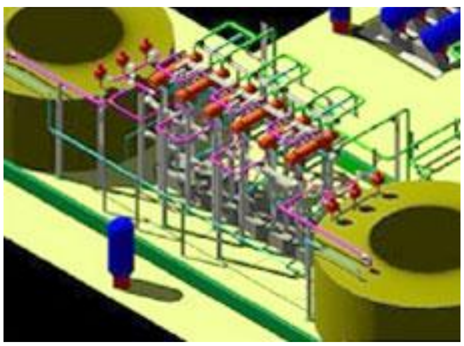
The Solar Two plant was a retrofit of Solar One to demonstrate the advantages of molten salt for heat transfer and thermal storage. Using its highly efficient molten-salt energy storage system, Solar Two successfully demonstrated efficient collection of solar energy and dispatch of electricity. It also demonstrated the ability to routinely produce electricity during cloudy weather and at night. In one demonstration, Solar Two delivered power to the grid 24 hours a day for almost 7 consecutive days before cloudy weather interrupted operation.

Spain has several power tower systems. Planta Solar 10 and Planta Solar 20 are water/steam systems with capacities of 11 and 20 megawatts, respectively. Solar Tres will produce some 15 megawatts of electricity and have the capacity for molten-salt thermal storage.

Thermal Storage Systems for Concentrating Solar Power
One challenge facing the widespread use of solar energy is reduced or curtailed energy production when the sun sets or is blocked by clouds. Thermal energy storage provides a workable solution to this challenge.
In a concentrating solar power (CSP) system, the sun's rays are reflected onto a receiver, which creates heat that is used to generate electricity. If the receiver contains oil or molten salt as the heat-transfer medium, then the thermal energy can be stored for later use. This enables CSP systems to be cost-competitive options for providing clean, renewable energy.
Several thermal energy storage technologies have been tested and implemented since 1985. These include the two-tank direct system, two-tank indirect system, and single-tank thermocline system.

Two-Tank Direct System

The two-tank direct molten-salt thermal energy storage system at the Solar Two power plant.
Credit: National Renewable Energy Laboratory

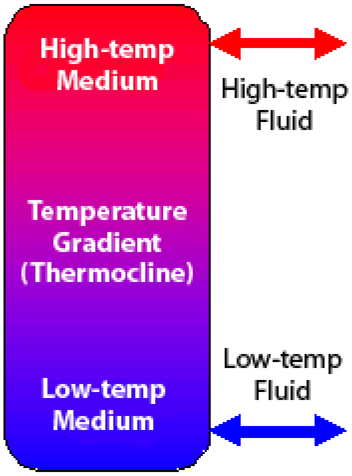


The two-tank indirect thermal energy storage system for AndaSol-1 and -2.
Credit: FLAGSOL

Solar thermal energy in this system is stored in the same fluid used to collect it. The fluid is stored in two tanks—one at high temperature and the other at low temperature. Fluid from the low-temperature tank flows through the solar collector or receiver, where solar energy heats it to a high temperature, and it then flows to the high-temperature tank for storage. Fluid from the high-temperature tank flows through a heat exchanger, where it generates steam for electricity production. The fluid exits the heat exchanger at a low temperature and returns to the low-temperature tank.
Two-tank direct storage was used in early parabolic trough power plants (such as Solar Electric Generating Station I) and at the Solar Two power tower in California. The trough plants used mineral oil as the heat-transfer and storage fluid; Solar Two used molten salt.

Two-Tank Indirect System
Two-tank indirect systems function in the same way as two-tank direct systems, except different fluids are used as the heat-transfer and storage fluids. This system is used in plants in which the heat-transfer fluid is too expensive or not suited for use as the storage fluid. The storage fluid from the low-temperature tank flows through an extra heat exchanger, where it is heated by the high-temperature heat-transfer fluid. The high-temperature storage fluid then flows back to the high-temperature storage tank. The fluid exits this heat exchanger at a low temperature and returns to the solar collector or receiver, where it is heated back to a high temperature. Storage fluid from the high-temperature tank is used to generate steam in the same manner as the two-tank direct system. The indirect system requires an extra heat exchanger, which adds cost to the system.
This system will be used in many of the parabolic power plants in Spain and has also been proposed for several U.S. parabolic plants. The plants will use organic oil as the heat-transfer fluid and molten salt as the storage fluid.

Single-Tank Thermocline System



A single-tank thermocline thermal energy storage system.

Single-tank thermocline systems store thermal energy in a solid medium—most commonly, silica sand—located in a single tank. At any time during operation, a portion of the medium is at high temperature, and a portion is at low temperature. The hot- and cold-temperature regions are separated by a temperature gradient or*thermocline*. High-temperature heat-transfer fluid flows into the top of the thermocline and exits the bottom at low temperature. This process moves the thermocline downward and adds thermal energy to the system for storage. Reversing the flow moves the thermocline upward and removes thermal energy from the system to generate steam and electricity. Buoyancy effects create thermal stratification of the fluid within the tank, which helps to stabilize and maintain the thermocline.

Using a solid storage medium and only needing one tank reduces the cost of this system relative to two-tank systems. This system was demonstrated at the Solar One power tower, where steam was used as the heat-transfer fluid and mineral oil was used as the storage fluid.

Daylighting

Daylighting is the use of windows and skylights to bring sunlight into buildings. Daylighting in businesses and commercial buildings can result in substantial savings on electric bills, and not only provides a higher quality of light but also improves productivity and health. Daylighting in schools has even improved student grades and attendance.

Today's highly energy-efficient windows, as well as advances in lighting design, allow efficient use of windows to reduce the need for artificial lighting during daylight hours without causing heating or cooling problems.

Passive Solar Design

The difference between a passive solar home and a conventional home is *design*. Passive solar homes and other buildings are designed to take advantage of the local climate. Passive solar design—also known as climatic design—involves using a building's windows, walls, and floors to collect, store, and distribute solar energy in the form of heat in the winter and reject solar heat in the summer. Learn how passive solar design techniques work.

Direct Gain

Direct gain is the process by which sunlight directly enters a building through the windows and is absorbed and temporarily stored in massive floors or walls.

Indirect Gain

Indirect gain is the process by which the sun warms a heat storage element—such as a Trombe wall—and the heat is later distributed to the interior space by convection, conduction, and radiation.

Isolated Gain

Isolated gain involves the collection of heat in one area—such as a sunspace on the south side of a house—and used in another.

Roof Overhangs

Roof overhangs are used to shade windows, walls, and doors from direct solar radiation.

Energy Savers

How a Passive Solar Home Design Works

A sunspace or attached greenhouse relies primarily on convection to move heat from the sunny space to other adjacent rooms.
Photo credit: Donald Aitken

To understand how a passive solar home design works, you need to understand how heat moves and how it can be stored.
As a fundamental law, heat moves from warmer materials to cooler ones until there is no longer a temperature difference between the two. To distribute heat throughout the living space, a passive solar home design makes use of this law through the following heat-movement and heat-storage mechanisms:

Conduction

Conduction is the way heat moves through materials, traveling from molecule to molecule. Heat causes molecules close to the heat source to vibrate vigorously, and these vibrations spread to neighboring molecules, thus transferring heat energy. For example, a spoon placed into a hot cup of coffee conducts heat through its handle and into the hand that grasps it.

Convection

Convection is the way heat circulates through liquids and gases. Lighter, warmer fluid rises, and cooler, denser fluid sinks. For instance, warm air rises because it is lighter than cold air, which sinks. This is why warmer air accumulates on the second floor of a house, while the basement stays cool. Some passive solar homes use air convection to carry solar heat from a south wall into the building's interior.

Radiation

Radiant heat moves through the air from warmer objects to cooler ones. There are two types of radiation important to passive solar design: solar radiation and infrared radiation. When radiation strikes an object, it is absorbed, reflected, or transmitted, depending on certain properties of that object.
Opaque objects absorb 40%–95% of incoming solar radiation from the sun, depending on their color—darker colors typically absorb a greater percentage than lighter colors. This is why solar-absorber surfaces tend to be dark colored. Bright-white materials or objects reflect 80%–98% of incoming solar energy.
Inside a home, infrared radiation occurs when warmed surfaces radiate heat towards cooler surfaces. For example, your body can radiate infrared heat to a cold surface, possibly causing you discomfort. These surfaces can include walls, windows, or ceilings in the home.
Clear glass transmits 80%–90% of solar radiation, absorbing or reflecting only 10%–20%. After solar radiation is transmitted through the glass and absorbed by the home, it is radiated again from the interior surfaces as infrared radiation. Although glass allows solar

radiation to pass through, it absorbs the infrared radiation. The glass then radiates part of that heat back to the home's interior. In this way, glass traps solar heat entering the home.

Thermal capacitance

Thermal capacitance refers to the ability of materials to store heat. *Thermal mass* refers to the materials that store heat. Thermal mass stores heat by changing its temperature, which can be done by storing heat from a warm room or by converting direct solar radiation into heat. The more thermal mass, the more heat can be stored for each degree rise in temperature. Masonry materials, like concrete, stones, brick, and tile, are commonly used as thermal mass in passive solar homes. Water also has been successfully used.

Five Elements of Passive Solar Home Design

The following five elements constitute a *complete* passive solar home design. Each performs a separate function, but all five must work together for the design to be successful.

Aperture (Collector)

The large glass (window) area through which sunlight enters the building. Typically, the aperture(s) should face within 30 degrees of true south and should not be shaded by other buildings or trees from 9 a.m. to 3 p.m. each day during the heating season.

Absorber

The hard, darkened surface of the storage element. This surface—which could be that of a masonry wall, floor, or partition (phase change material), or that of a water container—sits in the direct path of sunlight. Sunlight hits the surface and is absorbed as heat.

Thermal mass

The materials that retain or store the heat produced by sunlight. The difference between the absorber and thermal mass, although they often form the same wall or floor, is that the absorber is an exposed surface whereas thermal mass is the material below or behind that surface.

Distribution

The method by which solar heat circulates from the collection and storage points to different areas of the house. A strictly passive design will use the three natural heat transfer modes—conduction, convection, and radiation—exclusively. In some applications, however, fans, ducts, and blowers may help with the distribution of heat through the house.

Control

Roof overhangs can be used to shade the aperture area during summer months. Other elements that control under- and/or overheating include electronic sensing devices, such as a differential thermostat that signals a fan to turn on; operable vents and dampers that allow or restrict heat flow; low-emissivity blinds; andawnings.

Passive Solar Window Design

Properly designed, energy efficient windows represent a cost-effective way to use solar energy for heating.
Photo credit: Dwight Stone.

Windows are an important element in passive solar home designs, which can reduce heating, cooling, and lighting needs in a house. Passive solar design strategies vary by building location and regional climate. The basic techniques involving windows remain the same—select, orient, and size glass to control solar heat gain along with different glazings usually selected for different sides of the house (exposures or orientations). For most U.S. climates, you want to maximize solar heat gain in winter and minimize it in summer.

Heating-Dominated Climates

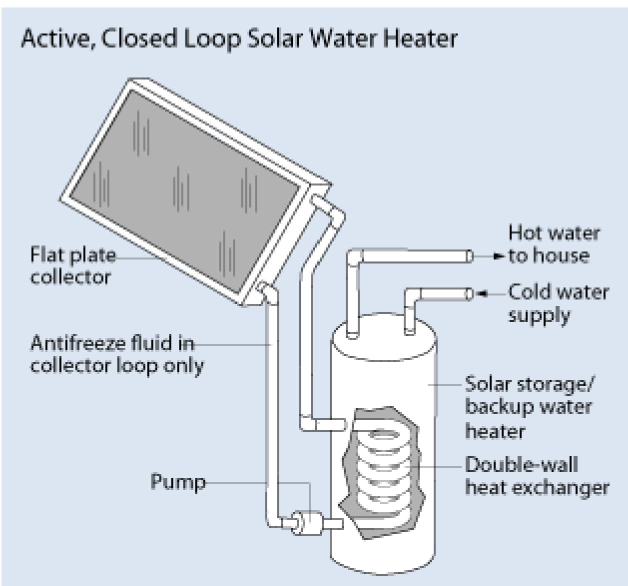
In heating-dominated climates, major glazing areas should generally face south to collect solar heat during the winter when the sun is low in the sky. In the summer, when the sun is high overhead, overhangs or other shading devices (e.g., awnings) prevent excessive heat gain.

To be effective, south-facing windows usually must have asolar heat gain coefficient (SHGC) of greater than 0.6 to maximize solar heat gain during the winter, a U-factor of 0.35 or less to reduce conductive heat transfer, and a high visible transmittance (VT) for good visible light transfer.
Windows on east-, west-, and north-facing walls are reduced in heating climates, while still allowing for adequate daylight. East- and west-facing windows are limited because it is difficult to effectively control the heat and penetrating rays of the sun when it is low in the sky. These windows should have a low SHGC and/or be shaded. North-facing windows collect little solar heat, so they are used just to provide useful lighting.
Low-emissivity window glazing can help control solar heat gain and loss in heating climates.

Cooling-Dominated Climates
In cooling climates, particularly effective strategies include preferential use of north-facing windows and generously shaded south-facing windows. Windows with low SHGCs are more effective at reducing cooling loads. The following types of glazing help reduce solar heat gain, lowering a window's SHGC:

Low-E
Tinted
Reflective
Spectrally Selective.
Most of these glazing types, except for spectrally selective, also help lower a window's VT.

Solar Water Heaters



Solar water heaters use the sun's heat to provide hot water for a home or building.

How Solar Water Heaters Work
Solar water heating systems include storage tanks and solar collectors. Solar water heaters use the sun to heat either water or a heat-transfer fluid in the collector.
Most solar water heaters require a well-insulated storage tank. The tank can be a modified standard water heater, but it is usually larger and very well insulated. Solar storage tanks have an additional outlet and inlet connected to and from the collector.
In two-tank systems, the solar water heater preheats water before it enters the conventional water heater. In one-tank systems, the back-up heater is combined with the solar storage in one tank.

Types of Solar Collectors
Solar collectors gather the sun's energy, transform its radiation into heat, and then transfer that heat to water or solar fluid. Three types of solar collectors are used in solar water heating systems:

Flat-plate collectors
A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-colored absorber plate. Unglazed flat-plate collectors—typically used for solar pool heating—have a dark absorber plate, made of metal or polymer, without a cover or enclosure.

Integral collector-storage systems

Integral collector-storage systems, also known as ICS or "batch" systems, are made of one or more black tanks or tubes in an insulated glazed box. Cold water first passes through the solar collector, which preheats the water, and then continues to the conventional backup water heater.

Evacuated-tube solar collectors
Evacuated-tube collectors can achieve extremely high temperatures (170°F to 350°F), making them more appropriate for cooling applications and commercial and industrial application. The collectors are usually made of parallel rows of transparent glass tubes. Each tube contains a glass outer tube and metal absorber tube attached to a fin. The fin is covered with a coating that absorbs solar energy well, but which inhibits radiative heat loss. Air is removed, or evacuated, from the space between the two glass tubes to form a vacuum, which eliminates conductive and convective heat loss.

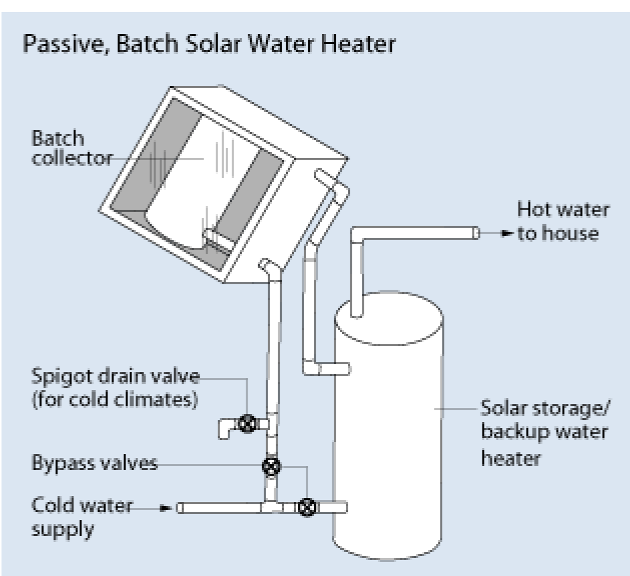
Types of Solar Water Heating Systems
There are two types of solar water heating systems: active, which have circulating pumps and controls, and passive, which don't.

Active Solar Water Heating Systems
There are two types of active solar water heating systems:

Direct circulation systems
Direct-circulation systems use pumps to circulate pressurized potable water directly through the collectors. These systems are appropriate in areas that do not freeze for long periods and do not have hard or acidic water.

Indirect circulation systems
Indirect-circulation systems pump heat-transfer fluids through collectors. Heat exchangers transfer the heat from the fluid to the potable water. They are popular in climates prone to freezing temperatures. Some indirect systems have "overheat protection," which is a means to protect the collector and the glycol fluid from becoming super-heated when the load is low and the intensity of incoming solar radiation is high. The two most common indirect systems are:
Antifreeze. The heat transfer fluid is usually a glycol-water mixture with the glycol concentration depending on the expected minimum temperature. The glycol is usually food-grade propylene glycol because it is non-toxic.
Drainback systems, which use pumps to circulate water through the collectors. The water in the collector loop drains into a reservoir tank when the pumps stop. This makes drainback systems a good choice in colder climates. Drainback systems must be carefully installed to assure that the piping always slopes downward, so that the water will completely drain from the piping.

Passive Solar Water Heating Systems



Passive solar water heaters rely on gravity and the tendency for water to naturally circulate as it is heated. There are two basic types of passive systems:

Integral collector-storage passive systems
Integral-collector storage systems consist of one or more storage tanks placed in an insulated box with a glazed side facing the sun. These work best in areas where temperatures rarely fall below freezing. They also work well in households with significant daytime and

evening hot-water needs. They do not work well in homes or buildings with predominantly morning draws because they lose most of the collected energy overnight.

Thermosyphon systems

Thermosyphon systems rely on the natural convection of warm water rising to circulate water through the collectors and to the tank (located above the collector). As water in the solar collector heats, it becomes lighter and rises naturally into the tank above. Meanwhile, the cooler water flows down the pipes to the bottom of the collector, enhancing the circulation. Some manufacturers place the storage tank in the house's attic, concealing it from view. Indirect thermosyphons (that use a glycol fluid in the collector loop) can be installed in freeze-prone climates if the piping in the unconditioned space is adequately protected.

Backup Systems

Solar water heating systems almost always require a backup system for cloudy days and times of increased demand. Conventional storage water heaters usually provide backup and may already be part of the solar system package. A backup system may also be part of the solar collector, such as rooftop tanks with thermosyphon systems.

Since an integral-collector storage system already stores hot water in addition to collecting solar heat, it may be packaged with a demand (tankless or instantaneous) water heater for backup.