

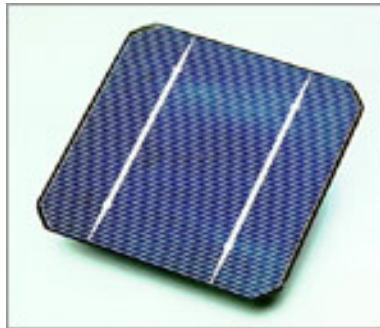
Appendix C: Solar Electric

C.1 PV Technology & Applications

Photovoltaic (or PV) cells are devices that use semiconductor materials—similar to those used in computer chips—to convert sunlight directly into electricity. The electric current can either be used immediately, or it may be stored, as in a battery, for later use.

Figure C.1 below shows a typical photovoltaic (PV) or solar cell which is the basic building block of a photovoltaic system. It might be a square that measures about 4 inches (10 centimeters) on a side. A cell can produce between 1 and 2 watts of power—more than enough to power a watch, but not enough to run a radio.

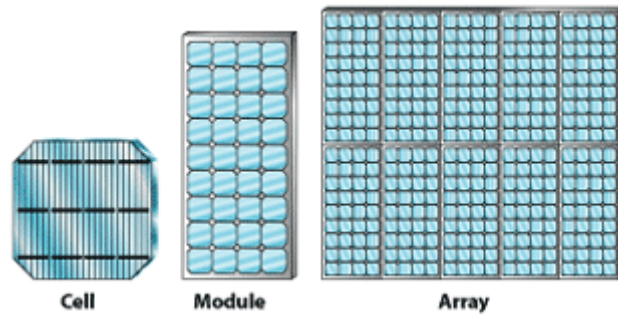
Figure C.1: The Solar Cell



The first conventional photovoltaic cells were produced in the late 1950's, and throughout the 1960's were principally used to provide electrical power for earth-orbiting satellites. In the 1980's, photovoltaics became a popular power source for consumer electronic devices, including calculators, watches, radios, lanterns, and other small battery charging appliances. Following the energy crises of the 1970's, significant efforts took place to develop photovoltaic power systems for residential and commercial uses for stand-alone, remote power as well as for utility-connected applications.

As shown in Figure C.2 below, when more power is needed, a group of PV cells can be connected together to form a "module." A typical module is powerful enough to light a small light bulb. For larger power needs, 10 or more such modules are mounted in PV "arrays," which can measure up to 6.5 feet (several meters) on a side. The amount of electricity generated by an array increases as more modules are added. A photovoltaic array surface area the size of roughly two football fields could produce 1000 kW of DC peak power.

Figure C.2: Solar Cell, Module, and Arrays



State-of-the-art PV modules are now available in a variety of colors and styles as shown in Figures C.3 and C.4 below, allowing designers to use them as aesthetic elements built right into roofs, skylights, awnings, entryways, and facades. Today's modules can even be specified to transmit a percentage—usually 80% to 90%—of natural light. Mixed with non-transmittance modules, these systems create a pleasant environment inside the building, helping to ventilate and heat the building at the same time.

Figure C.3: Solar Panel Material



Figure C.4: Solar Panel Material



The photovoltaic effect is the basic physical process by which a PV cell converts sunlight into electricity. Sunlight is comprised of photons, or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a PV cell, some are reflected, some absorbed, and some may pass right through; only the absorbed photons generate electricity. When the photon is absorbed, the energy of the photon is transferred to an electron in an atom of the cell material. With its newfound energy, the electron is able to escape from its normal position associated with that atom to create electron flow. By leaving this position, the electron causes a "hole" to form. That "hole" then provides a place for another electron to fill. This repeating process creates electrical current. It is this special electrical property of the PV cell—a built-in electrical field—that provides the voltage needed to drive the current through an external load (such as a light bulb). Figure C.5 demonstrates this concept.¹

Figure C.5: Inside a PV Cell

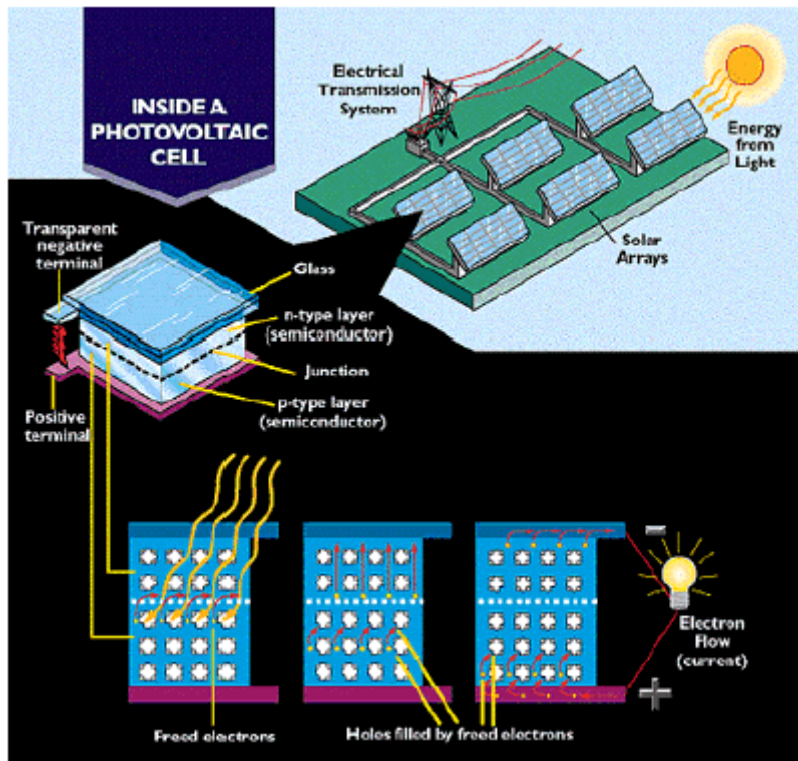
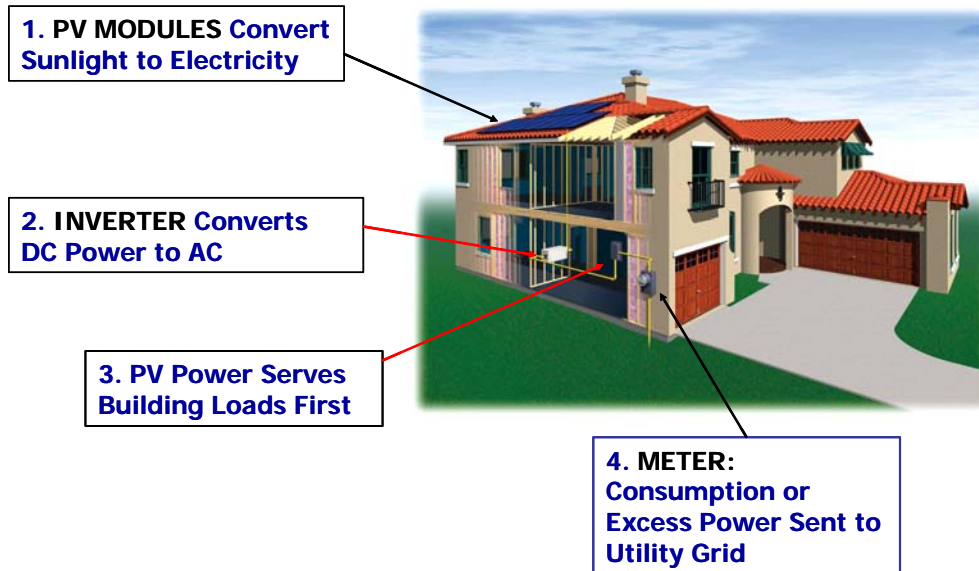


Figure C.6 shows a typical residential PV system. The simplest PV system generates direct-current electricity when the sun is shining and runs equipment such as DC water pumps or fans. A power inverter can convert direct current to alternating current. For powering equipment in remote locations, PV systems include batteries that store electricity for use at night or when the sun isn't shining.

¹ CEC.

Figure C.6: Typical Residential PV System ²

PV System Components



In some cases, power must be available on demand; especially where the electricity required exceeds the PV system's supply or time of availability. Here, an electric generator can work effectively with PV to supply the load. Remote locations, where diesel generators alone currently supply loads, are good candidates for PV systems with generators.

Solar PV technology has continued to improve with increasing conversion efficiencies and declining costs. Crystalline silicon cells connected together to form modules constituted about 90 percent of the solar cell market in 2001. Technology costs are subject to the relatively high cost of semiconductor material. PV cells can be made of many different semiconductors.

Commercial Technology Overview

Commercial photovoltaic systems use the same basic technology building blocks as residential. Photovoltaic cells are combined to make modules, modules are combined to make panels, and system panels are combined to make arrays. An inverter converts the DC voltage and current into AC and the balance of systems includes wiring and racking.

PV cells can be made of many different semiconductors. We will talk about "Thin Film" and "Crystalline Silicone." Crystalline silicon was the material used in the earliest

² Shea Homes.

successful PV devices. It is still the most widely used PV material. Although other PV materials and designs exploit the photoelectric effect in slightly different ways, understanding the crystalline silicon system will provide you with a basic understanding of how it works in all PV devices.

Outranked only by oxygen, silicon is also the second-most abundant element in the Earth's crust. However, to be useful as a semiconductor material in solar cells, silicon must be refined to a purity of 99.9999%.

In single-crystal silicon, the molecular structure, which is the arrangement of atoms in the material, is uniform, because the entire structure is grown from the same crystal. This uniformity is ideal for transferring electrons efficiently through the material. To make an effective PV cell, however, silicon has to be "doped" with other elements to make it n-type and p-type.

In the "Homo-junction" device, 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 amount of light is absorbed near it. The free electrons and holes generated by light deep within the silicon, diffuse to the p/n junction, and then separate to produce current if the silicon is of sufficient high quality.

One of the other types of photovoltaic modules is "Thin Film." The "Thin Film" term comes from the method used to deposit the film, not from the thinness of the film: thin-film cells are deposited in very thin, consecutive layers of atoms, molecules, or ions. Thin-film cells have many advantages over their "thick-film" counterparts. For example, they use much less material—the cell's active area is usually only 1 to 10 micrometers thick, whereas thick films typically are 100 to 300 micrometers thick. Also, thin-film cells can usually be manufactured in a large-area process, which can be an automated, continuous production process. Finally, they can be deposited on flexible substrate materials.

The amount of energy that a photovoltaic cell produces is determined by many factors. The main factor is the conversion efficiency. This is the amount of light hitting the photovoltaic surface that is actually converted into electricity. The typical range for crystalline modules is 10-15% of the light is converted directly into electricity.

Cell conversion efficiency and therefore energy production are affected by temperature. There is an inverse relationship between surface temperature of a photovoltaic cell and its conversion efficiency once the temperature crosses a threshold. The voltage drops by 0.5% per degree centigrade rise over 25 degrees centigrade. Meaning, for every degree above 25 degrees centigrade (77 degrees Fahrenheit) the voltage drops by .5%. When in operation under full sun, a solar module will heat up substantially, reaching inner temperatures of 50-70 °C, which in turn reduce the overall output power of the module.³

³ A GUIDE TO PHOTOVOLTAIC (PV) SYSTEM DESIGN AND INSTALLATION, CEC 2001.
http://www.energy.ca.gov/reports/2001-09-04_500-01-020.PDF.

Conversion efficiency only determines how much DC electricity a cell or module will produce. According to the CEC (California Energy Commission), there are many other factors that affect the amount of usable energy produced from an entire photovoltaic system, including system capacity at standard test conditions, dirt and dust, DC to AC conversion losses, mismatch and wiring losses, orientation and system tilt, and temperature

Standard Test Conditions - The DC output of solar modules is rated by manufacturers under Standard Test Conditions (STC). These conditions are used to allow comparisons of products between manufacturers. STC conditions are: a solar cell temperature of 25 °C (77 °F); solar irradiance (intensity) of 1000 W/m²; and solar spectrum as filtered by passing through 1.5 thicknesses of atmosphere (ASTM Standard Spectrum). It is under these conditions that a manufacturer rates a particular solar module output at 100 watts of power, and call the product a “100-watt solar module”. However, conditions in the field usually do not equal STC conditions. So, a 100-watt module will produce less than 100 watts of power under normal system operating conditions. In addition, a typical module will have a +/-5% production tolerance, so a module can produce 95 watts and still have a nameplate rating of 100 watts. The CEC recommends a STC reduction factor of 0.95 or 95% to account for the effects of normal operating conditions on modules. So, the 100-watt module is more accurately rated at about 95 watts.⁴

Temperature – Cell conversion efficiency and therefore energy production is affected by temperature. There is an inverse relationship between surface temperature of a photovoltaics cell and its conversion efficiency once the temperature crosses a threshold voltage drops by 0.5% for each degree rise in centigrade over 25 °C (77 °F). When in operation under full sun, a solar module will heat up substantially, reaching inner temperatures of 50-70 °C, which in turn reduces the overall output power of the module.⁵ For crystalline modules, a typical temperature reduction factor recommended by the CEC is 89% or 0.89. So a “100-watt” crystalline module will typically produce about 85 Watts (95 Watts per STC x 0.89 = 85 Watts) under full sunlight conditions.

In addition to the above factors, which affect the module itself, there are a number of other factors that affect the entire system.

Dirt and dust - Dirt and dust can accumulate on the solar module surface, blocking some of the sunlight and reducing output. Since wet winters and long dry summers characterize Southern California climate, it is likely that dirt and dust will accumulate during dry months. To account for this, it is realistic to reduce expected energy output due to dust. According to the CEC, a typical dust reduction factor is 93% or 0.93.⁶

DC to AC conversion losses – Since photovoltaics generate DC voltage and current, an inverter is necessary to convert the voltage and current to AC to be compatible with the utility power system. The inverter is not 100% efficient in this conversion, and some

⁴ Ibid.

⁵ A GUIDE TO PHOTOVOLTAIC (PV) SYSTEM DESIGN AND INSTALLATION, CEC 2001.
http://www.energy.ca.gov/reports/2001-09-04_500-01-020.PDF.

⁶ Ibid.

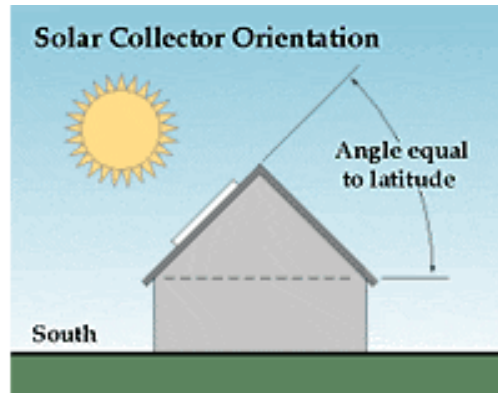
power is lost in the process. Modern inverters commonly used in grid connected PV power systems have peak efficiencies of 92-94%. Similar to photovoltaic modules, inverter efficiencies are measured under well-controlled factory conditions. Field conditions typically result in DC to AC conversion efficiencies of about 82-89%. Therefore, the CEC recommends using 90% or 0.90 as a compromise.

Mismatch and wiring losses – The maximum power output of the total PV array is always less than the sum of the maximum output of the individual modules. This difference is a result of slight inconsistencies in performance from one module to the next and is called “module mismatch.” This amounts to at least a 2% loss in system power. Power is also lost to resistance in the system wiring. These losses should be kept to a minimum but it is difficult to keep these losses below 3% for the system. A reasonable reduction factor for these losses is 95% or 0.95.

System angle and orientation - The angle at which photovoltaics arrays are installed and the orientation from due south will affect photovoltaic energy generation. The optimal orientation for maximum annual production is due south with the array at an angle equal to the latitude of the location where the system is installed as shown in Figure C.7 below. Different orientations and angles will alter the total amount of energy produced and when that energy is produced. For example, facing an array due west will shift its peak production later into the afternoon. According to the CEC, a system installed flat will generate 89% of the energy of a system installed at the optimal angle and orientation. There is no single energy reduction factor for angle and orientation. For San Diego specifically, the NREL has developed a table which takes into account climatic conditions and time-of-year when setting panel tilt.⁷

⁷ <http://redc.nrel.gov/solar/pubs/redbook/PDFs/CA.PDF>.

Figure C.7: Solar Collector Orientation for PV Panels.⁸



The angle of the sun and house orientation during the course of a day, the angle of sunlight striking the solar module will change during the day and throughout the year, which will affect the power output as shown in Figure C.8.

Figure C.8: Geographic Orientation of PV Panels⁹

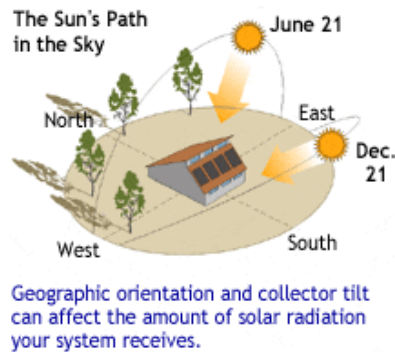


Table C.1 shows a range of factors based on system angle and orientation developed by the CEC. The output from the “100-watt module” will rise from zero gradually during dawn hours, and increase with the sun angle to its peak output at midday, and then gradually decrease into the afternoon and back down to zero at night.

⁸ CEC.
⁹ CEC.

Table C.1: Orientation Factors for Various Roof Pitches and Directions

Orientation	Roof Pitch					
	Flat	4:12 18.4°	7:12 33°	12:12 45°	21:12 60°	Vertical
South	0.89	0.97	1	0.97	0.89	0.58
SSE, SSW	0.89	0.97	0.99	0.96	0.88	0.59
SE, SW	0.89	0.95	0.96	0.93	0.85	0.6
ESE, WSW	0.89	0.92	0.91	0.87	0.79	0.57
East, West	0.89	0.88	0.84	0.78	0.7	0.52

In summary, the CEC recommends that following reduction factors¹⁰:

- Standard Test Conditions – 0.95 (i.e., a 5% reduction)
- Temperature Effects – 0.89
- Dirt and Dust – 0.93
- Current Mismatch/Wire Losses – 0.95
- DC to AC Conversion – 0.90

The CEC includes the following example: “So the ‘100-watt module’ output, reduced by production tolerance, heat, dust, wiring, ac conversion, and other losses will translate into about 67 Watts of AC power delivered to the house panel during the middle of a clear day (100 Watts x 0.95 x 0.89 x 0.93 x 0.95 x 0.90 = 67 Watts).”¹¹

Residential and Commercial Applications

Integrating PV into a commercial building can reduce the overall cost of the system because the solar feature provides two functions — it replaces the traditional building materials such as tile, brick, or glass, and it generates electricity.

There are several ways to install a PV array at a residence. Most PV systems produce 5-to-10 watts per square foot of array area. This is based on a variety of different technologies and the varying efficiency of different PV products. A typical 2 kW PV system will need about 200 square feet of unobstructed area to site the system.

Consideration should also be given for access to the system. This access space can add up to 20% of needed area to the mounting area required.

Often the most convenient and appropriate place to put the PV array is on the roof of the building as shown in Figures C.9 and C.10 below. The PV array may be mounted above and parallel to the roof surface with a standoff of several inches for cooling purposes.

¹⁰ Section 4.2.2 includes a detailed discussion of these reduction factors.

¹¹ A GUIDE TO PHOTOVOLTAIC (PV) SYSTEM DESIGN AND INSTALLATION, CEC 2001.
http://www.energy.ca.gov/reports/2001-09-04_500-01-020.PDF.

Figure C.9: PV Roof Tiles on Residential Roof

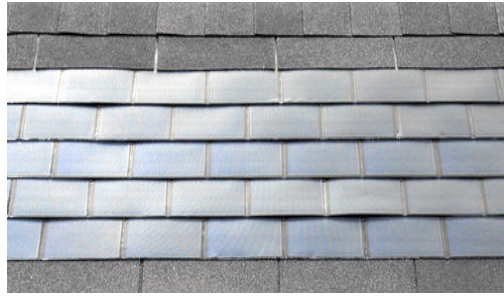


Figure C.10: PV Roof Tiles



A residential PV power system enables homeowners to generate some or all of their daily electrical energy demand on their own roof and with net energy metering, exchanging daytime excess power for future energy needs (i.e. night time usage). The house remains connected to the electric utility at all times, so any power needed above what the solar system can produce is simply drawn from the utility. PV systems can also include battery backup or uninterruptible power supply (UPS) capability to operate selected circuits in the residence for hours or days during a utility outage.

There are two general types of electrical designs for PV power systems for homes; systems that include battery backup as shown in Figure C.11, and systems that have no battery backup capability as shown in Figure C.12.

Figure C.11: PV System with Battery Backup System

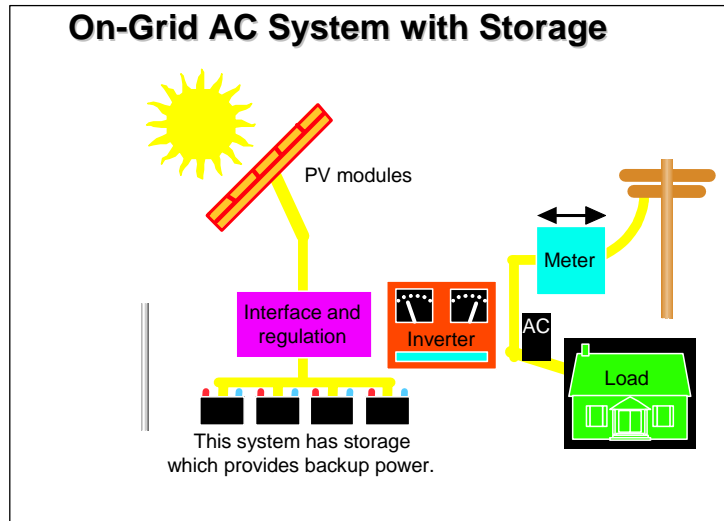
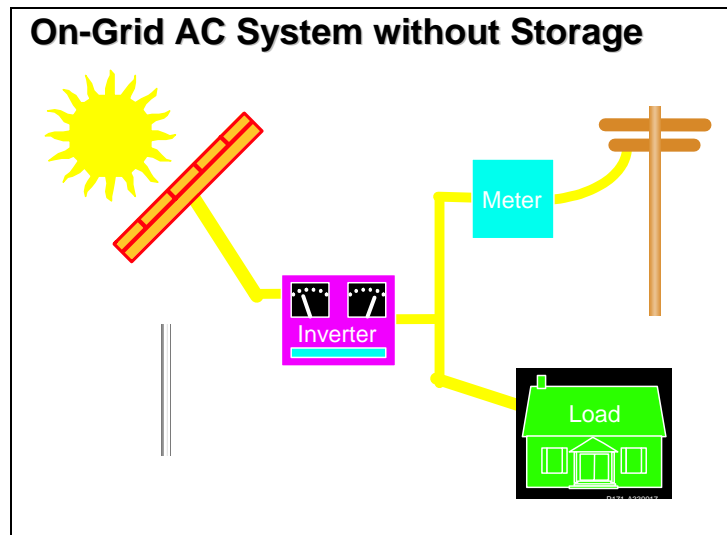


Figure C.12: PV System without Battery Storage



The PV system with battery backup is a system that incorporates energy storage in the form of a battery to keep “critical load” circuits in the house operating during a utility outage. When an outage occurs the unit disconnects from the utility and powers specific circuits in the home. These critical load circuits are wired from a sub-panel that is separate from the rest of the electrical circuits. If the outage occurs during daylight hours, the PV array is able to assist the battery in supplying the house loads. If the outage occurs at night, the battery supplies the load.

The amount of time critical loads can operate depends on the amount of power they consume and the energy stored in the battery system. A typical backup battery system may provide about 8 kWh of energy storage at an 8 hour discharge rate, which means that the battery will operate a 1 kW load for 8 hours. A 1 kW load is the average usage for a home when not running an air conditioner.¹²

The PV system without battery backup only operates when the utility is available as shown in Figure C.12. Since utility outages are generally rare, this system will normally provide the greatest amount of bill savings to the customer per dollar of investment. However, in the event of an outage, the system is designed to shut down until utility power is restored.

While residential applications drove early market penetration of photovoltaic panels and still represent a significant portion of the market, there is a growing trend of the commercial sector investing in photovoltaic systems. For the purposes of this study we define the commercial sector as all non-residential sectors including businesses, institutional, and governmental customers. We also define a commercial-scale photovoltaic system as 10 kW or greater in capacity. While there have been some residential photovoltaic systems installed that fall within this size range, there are not enough to be substantive.

There are two main systems PV material comes in: flat plate and concentrator. The flat plate system is discussed here. The concentrator system is discussed in a separate chapter.

The most common array design uses flat-plate PV modules or panels. These panels can either be fixed in place or allowed to track the movement of the sun. They respond to sunlight that is either direct or diffuse. Even in clear skies, the diffuse component of sunlight accounts for between 10% and 20% of the total solar radiation on a horizontal surface. On partly sunny days, up to 50% of that radiation is diffuse. And on cloudy days, 100% of the radiation is diffuse. The simplest PV array consists of flat-plate PV panels in a fixed position. The advantages of fixed arrays are that they lack moving parts, there is virtually no need for extra equipment, and they are relatively lightweight. These features make them suitable for many locations, including most residential roofs. Because the panels are fixed in place, their orientation to the sun is usually at an angle that, practically speaking, is less than optimal. Therefore, less energy per unit area of array is collected compared with that from a tracking array. However, this drawback must be balanced against the higher cost of the tracking system.

While the building blocks are the same, commercial installation configurations typically differ from residential installations. Most residential applications are installed either parallel to the roof plane or tilted up from the roof plane to improve performance. On the other hand, most commercial applications involve flat rooftops. There are ranges of commercial installation techniques ranging from racking modules off the roof to systems that are mounted flat on the roof. In addition, some commercial systems are mounted on

¹² http://www.energy.ca.gov/reports/2001-09-04_500-01-020.PDF.

the ground either as covered parking or in some agricultural applications have ground mounted fixed tilt arrays.

An additional difference between residential and commercial installations is the size/capacity of the system. Commercial photovoltaics systems are typically in the 30-200 kW range, with the majority in the 10 kW to 50 kW range. Statewide the average sized commercial system is 140 kW; the largest system is 1 MW.¹³

Figures C.13 and C.14 are examples of PV flat panel installed in commercial settings.

Figure C.13: Flat Panels Tilted on Commercial Building



Figure C.14: Flat Panels Installed on Commercial Building



Figure C.15 is a 48-story New York City skyscraper designed in the 1990s—features a photovoltaic "skin" that includes thin-film PV panels; they replace traditional glass cladding material. The PV skin extends from the 37th to the 43rd floor on the south and west walls and is a highly visible part of the midtown skyline.

¹³ Based on statewide data from the Self-Generation Incentive Program. See http://www.sdenergy.org/uploads/SelfGen_Statewide%20Data_Jan05.xls.

Figure C.15: Thin Film PV Panels Installed in Times Square



Today, the PV industry generates about 3,000 jobs for every \$100 million of module sales. If the industry continues to grow at the rate seen in the last few years—an average of about 36%—it could employ some 150,000 Americans in high-value, high-tech jobs within 20 years.¹⁴

Worldwide the photovoltaic industry is growing. In 2004, worldwide photovoltaic cell production was over 1,000 MW. Germany and Japan each have substantial solar programs and have installed hundreds of megawatts of photovoltaic cells in recent years. As a result, there is a well-established worldwide supply chain for photovoltaic modules and inverters. Products are widely available in the United State (US), particularly in California, which has the largest photovoltaic system market in the U.S.¹⁵

As of 2004, over 15 companies manufacturer photovoltaic modules worldwide. The leading manufacturers are all large multi-national companies. The leading manufacturer, Sharp, accounts for approximately 325 MW or 30% of worldwide production¹⁶ Other large multinational corporations including BP Solar, Kyocera, Shell Solar, Mitsubishi, and Sanyo account for another 36% of worldwide production.¹⁷ All manufacturers plan to expand their production capabilities in 2005 to meet the growing worldwide demand.

¹⁴ Solar Electricity: The Power of Choice, 2001.

¹⁵ The Photovoltaics Magazine - April 2004 Issue.

¹⁶ PV NEWS, Volume 24, Number 3, March 2005.

¹⁷ PV NEWS, Volume 24, Number 3, March 2005.

In addition, over 30 companies manufacture inverters worldwide. In the US, the main inverter suppliers include SMA, Xantrex, and Fronius. The major inverter manufacturers are also planning to increase production of inverters as the worldwide PV market grows. California has nearly 400 companies that sell and/or install photovoltaic equipment. Regionally, 39 companies in the San Diego region sell and/or install photovoltaic systems in 2004.¹⁸

¹⁸ CEC http://www.leginfo.ca.gov/pub/bill/sen/sb_0001-0050/sb_1_bill_20041206_introduced.html.