THE APPLICATION OF PHOTOVOLTAICS FOR BUILDINGS

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ABSTRACT

The concept of converting the sun's energy into useful power is not a new one. Basic principles governing the photovoltaic(PV) effect were documented in 1839 by Edmond Becquerel, have been refined and applied to the construction of clean and sustainable energy producing systems. NASA first developed early PV systems for use as a reliable source of energy in satellites. Soon after, the technology was applied to the building industry. Because PV cells produce electricity directly, with no harmful emissions, large-scale use of PV systems is an environmentally friendly alternative to the burning of fossil fuel. To be economically feasible, for large-scale use the scientific and engineering community must find ways to reduce the cost of the technology.

Three primary cost reducing measures are to increase the efficiency of the PV cell, develop large markets that take advantage of economies of scale, and design dual purpose PV panels into the building envelope. The dual-purpose panels serve first as a structural cladding or roofing elements, and second as a power generator. To accomplish this, the structural engineer must design the building façade to orient the PV panels to take maximum advantage of solar availability.

The information contained herein is intended to provide structural engineers with a basic understanding of solar availability, the basic components of a PV system, and the design issues associated with PV building envelopes. This discussion focuses primarily on grid connected systems and building design in urban environments and is intended to encourage engineers to incorporate innovative integrated PV systems in their designs.

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Chapter 1

Background

Building Shaded PV Integrated System
Handelshaus A. Wild, Innsbruck [22]

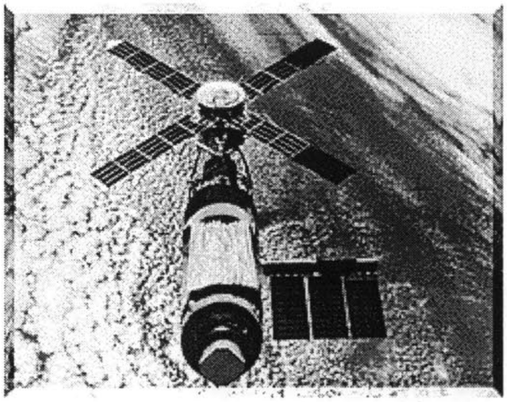
1.1 A Brief History

Photovoltaic systems convert light into electricity. "Photo" is a stem from the Greek word "phos" meaning light and "Volt" is named for Alexandra Volta, a pioneer in the study of electricity. A French physicist, Edmond Becquerel, first described the Photovoltaic (or PV) effect in 1839. Becquerel observed that certain materials would produce a small amount of electric current when exposed to light. The next step toward the development of PV cells occurred in 1873 when Willoughby Smith discovered the photoconductivity of selenium, paving the way for Charles Fritts, an American inventor, who described the first solar cells made from selenium. PV theory gained widespread acclaim in 1921 when Albert Einstein won the Nobel Prize for his theories explaining the photoelectric effect.

Einstein's theories made it possible for later scientists to develop photovoltaic cells, which utilized materials other than selenium. This next generation of PV cells was more efficient. By 1955 silicone cells were being developed to provide power supplies for the first US earth satellites. The first PV powered satellite was Vanguard I, launched March 17 1958. Other examples of early satellites, which were equipped with photovoltaic panels, include Explorer III-VII, Vanguard II and Sputnick-3. The first commercially available PV cells were produced in the in the 1950's. These PV cells were approximately 2% efficient and cost $1785 per Watt. By the early 1960's the efficiency of the cells had been increased to 14% and the cost had correspondingly decreased.

Figure 1.1 [14]

Typical Photovoltaic Powered Satellite



Throughout the sixties PV technology continued playing a prominent role for space programs in the US as well as Japan. PV technology was also finding applications outside of the space program and in1963 Japan installed a 242-W PV array on a lighthouse. At that time it was the worlds largest PV array. By 1966 an orbiting Astronomical Observatory was launched by the US, which utilized a PV array of 1 kW.

The 1970's saw PV systems become more diverse. In 1973 the University of Delaware built 'Solar One', one of the worlds first PV residences. The system was a PV-Thermal hybrid. The roof-integrated arrays fed surplus power through a special meter to the utility during the day and purchased power from the utility at night. PV power supplies were being used for a large variety of applications including vaccine refrigeration, room lighting, telecommunications, water pumping, grain milling, and classroom television. By 1977 total PV manufacturing production in the US exceeded 500kW and was increasing. In 1980 ARCO Solar Co. became the first company to produce more than 1 MW of PV panels in one year, and within 3 years worldwide PV production exceeded 21.3 MW with sales in excess of $250million.

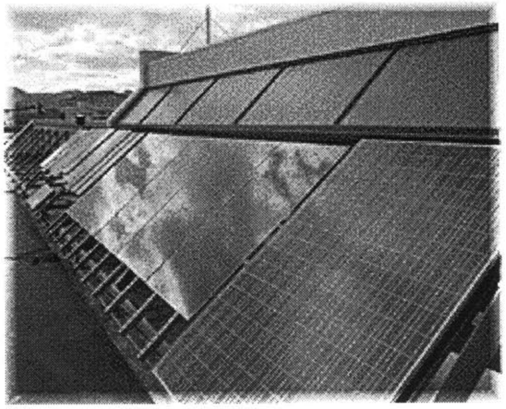
Throughout the 1980's the world developed PV systems which were capable of producing larger amounts of power and were more easily integrated into modern structures. In 1983 ARCO Solar dedicated a 6-MW PV station in central California. This unmanned facility supplied the local utility grid with enough power for 2000-2500 homes. PV power stations were constructed worldwide, bringing clean sustainable power supplies to areas like Kenya, Zimbabwe, and the Marshall Islands. ARCO Solar released the first commercially available thin film "power module" in 1986. The advent of commercially available thin film PV panels made it feasible to incorporate PV panels as an element of building facades. PV systems costs have been reduced 300% since 1982 in a market growing at a rate of 20% per year. The present cost of electricity from PV systems is 25-50 cents per kilowatt hour. The end of the 80's and 90's have seen many countries incorporating national initiatives encouraging the use of PV power systems. PV systems installed since 1988 provide enough electricity to power 150,000 homes in the US or 8 million homes in the developing world. PV systems generated more than 800 million kilowatt-hours of electricity in 1995[14].

1.2 The Advantages of PV Power Systems

There are many advantages to using PV power. The primary advantage of photovoltaic power generation is electricity is produced without pollutants, detectable emissions, or odors. It is a clean sustainable source of power requiring no fossil fuel. PV fuel comes directly from the sun and is abundant and free. Also, PV systems do not require any extra land area , have no moving parts and produce electricity silently making it possible to use photovoltaics in heavily populated areas. They also have a large degree of flexibility. They can be operated as free standing systems or combined with other power sources to form hybrid systems. PV systems are ideal for power generation in remote locations because they do not require connection to existing power supply or fuel source and can operate unattended for long periods of time.

Figure 1.2 [12]

PV Array for Power Generation In Remote Location



Their successful use on space shuttles is a testament to their free standing reliability and ability to withstand severe conditions including freezing temperatures and ice. However, if a power grid is available, the PV systems can be tied into the utility and extra electricity can be sold back to the local power company. The modularity of PV systems also enhances the flexibility of photovoltaic technology. As energy requirements for a particular operation increase, additional PV modules can easily be added to the system.

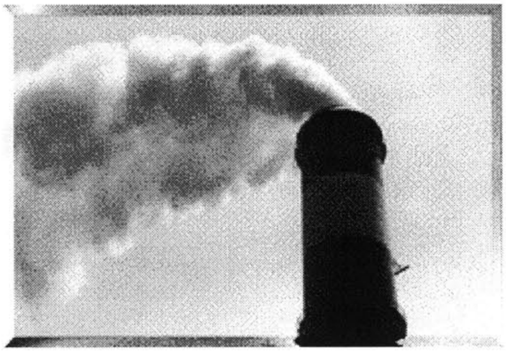
The large power requirements and corresponding large surface area of commercial and industrial buildings make them good candidates for PV power systems. These types of structures commonly require a hybrid system working in conjunction with the local utility. The advent of "thin" PV panels is the key to large facility PV utilization. Using modern glazing techniques, thin panels can be incorporated into a buildings curtain wall system as easily as conventional glass panels. Roof tiles have also been developed as PV panels. PV panels in both cases serve dual purpose providing shelter as well as power. The current emphasis in PV research and development is to provide more cost efficient methods of incorporating the technology into structures as dual purpose building elements. As the cost of PV power systems continues to decline, and the earth's pollution related atmospheric problems continue to expand, the role of PV power systems for large scale building projects can be expected to increase.

1.3 The Need for Clean, Sustainable Energy

Currently, the world depends mostly on fossil fuels as its primary source for power generation with petroleum providing 40%, coal 27% and natural gas 22% of the worlds electrical energy. The world now consumes the equivalent of 175 million barrels of oil each day. Buildings continue to play a significant role in the global energy balance, accounting for 20-30% of the total primary energy requirements of industrialized countries. Environmental problems, which are a direct result of the worlds addiction to fossil fuels, include, acid rain, urban smog and global warming[12].

Figure 1.3. [12]

Emissions Stack From Fossil Fuel Burning Power Facility



Global warming is the result of greenhouse gasses settling in the earth's lower atmosphere. The carbon dioxide which is a byproduct of fossil fuel combustion is the primary greenhouse gas. As carbon dioxide lingers in increasing quantities in the lower atmosphere, long wave solar radiation originating from the sun is allowed to reach the surface of the planet and the reflected short wave radiation is trapped in the lower atmosphere by the greenhouse gasses increasing overall global temperature. Many scientists predict devastating global effects if this trend is allowed to continue.

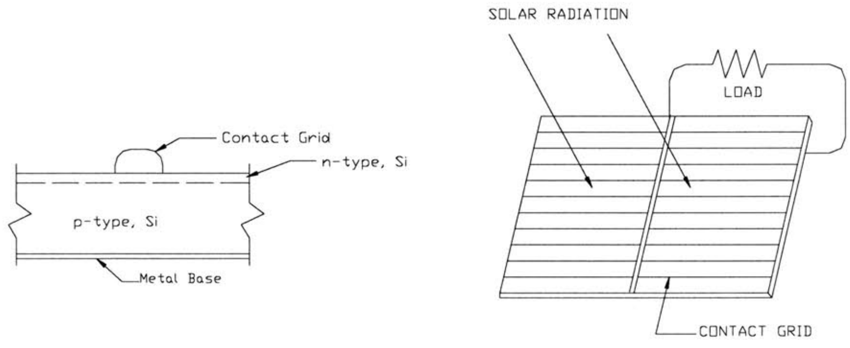
1.4 Photovoltaic Principles and Fundamentals

1.4.1 Cell Structure

The basic element of a photovoltaic system is the solar cell. The solar cell absorbs sunlight and converts it directly into electricity as a result of separate semiconductors being sandwiched together. A semiconductor is an element , whose electrical properties lie between those of conductors and insulators and for the purpose of this discussion, we will use silicon. Silicon was the semiconductor material used in the earliest successful PV devices and is still the most commonly used PV material. Although other materials may be used to exploit the PV effect, understanding how the property works in silicon will give a basic understanding of how the PV effect is exploited in all devices. Through a process called 'doping', impurities are introduced into the semiconductors, creating p-type and n-type layers. The "p" and "n" correspond to positive and negative and is related to the amount of excess electrons or holes in the material. Although both materials are electrically neutral, n-type silicon has excess electrons and p-type has vacancies of electrons or holes. Silicone doped with phosphorus is used for the n-type layer and silicone doped with Boron makes the p-type layer. Sandwiching them together creates a p/n junction at the interface[2].

Figure 1.4

Basic Structure of a PV Cell



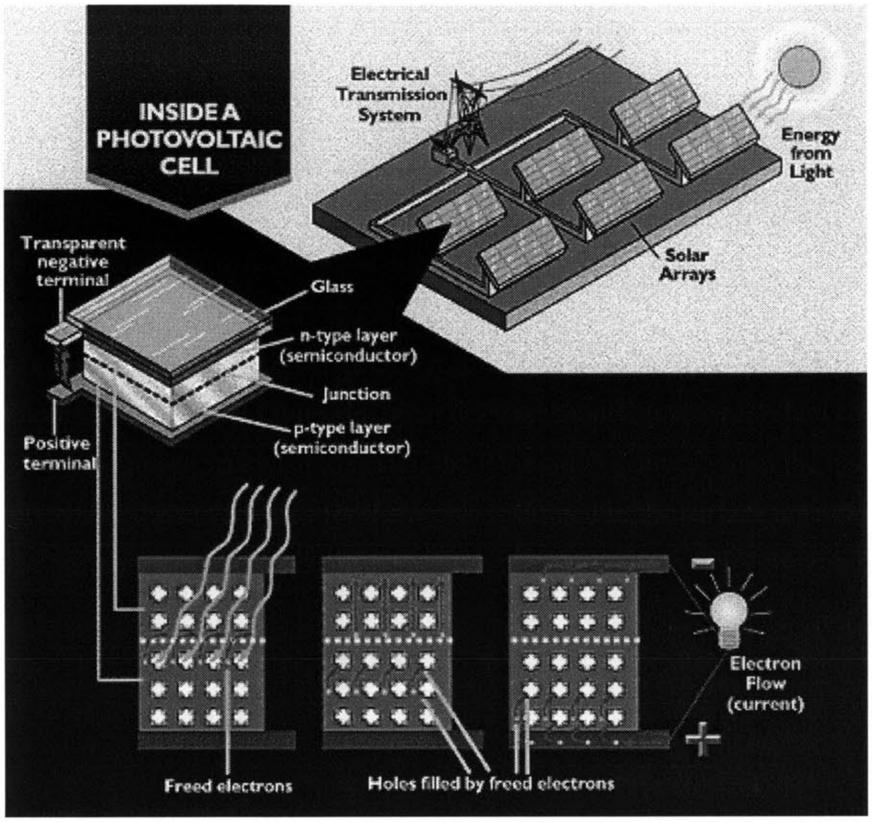
SECTION OF A SILICONE SOLAR CELL

SCHEMATIC OF A CELL

At the P/N interface , the excess electrons in the n-type material flow to the p-type, and the holes thereby vacated in this process flow to the n-type. Through this electron and hole flow, an electric field is created at the P/N junction. It's this field that causes the electrons to jump from the semiconductor out toward the surface and make them available for the electrical circuit. Now the holes move in the opposite direction, toward the positive surface, where they await incoming electrons. As sunlight passes throughout the thin window layer of silicon, the major part of the light is absorbed in the absorber layer where it creates the free electrons that can flow through a wire connected to both sides of the cell. It is important to note, that in this process, the current produced by the cell is proportional to the amount of incident light absorbed. Current increases with light intensity as well as surface area of the cell and unlike current, the voltage increases to some assumtotic value that is dependent upon the material used and independent of the cell area. Silicon cells of any size, produce approximately 0.5V. Higher voltages are obtained by connecting PV cells in series. Figure 1.5 demonstrates a typical configuration for a PV system.

Figure 1.5 [13]

Photovoltaic Cell



The average amount of power generated by a typical PV cell is approximately 1 watt with output increasing by connecting cells in series to form larger units known as modules. The modules are most often encapsulated and sealed with a tempered glass cover and a soft plastic backing sheet. This encapsulation process protects the electrical circuits from the weather and provides for a long circuit life span. Modules can be connected together to form arrays. The modules are connected in series to obtain higher voltages or in parallel to obtain higher amperage. The arrays are in turn connected together to form larger arrays. The total size of the PV system is determined by the amount of electricity that the designer wishes to produce. The modular nature of the system facilitates the installation of just the amount of power required, as well as the flexibility for adding arrays if the future electrical demand should increase. When considering large buildings, the engineer may wish to design the PV modules directly into the building skin as facade elements where the surface area for the arrays is limited to the surface area of the building exterior. At the current state of PV system efficiency, the built in facade PV system cannot produce the total amount of power required by a large facility in most cases and is therefore supplemental to the main power grid. The system efficiency or conversion efficiency refers to the proportion of solar radiation that the cell can convert into electrical energy. The early PV cells were 1-2% efficient with today's commercially available PV cells being 7-20% efficient. The main focus in PV research is devoted to developing more efficient cells more economically[2].

1.5 Types of PV Cells

The most commonly used material for commercial PV cells today is silicon. Because of its high degree of distribution, second only to oxygen. It must be refined 99.9999% pure in order to be useful. The two categories suitable for PV cells are Thick Crystalline solar cells and Thin-Film solar cells[5].

1.5.1 Thick Crystalline Solar Cells

Single Crystalline Materials

Single-crystal silicon or monocrystalline cells are sliced from single-crystal boules of silicon grown from a single crystal with uniform molecular structure. These silicon cells referred to as wafers are cut as thin as 200 microns making them ideal for transferring electrons through the material. Laboratory cells demonstrate close to 29% efficiency which is the theoretical limit of silicon. There are available on the commercial market today monocrystalline cells with an efficiency of 20%[9].

Polycrystalline Materials

Polycrystalline silicon wafers are produced from blocks of cast silicon. Efficiency is slightly less than that of single-crystal wafers because these types of cells are cut from several small crystals or "grains" which introduce boundaries. The boundaries impede the flow of electrons. Research cells approach 18%, whereas commercial modules are approximately 14% efficient. However, polycrystalline wafers are more widely used in industry because the production cost for this type of cell is more economical than that of the single-crystal cell and researchers are working on ways to minimize the effect of grain boundaries.

Gallium Arsenide (GaAs)

Gallium Arsenide (GaAs) is another type of Thick Crystalline material which is often used in high efficiency space ststems. It is a III-V semiconductor material. Multijunction cells based on GaAs have exceeded 30% efficiency[9]. But, they are very expensive to produce and at this time are not now a practical option for commercial buildings.

1.5.2 Thin Film Solar Cells

Thin film solar cells are being developed for the commercial market which use less material and are more economical to produce than the thick crystalline materials. However, the thin films are not as efficient at the present time.

Amorphous Silicon (a-Si)

The major work in thin film technology since 1974 has been with Amorphous Silicon (a-Si). A-Si cells accounted for more than 15% of the worldwide PV production in 1996. These cells are produced with a p-i-n design in which an intrinsic layer is placed between a p and n type layer. Amorphous silicon has unique properties which allow the cells to be designed with an ultrathin p-type top layer (0.008 micron) bonded to a thicker intrinsic layer generally ranging from .5-1 micron and a thin n-type bottom layer approximately 0.02 micron is added. The top layer is made so thin and transparent that most incident light is allowed to pass through where it generates free electrons in the intrinsic layer. The cell n type layers create an electric field across the entire intrinsic region to induce electron movement in that region. Experimental efficiencies with thin film have yielded efficiencies over 10% but in actuality this initial value is reduced approximately 30% by a light induced instability known as the Stabler-Wronski effect which occurs over the first 6 weeks of life. Commercial modules being used in the field have efficiencies in the range of 5-7 percent. Amorphous Silicon technology shows great promise for use in building integrated systems. Thin film semi-transparent a-Si panels can replace tinted glass glazed into the building facade giving the additional advantage of being a weather shield as well producing electricity that reduces the break-even point for the system[8].

Cadium-Telluride (CdTe)

Advanced manufacturing techniques show promise for low cost PV cells using CdTe with laboratory efficiencies in the order of 15 percent and commercially produced cells in the range of 7-8%[9].

Copper-Indium-Diselenide ($CuInSe_2$ or CIS)

The research efficiency for this type of thin film polycrystalline material in 1996 was 17.7 percent with a prototype module boasting an efficiency of more than 10%. But, difficulties in production must be surmounted before these types of panels can be commercially viable.

1.6 Types Of Photovoltaic Systems

There are basically 2 types of PV systems, free standing and grid connected. The main difference being how the electricity is stored and how the system is guarded against fluctuating power. A grid connected system is tied into the local power grid and which becomes the storage medium. Free standing systems require storage batteries and frequently a backup generator is installed to insure continuos power. Building integrated systems have an economic advantage over non integrated systems by becoming an element in the building envelope, replacing conventional facade or roof materials. A high end building facade will often cost as much or more than PV modules. This reduces the break-even point to an immediate or short term pay back for the system and a PV facade can be designed to provide passive solar control through shading which further reduces the break-even point by reducing the facilities cooling costs.

1.6.1 Stand Alone System

Free Standing systems are the most prevalent today. Their high reliability and low maintenance make them ideal for unattended sites. Applications include power for remote homes and cabins, telecommunication stations, water pumping navigational aids and satellite power. It is often more economical to install a PV free standing system than to extend the Power grid to the site. Over 25 MW of free standing PV systems have been installed in the US. It is estimated that the cost of extending power lines in nonurban areas ranges from $20,000-$80,000. Considering the cost advantage of free standing systems versus power grid extension for the average single-family home requiring a 1-2 (kW) PV system costing approximately $12,000/kW installed. Once the system is paid for there are no further utility bills[5].

PV systems have become the power system of choice for telecommunication repeater stations on mountaintops and other remote locations worldwide, often replacing unreliable, high maintenance diesel generators.

The largest disadvantage to the PV free standing systems is caused by the variable nature of the PV fuel supply, the sun. In order for the system to be reliable for worst case situations the system needs to exercise one of 2 options. First, an oversized array with extensive battery storage banks can be installed, an expensive option. The second option being to design a hybrid system. This system may include a backup generator, or some other type of sustainable energy source. Often PV systems are combined with wind turbines because often the available wind energy is high at the times when solar radiation is low.

1.6.2 Grid-Connected Systems

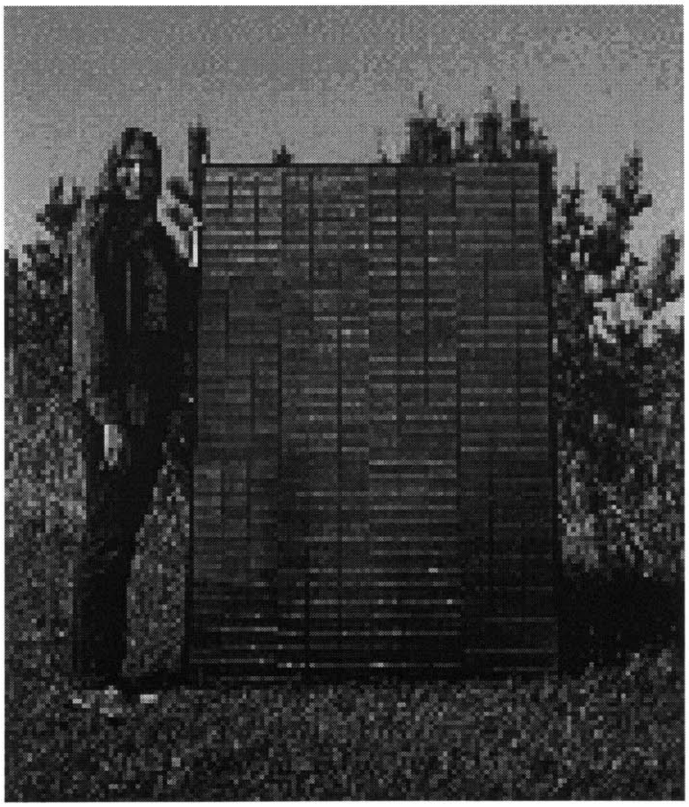
A PV system may be connected to the public grid through the use of a power inverter. The power inverter is necessary to convert the direct current electricity produced by PV modules into alternating current electricity at the voltage level as is used in utility power grids. The electricity fed back into the grid is bought back by the local power company. Forming a partnership of sorts . Some utilities, in an effort to promote PV use buy back the power at a higher price than their prevailing rate. In other locations a one to one ratio where the price per kWh is the same in both directions of flow is used. An example of a progressive partnership between a local utility and PV users can be found in Southern California. The Sacramento Municipal Utility District (SMUD), has implemented grid-connected PV programs to capture distributed generation benefits, testing new business opportunities and increasing grid-connected PV commercialization. As of spring of 1997 the SMUD has placed over 5 MW of distributed PV generation on its system expecting to add in excess of 11 MW from 1997 to 2002[5].

To truly gain widespread use, grid connected systems must be able to compete on an economic level with the cost of conventional power. Efficiencies must rise, costs for the systems must decrease and the systems must be utilized in the most productive manner. PV systems are most cost effective when the utility load and solar resource profiles are well matched. This would be the case where the cooling loads peak and of peak solar radiation coincide.

Chapter 2

The Availability of Solar Energy

Large PV panel Developed for integration into Buildings [22]



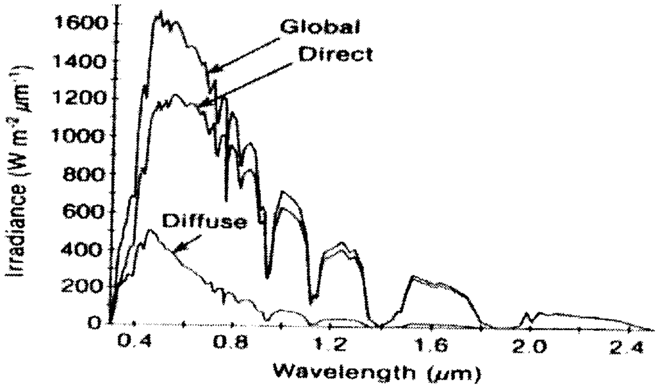
2.1 The Sun

The sun is the origen of all energy on Earth, providing all the energy required by natural global systems and cycles. The diameter of the sun is 1.39x10^9 and is 1.5 x10^{11}m from earth or about 12 times the earth's diameter away. The earth revolves around the sun in a slight elliptical orbit with the sun being located at one focus of the ellipse. The elliptical shape is nearly round with a major axis of 1.4968x10^8km, a semi-minor axis of 1.4966x10^8 and an eccentricity of 0.0167. This means that the epogee as opposed to the apogee of the earth as compared to the sun, varies by 1.7%. The sun is basically a sphere comprised of intensely hot gaseous matter with a black body temperature of 5777K that emanates huge amounts of radiation into space[2].

A constant amount of fixed intensity radiation envelopes the outer atmosphere of the earth and is known as extraterrestrial radiation. The World Radiation Center determines' that the level of extraterrestrial radiation at the outer edge of the earth's atmosphere is equal to 1367 W/m^2 with an uncertainty of 1%. Solar radiation entering the earth's atmosphere is subjected to two phenomenon, atmospheric scattering by air molecules and dust, and atmospheric absorption by O_3, H_2O, and CO_2 , which reduce the amount of radiation penetrating to the surface (incident radiation). These 2 phenomenon also serve to absorb and reflect most x-rays and ultraviolet rays. The total amount of incident radiation at the earth's surface can be divided into 2 distinct parts, direct and diffuse. The direct radiation results from direct sunlight, whereas the diffuse radiation is always available. Diffuse radiation in some instances contributes significantly to the total incident radiation.

Figure 2.1 [6]

Solar Radiation



Diffuse radiation contributes as much as 40% of the total during the summer months and 80% during the winter, in the US, and the seasonal changes are a result of the tilt of the earth on its axis[4]. These changes have larger effects on available radiation in areas at higher latitudes (degrees north or south from the equator). Therefore annually available global radiation may vary by a factor of 2.5 from year to year. The clearness index is the ratio of total incident radiation as compared to the extraterrestrial radiation. Figure 2.2 demonstrates the clearness index, and percent of diffuse radiation for variable weather conditions.

Table 2.1 [2]

Clearness Index

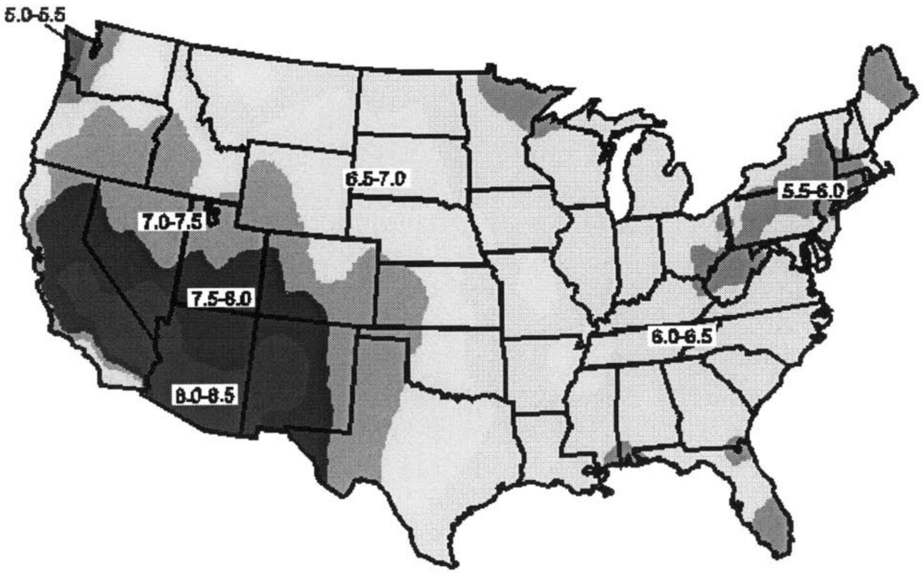
Weather Conditions	**Clearness Index** (incident/1367) x 100%	**Diffuse part of Radiation**
Very Clear Day	44% - 73%	10% - 20%
Misty... partial Sun	14% - 29%	20% - 80%
Cloudy Day	3% - 11%	80% - 100%

The amount of energy that comes into contact with the surface of the earth each minute is greater than the amount of energy that the entire population uses in one year. When the sunlight reaches the Earth's surface it is not evenly distributed with the areas near the equator receiving more radiation than those towards the poles. The quantity of solar radiation striking the earth varies by region, season, time of day and other factors. Figure 2.3 shows the variation of energy, in kWh/m^2, striking the US on an average June day.

Solar energy incident on our planet is the only continuous source of exergy. Exergy is the valuable part of energy and is irreversibly transformed into anergy, the less useful portion of energy, during each transformation process. The use of solar radiation instead of fossil fuel combustion means saving exergy that was stored over a time period of thousands of years instead of consuming it within a couple of hundred years.

Figure 2.2 [26]

U.S. Solar Zones

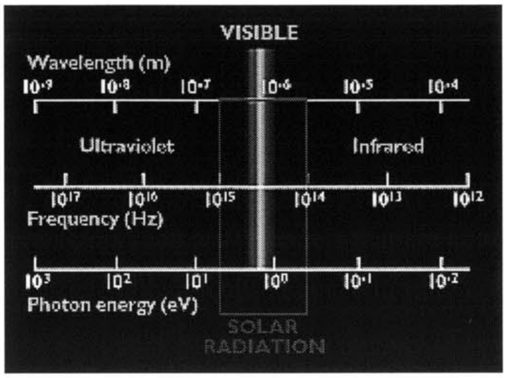


2.2 The Nature of Solar Energy

Over 95% of the suns energy is released as visible light. These light waves are generated in a wavelength spectrum ranging from $2\text{x}10^{-7} - 4\text{x}10^{-6}$m[6]. Each wavelength corresponds to a particular frequency and energy level. The shorter the wavelength, the higher the frequency and the energy level, correspondingly the longer the wavelength the lower the frequency and energy level. Red light, for example, has a long wavelength and low energy level, whereas violet light has a short wavelength and corresponding high energy level. Figure 2.4 shows the relationship between wavelength, frequency, and energy and shows where in the spectrum solar energy exists.

Figure 2.3 [13]

Solar Radiation Spectrum



2.3 Factors Affecting Solar Energy Availability

There are 7 primary factors affecting the amount of energy available to the designer of a PV building system.

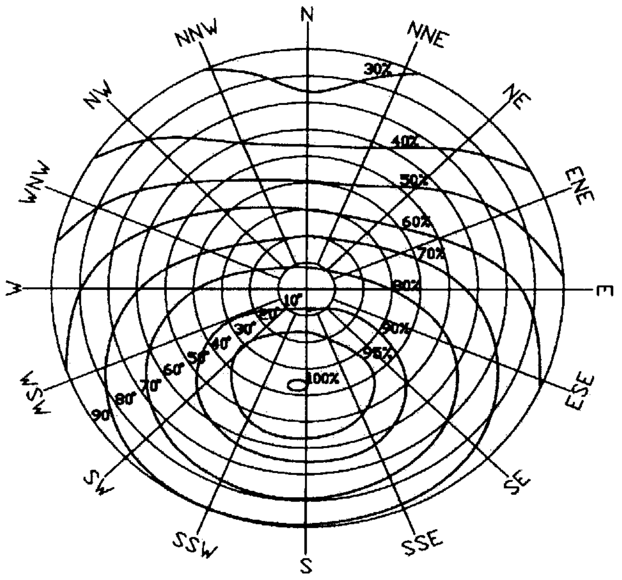
1. Geographic Location- more radiation is available nearer to 0 latitude. Generally, there is more solar energy available in sunny regions as opposed to cloudy or rainy areas and the available solar energy increases slightly with increase in altitude.
2. Site Location of the Collector- Collectors should be placed in direct sun light as opposed to areas shaded by building or trees.
3. Time of Day- More radiation is available during sunlight hours especially during the part of the day when the solar angle is greatest.
4. Time of Year- More radiation is available in summer as opposed to winter due to the inclination of the earth's axis.
5. Atmospheric Conditions- More Solar radiation is available on sunny days
6. Collector Design- Solar collectors such as PV panels that are able to utilize both direct and diffuse radiation are more efficient than focused concentrating collectors.
7. Collector Orientation- In order to take maximum advantage of solar energy the orientation of the PV modules is an extremely important consideration. The intensity of solar radiation is maximum when a flat surface is tilted normal to the suns rays. Therefore the intensity that a

PV panel receives is a function of both its slope or tilt angle, measured from the horizontal, in relationship to the solar incident angle, and the azimuth from due South. The earth sun vector moves in an ecliptic plane and the solar incident angle is the angle formed between the horizontal and the PV panel. The azimuth measured from due south can be expressed as follows: due south = 0°, due east=-90°, due west=90°, North=180°or -180°.

Figure 2.5 demonstrates how solar intensity is related to slope and azimuth. There is a large range of inclinations that will allow flat panels that are oriented in a southerly direction allowing absorption of over 90% of the available incident radiation. Designers of PV systems for buildings have a large degree of flexibility in the design of the building skin.

Figure 2.4

Effect of Tilt Angle and Orientation



Effect of slope (tilt angle) and azimuth (orientation) on the annual incident energy in Central Europe (© Ecofys)

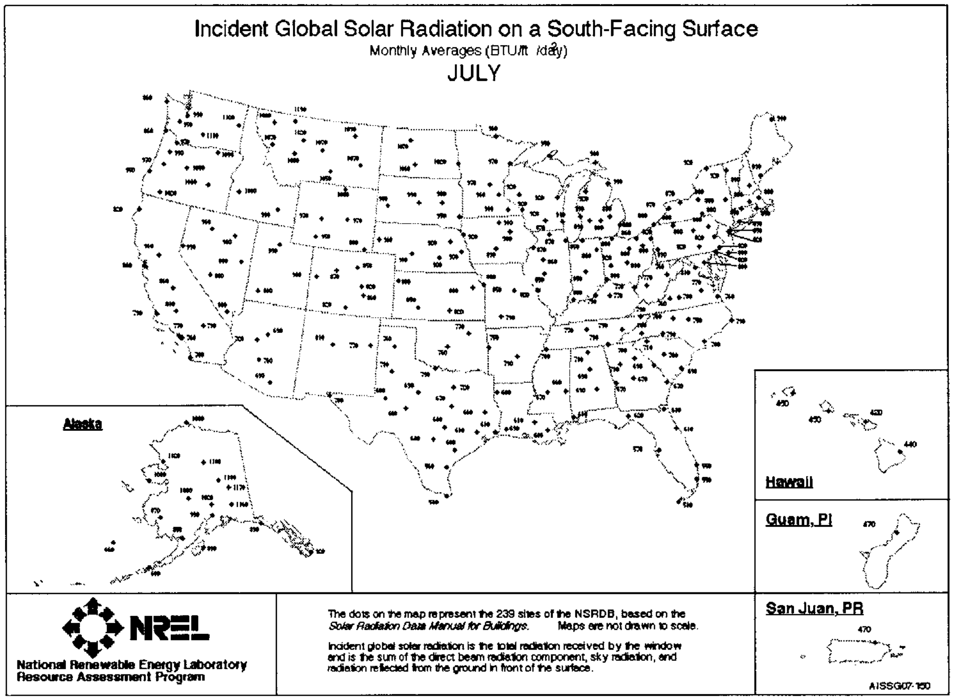
2.4 Calculations for Solar Availability

2.4.1 General Calculations

Solar energy is a variable energy source but can vary dramatically from one year to the next.. The amount of energy that any PV system can generate is directly dependent upon the amount of solar radiation available. To calculate the amount of solar radiation that a particular PV module will be exposed to is by utilizing data that has been accumulated for the nearest locations at which the system is to be installed. Starting with a value for total incident radiation and adjust these values to compensate for less than ideal slope and azimuth configuration. The primary source of data for areas inside the US is the Solar Radiation Data Manual for Buildings published by the US Department of Energy (Available free of charge online at (http://rredc.nrel.gov/solar/pubs/bluebook/). This manual uses data collected over a 30 year period, from 1961-1990, at 239 stations located in the US and its territories, giving solar radiation and illumination values to enable quick estimates of the incident solar energy for common window orientations. The solar radiation and illuminance values were computed using models and National Solar Radiation Data Base hourly values for direct beam, global horizontal and diffuse horizontal solar radiation and dew point temperature.

Figure 2.5 [15]

Example of Solar Radiation Availability Map



The dots on the map represent the 239 sites of the NSRDB, based on the *Solar Radiation Data Manual for Buildings*. Maps are not drawn to scale.

Incident global solar radiation is the total radiation received by the window and is the sum of the direct beam radiation component, sky radiation, and radiation reflected from the ground in front of the surface.

More accurate estimates of solar availability, which account for variable azimuth and slope of PV arrays, can be calculated by estimating the total available incident radiation, I_T , at the location of the PV system and applying a weighted average to the values obtained from the three closest observation stations. Three stations should be sufficient due to the large distances between stations. Designers must also take into account altitude at the target area. Since solar radiation increases as distance above sea level increases, a designer should be careful not to include values from observation stations in the analysis that vary significantly in altitude from the site of the proposed PV system. One weighting average approach is the inverse distance squared technique, which assigns more weight to the closer observation stations[7].

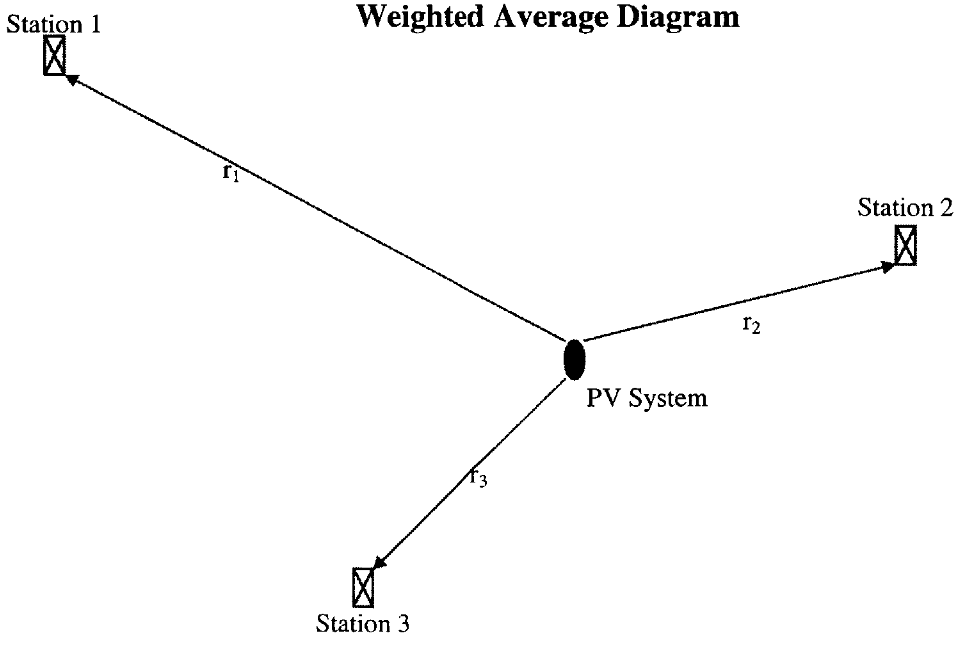
$$I_T = (W_1)(I_{T1}) + (W_2)(I_{T2}) + (W_3)(I_{T3})$$

where: W_i = weighting factor

$$W_i = \frac{\left(\frac{1}{r_i}\right)^2}{\sum_{j=1}^{3}\left(\frac{1}{r_j}\right)^2}$$

Example 2.6

Weighted Average Diagram



where: r = the distance from the PV system to the observation station

r_1=300 km, r_2=200km, r_3=100km

I_{T1}=1.0kWh/m^2, I_{T2}=0.7kWh/m^2, I_{T3}=0.9kWh/m^2

$$W_1 = \frac{\left(\frac{1}{300}\right)^2}{\left(\frac{1}{300}\right)^2 + \left(\frac{1}{200}\right)^2 + \left(\frac{1}{150}\right)^2} = 0.138 \qquad W_2 = \frac{\left(\frac{1}{200}\right)^2}{\left(\frac{1}{300}\right)^2 + \left(\frac{1}{200}\right)^2 + \left(\frac{1}{150}\right)^2} = 0.310$$

$$W_3 = \frac{\left(\frac{1}{150}\right)^2}{\left(\frac{1}{300}\right)^2 + \left(\frac{1}{200}\right)^2 + \left(\frac{1}{150}\right)^2} = 0.552$$

Check: $0.138 + 0.310 + 0.552 = 1$ OK.

Answer: $I_T = (0.138)(1.0) + (0.310)(0.7) + (0.552)(0.9) = 0.752 \frac{kWh}{m^2}$

The following quantities will be necessary for the purposes of estimating the solar availability:

Solar Declination Angle:

The plane containing the earth's elliptical orbit is called the "ecliptic plane. The equatorial plane contains the earth's equator. The angle between the earth-sun vector and the equatorial plane is the solar declination angle, δ, which is positive when the earth-sun vector points northward relative to the equatorial plane.

$$\delta = \sin^{-1}\left[0.39795 \cos\left(0.98563(N - 173)\right)\right]$$

where: N = number of the day from 1 to 365

Solar Altitude Angle, α = angle of the suns rays measured from horizontal

$$\alpha = \sin^{-1}\left[\cos L \cos\delta \cos h_s + \sin L \sin\delta\right]$$

where: L = latitude, taken positive north of the equator

h_s = hour angle (unit of angular measurement of time)

positive before solar noon and negative after solar noon

h_s = (hours away from solar noon) x h

24h=360° h=15°/hour

example: $h_s|_{8am} = (12\text{-}4) \text{X } 15 = +60°$

$h_s|_{9pm} = -(9) \text{ x } 15 = -135°$

Solar Azimuth, A_s = number of degrees a panel is rotated from due south

$$A_s = \begin{cases} \sin^{-1}\left(\dfrac{\cos\delta \ \sin h_s}{\cos\alpha}\right) & \text{for } \cos h_s \geq \dfrac{\tan\delta}{\tan L} \\ 180°\text{-}\sin^{-1}\left(\dfrac{\cos\delta \ \sin h_s}{\cos\alpha}\right) & \text{for } \cos h_s \leq \dfrac{\tan\delta}{\tan L} \end{cases}$$

Solar Time

Since a solar day is 3.95 minutes longer than 1 complete rotation of the earth about its axis, it is necessary to use solar time when calculating incident radiation.

$$SolarTime = LST - EoT - LA$$

LST=Local Standard Time

Eot=Equation of Time

LA=Longitude Adjustment = [(Local Longitude-(Longitude of Local Time Meridian)]/15

$$Eot = 12 + (0.1236\sin x - 0.0043\cos x + 0.1538\sin 2x + 0.0608\cos 2x)h$$

$$x = \frac{360(N-1)}{365.242°}$$

Sunrise and Sunset

Sunrise and sunset occur when the solar altitude angle = 0

$$h_{sr} = \cos^{-1}(-\tan L \tan\delta)$$

$$Sunrise\ in\ Solar\ Time = \frac{h_{sr}}{15}$$

$$Sunset\ in\ Solar\ Time = -Sunrise$$

Maximum solar altitude angle occurs at the median time between sunrise and sunset

2.4.2 Intensity Calculations

The total intensity of incident solar radiation on a surface perpendicular to the solar altitude angle , I_T, can be broken into Intensity from direct radiation, I_B, and intensity from diffuse radiation, I_D. The example values given for I_{ext}, w, and m_o in the following table are for the Boston MA area. Values for other areas may be obtained in reference 1.

Note: The following intensity calculations are for instantaneous intensity. To calculate average daily values, these intensity calculations must be integrated from sunrise to sunset.

$$I_T=I_B+I_D$$

For direct radiation under clear skies, I_B is equal to:

$$I_B = I_{EXT}\exp\left[-0.1457\left(\frac{pm_o}{1000}\right)-0.1617\left(wm_o\right)^{0.25}\right]$$

where: I_{EXT}= extraterrestrial Solar Radiation
p= local atmospheric pressure in millibars
m_o= sea level air mass
w=atmospheric water vapor content in centimeters

Table 2.2 I_{EXT} [4]

The Intensity of Extraterrestrial Solar Radiation on the 21st Day of Each Month (kWh/m^2)

Date	21-Jan	21-Feb	21-Mar	21-Apr	21-May	21-Jun	21-Jul	21-Aug	21-Sep	21-Oct	21-Nov	21-Dec
Intensity	1.41	1.40	1.38	1.36	1.34	1.33	1.33	1.34	1.36	1.38	1.40	1.14

Table 2.3 m_o [4]

Optical Air Mass at Sea Level

zenith angl z	0	30	60	70	80	85	86	87	88	89	90
air mass, m	1	1.15	2	2.92	5.63	10.69	12.87	16.04	20.87	28.35	29.94

Table 2.4 w [4]

Mean Monthly Values of Total Precipitable Water for Clear Sky Conditions (centimeters)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Boston MA	0.74	0.7	0.84	1.16	1.63	2.23	2.60	2.51	2.14	1.53	1.16	0.84

For a tilted surface, the intensity, I_{BT} and I_{DT} must be adjusted for.

$I_{BT} = I_B \cos i$

where i= $\cos\alpha\cos A_s\sin$(surface tilt angle) + $\sin\alpha\cos$(surface tilt angle)

$I_{DT} = 0.5(1+\cos\beta)I_D + 0.5(1-\cos\beta)\rho I_T$

where: $0.5(1-\cos\beta)\rho I_T$ account for reflective qualities of the ground

Typical values for ρ:

0.1-0.2 terrain clear of snow cover

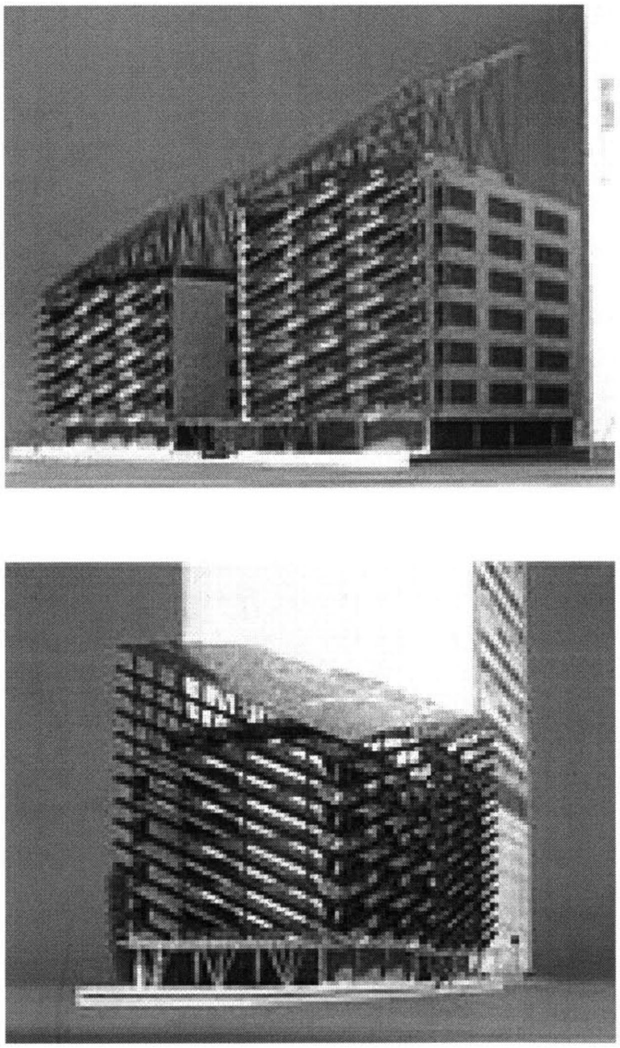
0.7 complete snow cover

β = surface tilt angle

Chapter 3

PV System Components

Roof and Façade Integration of 2 Office Buildings in the Hague [25]



3.0 Introduction

A complete photovoltaic system is comprised of 3 subsystems, the PV generator, the Balance of the System (BOS) and the intended load. The PV generator consists of the modules and arrays which produce the electricity. The BOS are the installed devices which allow the electricity produced by the PV generator to be applied to the load, including mounting structures for the PV arrays, which will be discussed in a later section, energy storage components and power-conditioning equipment.

3.1 Photovoltaic Generator

The PV generator is the portion of the PV system which converts solar energy into electricity. This portion of the system includes strings(modules connected together in series) of PV modules and arrays as well as the components necessary to connect them.

3.1.1 PV Modules

PV modules are the components of the system that actually convert the energy from the sun into usable electric energy. The current of the plant is determined by the number of modules that are connected in parallel, whereas the voltage is determined by the number of modules connected in series. A typical silicon solar cell, in full sunshine, with a surface area of 100cm2 provides a current of 3amps and 0.5V. PV systems that were designed to charge 12V batteries would commonly be designed with a maximum capacity of 13-15V. This system would require 30 to 36 cells connected in series providing a peak power output of approximately 50W. Grid systems for buildings have been constructed with power capacities as high as several thousand kW. The maximum voltages for these systems may be as high as 500-1000V. These building integrated systems have been constructed using specialized large area modules with surface areas up to several m^2 and peak power output of several hundred watts[2].

Standard PV modules are normally installed within structural aluminum frames which allows them to be easily mounted on the side or roof of a building. Special laminate modules have been developed for integration into the building façade and have been designed free of the structural aluminum frame and can be mounted into the façade using the exact same glazing procedures that are used for mounting glass panels. PV tiles have been constructed for roof integration using a combination of old and new technology and have been designed to visually represent conventional roof types.

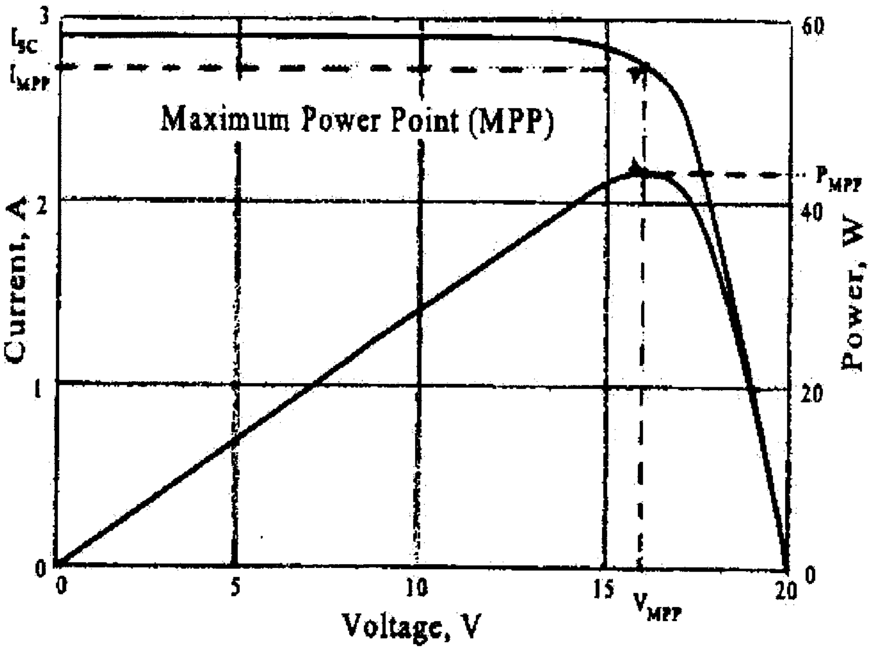
To compare PV modules standard test conditions (STC) have been established and are as follows:

- Irradiance = 1000W/m^2
- Air Mass = AM1.5
- Cell Junction Temperature = 25° C

PV panels are generally compared on the basis of Open circuit voltage, V_{oc}, short circuit current, I_{sc}, nominal power P_n and the maximum power point, MPP. Figure 3.1.1 shows the relationship between these quantities.

Figure 3.1 [2]

Current v. Voltage Diagram



Open Circuit Voltage, V_{oc}

Open circuit voltage V_{oc} is temperature dependent, decreasing with increasing temperature. A standard devaluation formula is to decrease V_{oc} by 0.0022V/K for every degree change above STC. The opposite condition also exists. One can expect the V_{oc} to increase at a corresponding rate when the temperature falls below STC.

Short Circuit Current, I_{sc}

A unique characteristic of PV cells is that the short circuit current is only slightly higher than the operational current. As the temperature increases there is a small increase in short circuit current, 0.07%/K.

Nominal Power, P_n

Nominal power is commonly referred to as peak power, W_p, having corresponding voltage V_n, and current, I_n.

The nominal power that a module can produce is required to be written on each module and the manufacturers specification plate is usually mounted on the back side of the module.

Maximum Power Point, MPP

The MPP is the operating point on a current-voltage curve where the maximum power is produced, with silicon cells producing approximately 0.45V. Since free standing systems will not always be operating at peak efficiency due to overcast weather conditions, dirty cells, etc., it is important to design the systems with V_{MPP} exceeding the battery requirements by 1.5V.

Note:
As of yet there is no standardized form or method to report the PV module specifications. Figure 3.1.2 shows a sample data sheet.

Table 3.1 [16]

Module Specifications

Module Specifications for XYZMOD	
Electrical Specifications	
Short Circuit Current, Isc	3.3A
Open Circuit Voltage, Voc	21.3V
Current at Peak Power, Impp	3.0A
Voltage at Peak Power, Vmpp	16.7V
Maximum Power Oupput at 1000W/m62 and 25degrees C	48.6W
Variation(spread) +-10%	0.0022V/K/cell
Voltage decrease with temperature increase	
Mechanical Specifications	
Front Cover	Low Iron tempered glass
Encapsulant	Ethylene Vinyl Acetate (EVA)
Backing	White Tedlar
Solar Cells	100mmX100mm square cells 36 in series
Edge Sealant	Butyl rubber
Frame	Silver anodized structural aluminum
Termination	Waterproof junction box
Electrical Isolation	300 VDC 10 microamps (TYP)
Weight	6.2 kg
Environmental Conditions	
Ambient Temperature	(-)40degC to 90degC
Wind Loading	mav. 80km/h
Reletive Humidity	0 to 100%

3.1.2 Issues affecting PV Generators

As seen in chapter 2 , there is a wide range of orientations which can be used on southerly facing modules that will utilize upwards of 90% of the available solar radiation. Factors independent of orientation that reduce the power output of PV generators including, module temperature, shading of cells, mismatch of string modules and module soiling.

Shading

Even small shadows can severely decrease the power output. The cell in the module with the lowest degree of exposure to solar radiation determines the operating current for the entire string. If one thinks of electrical flow as water flowing through a hose, a shaded cell is analogous to a restrictive kink in the hose. The volume of water flowing from the far end cannot exceed the volume of water flowing through the restricted area. Cells, which are partially shaded, will have current reductions proportional to the shaded area. Adding bypass diodes that provide an alternate path for the current to flow can reduce the problems caused by shading.

Module Mismatch

In cases where modules with different I-V curves are connected in series, the module with the least ability to generate current will determine the current for the entire string.

Temperature Control

To avoid module heat up and a corresponding reduction in efficiency, modules should be freely vented. This normally can be accomplished by leaving a 10cm air space at the front and back faces of the panels.

Module Soiling

Dust that accumulates on the face of PV panels can be responsible for significant power reduction, in some cases exceeding 10%. Panels that are inclined at angles greater that 15degrees from horizontal, reach a steady state between dust accumulation and self cleaning within a few weeks after installation.

Safety Concern

It is worth noting that unlike other electrical generators, PV modules can not be turned off. As long as a module is illuminated it will produce electric current. When working on PV systems appropriate safety measures must be used.

3.1.3 PV Generator Connectivity

The electrical components necessary to regulate the electricity produced by the PV panels include, bypass and blocking diodes, fuses, cables, connections, circuit breakers and overvoltage protection devices.

Bypass Diodes - These are usually installed in PV strings with open circuit voltages exceeding 30V. They provide alternate paths for current to travel in strings that have been blocked or restricted by shaded or defective cells.

Blocking Diodes - In the event of ground faults or short circuits, blocking diodes prevent the destruction of cables and modules by preventing current from flowing backwards in a string.

Fuses - These are used if a large number of strings are connected in parallel. Thereby protecting cables from over-current.

Cables - Cable size is determined by the allowable voltage drop along the string at nominal current. The cables must be double insulated and UV protected.

Connections - There are a large number of module connections in any building PV system. Improper connections can render individual modules ineffective and significantly reduce the efficiency of the entire system. Union connectors have been developed which make module installation and subsequent replacement easy and efficient.

Overvoltage Protection Devices - Surge arrestors with a minimum of 5kA peak ratings should be incorporated into the system to protect inverters and bypass or blocking diodes.

Circuit Breakers - Circuit Breakers should be installed between the PV generator and the inverter or charge controller. They must be rated for the system nominal short circuit current and open circuit voltage and for direct current.

A PV system designer must provide locations for connective components in the formof junction boxes. The junction boxes should be weather resistant and located so as to be easily accessed for inspection and maintenance.

3.2 Balance of the System (BOS)

The BOS are the devices that allow the electricity produced by the PV generator to be applied to the load. They include mounting structures for the PV arrays, which will be discussed in a later section, energy storage components and power-conditioning equipment.

3.2.1 Energy Storage

The need for energy storage is due to a temporal discrepancy between electrical production and electrical load demand. Therefore, a medium is required for storing the energy produced until it is needed. For a freestanding system this is accomplished by banks of batteries. Either, Lead-acid (Pb-acid) or Nickel/Cadmium (Ni/Cd) batteries are used. The limitations inherent in these batteries in the areas of energy density, cycle life temperature of operation and their high level of toxicity have caused researchers to try to develop more efficient energy storage systems. Typically, the "weak link" in a free standing system is the energy storage component. However, the scope of this discussion is limited to large scale structures which have access to a local utility grid. For grid connected systems, electricity produced in excess of the instantaneous load requirement is diverted by means of an inverter into the local utility grid.

3.2.2 DC Power Conditioning

PV generators produce DC currents and voltages which can be used in several different ways, directly by DC devices, stored in batteries or converted to Ac power and fed into the local electric utility grid. Power-conditioning units are needed for each of these options. The various types of power conditioning units include DC to AC converters (inverters), matching DC/DC converters or charge controllers. For grid systems only inverters are required.

Inverter

PV systems that are tied into the local electrical utility grid by a utility interactive (also called a line-tied) inverter becomes part of the utility system. The inverter is the interface between the PV generator and the utility grid with its primary function to convert the DC electricity produced from the PV generator to AC electricity which integrates smoothly with the voltage and frequency characteristics of the utility generated power present on the distribution line. The inverter serves as the system control. The utility prevailing line frequency is used as the control parameter and the operating voltage of the PV generator is synchronized accordingly. The control algorithm should be designed to protect against earth fault on the DC side and abnormal utility conditions on the grid side. The inverter should switch itself off in the event of overheating and at night.

Line-tied inverters equipped with Maximum Power Point Tracker units(MPPT units) that allow the inverter to adjust for solar array variances due to module temperature, shadowing, etc., and extract the maximum power from the PV generator. The MPPT unit varies the input voltage until the maximum power point on the module I-V curve is found. This process is repeated at a minimum of once every 1 to 3 minutes and overall conversion efficiency for the converter should be greater that 92%[2].

Before specifying a specific inverter for a PV system the local power utility should be consulted for specific power conditioning requirements.

Information to be obtained from the inverter manufacturer:

- Cost
- Array Compatibility - number of modules per string power tracking capability
- Utility compatibility - power quality, harmonics, power factor, etc.
- Energy Performance - weighted average efficiency
- Warranty provisions
- Maintenance and repair specifications

Site Information Needed:

- PV system size - kW_{peak}
- Electrical Environment - DC voltage, local safety code requirements, phase
- Physical environment - humidity, dust, temp, noise
- Utility connection requirements

Recommended inverter specifications:

- High conversion efficiency > 92% for $P/P_n > 0.1$

- Low start-up and shut-down thresholds
- Power Factor > 0.85
- Low total harmonic distortion of output current
- Maximum power point operation
- No shut-down if the array power exceeds rated power: ->current limiting function
- Low power consumption at night
- Automatic disconnect at utility fault conditions
- Automatic restart after fault is cleared
- AC-ripple of array voltage < 3%
- Low level of audible noise
- Low level of RF-emissions measured on AC and DC side, VDE 871B(1.1.1996)
- Fan cooled
- Electric isolation between AC and DC side
- Overvoltage protection on both sides
- High Availability

Chapter 4

Photovoltaic Advocates

Research Center Outer Wall-Integrated PV System Located in St. Gallen, Switzerland [22]

Introduction

PV technology must have the support of institutions that are in a position to fund development and public interest in the technology if it is to survive and flourish and eventually compete effectively with conventional power generation methods it. Practically speaking, this will have to be undertaken by the governments of countries interested in clean sustainable energy. This section will introduce the primary agencies and incentives within the U.S. which champion PV technology in buildings and will also discuss the primary international organization funding the development of PV in buildings as well as point out several PV programs incorporated in various other countries.

4.1 U.S. Government PV Programs

Responding to the oil embargo in 1973 - 74 the U.S. Department of Energy funded the Federal Photovoltaic Utilization Program. Nine federal agencies participated in the installation of over 3100 PV systems. Many of these systems are still in operation and stand as a testament to the reliability of PV systems in practical field applications. As the oil embargo ended and the price of oil dropped federal funding for alternate sources of energy began to flounder. As the end of the 1980's came around and the general population started to understand the detrimental affects of green house gasses, that are caused by burning fossil fuel on global climate change a renewed vigor for clean energy began to emerge.

4.1.1 DOE Photovoltaic Program

Today the Department of Energy(DOE) has a very active Photovoltaic Program. Their stated mission is to make photovoltaics a significant part of the domestic economy as an industry and an energy source. The Photovoltaic Program activities include supporting basic research projects and R&D collaborations in order to refine PV technology and assist the industry in becoming self-sustaining. The program will be successful when photovoltaics are able to meet a significant portion of the U.S. energy requirements. More information about the DOE Photovoltaic Program is available on the internet at http://www.eren.doe.gov/pv/program.

The DOE also operates a facility known as the National Center for Photovoltaic Research where they perform world class research focused on increasing PV efficiencies and developing PV components that are more economical to produce.

4.1.2 American Solar Energy Society (ASES)

The American Solar Energy Society(ASES) is a national organization, with its headquarters located in Boulder, Co., dedicated to advancing the use of solar energy for the benefit of U.S. citizens and the global environment. They promote widespread near and long term use of solar energy through sponsoring the National Solar Energy Conference and publishing several magazines dedicated to solar power. The ASES is active in promoting legislation favorable to renewable energy and sponsors issue Roundtables in Washington. The ASES also serves as the United States Section of the International Solar Energy Society. They can be contacted at ases@ases.org.

4.2 U.S. Initiatives

4.2.1 The Million Solar Roof Initiative

On June 27, 1997 President Clinton in a speech to the United Nations said "By capturing the sun's warmth, we can help turn down the earth's temperature". The next day Secretary of Energy Federico Pena announced the conception of the "Million Solar Roofs Initiative", which is a program designed to push PV technology and implementation. Pena states "By putting solar cells on the roof, we're going to send solar sales through the roof". The program has a goal of getting 1 million solar energy systems installed on the roofs of buildings and homes in the U.S. by the year 2010[17].

The Department of Energy plans to accomplish their million PV system goal by leveraging existing federal resources to promote solar sales and to work with local communities, businesses and utilities to find ways to expand PV use:

1. Executive order 12902, signed by President Clinton in 1994 calls for the federal government to accelerate their purchases of PV systems to be installed on federal buildings. Considering that the U.S. federal government is the worlds largest owner of buildings in the world and purchases over $3billion worth of electricity per year, an aggressive approach to outfitting their buildings with PV systems can give the market a significant boost.
2. The EPA and Departments of Energy, Defense, and Commerce can use existing federal grant programs to buy down costs to make PV systems more affordable.
3. Eight federal low interest lending programs administered by the Small Business Administration, the Departments of Housing, Urban Development and Agriculture could be tapped to make PV systems easier to finance.

The long term goal of the Million Solar Roof Initiative is to spur widespread demand for PV systems in the U.S.. Increased commercial demand will incorporate economies of scale, lowering the cost of the technology. Lower overall costs will allow American solar power companies to compete more effectively for market share in the rapidly expanding international sustainable energy market. According to recent government analysis the Million Solar Roof Incentive program is well ahead of its 2010 completion date with nearly 500,000 systems already installed or scheduled for installation.

4.2.2 Solar Buildings Program

The U.S. Department of Energy runs the solar buildings program. Their objective is to advance the development of competitive solar technologies for use in buildings and other applications, both foreign and domestic. DOE research determines that buildings consume in excess of one third of all U.S. annual energy consumption. The program uses a customer-focused strategy based on gathering information from owners, contractors, and utility companies to identify road blocks hindering PV power system application. The DOE then supports research focused on overcoming these obstacles and developing PV systems that can compete on an economic level with conventional power production.

The program also offers hands on assistance to builders in the form of technical assistance, cost-shared products and educational materials. These services are being offered in by the DOE in conjunction with their office of Building Technology, state and community programs. To find more information about the DOE Solar Buildings Project one can consult the internet at http://www.eren.doe.gov/solarbuildings/progdescr.html.

4.3 Proposed Government Incentives

4.3.1 $2000 Solar Tax Credit

In January of 1998 Vice President Al Gore proposed a $2000 tax credit to help American homeowners and businesses adopt clean energy technologies that create jobs and fight global warming. During his announcement Gore states "By cutting taxes for those who help us cut pollution-by promoting cutting-edge industries and technologies that help clean up our environment-we will meet the challenge of global warming for tomorrow, while creating new jobs for today".

The solar tax credit was part of a $6.3 billion package of tax incentives announced by President Clinton in his State of the Union Address. The mechanics of the credit work as follows: a tax credit of 15% of the cost of a rooftop solar system - up to $1000 for water heating systems, and up to $2000 for photovoltaic panels. The tax credit would apply to systems installed in 1999 and extend to the year 2005 for the PV systems.

According to Gore, solar energy use in the U.S. is expected to increase 300-fold by the year 2015. If this increased usage is realized it will cut carbon dioxide emissions by 5 million tons a year - the equivalent of taking more than 3 million cars off the road. Significant increases in renewable energy technologies also create thousands of new American jobs.

4.3.2 The Comprehensive Electricity Competition Plan

In March of 1998 The Clinton administration announced its comprehensive Electricity Competition plan. The plan is designed to give the customer choice of electric suppliers by 2003. The plan includes several provisions that benefit the Photovoltaic power generation market. First, the plan provides for a Renewable Portfolio Standard that insures 5.5% of all electricity sales include generation from renewable energy sources by the year 2010. Second, a Public Benefits Fund was established to provide matching funds for low-income assistance, energy-efficiency programs, research and development, and renewable technologies. Clinton believes that his plan will benefit both the economy and the environment.

The facts are that the U.S. has a long way to go to catch up to its European counterparts in the area of supporting renewable energy technologies. However, the previous examples are clearly steps in the right direction. As the cost of burning fossil fuels increases incorporating environmental clean up costs and health care costs there will be more incentive to produce clean sustainable energy and more penalties for polluters.

4.4 PV Buildings Outside the U.S.

4.4.1 International Energy Agency (IEA)

On a worldwide level, by far, the most active organization in supporting the development of PV technology is the IEA. The IEA was founded in 1974 and maintains its headquarters in the Eiffel tower in Paris France with 24 member countries. One of the five major goals of the IEA is to improve the world's energy supply and demand structure by developing alternative energy sources and increasing the efficiency of energy use. Collaborative programs in the various energy technology areas are conducted under Implementing agreements, which are signed by contracting parties. There are 40 Implementing agreements covering fossil fuel technologies, renewable energy technologies, efficient energy end use technologies, nuclear fusion science and technology, and energy technology information centers.

IEA Philosophy Toward Photovoltaic Power Systems

In the near future primary PV applications for member countries are expected to be for use as decentralized generators connected to the utility grid, either integrated into buildings or ground based plants to provide grid support and peak power, especially when cost reductions make widespread use practical. The Agreement's mission is to "Enhance international collaboration to make photovoltaic energy a significant energy option in the near future". Its objectives are to reduce costs, increase awareness and promote market deployment by removing non-technical barriers.

Dissemination of information concerning technology, economics and environmental impacts as well as information on design and operational performance of the PV systems and components is one of the most important functions carried out by contracting parties from the 24 participating countries. The members also verify and document technical guidelines and establish procedures for implementation in developing countries.

IEA Solar Heating and Cooling Program

The Solar Heating and Cooling Program was one of the first IEA Implementing agreements to be established. Since 1977 its 19 participating members have conducted a variety of collaborative projects in passive solar and active solar as well as PV systems, primarily for building applications. There is a total of 26 collaborative ventures or tasks started since the conception of the program and 2 Tasks that are in the process of being adopted.

Table 4.1 [16]

Solar Heating and Cooling Member Countries

Solar Heating and Cooling Program 19 Member Countries

Australia	Finland	Spain
Austria	France	Sweden
Belgium	Italy	Switzerland
Canada	Japan	United Kingdom
Denmark	Netherlands	United States
European Commission	New Zealand	
Germany	Norway	

Table 4.2 [16]

Solar Heating and Cooling Completed Tasks

Completed Tasks

Task 1	Investigation of the Performance of Solar Heating and Cooling Systems
Task 2	Coordination of Solar Heating and Cooling R&D
Task 3	Performance Testing of Solar Collectors
Task 4	Development of a Insolation Handbook and Instrument Package
Task 5	Use of Existing Meteorological Information for Solar Energy Application
Task 6	Performance of Solar Systems Using Evacuated Collectors
Task 7	Central Solar Heating Plants with Seasonal Storage
Task 8	Passive and Hybrid Solar Low Energy Buildings
Task 9	Solar Radiation and Pyranometry Studies
Task 10	Solar Materials R&D
Task 11	Passive and Hybrid Solar Commercial Buildings
Task 12	Building Energy Analysis and Design Tools for Solar Applications
Task 13	Advanced Solar Energy Buildings
Task 14	Advanced Active Solar Systems
Task 16	Photovoltaics in Buildings
Task 17	Measuring and Modeling Spectral Radiation
Task 18	Advanced Glazing and Associated Materials for Solar and Building Applications

Table 4.3 [16]

Solar Heating and Cooling Current Tasks

Current Tasks and Working Groups

Task 19	Solar Air Systems
Task 20	Solar Energy In Building Renovation
Task 21	Daylight in Buildings
Task 22	Building Energy Analysis Tool
Task 23	Optimazitation of Solar Energy Use in Large Buildings
Task 24	Solar Procurement
Task 25	Solar Assisted Cooling Systems for Air Conditioning of Buildings
Task 26	Solar Combisystems

Task 16, ‘Photovoltaics in Buildings’, has 17 demonstration projects. Several innovative PV building designs have recently been demonstrated in Task 16. The largest PV building in northern Europe and 2 innovative PV modules are demonstrating that PV modules not only supply energy, but can be integrated into the building facade to also serve as part of the weatherskin. A PV facade was installed on the south-facing elevation of the Northumberland building, located at the University of Northumbria in UK. The PV generator is rated at 39.5kWp and provides power for the University computer center. When electrical production exceeds demand the excess power is fed into the local utility grid. The PV laminate panels are integrated into the rainscreen of the building and are inclined at a 65degree angle to the horizontal. The inclined panels not only increase the overall output of the PV generator but also provide shading to the rooms below.

The Task 16 Demosite located at Ecole Polytechnique Federal de Lausanne and funded by the Swiss Federal Office of Energy was established to test and demonstrate the best methods for integrating photovoltaics in buildings. Two new pavilions were constructed there in 1995 that utilize innovative PV modules. The first demonstrates an innovative technology, flexible PV cells that are not encapsulated in glass. Thin layers of amorphous silicon alloy material are deposited on stainless steel substrates. This product has extensive architectural possibilities due to its non-glass structure. This material was used to develop a PV roof tile, which is both practical and aesthetically pleasing. The second new product is also a roofing material. Solarex Co. in conjunction with Misawa Prefabricated Homes of Japan have developed a light weight PV roof tile measuring 91cm square, with 49 cells per tile and a nominal power of 82W. The tile is light enough for easy handling yet large enough for quick mounting[2].

Some of the ongoing Tasks, which might be of interest to individuals designing PV facades for buildings, might include Tasks 22, 23, and 25.

More information about the IEA Solar Heating and Cooling Program can be seen on the internet at http://www.iea-shc.org

4.4.2 Government Incentives Outside the U.S.

Many European countries have aggressive government policies and programs involving the use of PV in buildings, which invest directly in new development and distribution methods. It may be possible through legislation to incorporate similar programs in the U.S.. Several examples follow.

Germany

In the 1980's the German government directly financed the installation of PV panels in 2000 homes. This program ended in 1992 and since that time the German utility companies have continued advancing PV use by offering customers somewhat inflated prices to buy electricity they generate using new PV systems. This allows the owners of newly installed systems to recoup much of the initial cost of the system in a short period of time. Charging all utility customers a 'Solar Levy' equivalent to about 7 US dollars per year funds the program.

Holland

The government of Holland intends to supplement the costs of installing 100,000 new PV systems in homes by the year 2010. This is similar to the U.S. program but is funded more heavily by the government.

Switzerland

In Switzerland the government and utility companies support solar projects concerning schools and office buildings. The Swiss Reinsurance Co., the worlds second largest reinsurance company, in 1997 invested $2.75M in SunLight Power a start-up company who's strategy is to develop operations in 5 countries and 3 continents whose goal is to install 1 million PV systems in the first 7 years.

Austria

The Austrian government recently launched a "solar demonstration programme" with the purpose of installing solar power on domestic and commercial buildings.

Japan

The Japanese government has incorporated their "sunshine project" that is designed to install PV panels on 70,000 homes by the year 2005 by offering "solar grants" to people who have solar panels installed on their homes.

Chapter 5

Design Options & Considerations

German Presidential Office Building Berlin [22]

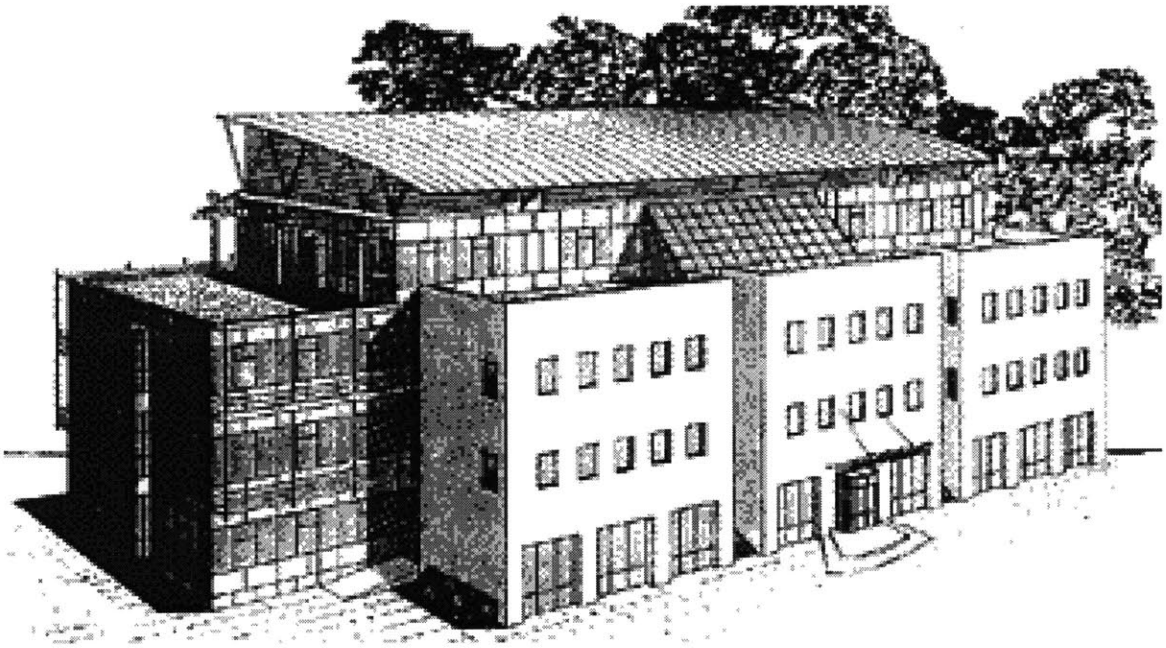
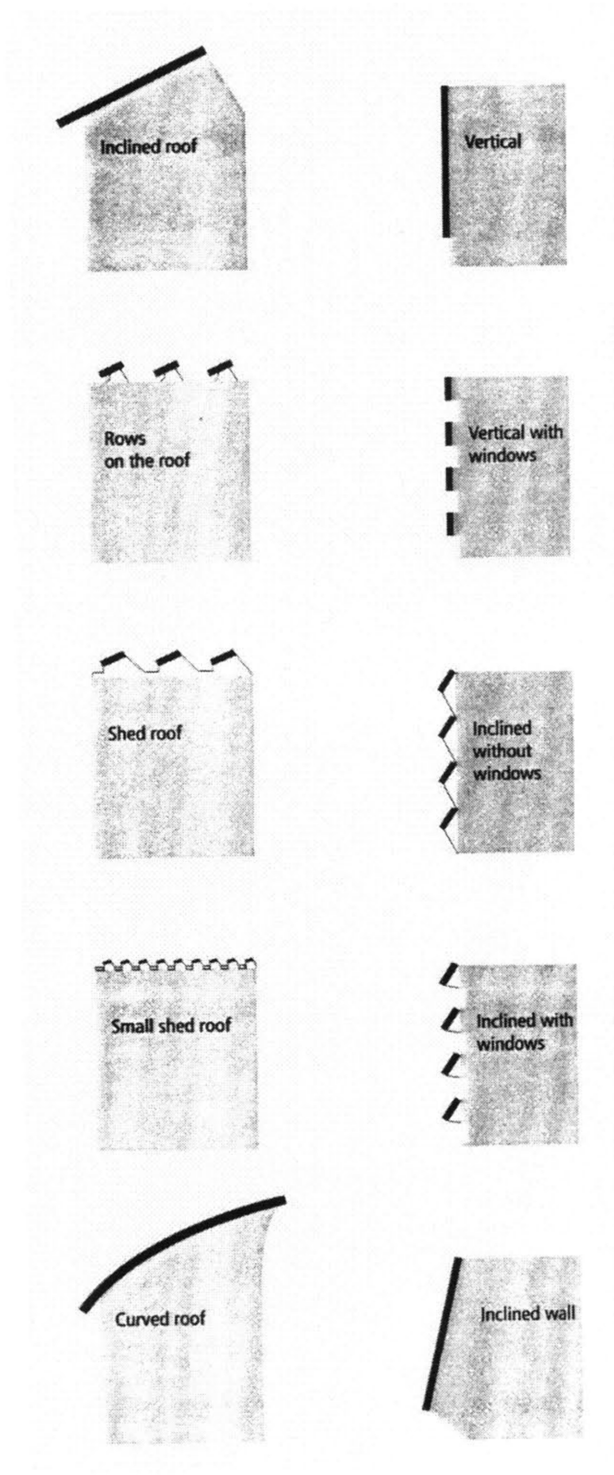


Figure 5.1 [2]

PV Envelope Configurations



Introduction

Integration of PV systems into buildings requires a multidisciplinary approach. Input may be required from electrical, HVAC and structural experts. The designer must also rethink conventional design alternatives taking into consideration new framing techniques and mounting systems that may better accommodate the PV power generation system. Conventional dimensions for the PV panels may need to be modified For optimum efficiency. The primary objective for any PV system is to maximize the system's power output, by considering the location of the facility, the orientation of the building and the available surface area to which panels can be affixed. The design must also consider non-tangible factors such as aesthetics, and social, economic, environmental, energetic, and ecological impacts.

5.1 Design Considerations

The primary design considerations common to all PV systems are location, orientation, and available surface area on which the panels can be installed. A PV system is sized by making assumptions concerning the efficiency of all key components and utilizing averaged weather data for available solar radiation to achieve calculated results. Also, significant rises in elevation can result in significant increases in available solar radiation.

Orientation- Predominantly south facing structures can be exposed to 90 – 95% of the total available incident radiation (see table 2.5). East and west facing panels set at steep angles can utilize approximately 60% of the south facing incident radiation due to small solar angles during early morning and evening hours.

Location- the amount and intensity of solar radiation is a function of the latitude and longitude of the design site. Elevation can also have an effect on solar availability.. The orientation of the panels, known as tilt angle, will also impact the amount of utilized solar energy. Panels that are orientated normal to the suns rays, or photons, collect more energy(see chapter 2 for detailed analysis). Figure 5.1 demonstrates PV envelop configurations.

Available Surface Area- The size of PV systems that are integrated into building envelopes are limited by the surface area of the building itself. Considering the average electrical load requirements, the amount of exterior surface area per floor area and the current efficiency of PV panels it is not possible to generate 100% of a facilities electrical requirements with a PV integrated envelope. However it may be possible to generate more instantaneous power than required for periods of high solar radiation in which case the excess power is sold back into the electric utility grid.

5.2 Sizing the System

The amount of power available from a PV system is calculated by determining estimates for the efficiencies of the PV modules as well as the efficiencies of the inverter and load carrying capacity of the electrical wiring. Power generation reductions must also be considered that result from temperature fluctuations, dirty panels and other miscellaneous reducers. Once the power available from the PV generator is known it should be compared to the facility load requirements.

The Nominal power of the PV generator is:

$$P_{PV} = \eta_{PV} * A_{PV}$$

Where: P_{PV}(kW) = Nominal power of the PV array for STC
η_{PV} = Fraction of efficiency of the PV modules at STC
A_{PV} = Surface Area of PV modules

The Energy production of the system is:

$$E_{PV} = \eta_{BOS} * K_{PV} * P_{PV} * S$$

Where: $S(kWh/M^2)$ = Annual solar radiation on PV array (accounting for panel orientation and tilt angle)

K_{PV} = Reduction factor for dirty modules, temperature variations, misalignments etc..

η_{BOS} = Balance of the system efficiency (not including module efficiency). For grid connected systems this efficiency depends mainly on the inverter and wiring losses. Typical wiring loss = 10%. Typical inverter loss = 15%. Typical value for $\eta_{BOS} = 0.75$

The ratio of PV generated electricity to facility electrical demand = E_{PV}/E_{load}.

5.2.1 PV Generator Sample Calculation

The following calculation was performed in 1999 for the Massachusetts Institute of Technology department of civil and environmental engineering design competition for a new CEE facility. As is demonstrated in table 5.2.1, solar arrays with 60 Degree tilt angles generate significantly more power than vertical panels. Therefore a horizontal saw-tooth façade was designed. This type of design has the added benefit of providing window shading during the hottest months of the year. Thirty-year average solar availability data from reference [4].

Table 5.1

Average Daily Solar Availability on South-Facing Wall for Boston Area

Angle To Horizontal	Spring	Summer	Fall	Winter
90Degree	3.9	4.1	3.5	2.7
60Degree	2.7	2.6	2.7	2.3
60Deg. Vs 90 Deg.	31.2%	36.6%	22.9%	15.2%

Figure 5.2

3-d Projection of CEE Facility

Table 5.2

Power East Facing Wall 60 Deg. Angle

Month	East Facing Avail. Avg. Solar Radiation **60deg**. Angle From Horizontal kWh/m^2/day	PV Surface 60deg Angle m^2	Available Power KW
January	1.4	278.9	16.27
February	1.4	278.9	16.27
March	3.6	278.9	41.84
April	3.6	278.9	41.84
May	3.6	278.9	41.84
June	3.9	278.9	45.32
July	3.9	278.9	45.32
Aug	3.9	278.9	45.32
Sept	3.7	278.9	43.00
Oct	3.7	278.9	43.00
Nov	3.7	278.9	43.00
Dec	1.4	278.9	16.27
			13178.03

Table 5.3

Power East Facing Wall 90 Deg. Angle

Month	East Facing Avail. Avg. Solar Radiation **90deg**. Angle From Horizontal kWh/m^2	PV Surface 90deg. Angle m^2	Available Power KW
January	1.2	87.14	4.36
February	1.2	87.14	4.36
March	2.5	87.14	9.08
April	2.5	87.14	9.08
May	2.5	87.14	9.08
June	3	87.14	10.89
July	3	87.14	10.89
Aug	3	87.14	10.89
Sept	2.7	87.14	9.80
Oct	2.7	87.14	9.80
Nov	2.7	87.14	9.80
Dec	1.2	87.14	4.36
			3071.69

Table 5.4

Power South Facing Wall 60 Deg. Angle

Month	South Facing Avail. Avg. Solar Radiation 60deg. Angle From Horizontal kWh/m^2	PV Surface 60deg Angle M^2	Available Power KW
January	2.7	1301	146.36
February	2.7	1301	146.36
March	3.9	1301	211.41
April	3.9	1301	211.41
May	3.9	1301	211.41
June	4.1	1301	222.25
July	4.1	1301	222.25
Aug	4.1	1301	222.25
Sept	3.5	1301	189.73
Oct	3.5	1301	189.73
Nov	3.5	1301	189.73
Dec	2.7	1301	146.36
			69278.25

Table 5.5

Power South Facing Wall 90 Deg. Angle

Month	South Facing Avail. Avg. Solar Radiation 90deg. Angle From Horizontal kWh/m^2	PV Surface 90deg. Angle M^2	Available Power KW
January	2.3	407	39.00
February	2.3	407	39.00
March	2.7	407	45.79
April	2.7	407	45.79
May	2.7	407	45.79
June	2.6	407	44.09
July	2.6	407	44.09
Aug	2.6	407	44.09
Sept	2.7	407	45.79
Oct	2.7	407	45.79
Nov	2.7	407	45.79
Dec	2.3	407	39.00
			15720.38

Table 5.6

Available Solar Power

Power Available	Power Available	Anticipated Demand
South Wall	East Wall	.003kW/sf
84998.63kW	16249.72kW	3942000kWh/yr

$A_{PV} * S = (84998.63 + 16249.72)*24 = 2429960.4\text{kWh/yr}$
Assume: $D_{BOS} = 0.75$, $D_{PV} = 0.1$, $K_{PV} = 0.9$,

$E_{PV} = D_{BOS} * K_{PV} * S * D_{PV} * A_{PV} = 0.75 * 0.1 * 0.9 * 2429960 = 164022\text{kWh/yr}$

Using the Average cost for electricity in the Boston area to be $0.10 the PV system generates $16402.20 worth of electricity annually

5.3 Design Considerations

The designer of a PV system must consider several factors that are unique to PV facades including:

- *Shading*- It is critical that PV modules are not shaded in any way by trees, utilities or other buildings. If there is a high probability that a new facility built in close proximity to the site in question might be constructed at some future time, the site is not suitable for a PV generator. Several tall buildings have been equipped with PV modules located only in the upper stories to negate shading problems.
- *Insulation*- An energy efficient facility should be insulated at the building envelope. Some types of PV panels have been manufactured with an insulation layer laminated directly into the panel. Other PV provide insulation by utilizing multi-layer air or gas filled design similar to that of thermal insulated glass panels.
- *Weather Resistant Electrical Connections*- Locations where electrical connections are exposed to the weather are subject to corrosion and should be designed with non-corrosive material.
- *Rise in Module Temperature*- As PV modules increase in temperature they decrease in efficiency. Therefore proper ventilation should be designed at the back face of the arrays to allow panel cooling by airflow. Also, the design must allow for thermal expansion of the panels.
- *Water Condensation*- PV panels can be subject to condensation on both the inside and the outside surfaces.
- *Physical Characteristics for PV panels*

Table 5.7 [4]

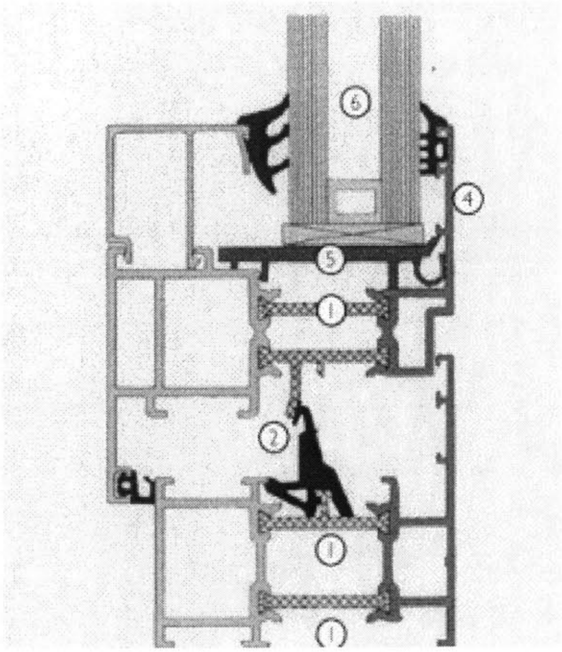
Physical Characteristics for Panels

Expansion coefficient	0.5 – 10E6m/mK
Heat Transmission Coefficient	4.5 W/m^2 K
Steam Permeability	0
Noise Insulation	25dB
Light Transparency	10%
Total Energy Transmission (g-Value)	54%
Light Reflection	8%

- *Aesthetics*- PV panels are available in a wide variety of colors, brilliance, reflectivity, and levels of transparencies. Semi-transparent panels are often used for Atrium Space.
- *Communications Interference*- Communications arrays should be located away from or shielded from the PV power inverter.
- *Mounting Techniques*- PV panels can be integrated as elements into the building envelope using the same techniques by which glass panels are mounted, pressure plate retention and glazing. Interior glazing is commonly used for curtain wall installation. This is accomplished by splitting the mullion and mutin extrusions into separate elements which snap into place in the field (see Figure 5.3.1). Pressure plate retention utilizes a retainer member that can easily be removed to replace the PV panels (see Figure 5.3.2).

Figure 5.3 [18]

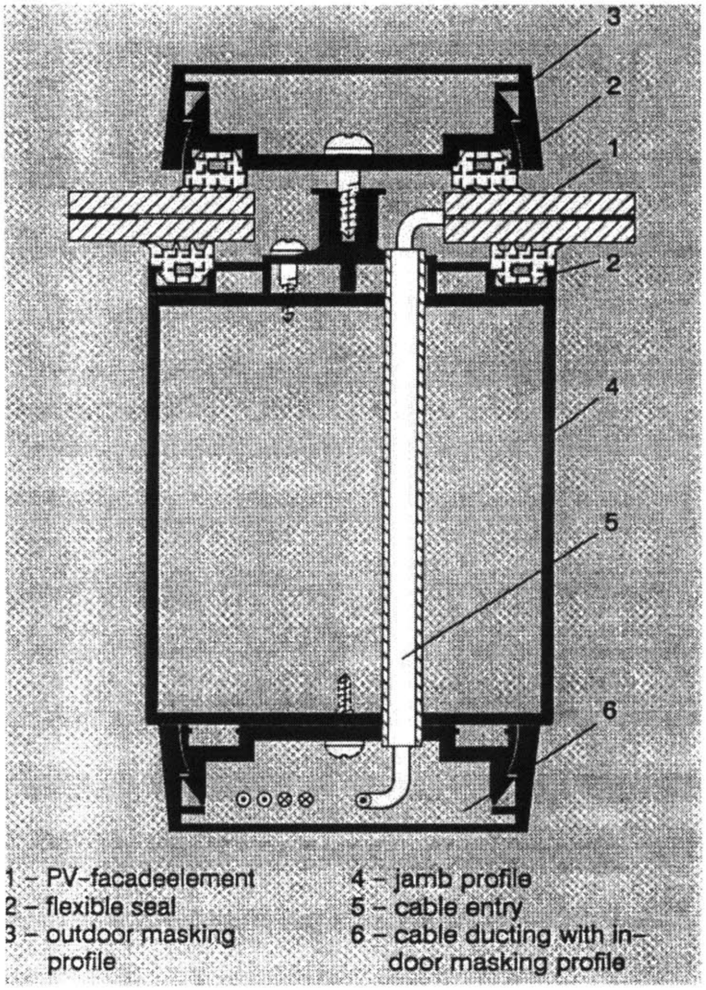
Structural Glazing Section



- Insulating strips consisting of polyamide 6.6 reinforced with glass fibres and fitted with adhesive inserts (1).
- Stop of the central gasket connects with the insulating strip providing better insulation (2).
- Central gasket is in epdm for excellent wind and watertightness (3).
- Rebate height increased to 25mm permitting the fitting of special glass types (4).
- Glass support (5).
- Double glazing up to 50mm (6)

Figure 5.4 [1]

Pressure Cap System Section



5.4 Panel Degradation for Amorphous Silicon (a-Si)

Cost savings for a-Si panels are rapidly making them the PV panel of choice. For system designers as well as owners it is essential to be able to predict changes in panel efficiency over time due to light induced degradation and the effects of annealing(heating and slow cooling). A successful model based on laboratory experiments and tuned to field conditions as presented by E.D. Dunlop and H.A. Ossenbrink at the 13th EC Photovoltaic Solar Energy Conference in Nice France 1995 is as follows:

The efficiency of a-Si PV modules = η_n

$$\eta_n = A * \exp(-(\tau*\upsilon)^{1/2}) + \eta_{min}$$

where:

υ= decay constant (0.1 – 0.045)
τ= Elapsed time
η_{min}= Minimum stable efficiency at temperature T

$$\eta_{min} = m*T^{3/2}$$

where : $m = 1.07 * 10^{-4} *K^{-2/3}$

$$A = \text{Fractional Degradation} = m*(T_i^{3/2} - T_{new}^{3/2})$$

where:

Ti =Initial module temperatures
T_{new} = new module temperature

For a thorough explanation of the Model refer to E.D. Dunlop and H.A. Ossenbrink at the 13th EC Photovoltaic Solar Energy Conference in Nice France 1995 or the internet at http://www.ibmpcug.co.uk/~djl/nice2.html.

Chapter 6

Façade Examples

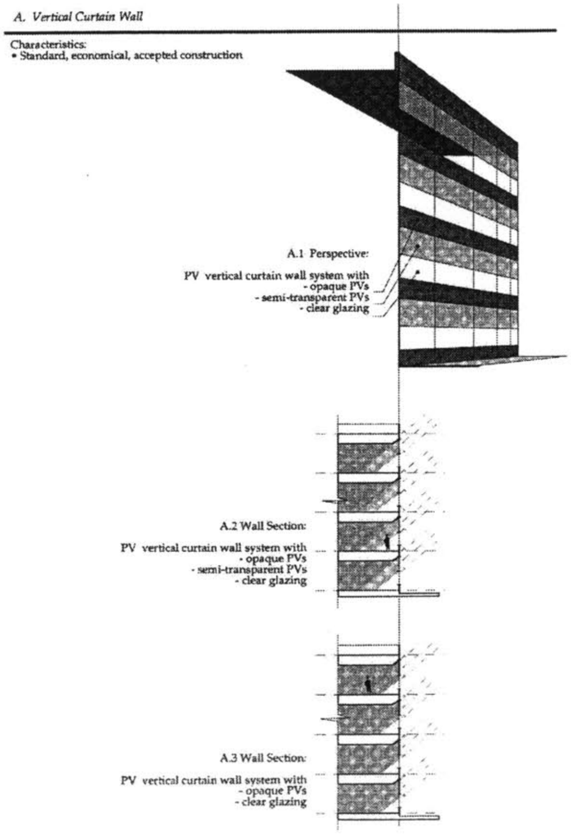
Strict Geometric Pattern
Office Building, Cremona/I. [23]

Introduction

Standard commercial building facades are non- load bearing and can be referred to as curtain walls. Their function is to shield the contents of the building from the weather, regulate heat loss, regulate the entry of light, provide a sound barrier, offer easy maintenance, and provide an aesthetically pleasing and interesting appearance. PV integrated curtain walls provide the added function of power generation. The purpose of this section is to demonstrate several of the more commonly utilized façade configurations for PV integrated facilities and to introduce several unique product designs.

6.1 Basic Configurations

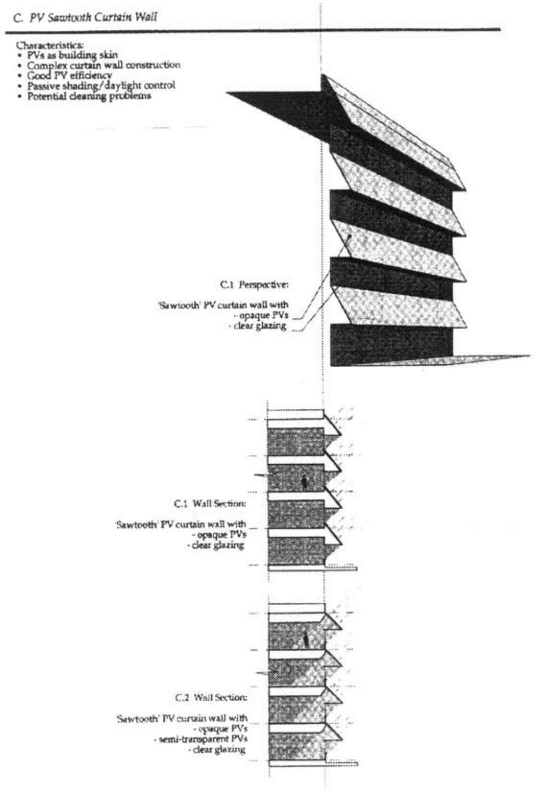
Figure 6.1 Vertical Wall [2]

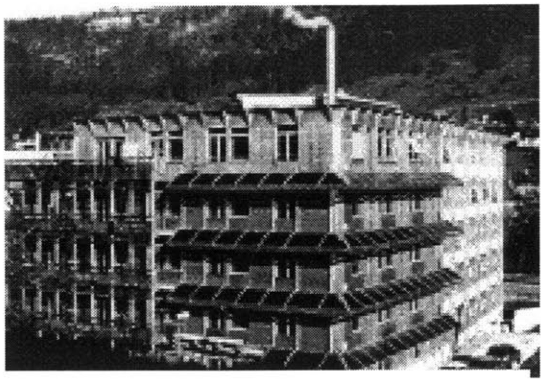


Elegant structural glazing
Office Building, Penzberg/D [23]

Vertical wall gives a traditional design approach. The vertical panels do not optimize solar availability.

Figure 6.2 Horizontal Sawtooth [2]





Office Building
Liestal Switzerland [23]

The angle of the PV panels allow them to absorb most of the available solar radiation as well as providing valuable shade during the warmest months

Figure 6.3 Vertical Slope [2]

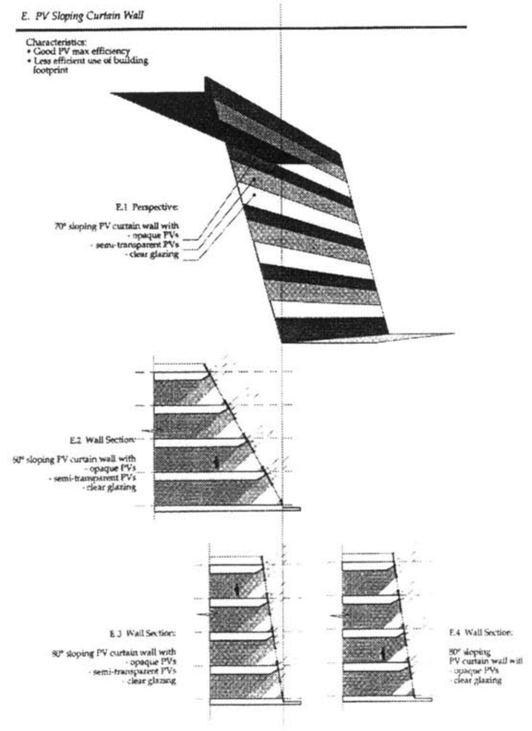
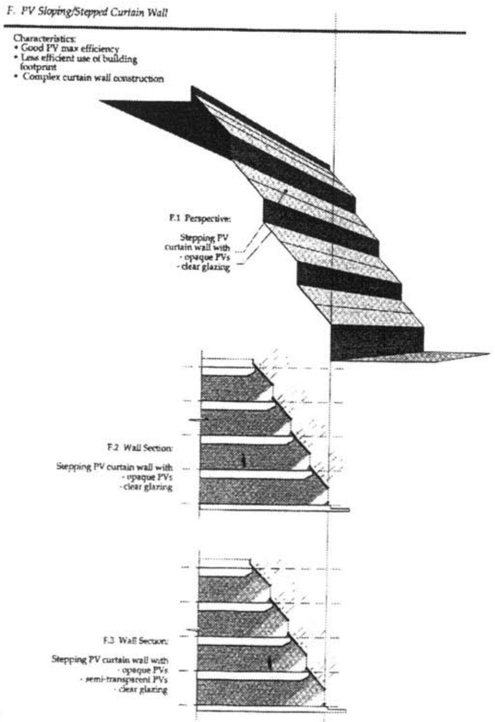
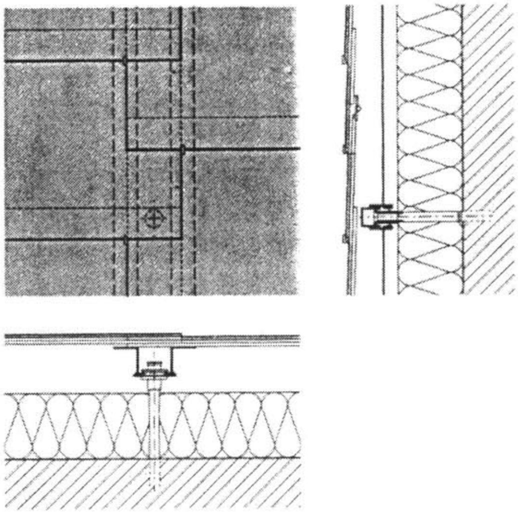


Figure 6.4 Vertical Sawtooth [2]



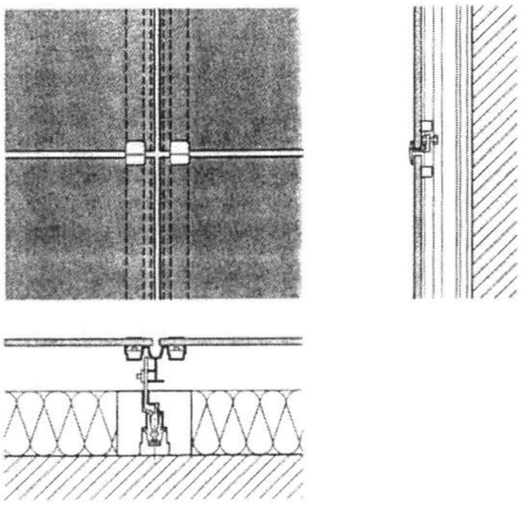
6.2 Innovative Mounting Techniques

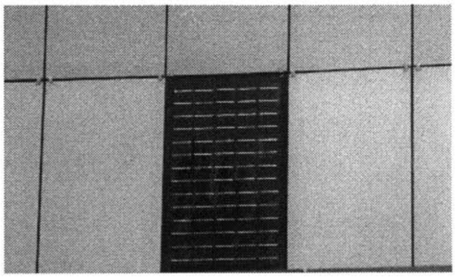
Figure 6.5 [1]



A shingled Façade with an aluminum sub-construction

Figure 6.6 [1]

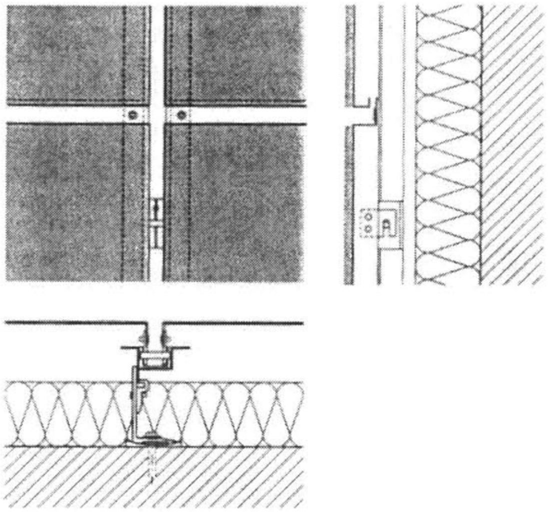




With this option, any elements either with or without PV cells can be secured.

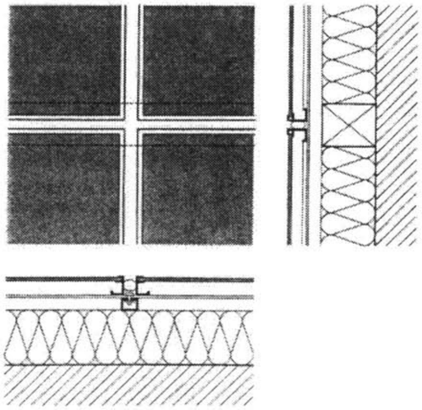
Source: Roethlisberger and Associates, Brugg, Switzerland.

Figure 6.7 [1]
Suspended Adapter Façade System



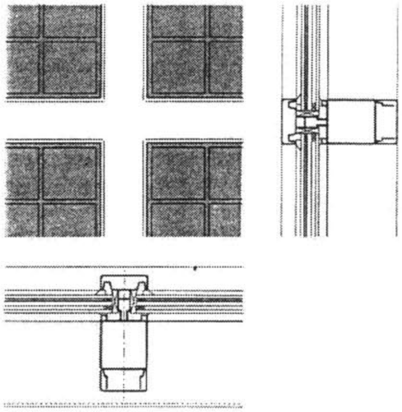
Façade system with suspended adapters which can best be fitted with PV cells

Figure 6.8 [1]
"Rutihof" System



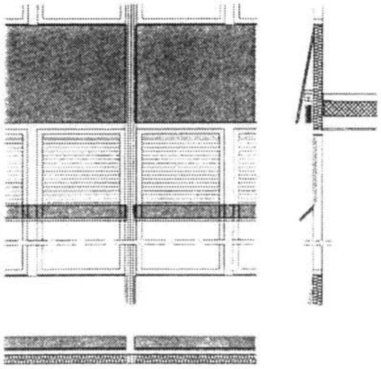
The "Rutihof " façade system is only suitable for facades with smaller surfaces as the tolerance for thermal contraction is low

Figure 6.9 [1]
"Flagsol" System



The German product "Flagsol" uses photovoltaic cells placed between two glass screens. Depending on requirement insulation or noise proofing is used.

Figure 6.10 [1]
"Fassade 2000"

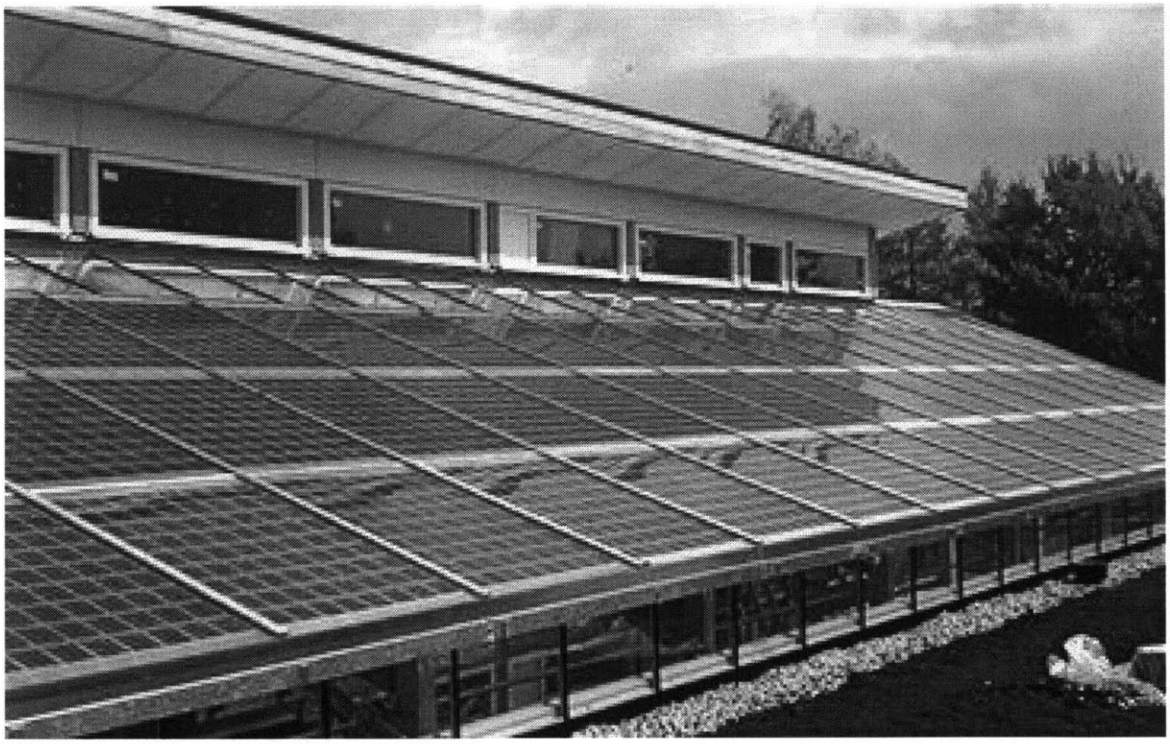


Fassade 2000" is the name of one solution currently at project stage. This is a combination of daylight use, power production with PV cells, heat protection in summer and shading as well as solar energy use through the windows (direct gain) in winter.

Chapter 7

Roof Examples

PV Roof at "The Small Earth" Visitors Information Center
Netherlands [24]



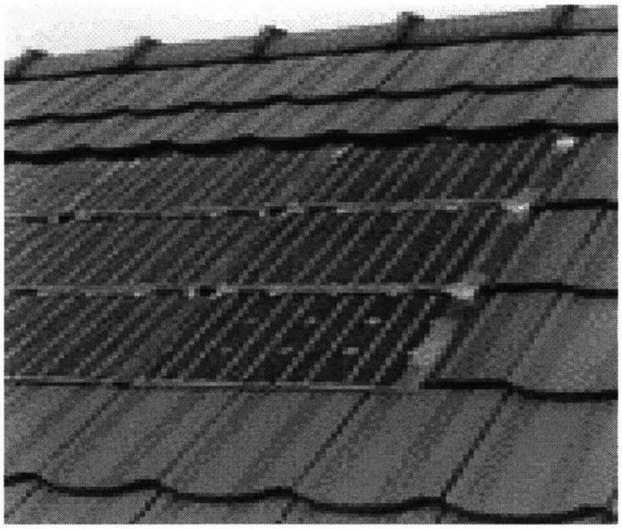
Introduction

This section will demonstrate several commonly used PV roof integration configurations. Installation of PV panels on a tilted roof should satisfy 2 criteria, tightness of the roof and physical condition. Integration on the roof tends to create a condensation problem on the back side of the panels. To solve this problem trapeze-shaped profiled tin sheets can be installed under the PV panels to catch and shed the condensed moisture.

One very common integration method is through the use of PV roof tiles which, have been developed to be easily integrated with conventional roofing materials.

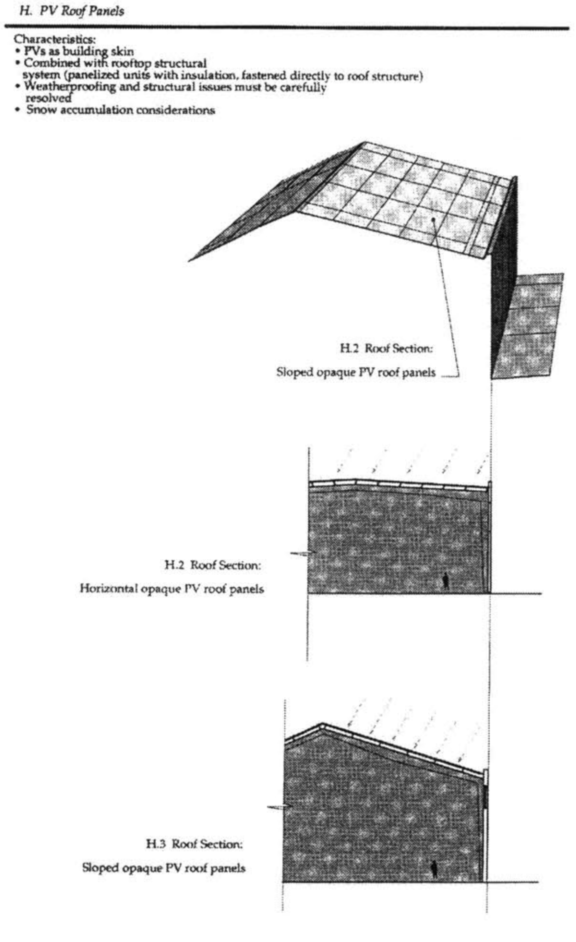
Figure 7.1 [22]

Austrian PV Roof Tile



6.1 Examples of Geometric Configurations

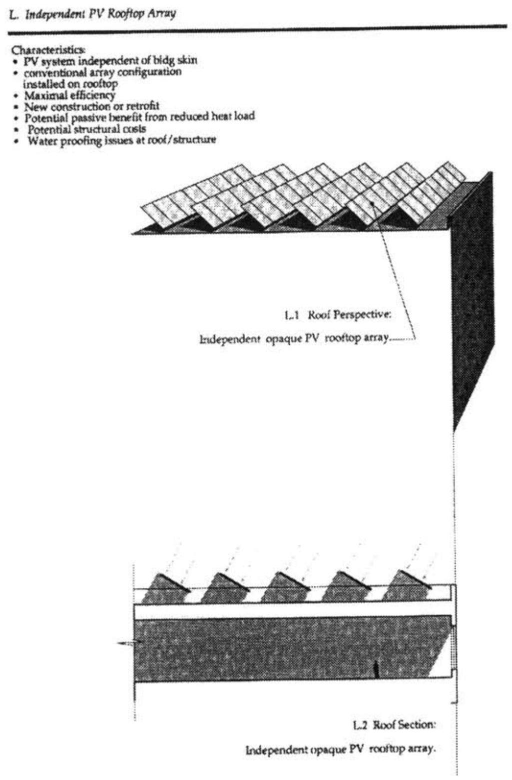
Figure 6.2 [2]
PV Roof Panels



H. PV Roof Panels

Characteristics:
- PVs as building skin
- Combined with rooftop structural system (panelized units with insulation, fastened directly to roof structure)
- Weatherproofing and structural issues must be carefully resolved
- Snow accumulation considerations

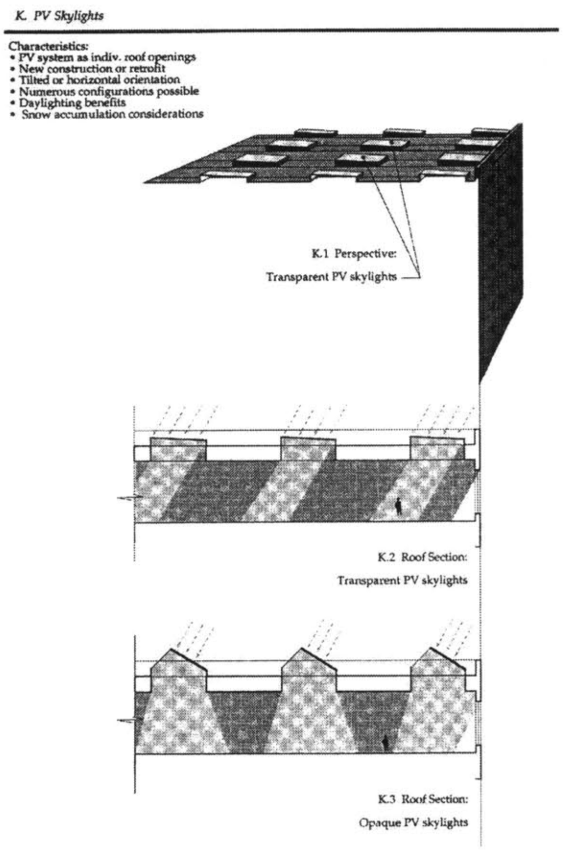
Figure 6.3 [2]
PV Rooftop Array



L. Independent PV Rooftop Array

Characteristics:
- PV system independent of bldg skin
- conventional array configuration installed on rooftop
- Maximal efficiency
- New construction or retrofit
- Potential passive benefit from reduced heat load
- Potential structural costs
- Water proofing issues at roof/structure

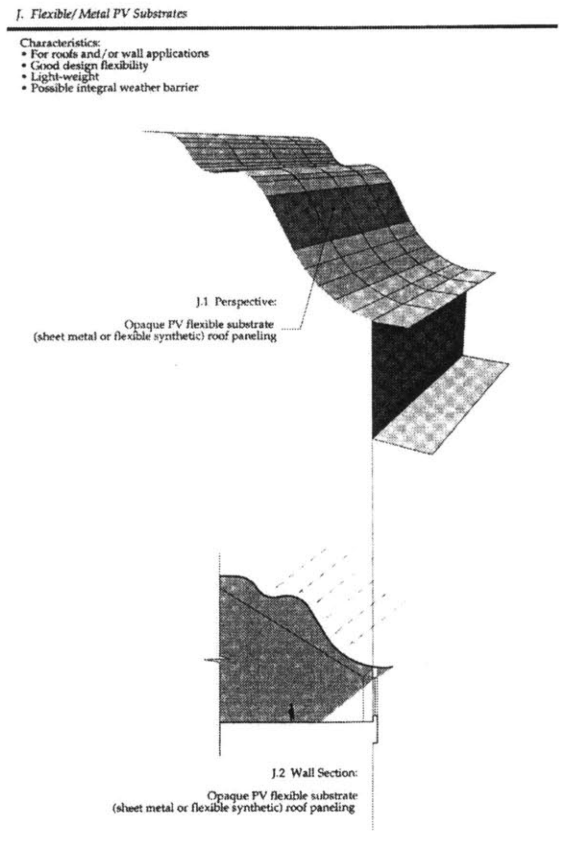
Figure 6.4 [2]
PV Skylights



K. PV Skylights

Characteristics:
- PV system as indiv. roof openings
- New construction or retrofit
- Tilted or horizontal orientation
- Numerous configurations possible
- Daylighting benefits
- Snow accumulation considerations

Figure 6.5 [2]
Flexible Metal Substrate



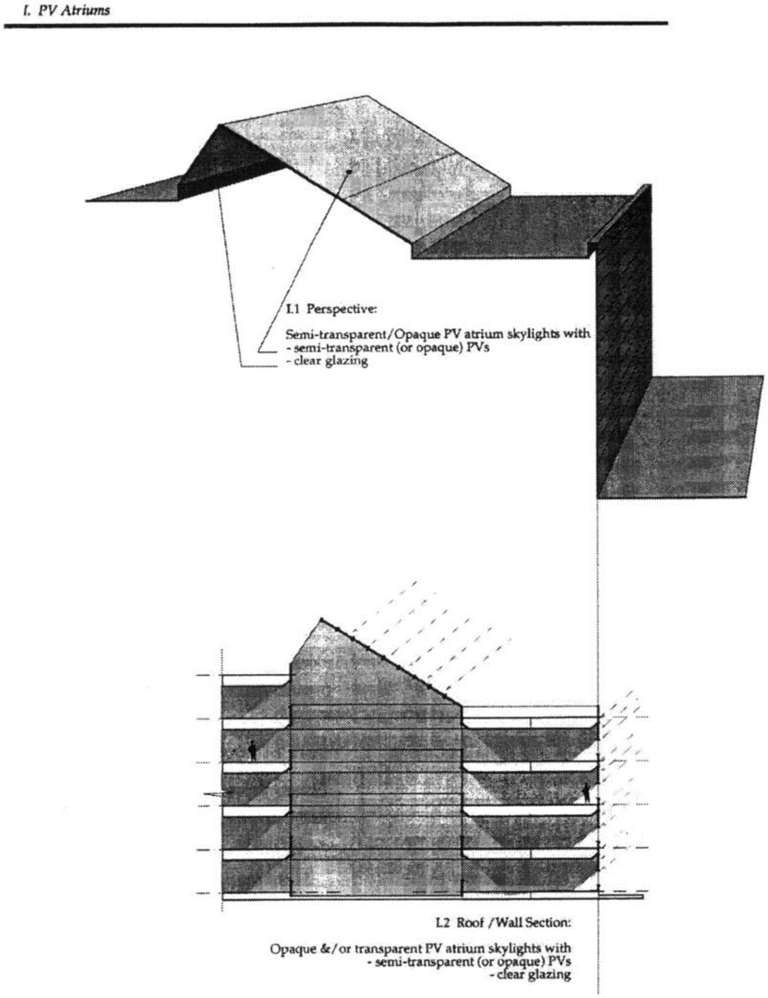
J. Flexible/ Metal PV Substrates

Characteristics:
- For roofs and/or wall applications
- Good design flexibility
- Light-weight
- Possible integral weather barrier

With the advent of semitransparent PV panels, photovoltaic atrium space has grown in popularity.

Figure 6.6 [2]

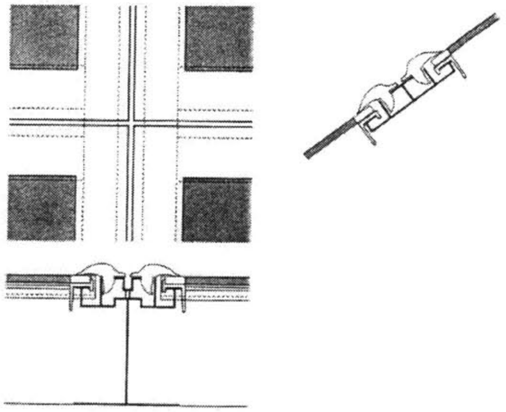
PV Atrium Panels



6.2 Construction Systems

Figure 6.7 [1]

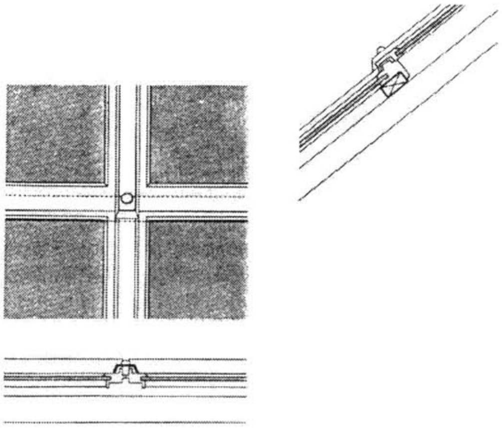
Schweizer System



The “Schweizer System consists of special aluminum profiles, combined with rubber joints.

Figure 6.8 [1]

Standard Roof Tile



The solar roof tile lies on th esame subconstruction as ordinary roof tile. The example shows a system from Switzerland with a grid of 50 to 75 cm.

Chapter 8

Cost

Solar Stock Exchange
Zurich, Switzerland [27]

Introduction

One of the first questions that any owner will ask when confronted with a new product is "How much will it cost me?". The simple answer is, at current rates the payback period for a PV facade is upwards of 30 years on a product that is only rated for a 25 year life. As module efficiencies improve and economies of scale take effect the price of PV systems will decrease. However, for the near future it is clear that PV systems for buildings will not penetrate the commercial market in any significant way without the support of government programs. The first part of the discussion in this section labeled 'Micro View' considers first cost issues facing building owners . From the perspective of those who would bear the burden of government support for the PV industry, a fair question for a taxpayer to ask is "Why should I supplement the PV industry building owners already have more money than me?". The second part of this discussion labeled 'Macro View' will demonstrate that it does make sound economic sense to promote renewable energy in the U.S..

8.1 Micro View

The cost of a PV system is determined by the cost of the individual components as opposed to the value of the electricity that is produced. A general cost relationship between PV system components as related to the total cost of the system is, modules 60%, Inverter 13%, Labor 15% and BOS 12%. The U.S. Department of Energy Photovoltaics Program (USDEPP) estimates that for PV generated power to be competitive with conventional power generation the price per watt must be below $3.00. The current cost is approximately $7.00[11]. They have funded research designed to transform PV power systems from an interesting novelty to a viable option for power production. The following figure demonstrates projections by the USDEPP. Reductions in the costs of PV power systems will be the result of increased module efficiency, reduced costs for large scale production of components and the advent of more efficient methods to incorporate PV panels into structures. Another consideration is the cost of conventional power is in direct correlation of the cost of oil. Increases in oil costs will make PV power immediately more attractive. Once installed the fuel supply for PV power generation is abundant and free.

Table 8.1 [9]

DOE Long Term Goals

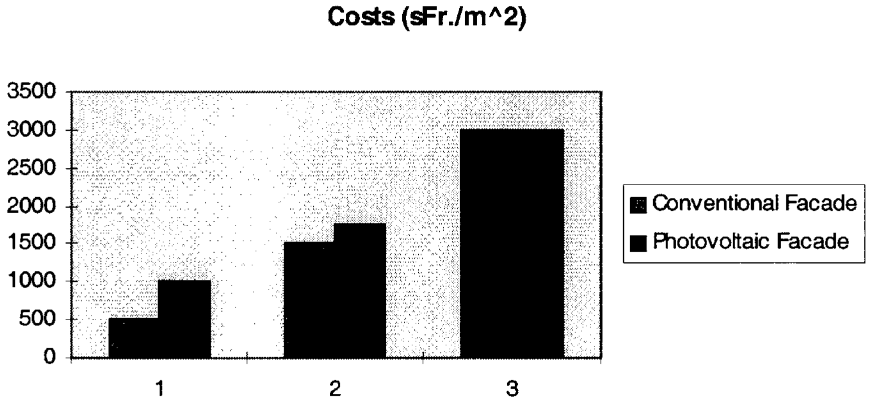
1998 U.S. Department of Energy Photovoltaics Program Long Term Goals

	1991	1995	2000	2010-2030
Electricity Price (cents/kWh)	40 to 75	25 to 50	12 to 20	<6
Module Efficiency (%)	5 to 14	7 to 17	10 to 20	15 to 25
System Cost ($/W)	10 to 20	7 to 15	3 to 7	1 to 1.5
System Lifetime (years)	5 to 10	10 to 20	>20	>30
U.S. Cumulative Sales (MW)	75	175	400-600	>10,000

PV power systems, which are incorporated as elements into a building facade, may realize a much shorter break-even point. Studies performed in Switzerland comparing specific costs of conventional and photovoltaic facades determined that facades with integrated PV cells cost no more than high-end conventional facades such as natural stone or glass. In comparison to cost-effective standard designs PV facades are significantly more expensive. The following figure shows cost comparisons for low end, mid range and high end facades.

Figure 8.1 [1]

Conventional V. PV Facade



8.2 Macro View

In order to answer the question "Why should the U.S. government supplement PV application?" one must consider all economic issues related to photovoltaic energy production and not confine ones self only to first cost. One such issue is America's dependency on foreign oil being produced in unstable regions of the Middle East. In 1992, oil imports contributed more than $50 billion to the U.S. trade deficit. PV production would help to decrease the deficit while at the same time increasing jobs at home. A report addressing the economic impact of PV manufacturing was done in May of 1992 for the DOE. The report specifically focused on the Advanced PV System manufacturing facility in the San Francisco Bay area that could produce 10MW's annually. Some of the results of this study include[18]:

- The facility will employ 80 people during operation and 60 people during construction
- Direct annual sales at full operating capacity = $40 million
- Direct annual sales will lead to a total of almost $55 million annually in direct and indirect impacts on the regional economy
- Given the above figures and national production of 14MWs of PV modules in 1990, direct sales for the U.S. amounted to $73.8 million and 1,558 jobs.
- The national direct impact figures lead to a direct and indirect sales impact nationally of $218.8 million with employment of 2,845 people.

Extrapolating from the above data and using 34.2 MWs of PV production in 1995, leads to direct and indirect sales of approximately $180 million and 3800 jobs. Considering direct plus indirect impacts of PV and related manufacturing, the figure is $534 million and 6,942 jobs.
It is estimated that every $100 million in direct PV sales requires 3800 U.S. jobs.
Every dollar the manufacturing company earns and every dollar each employee earns is taxed and earns revenues for the U.S. government. Supplementing the initial phases of PV entry into the commercial market is a sound economic strategy.

Other notable economic studies include The Law and Water Fund of the Rockies released March, 1996, the Skip Laitner and Marshall Goldberg of Economic research Associates report of 1996, and the Douglas Ogden report released by Environmental Media Services and Environmental Information Center in Jan. 1996. The results of each of these reports carries a common theme:

Pursuing PV applications will cause our nation to grow economically, add jobs, and become more internationally competitive while cutting green house gas emissions.

Another factor favoring government subsidies is that the U.S. government is no stranger to giving money to the power industry. In 1995 the federal government contributed $3 billion to the development of new cleaner coal-burning technologies while the $300 million renewable energy budget faced reduction[18]. It is estimated, fossil fuel emissions will cost ratepayers an additional $4 billion per year to clean up. The time has come for the U.S. to focus on clean sustainable energy sources and allow the burning of fossil fuel go the way of the dinosaur.

Appendix 1

Helpful Conversions

Table A1

Conversions

To Convert	Into	Multiply By
BTU per square foot	kilowatt-hours per square meter	0.003152
BTU per square foot	Megajoules per square meter	0.01135
BTU per square foot	Langley	0.2712
BTU per square foot	calories per square centimeter	0.2712
degrees Fahrenheit	degrees Centigrade	(F-32)/1.8
degree days (base 65 degrees Fahrenheit)	degree days (base 18.3 C)	0.5556
degrees (angle)	radians	0.017543
feet	meters	0.3048
lux	foot-candles	0.0929
miles per hour	meters per second	0.447
pounds per square inch	atmospheres	0.06804
pounds per square inch	millibars	68.97
pounds per square inch	kilograms per square meter	703.1
pounds per square inch	kilopascals	6.897

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