energydesignresources

design brief

BUILDING INTEGRATED PHOTOVOLTAICS

Using building integrated photovoltaic technology, design teams may supply solar energy to building systems, integrate the technology seamlessly into the building design, and provide an economical renewable energy source for building owners.

Summary

A sustainable technology that provides the opportunity for generating electricity and replacing conventional construction materials is building integrated photovoltaics (BIPVs). BIPV systems generate electricity by converting solar energy into useable power to supply building electrical loads. As a leading renewable technology, it is poised for widespread use by design teams in the non-residential construction industry in California and across the United States.

With an abundance of accessible solar energy, California is a prime location for photovoltaic technology and BIPV applications. This technology has the potential to generate substantial electricity capacity for the state. Currently, it is estimated that only about 0.3 percent of California's total electricity generation is produced using solar energy. However, photovoltaic technology has the potential to take a much larger role in supplementing or replacing nonrenewable generation sources for electricity in the future.

California's commercial building owners and designers who integrate BIPV in new and existing buildings may reap numerous economic and environmental benefits. However, designing with BIPVs requires a "whole building" approach that focuses on the interaction of all the energy systems in a building. By evaluating the interoperability of all systems, energy savings may be compounded, and full economic and environmental advantages may be realized.

CONTENTS

Introduction 2
Building Design Strategies for BIPV 4
BIPV Applications 10
BIPV Systems 12
BIPV Integration 17
Economics of BIPV 19
Conclusion 25
For More Information 27
Notes 28

When designing a BIPV installation, it is important to note that photovoltaic technology has the advantage of generally matching peak demand with peak output. In other words, commercial buildings typically reach peak energy use in the afternoons when the energy output of BIPV installations is the greatest. Other key elements discussed in this design brief include the following topics.

- Building Design Strategies for BIPV
- BIPV Applications
- BIPV Systems
- BIPV Integration
- Economics of BIPV

BIPV has the potential of becoming an industry-leading, reliable, renewable, and cost-effective energy source. New and improved photovoltaic products are continually being developed and BIPV costs are becoming more competitive. Additionally, the inventory of new buildings successfully designed with BIPV is growing. As the demand grows for electricity generation, the price for electricity fluctuates, and the BIPV market matures, more building owners and design teams will take advantage of photovoltaic technology and BIPV applications.

Figure 1: BIPV adds architectural distinction to roof components of this new building

Source: National Renewable Energy Laboratory

Introduction

Buildings account for 20 to 30 percent of the total primary energy consumption in the United States. Past decades have seen alarming fluctuations in energy prices, reliability issues, and increasing awareness regarding buildings' intensive energy consumption and environmental impact. The building industry is recognizing the increasing importance of energy efficiency. After energy conservation, supplying reliable, renewable, on-site energy to buildings is fast becoming an inviting solution.

Electrical and space-conditioning inefficiencies squander energy. Designers are attempting to minimize energy consumption by specifying increased thermal insulation, higher-efficiency lighting, high-performance glazing and HVAC equipment, air-to-air heat exchangers, and heat-recovery ventilation systems. After minimizing the overall building load, using renewable energy to meet the remaining loads is the preferred sustainable approach. A leading technology in the field of renewable energy is photovoltaic (PV) systems.

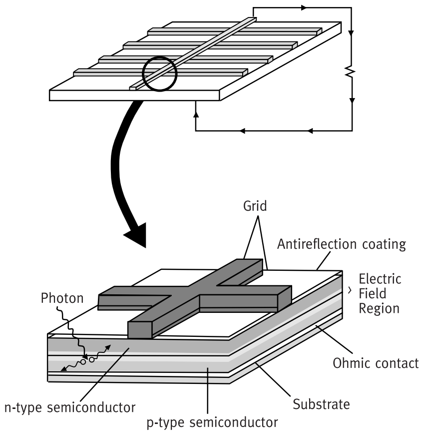
A technology sometimes referred to as solar electric or solar cells, the photovoltaic effect is an innovative power source that generates electricity with light (photo) and chemical action (voltaic). In the building industry, photovoltaics can produce on-site electricity, directly from the sun, with no harmful emissions. In such a scenario, the sun supplements the electric grid as an independent power source, producing valuable demand-side electricity for the building systems. Additionally, PV systems are modular and may be suitably sized for any application.

Among commercially available PV technologies, BIPV systems are capturing a growing portion of the renewable energy market. BIPVs are products that integrate photovoltaic technology into traditional building components (fenestration, roofing systems, awnings, etc.), resulting in multifunctional construction materials. BIPV products serve dual roles, being both part of the building's construction and electricity generators. As such, they provide both shelter and power, bringing "added value" to building materials. Although current economics still dictate that the technology is an expensive way to produce electricity, many other factors make BIPV an attractive alternative. It is estimated that over 60 MegaWatts (MW) of BIPV are currently installed worldwide in new construction and building retrofits each year.[1]

Designing a BIPV system requires skill and in-depth knowledge of the building profession. This design brief illustrates in general

Figure 2: The photovoltaic effect

The photovoltaic effect generates electricity in the following way: light, which is a form of energy, enters a photovoltaic cell and transfers enough energy to cause the freeing of electrons. A built-in potential barrier in the cell acts on these electrons to produce a voltage that can be used to drive a current through an electric circuit.



terms how to best integrate BIPV design strategies into current building practices by:

- Minimizing electric loads
- Optimizing system configuration and electricity generation
- Maximizing efficiency of energy storage, if applicable
- Meeting aesthetic criteria

The electrical potential of a BIPV system depends on the availability of and access to solar radiation, building surface geometry, and PV system efficiency. The system configuration should be optimized according to a building's electric load profile, PV output, and balance of system (BOS) characteristics. Economic viability depends on factors such as electric loads and local utility prices. Finally, factors such as building design constraints, building location, offset costs, climate, future growth, and seismic considerations should also be taken into account.

Understanding the basics of BIPV design strategies and architectural applications, the principles of BIPV systems and integration, and the various economic and non-economic factors is critical to the success of a BIPV project.

Building Design Strategies for BIPV

Design strategies for BIPV capitalize on the multifunctional nature of building components that also generate electricity. When integrating BIPV into a building, design teams should consider using an integrated design approach to successfully address issues surrounding aesthetic and construction requirements, and electricity demand and generation. Outlined below are topics for consideration when integrating BIPV into a building.

Minimize Electric Loads

The first consideration in BIPV applications is to maximize efficiency in the building's energy demand or load. Designers should minimize the electricity load by utilizing integrated energy design strategies such as building envelope improvements, daylighting techniques, and natural ventilation applications (refer to various Energy Design Resources design briefs). Additionally, installing energy-efficient lighting and cooling equipment throughout a building minimizes energy loads. In BIPV applications, the goal is to minimize the building's energy needs and then supplement the remaining loads supplied by the local utility grid with PV-generated electricity. By minimizing the electricity needs and utilizing BIPV, the designer maximizes the potential energy cost savings.

The Visitor Center at Mt. Zion National Park is an example of a building where energy-saving and sustainable features were integrated throughout the design (**Figure 3**). Electric loads were first minimized. Then, utility electricity demand was further reduced using supplemental electricity generated by PV technology.

Optimize the Generation of Electricity

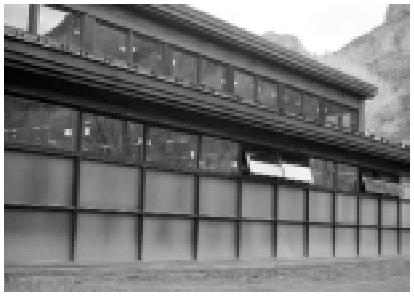
Just as a building should be designed to maximize energy efficiency, a BIPV system should be designed to optimize electrical output. It is important to note that the availability of solar radiation generally matches commercial building electric loads throughout the day and throughout the year. For example, typical energy use for office buildings peaks near midday and during the summer season, the time when there is the greatest solar potential.

For maximum energy output, it is important to determine the orientation, tilt angle, size and location of the BIPV system in relation to the building site and design. Flexibility exists in the placement (tilt and orientation) of BIPV, so it is best to match the time of day, month, and season when peak solar generation occurs with the peak electrical needs of the building.

Figure 3: Zion Canyon Visitor Center, Zion National Park, Springdale, Utah

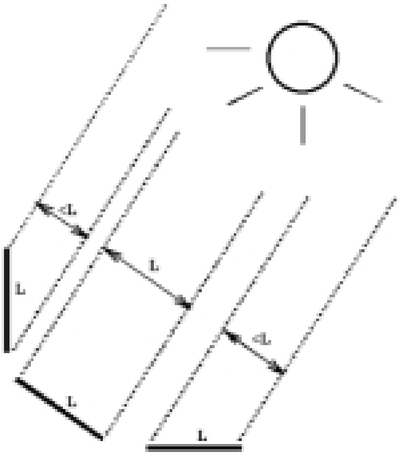
The 7,600 ft^2 (706 m^2) Visitor Center at Mt. Zion National Park is one of the National Park Service's (NPS) most efficient buildings. Building features include daylighting, Trombe walls for passive solar heating, downdraft cooling towers for natural ventilation cooling, energy-efficient lighting, and advanced building controls. The center estimates these features result in approximately 10 kW reduction in the building's electrical demand.

A roof-mounted photovoltaic system provides approximately 30 percent of the remaining electricity needed. Since battery storage was already part of the uninterrupted power system design, by adding a converter it was easy to integrate a PV system into the building's design.



Source: National Renewable Energy Laboratory

Figure 4: Amount of solar radiation striking surfaces of different tilts



SEASONAL ADJUSTMENTS FOR BIPVS

Optimal performance is related to the electric load shape of the building. Optimal tilt may vary plus or minus approximately 15 degrees of the site latitude depending on when the peak load occurs. In general, if peak performance is desired in the summer, mount PV panels at a lower tilt angle to collect greater amounts of the high altitude summer sun.

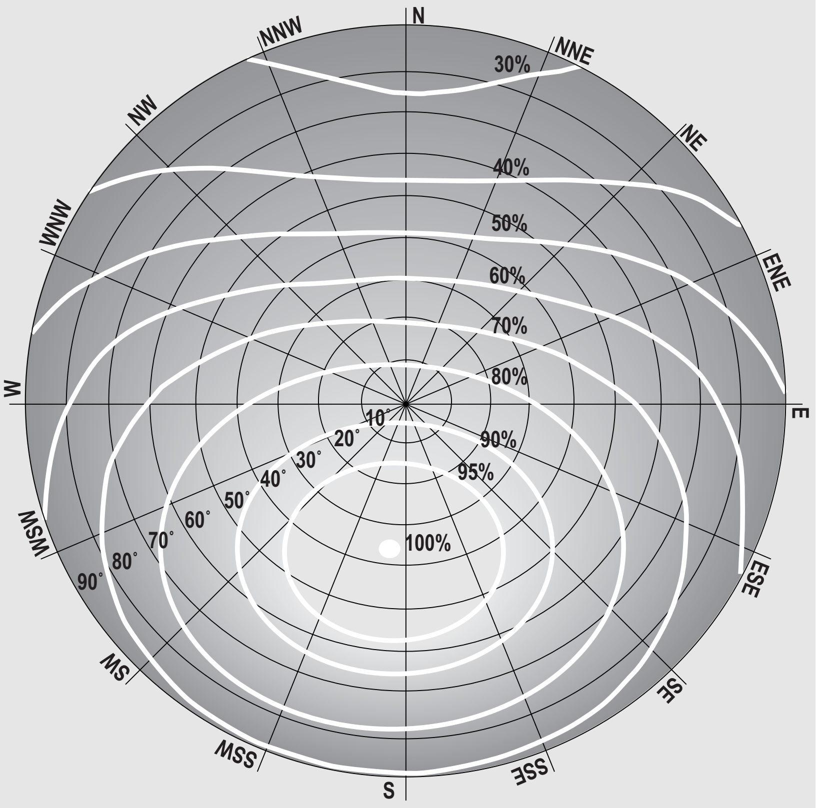
- *Tilt*. Maximum solar intensity occurs on a flat surface perpendicular to the sun's rays (**Figure 4**). Inclining the panels toward the sun increases the amount of sunlight striking the surface and will increase the output. The sun's path sweeps a daily arc that changes seasonally throughout the year. In this way, the sun follows a prescribed solar position described by an altitude angle (vertical) and azimuth angle (horizontal). By orienting the BIPV panels to be perpendicular to the sun at certain times of day and year, it is possible to optimize solar exposure to match loads. Studies have shown that, because of the relationship between tilt and output, the tilt of the installation directly affects the economics associated with energy savings.

  As a general rule of thumb in the Northern Hemisphere, BIPV installations produce the most energy over the course of a year when oriented true south and tilted at an angle equivalent to the site latitude. However, instantaneous output varies depending on cloud cover and the sun's position. As a panel gets farther from a tilt equivalent to the site latitude, the total annual output decreases. A vertical surface orientation may produce approximately 30 percent less electricity, while a horizontal surface orientation may produce approximately 10 percent less electricity than an optimally inclined installation.

- *Orientation.* The total amount of energy that strikes a surface is a function of both tilt and orientation. On east- and west-facing façades, BIPV systems are less efficient than systems oriented south. Nevertheless, vertically mounted BIPVs with east/west orientation can yield up to 60 percent of the optimally inclined southern orientation. For these east/west orientations, low sun angles at the beginning and end of the day account for the majority of the power generated. **Figure 5** shows the distribution of annual incident energy striking a surface in Southern California. In general, largely horizontal southern or vertical western

Figure 5: Distribution of annual incident energy typically striking a surface in Southern California

Efficiency relative to tilt and orientation at 35° latitude indicates that a large number of tilt and orientation combinations provide 90 percent of maximum generation, demonstrating significant flexibility in BIPV siting. Since BIPV can be used in a variety of configurations, it can be viewed as a widely applicable building material.



installations are best to supply typical commercial daytime applications.

- *Sizing.* Even with supplemental on-site PV generation, commercial buildings generally remain net importers of electricity because of their significant energy requirements. Design constraints (space availability, efficiency of placement, building envelope requirements, and costs) typically determine the capacity of BIPV systems rather than electric load requirements. For this reason, commercial BIPV systems are often designed to serve a dedicated (frequently DC) load, such as landscape lighting or irrigation control, to more directly link output to demand.

Figure 6: Locations with optimum tilt and associated solar energy output

Location	Orientation (Longitude, Latitude)	Optimum Tilt Angle °	Energy Output kWh/m^2/y
Berlin	13, 52	35	121
London	0, 52	35	111
Madrid	4, 40	35	201
Lisbon	9, 39	30	201
Rome	13, 42	35	191
Amsterdam	5, 62	40	129
Geneva	6, 46	30	143
Krakow	20, 50	35	124
Oslo	11, 60	45	130
Athens	23, 38	30	183
Budapest	19, 47	35	143
Vienna	16, 48	35	132
Istanbul	29, 41	30	176
Abu Dhabi	55, 25	25	223
Perth	116, –32	30	227
Melbourne	145, –38	30	182
Brisbane	153, –28	25	189
Mexico City	–99, 19	20	205
Miami	–30, 26	25	220
Los Angeles	–117, 33	30	233
New York	–74, 41	35	169
Seattle	–122, 47	35	147
Tucson	–111, 32	30	253
Buenos Aires	–58, –34	30	201
Cape Town	18, –35	30	232
Nairobi	36, –1	5	203
Bangalore	77, 13	15	217
Delhi	77, 28	30	233
Tokyo	140, 35	30	149
Singapore	104, 1	0	171
Hong Kong	114, 22	20	156
Moscow	56, 37	40	119

Source: BP Solarex

Seasonal climatic conditions (temperature and solar radiation) and available surface areas also affect the sizing of BIPV systems. For initial estimates, 10W/sqft (100W/sqm) may be used to roughly estimate BIPV capacity based on size. Designers may want to consult with a PV specialist, system integrator, or consultant to provide array sizing according to desired output, or use one of numerous software tools, worksheets, and charts currently available. Additional reference information is available in the Appendix of this document.

- *Location*. BIPVs should be placed where they have secured long-term solar access. It is critical not to locate BIPV panels where neighboring landscapes or structures that may shadow the system are present or anticipated in the future. Full or partial shading of the panels inhibits the production of electricity. The system performs best if there is homogeneous solar access because the solar cell with the lowest illumination level determines the operating current for all of the cells wired in that series.

  Figure 6 indicates the optimum tilt and the associated solar energy output for various geographic locations. Clearly, Los Angeles is a location particularly well suited for the generation of electricity from solar energy with a potential annual energy output of 22 kWh/ft^2/y (233 kWh/m^2/y). An optimally placed, 1,000 sqft PV array on a 10,000 sqft office building in Southern California may potentially provide up to 20 percent of the annual energy load.

Maximize Efficiency of Energy Storage

Since BIPVs only generate electricity while the sun is shining, proper energy storage is critical. In most commercial applications, integration with the electric grid is advisable. Hybrid systems, which are battery plus grid-connected configurations, provide the added benefit of protection from power interruptions. Additionally, battery-stored energy may provide peak shaving opportunities by offsetting grid-power needs during periods of high-energy costs. The following considerations are important when sizing a battery for proper PV energy storage:

1) Assess the anticipated time period when the system is expected to provide power without receiving an input charge from the solar array.
2) Multiply the time period by the daily power requirement (amp-hours).
3) Add a safety factor to the battery sizing equation for the depth of discharge. This is a safety factor to avoid over-draining of the battery bank.
4) In certain climates, a multiplier may be necessary to account for reduced performance due to extreme ambient temperature conditions.

Meet Aesthetic Goals

Most importantly, BIPV products on the market today make visual statements by adding patterns, textures, colors, and visual notoriety to the roof or façade of a building. Whether it is the shiny exterior of a BIPV curtain wall or the inscribed patterns of semitransparent BIPV glazing products, architects may design visually distinctive applications.

Additionally, buildings that employ new and emerging technologies like BIPV tend to have a higher profile than standard designs and may be distinguished as “green.” Several prominent architectural firms have used BIPV designs to achieve a dual image of being aesthetically appealing and environmentally responsive. Consequently, BIPV integrated designs have brought added value and recognition to both designers and owners of numerous public and private buildings across the United States.

To maximize the aesthetic benefit, BIPVs should be fully integrated into the design, rather than appliquéd. By using a “whole building” approach, it is possible for the BIPV elements to complement rather than compete with other attributes of the building. For designers that wish to create an aesthetically appealing building with distinctive "architectural features," BIPV may be an appropriate and welcome addition to any architectural program.

BIPV Applications

Applications of BIPV systems are designed to effectively displace traditional construction materials. Due to the cross-functional roles of BIPV systems, applications typically require a multi-disciplinary approach. For example, a BIPV skylight is considered a part of the building envelope, a solar generator of electricity, and a daylighting element. All three of these functions impact various design aspects of a project and should involve interaction among the architect, mechanical engineer, electrical engineer or lighting designer, electrician, and building contractor.

There are three main architectural applications for BIPV systems: wall and façade elements, roof and large coverings, and light filtration and screening elements. Each application is discussed in greater detail below.

Figure 7: Example of wall façade

Source: National Renewable Energy Laboratory

Wall and Façade Elements

Opaque façade systems for BIPV include curtain-wall products and spandrel panels. As a façade system, BIPVs are designed to be part of the building envelope and act as an outer skin and weather barrier. BIPV curtain-wall applications may require complex detailing to coordinate framing and wiring, minimize any shading from the mullions, and minimize sealing problems. In some instances, BIPVs are installed as a second (nonsealed) outer layer to avoid some of the inherent complexities. However, such a solution reduces the associated savings of construction material, a displacement that may be critical to project economics.

BIPV products are also fabricated as spandrel panels. Spandrel panels are opaque glass panels frequently used between floors or at the bottom three feet of wall in curtain-wall systems. These panels can be made in standard or custom sizes for all commercial wall applications. Either crystalline or thin-film technology may be used. Spacing between the solar cells determines the power output, and in some cases mock cells may be used to maintain uniform appearance while reducing costs.

Roof and Large Coverings

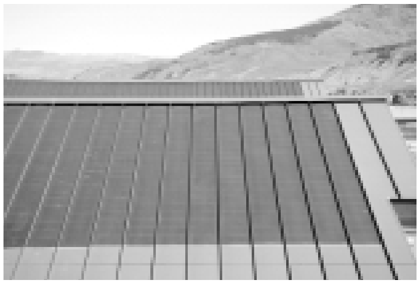
Roofs and large coverings are frequently the most attractive opportunity for BIPV installations because of their substantial solar access. Roofs require little compromise regarding placement and solar orientation of the solar cells, and transform the roof into valuable and productive space. On the other hand, issues may arise regarding proper weatherproofing and structural load considerations for BIPV-integrated rooftop systems. For these reasons, some designers may choose standoff framed PV modules or other BIPV applications. By doing so, the designers lose the cost-savings opportunity of replacing standard construction roofing material with the BIPV system.

BIPV roof products such as standing-seam metal roof or a PV roof shingle replace standard roofing materials like the ever-present asphalt shingle. Also available is a tile-like module, developed as a direct-mount product for sloped roofs, that replaces and/or complements roof tiles. Large-area glass PV modules may also be integrated into the roof.

Light Filtration and Screening Elements

Both crystalline and thin-film materials have been incorporated into insulated glass products. These glazing products can be specified with a range of transmissivity, while providing the same thermal characteristics as conventional architectural glazing products. For the opaque crystalline cells, the amount (and translucency) of space between the cells determines the overall transmissivity and appearance of the panel. In thin-film products, the modules can be laser-etched. Laser etching can produce an infinite variety of patterns, from company logos to cartoons,

Figure 8: Example of standing seam roof



Source: National Renewable Energy Laboratory

Figure 9: Cross-section of BIPV roofing product

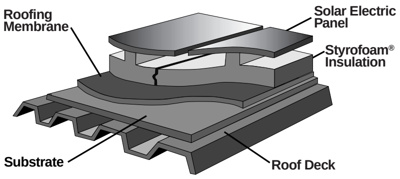


Figure 10: Example of PV skylight

Source: National Renewable Energy Laboratory

Figure 11: Example of BIPV atrium

Source: National Renewable Energy Laboratory

resulting in a wide range of light transmission levels. Some thin-film PV materials themselves are inherently semi-transparent. In general, as the transmissivity of a BIPV glass element increases, the solar performance decreases (a result of reduced solar cell area). The designer should consider acceptable trade-offs between desired outside views, typical glazing characteristics, and electricity generation requirements when specifying BIPV glazing products.

Additionally, awnings and shading systems are a rapidly growing application of BIPVs and may be designed with varying degrees of thermal and transmissive characteristics. Integrating photovoltaic technology into sun shading systems adds electricity generation to the traditional benefits of reducing heat gain and glare control.

BIPV Systems

BIPV systems capture sunlight and convert it into electricity and heat. The electricity generated is direct current (DC) and is able to power appliances that use direct current. The BIPV-generated current may be stored in (DC) batteries, or converted to alternating current (AC) electricity for general application or connection to the utility grid.

The basic building block of BIPV technology is a PV module. Solar cells are assembled to form a module, and modules are wired together to form a site-specific array. Since PV systems produce direct current, they are usually connected to batteries and/or inverters. Additional components and wiring are referred to as "balance-of-system" components.

PV cells consist of a thin layer of semiconductive material. In most cases this layer is made of silicon that is "doped" with a small amount of impurities. The silicon creates an interface between a layer with excess electrons (n-type) and a layer with excess protons or "holes" (p-types). It is because of this junction between the n- and p-type layers that current is generated when solar radiation strikes the cell. The current produced is proportionate to the amount of solar radiation striking the cell, which is related to the cell area and light availability. System wiring (in parallel or series) on both the module and the array level then determines the overall system voltage and amperage. The amount of power available from a photovoltaic device is basically determined by three factors: the type and area of the material; the intensity of the sunlight; and the wavelength of the sunlight.

Primarily, two families of PV cells exist. The crystalline family (single-crystalline, polycrystalline, or crystalline ribbon) tends to be more expensive than the thin-film technologies (made from amorphous silicon (a-SI), cadmium-telluride (CdTe), or copper indium deselinide (CIS). The crystalline family delivers 10 to 14 Watts per square foot and is approximately 17 percent efficient under full sun, whereas the thin-film family delivers 6 to 9 Watts per square foot and is approximately 11 percent efficient under full sun. Crystalline technology produces components that are made up of hard opaque cells (usually about 4.5 inches square) and usually black or deep blue in color. Conversely, thin-film technology produces components using very thin films that are vacuum-deposited onto glass or substrate, such as stainless steel or plastics.[2] When this material is applied to glass, it resembles black glass; when applied to stainless steel, the sheets may be flexible and appear medium blue to purple in color. Of the thin-film options, amorphous silicon products are currently the most widely available for BIPV applications.

All BIPV products are rated and sold based on their electrical output. Though all BIPV systems have a fairly competitive electrical output relative to cost, there are trade-offs between area coverage, electrical output, and material expense. In general, crystalline systems are more efficient but are also more expensive by area. In contrast, thin-film products cover more than twice the square footage for the same investment and electrical output. Thin-film products may be advantageous for many building integrated applications where large surface areas are to be covered.

Table 1: Typical photovoltaic efficiencies

Typical photovoltaic technology efficiencies vary according to different manufacturers. Yield is defined as energy production independent of quantity or operating conditions (temperature, etc.). DC yield (kWh/kWp) is how much energy (kWh) is produced by a certain quantity of installed solar panels (1 kWp). By dividing by kilo-Watt-peak, the yield accounts for installed peak-power; AC yield is also a measure of power production but includes inverter losses. The last two columns represent energy production per square foot and meter.

Technology	DC Yield kWh/kWp	AC Yield kWh/kWp	AC Yield kWh/ft^2	AC Yield kWh/m^2
Amorphous Silicon (a-Si)	1001–1164	888–1038	4-6	47–64
Edge-Defined Film-Fed Grown Silicon (EFG-Si)	966	857	10	104
Mono Crystalline Silicon (mono-cSi)	963–977	855–868	10–11	110–117
Multi Crystalline Silicon (multi-cSi)	961–964	853–856	8–10	90–105
Copper Indium Diselenide (CIS)	930	824	6	67

Currently, many major PV manufacturers offer power production and electrical component warranties that range from 10 to 25 years depending on the BIPV systems. Additionally, limited 12-month warranties may be available that guard against defects and ensure system repair and product replacements.

It is important to evaluate all factors specific to the project, such as area coverage requirements, desired electrical output, material costs, and economic impact, when selecting the appropriate BIPV product for a project.

Balance of System Components

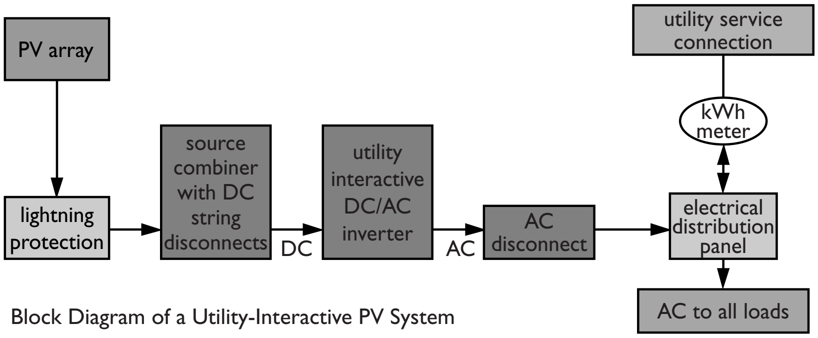
To provide a complete BIPV system, design teams must consider the balance of system components involved with BIPV products. These components include the associated equipment required to convert, use, and store the electricity and significantly impact the success of an application. BIPV products function and produce electricity as part of a total building electrical system. In addition to collectors, the system consists of an inverter, switches, controls, meters, power conditioning equipment, supporting structure, and storage components. These supporting components are called the balance of system (BOS).

Two basic types of BIPV systems exist: "stand-alone," which requires batteries for storage, and "grid-connected," which uses the electric grid as the storage component. Although the collection process can be similar in these two setups, the nature of the BOS is significantly different. In the first case, batteries serve as the only buffer for any delay between electricity generated and the building's electric load. A stand-alone system has as much backup electricity as the batteries can store. It can deliver electricity only when the sun is shining or there is a charge remaining in the batteries. Such systems frequently have backup generators. In the case of a grid-connected system, the utility grid works as the backup and serves as an infinite buffer and storage component.

Figure 12: Grid-connected PV system

A grid-connected system, by design, establishes a two-way flow of electricity. Some inverters cannot operate when the grid is down. Other inverters come with the option of working in either "backup" or "sell" mode.

An inverter requires its own small amount of electricity to operate. Electricity, other than that which the inverter is converting, must be available in order for the system to work. Disconnect switches are connected to either an inverter's input or output and frequently include overcurrent protection.



Block Diagram of a Utility-Interactive PV System

ELECTRICAL ISSUES

- Protection of humans from electric shock
- Wiring system (grounding, etc.)
- Protection of equipment from hazards due to equipment failure
- Requirements for equipment and components
- Disconnect switch

GRID CONNECT ISSUES

- Protection of system when grid fails
- Quality of supply: harmonics, flicker, overvoltage, etc.
- Reverse power flows
- Grid capacity, metering, buy-back
- Grid supply availability for periods of low/insufficient irradiance
- Short circuit capacity
- Auto reconnect after trip
- AC side disconnect switch
- AC module

Inverters

Inverters are central to both stand-alone and grid-connected systems. PV technology generates only direct current (DC) electricity. Inverters convert DC output to the more standard alternating current (AC) electricity. Some electronic devices may use DC current directly, such as battery chargers, DC pumps, appliances, etc. However, most electronic devices and the electric utility grid require AC current. Only a stand-alone system that supplies DC loads exclusively does not require an inverter. Inverters are specified in terms of capacity (Watts), output voltage (e.g., VAC), and power quality. Grid-connected inverters produce output that conforms to utility power quality standards.

As a safety consideration, an inverter should automatically disconnect the BIPV system from the utility grid when there is a power outage to prevent the introduction of unwanted electrical current back into the utility system. At the same time, a BIPV system should maintain on-site operation, drawing the additional power necessary to operate from a battery bank rather than the grid. A combination or hybrid system of a battery backup with a utility interconnected system provides the most reliable power source for a building owner, providing emergency generation should the utility grid go down.

Batteries

Lead-acid (Pb-acid) batteries and nickel/cadmium (Ni/Cd) batteries are most often used in BIPV applications. For small PV systems (up to about 120 amp-hours [Ah]), modified car or truck batteries are typical. These batteries are reliable and have a relatively low cost. The characteristics of battery storage include cost, cycle life, energy density, and ease of operation and maintenance (temperature of operation and toxicity). Nickel/cadmium batteries are of higher cost than lead-acid batteries, but have a longer life and can be operated at low temperatures. Finally, Ni/Cd batteries do not need to be fully charged, and work at higher efficiencies if they are not fully charged.

In general, batteries are sold by amp-hours of nominal capacitance. Nominal capacitance marks how much energy can be removed in a single discharge. The most common failure of batteries results from degradation caused by cycling or corrosion. Batteries are frequently the most expensive and space-consuming element of a BIPV system. Storage capacity issues rather than PV size frequently limit overall electrical output.

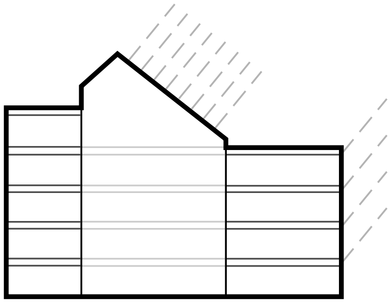
BIPV Integration

In general, the performance of a BIPV system is optimized when it is integrated into a building during the initial stages of design. However, decisions regarding where and how to best integrate BIPVs into building designs are greatly influenced by the potential amount of electricity generated from a specific application and its cost effectiveness. For example, horizontal applications like roof BIPVs and vertical applications like curtain walls have different material/installation costs and electrical output curves due to each one's position relative to the sun. Optimum BIPV integration utilizes the specific characteristics of a project, such as building layout (i.e., low-rise or high-rise), siting (i.e., topography, views, and orientation), and surroundings (i.e., landscape, height limits, and adjacent shading elements) to evaluate and select the best integration strategy for BIPV applications. As a result, different BIPV applications can have markedly different efficacies. **Figure 13** (page 18) shows various strategies for the integration of BIPV into a building design. Façade applications typically include vertical curtain wall, inclined curtain wall, and stepped (recessed) curtain wall; roof applications normally include inclined roofs and skylight monitors.

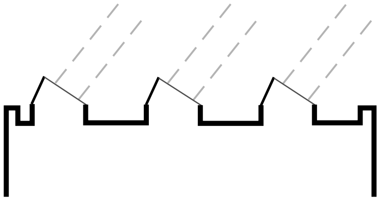
A computer simulation study by the Illinois Institute of Technology evaluated the quantitative performance on the horizontal and vertical surface of a commercial building for several different BIPV strategy options.[3] The tests were performed for Chicago (latitude 41.6 N, longitude 87.4 W, altitude 177 m). In the study, 538-sqft (50-m^2) standard module south-facing collectors were used for each configuration with a PV-field

Figure 13: Strategies for PV building integration

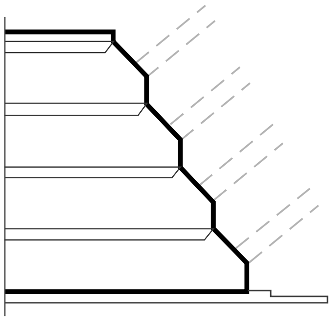
1. Inclined Roof/Atrium Space



2. PV Skylights (shed roof system)



3. Inclined PV/Stepped Curtain Wall



nominal power of 5.3k Wp. The results, shown below, indicate annual energy yield and specific yield for each design strategy. For the study, annual energy yield is defined as the total MegaWatt-hours generated in a year and specific yield is the average kiloWatt-hour output per 5.3 peak kiloWatts of PV installed.

1. Inclined Roof/Atrium Space

Tilt	Annual Energy Yield	Specific Yield
30°	6.61 MWh	1258 kWh/kWp

An inclined roof is one of the most efficient BIPV collection strategies. Tilt angle and orientation may differ depending on desired seasonal performance (See **Figure** 4, page 6). As a roof element, the PV system is part of the building skin and requires attention to weatherproofing, structural, and snow accumulation issues.

2. PV Skylights (shed roof system)

Tilt	Annual Energy Yield	Specific Yield
56°	6.47 MWh	1258 kWh/kWp

PV skylights combine daylighting benefits with good overall PV efficiency. PV skylights can also be easily used in existing building renovations.

3. Inclined PV/Stepped Curtain Wall

Tilt	Annual Energy Yield	Specific Yield
60°	6.02 MWh	1147 kWh/kWp

A PV system on an inclined wall is an efficient collection strategy. It is a less efficient use of the building footprint and requires a more complex curtain-wall construction.

4. Vertical Curtain Wall (with windows)

Tilt	Annual Energy Yield	Specific Yield
90°	4.31 MWh	821 kWh/kWp

Relatively complex detailing may be required to successfully integrate PV panels into a curtain wall (to minimize sealing problems and avoid overshadowing). In general, vertical curtain-wall applications with an opaque PV, semitransparent PV, or clear glazing can be used as a fairly economical and standard construction strategy.

5. Sawtooth Vertical Curtain Wall

Comparison values not available in the study.

A sawtooth vertical curtain wall can work efficiently for certain orientations. It provides passive self-shading/daylighting control and multiple "corner" windows.

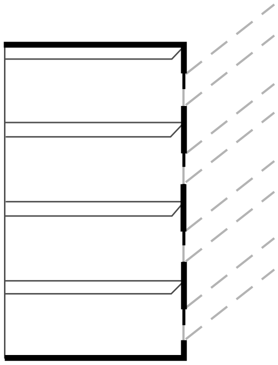
Economics of BIPV

Comprehensive economic analysis of BIPV is highly project-specific; however, a few economic issues may be highlighted to assist the designer considering BIPV applications. Gathering accurate and current information on PV efficiency and pricing may be difficult as the market continually changes. Nevertheless, the general economic trend is clearly toward more efficient and lower-priced PV products. Current analysis reveals significant increases in the number and variety of viable applications for PV power and BIPV materials.

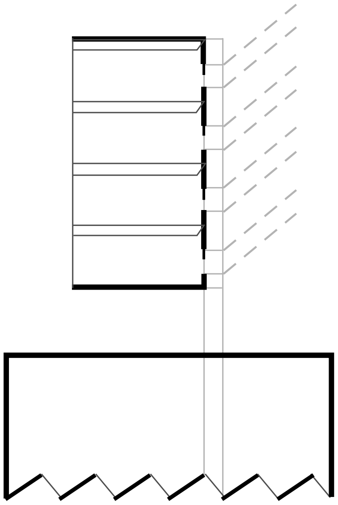
Although costs for PV-generated electricity have decreased nearly 96 percent over the past 30 years, PV power generally remains more expensive than conventional utility-supplied electricity. PV electricity with costs estimated as low as $0.21 per kWh is still nearly twice as expensive as a utility supplier estimated at $0.12

Figure 13: (cont'd) Strategies for PV building integration

4. Vertical Curtain Wall (with windows)



5. Sawtooth Vertical Curtain Wall



per kWh using a typical California rate. Additionally, stand-alone systems are typically more expensive than grid-connected systems since batteries add considerably to already high initial costs.

Table 2: Historical cost per kiloWatt/hour of electricity from PV cells

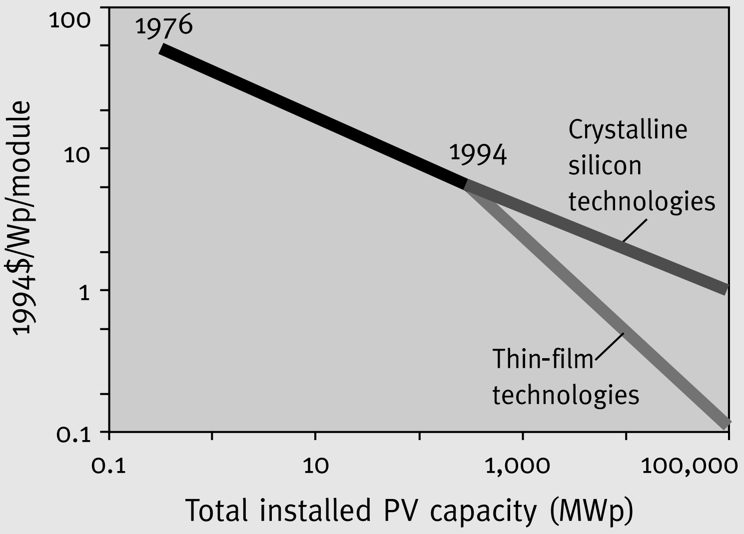
1970	1975	1980	1985	1990	1995	2000
$5.00	$2.50	$1.00	$0.50	$0.25	$0.25	$0.21

A combination of many factors may contribute to economic viability, and BIPVs are becoming increasingly economical as a result of project-specific savings and general market economies. In addition, there are many market externalities that may further increase the value of BIPVs.

Figure 14: Photovoltaic price trends

The photovoltaic cost-reduction curve

Economies of scale (reflected in the amounts of total installed photovoltaic capacity) and technological improvements, such as the development and deployment of thin film-technologies, make the unit cost of photovoltaics more economically feasible.



Market Economies

At the state and federal levels, two primary incentives exist for promoting the use of BIPVs. Both tax credits and accelerated depreciation make the cash flow of using BIPV more attractive (see sidebar on page 22). To correctly evaluate BIPV costs, it is important to include factors such as tax credits, financing options, and the value of electricity in addition to equipment, installation, and operational costs in economic calculations. Designers should utilize a BIPV consultant or software tools for assistance in properly and accurately combining these factors to determine the life-cycle cost of BIPV systems.

On a facility level, BIPVs are a form of distributed generation because the systems generate electricity on-site. Distributed generation, defined as small, modular power generation close to the electric power user, is growing in popularity and provides practical flexibility in today's volatile energy market. In the traditional centralized power plant paradigm, costs associated with the generation and distribution of conventional electricity are considerable because power plants generally require large tracts of land, site development, support structures, electrical distribution systems, utility interface, and enormous capacity. Losses in grid transmission and distribution, and additional infrastructure needs add more costs to grid electricity, especially as power is transmitted over greater and greater distances. For most of the U.S., roughly 33 percent of the fuel energy used in the generation process is available as on-site electricity. As a result, retail energy costs to end-users may be markedly higher than wholesale energy costs. Various savings associated with using distributed generation such as BIPV systems to supplement grid electricity include the following:

- Demand charge reduction
- "Free" real estate for electric generation
- Potential for a more diverse and resilient energy system
- Possibility of increased reliability

Figure 15: Cost of building materials

Polished Stone	$215 - $255 ft^2
Photovoltaics	$45 - $135 ft^2
Stone	$75+ ft^2
Glass Wall Systems	$50 - $75 ft^2
Stainless Steel	$25 - $35 ft^2

- Elimination of costs and losses in transmission and distribution
- Mitigation of additional infrastructure installations

If power plants used PV technology to generate electricity at the wholesale level, the value of the generated electricity would be at a minimum when added to the grid. However, electricity generated at the end-user's building site from BIPV applications has the potential to displace utility energy valued at the higher retail level. Consequently, BIPV-generated electricity may render significant cost savings for building owners by displacing retail-level utility costs. In many cases, additional cost savings may be achieved by using PV-generated electricity as part of demand reduction strategies during high-priced utility periods.

The economic viability of BIPV applications increases as PV output is designed to closely match energy load profiles. Conversely, BIPV systems are not as economically attractive for commercial buildings where peak energy demand or costs do not coincide with peak solar availability. For example, some retail stores, movie theaters, or restaurants may peak in electrical usage at dusk or during evening hours. These building types are not best suited for BIPV applications. However, a majority of California's commercial buildings have electric loads that peak in the early to late afternoon hours during the heat of the summer. The buildings have internally driven loads like lighting and computers that require continuous cooling during peak solar hours. By closely matching the natural cycle of solar availability with a building's electric load curves, a designer increases the usefulness and improves the economics of PV power generation.

On a construction level, BIPVs may be considered value-added building materials. The cost of traditional construction materials may be fully or partially incorporated into the costs of BIPVs. In this vein, some designers prefer to think of BIPVs in terms of dollars per square foot rather than dollars per Watt since it is a

PROGRAMS OF THE STATE OF CALIFORNIA

California has several programs providing economic incentives or support for BIPV. The State offers rebates to offset the cost of installed solar systems for both commercial and residential consumers. For more information, contact the California Energy Commission at (800) 555-7794 or visit their website at www.energy.ca.gov/renewables.

unit more frequently used to calculate traditional material costs. In some cases, the marginal cost increase of installing BIPV may be as little as two to five percent over the total construction cost. As the production of PV modules continues to increase around the United States and the world, it is likely that the unit cost will continue to decrease.

Additional Project Savings

Other factors, both tangible and intangible, may also contribute to the economic viability of BIPV applications. On a project-by-project basis, construction factors such as site, climate, specific design requirements, and electrical needs may provide more opportunities for savings. Additionally, BIPV materials are visible symbols of sustainable architecture and, as such, may provide value by providing architectural distinction, recognition for innovative thinking, and an image of environmental responsibility. In turn, these intangible benefits may translate into marketing advantages and increased employee/customer loyalty for design teams and building owners.

Tangible benefits of BIPV technology may include:

- Suitability in densely populated areas.
- Usability where grid connection is not available.
- Ability to generate electricity during peak usage times, thus reducing the utility's peak delivery requirements.
- Integration with the maintenance, control, and operation of other installations and systems in the building.
- Increased reliability, particularly where uninterrupted power supply is at a premium.

The best way to assess the economic attractiveness of a building strategy like BIPV is to evaluate the total cost of the system over time. This is accomplished by performing a life-cycle cost (LCC) analysis. LCC analysis gives the total cost accounting for

Figure 16: Case Study

Discovery Science Center
Santa Ana, California

PV system: 20 kWp, 50° tilt, thin-film photovoltaic system
Size: 4,334 ft^2
Number of Inverters: four, utility grid connected

There are 464 photovoltaic panels integrated into the southwest side of the Discovery Science Center's 10-story-tall Cube. Altogether, these panels form one of the largest building integrated thin-film applications to date.

They provide the Science Center with up to 20 kiloWatts of DC power at midday (30,000 kWh of electricity per year), or about 10 percent of the electricity needs of the Science Center. In comparison, one house uses about 2 kiloWatts of power. The solar energy system is connected to the Discovery Science Center's main utility line.

Figure 17: Case study

Thoreau Center for Sustainability
Presidio National Park
Building 1060
San Francisco, California

PV system: 1.25 kWp
Size: 215 ft^2
Number of Inverters: one (four kW), utility grid connected

The exterior and interior skylights over the entry to Building 1016 are laminated with 24 photovoltaic panels. The BIPV system produces electricity and serves as shading and daylight design elements. The energy generated by the panels is converted into AC electricity and fed into the building's power grid. At peak capacity the system can generate enough electricity to power 65 energy-efficient light fixtures.

The spacing of square polycrystalline cells allows 17 percent of the light striking the surface to enter the space providing additional daylighting benefits. The PV modules do not serve, however, as the weathering skin of the building. Due to seismic considerations, the PV panels are stacked above traditional skylights.

Source: National Renewable Energy Laboratory

all expenses incurred and cost savings gained over the life of the system. It allows the designer to compare the economics of different power options as well as determine the most cost-effective system design for the PV array. Most LCC analysis includes capital costs, maintenance costs, energy costs, replacement costs, energy cost savings, and salvage value. When using LCC to compare different systems, it is important that each system configuration performs the same work with the same reliability.

Project cost savings is achieved by replacing construction material with BIPV products and displacing grid-generated electricity. It is important to have a full understanding of building material characteristics and utility rate structures regarding energy demand and time-of-use charges when evaluating potential BIPV projects.

Economic Externalities

Several benefits of BIPV applications are classified as economic externalities or costs that do not enter into conventional economics. However, economic externalities such as environmental or social issues may contribute significantly to the overall well-being of the country and should not be discounted.

PV technology is a renewable energy source that is reliant on the sun for power. Generation of electricity using PV technology is recognized as being renewable, sustainable, energy-efficient, and “green,” and has additional benefits not typically accounted for in life-cycle cost or simple payback analysis. These economic externalities benefit the consumer indirectly and are difficult to assign a dollar value. They include the following:

- Offsets of fossil fuel depletion.
- Reduction of environmental degradation with no associated CO_2 emissions.
- Promotion of energy-efficient buildings.
- Ability to help meet peak demand needs.
- Mitigation of utility substation and distribution limitations.

For example, displacing one Watt of energy generated from fossil fuel for one year saves three tons of air pollution, and the population at large benefits from the pollution reduction. As the use of renewable energy grows, environmental degradation will be significantly reduced in the United States and throughout the world. In general, using BIPVs and renewable energy directly improves our environmental quality.

Conclusion

With its multifunctional nature, BIPV technology adds a new dimension to the design and construction fields. In addition to replacing traditional building envelope materials, BIPV products provide a natural source for supplementing grid-generated electricity. When a building is designed with a BIPV system, the application becomes a contributing component to the operation of the facility over the building's life. Thus, significant knowledge about building design strategies, BIPV systems and integration, and contributing economic factors is recommended for a successful project, as well as frequent interaction between various design and construction disciplines.

Designing with BIPV requires a high level of sophistication from the design team, one that relies on a "whole building" approach to design. The team should first design the building to be energy-efficient. By reducing electric loads through design strategies and energy efficiency equipment, the supplemental electricity generated from BIPVs is able to displace a larger percentage of the grid-energy load. Another consideration for designers is to optimize the BIPV system configuration and electricity generation. Designers should work to closely match the BIPV peak output to the building's peak energy demand. It is also important to properly design a storage system (grid-tied, hybrid, or stand-alone) and the balance of system components to fully maximize the BIPV application. Finally, BIPV may be seen as a suitable addition to architectural programs where designers and owners want to create an aesthetically appealing building with distinctive and useful "architectural features."

Economic trends indicate that the price of BIPVs will continue to decrease while the efficiency of PV-generated electricity will continue to increase. Thus, the economic potential for BIPV in the building industry is enormous. In commercial buildings across the country, BIPV systems are becoming a strong presence in a growing market. The economic advantage gained from using BIPVs is based on project savings from replacing construction materials with BIPV products and energy cost savings from displacing grid-generated electricity. Associated advantages include intangible benefits such as environmental and innovative recognition for design teams and building owners. In the future, economic and intangible benefits may become even more significant as the dynamics of the energy and construction markets change.

By taking energy from the sun and turning it into useable electricity for a building, BIPVs are a reliable and environmentally responsive source of renewable energy. With the high solar availability throughout California, BIPV applications offer a tremendous opportunity for designers to provide energy cost savings to building owners, reduce peak energy loads for utilities, and minimize environmental degradation for everyone. It may be said that when a BIPV system generates electricity, it also generates savings for the building, the building owner, and the environment. Though high initial costs and design constraints have impeded the economic progress of BIPV applications, the economic and environmental attractiveness of Building Integrated Photovoltaics continues to grow.

FOR MORE INFORMATION

National Renewable Energy Laboratory (NREL)–
National Center for Photovoltaics:
www.nrel.gov/ncpv/

Department of Energy–Photovoltaics Program:
www.eren.doe.gov/pv

NREL–Center for Basic Sciences:
www.nrel.gov/basic_sciences

Measurement and Characterization:
www.nrel.gov/measurements

Million Solar Roofs:
www.eren.doe.gov/millionroofs

Photovoltaic Manufacturing Technology:
www.nrel.gov/pvmat

PV Silicon Materials Research:
www.nrel.gov/silicon

Surviving Disaster with Renewables:
www.nrel.gov/surviving_disaster

PV Power:
www.pvpower.com

Department of Architecture and Urban Design,
University of California at Los Angeles:
www.aud.ucla.edu/energy-design-tools

Building Energy Tools Directory:
This is a directory of more than 125 computer software programs for the analysis of energy efficiency, renewable energy, and sustainability in buildings.
www.eren.doe.gov/buildings/tools_directory/

Energy Efficiency and Renewable Energy Clearinghouse (EREC)
P.O. Box 3048
Merrifield, VA 22116
Phone: (800) DOE-EREC
E-mail: doe.erec@nciinc.com

Energy Center of Wisconsin
595 Science Drive
Madison, WI 53711
Phone: (608) 238-4601
Fax: (608) 238-8733
www.ecw.org/projects/bipv.html

Notes

1 Environmental Design & Construction, March/April 2000, Specifying Building-Integrated Photovoltaics, Steven J. Strong, pp. 20–24

2 NCPV, PV Hotline press release. SolarFlex Technologies Inc. announced on July 25, 2000, that it is "in the final stages of developing a flexible and lightweight plastic substrate solar cell technology."

3 Sozer, H. "A Methodology to Determine the Optimum Location for Integrating PV Cells into Buildings." Illinois Institute of Technology. International Solar Energy Conference, Solar Engineering, June 2000.

PG&E Pacific Gas and Electric Company™

SDGE®

A Sempra Energy℠ company

SOUTHERN CALIFORNIA EDISON

An *EDISON INTERNATIONAL*℠ Company

Energy Design Resources provides information and design tools to architects, engineers, lighting designers, and building owners and developers. Energy Design Resources is funded by California utility customers and administered by Pacific Gas and Electric Company, San Diego Gas and Electric, and Southern California Edison under the auspices of the California Public Utilities Commission. To learn more about Energy Design Resources, please visit our Web site at www.energydesignresources.com.

This design brief was prepared for Energy Design Resources by Architectural Energy Corporation, Boulder, CO.