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Optimal Building-Integrated Photovoltaic Applications

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I. INTRODUCTION

Photovoltaic (solar electric) modules are clean, safe and efficient devices that have long been considered a logical material for use in buildings. Recent technological advances have made PVs suitable for direct integration into building construction. PV module size, cost, appearance and reliability have advanced to the point where they can function within the architectural parameters of conventional building materials. A building essentially provides free land and structural support for a PV module, and the module in turn displaces standard building components.

This report identifies the highest-value applications for PVs in buildings. These systems should be the first markets for BIPV products in the commercial buildings, and should remain an important high-end market for the foreseeable future.

Optimizing BIPV applications is a function of many variables: construction methods and materials, photovoltaic technology and module fabrication, insolation levels and orientation, and electrical costs. This report addresses these variables in the following order:

- Architectural application (curtain walls, skylights, etc.).
- Construction material credits (the type and value of conventional building materials displaced).
- Additional BIPV construction costs (wiring, ventilation).
- Location parameters (insolation, construction costs, electrical rates).
- PV technology (crystalline silicon, amorphous silicon, advanced thin-films).

Using these variables,the most promising BIPV applications, building locations and PV technologies are selected and evaluated in a simple payback analysis.

Previous Study

An earlier study by the same authors, entitled Building-Integrated Photovoltaics: A Case Study, completed in February 1995, evaluated the performance and economics of a series of roof-integrated photovoltaic systems in high-end commercial buildings. Results from that case study confirmed that infrastructure costs for PV systems are significantly reduced with building integration. The study found, however, that building-integration introduces a complex set of issues which greatly affect PV performance and viability. Figures 1-3 illustrate the primary advantages and disadvantages identified by the study for building-mounted and building-inte-

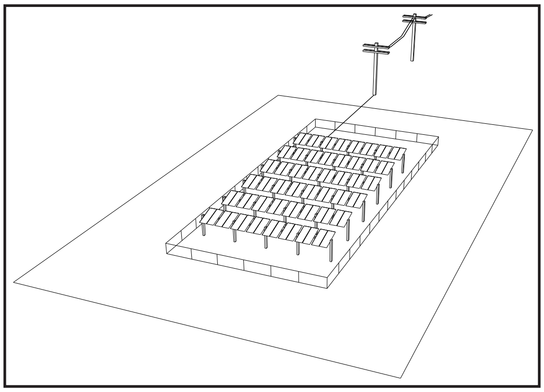

Fig. 1: Field-mounted PVs.

Advantages

- •Unconstrained orientation.

Disadvantages:

- •Land and maintenance costs.
- •Support structure costs.

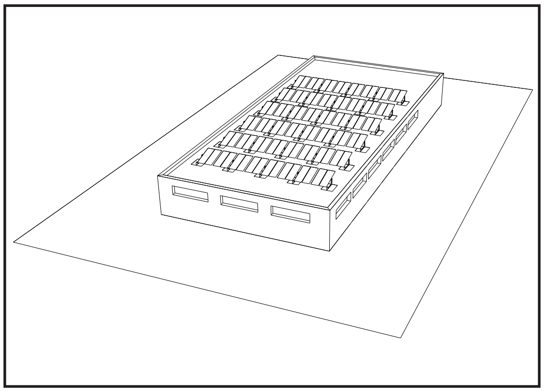

Fig. 2: Building-mounted PVs.

Advantages:

- •Simple support structure minimizes roof penetrations.

Disadvantages:

- •Orientation partly constrained by building position, structure and roof equipment.
- •Potential complications re: structure and waterproofing.
- •Potential code problems without mechanical attachment.

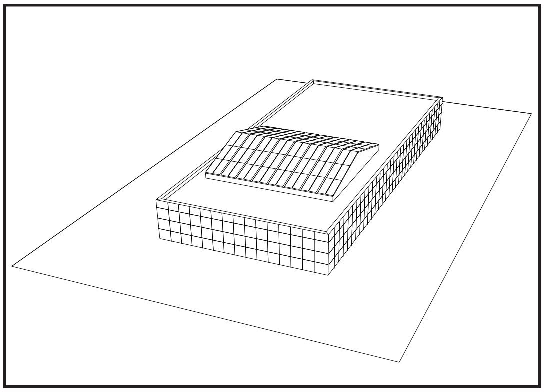

Fig. 3: Building-integrated PVs.

Advantages:

- •Low structural and installation cost.
- •Credit for offset construction materials.

Disadvantages:

- •Orientation constrained by architectural requirements.
- •Potentially higher PV operating temperatures.
- •Safety, waterproofing, aesthetic risks.

grated PV installations compared with traditional field-mounted installations.

The case study was designed to evaluate the architectural and economic implications of integrating PVs into the roof of a commercial building. Five different roof construction systems were studied, ranging from ballasted (gravity-mounted) PVs on a conventional roof (fig. 2), to a fully integrated PV roof with light monitors and active heat recovery. The five systems were evaluated in six different locations around the United States. Analyses included a building energy balance model, PV output calculations, construction cost estimates, utility rate calculations, and a simple payback analysis.

Payback results from the case study indicated that with current PV technologies and utility rates, some BIPV systems are economically viable today. Under the right conditions (insolation and utility rates), payback periods for some BIPV roofs are under 20 years, an acceptable return on investment for some long-term institutional and utility investors. The report concluded that opportunities for economically competitive BIPV systems can only increase with advances in PV technology, higher utility rates and/or better tax credits and government incentives. These additional factors, some of them available today, were not evaluated in the study.

Equally importantly, the study demonstrated the benefits of PV integration into architectural systems with high displaced material credits and low additional construction costs. A BIPV atrium roof, for example, requires little or no additional construction to incorporate PVs and offers a high material credit for displacing laminated, overhead glazing. This roof type performed particularly well in the payback analysis.

Although promising BIPV roof types were identified, the previous study did not attempt to seek out the most optimal BIPV applications. A broad range of roof types was chosen and roofs were compared against each other under various conditions. Research from the case study provides much of the background for the choice of construction systems and locations used in this report. This report builds upon the assumptions made in the case study and sets out to identify, optimize and analyze niche applications for BIPV.

II. ARCHITECTURAL APPLICATIONS FOR PV INTEGRATION

Any building surface that intercepts the sun is a candidate for PV integration. Many buildings incorporate semi-attached elements in addition to walls and roofs, such as awnings, light shelves, canopies and fences. All of these surfaces can deliver the multiple benefits of BIPV: producing energy while performing other architectural functions. This report concentrates on two of the most straightforward applications: atria / sloped glazing and curtain walls. In these systems, PVs form the weathering skin for a building while directly replacing expensive glazing.

Glass-based PVs are the only PV products available today that can be readily integrated into existing construction systems. Metal substrate PVs are being developed, which promise to be able to replace sheet metal in building roofs and skins. Since little cost or performance data is yet available for these products, this study focuses on glass-based BIPV installations.

BIPV systems may be built as part of new construction, or retrofit to existing buildings. This report evaluates only new construction, since there are many additional constraints and unpredictable costs associated with retrofitting an existing structure. Recladding a building with a PV curtain wall, for example, is a very similar process to recladding with a conventional curtain wall, with the exception that wiring must be accommodated. Depending on the existing construction, wiring may be difficult or even hazardous. In the best cases, retrofit applications will perform as well as new installations, but each retrofit project must be evaluated individually.

BIPV Atria/Sloped Glazing

For the purposes of this report, atria are defined as overhead, semi-transparent glazing systems, framed with aluminum extrusions, containing tinted, laminated or wire glass or plastic glazing units. Sloped glazing, as in sunspaces, greenhouses, or tilted walls, is usually constructed with similar framing and glazing. Medium to large area skylights often fall into this category but small skylights do not; they are normally prefabricated units consisting of a metal curb and a plastic dome.

Many off-the-shelf PV modules are suitable for direct installation into these glazing systems, since they are the same size and shape as tinted, laminated glazing units. PVs also transmit a comfortable amount of diffuse light, either through a crystalline pattern or scribe lines in thin films. Diffuse daylighting is frequently a desirable condition in overhead glazing since too much sunlight will overheat interior spaces and cause excessive glare. At the APS facility in California, a PV skylight incorporates amorphous PV modules with standard skylight framing members (fig 4). The standard amorphous modules transmit 5% daylight – a comfortable amount for the work environment below. In other situations, customized modules may be fabricated for specific size, strength, transparency, color and other criteria.

Fig. 4. PV skylight at APS facility, Fairfield, California. A standard skylight framing system mixing amorphous silicon PVs with tinted laminated glass. The PVs transmit 5% daylight.

Atrium systems are potentially the highest-value application for BIPV. They offer:

- Potential optimal orientation for maximum PV output. Subject to the building's orientation and geometry, PV atrium units can be designed at any tilt and azimuth.
- No additional cost for structure or installation of module. Laminated glass PV modules can directly replace standard laminated glass.
- Lower costs due to balance of systems costs that include only wiring and power conditioning.
- A high material credit for the replacement of expensive laminated skylight glazing.

BIPV Curtain Walls

Curtain walls have many of the same construction characteristics as atria/sloped glazing, but they suffer from reduced PV output as a consequence of their vertical orientation. Nevertheless, the market size for curtain walls is substantially greater than for atria, and products developed for atria should be usable in curtain walls with little or no modification.

In addition, a wider range of PV products is suitable for curtain walls than for atria. Curtain walls often contain opaque surfaces (spandrel areas), where non-transparent modules can be used. Vision glass areas will require highly transparent PVs with good optical properties; no such modules exist yet, but they may be developed in the future. Semitransparent PVs with medium optical quality might be used in parts of curtain wall glazing, such as high glazing in tall spaces, where daylighting is the primary criterion and view is secondary.

At the APS facility, amorphous PV modules are combined with vision glass panels in standard curtain wall framing (fig 5). The PV modules are sealed at the back with an opaque insulating panel, much like spandrel panels in a multi-story curtain wall. From the exterior, the clear vision glass and PV modules look the same. Figure 6 shows an interior view of the vision glass and sealed PV panels. Two of the PV panels are left unsealed to compare their transparency with the adjacent vision glass. In addition, large-area amorphous modules (2.5' by 5') were used to fit standard curtain wall framing dimensions. To penetrate the curtain wall market, PV modules should be available in dimensions compatitible with curtain wall standards.

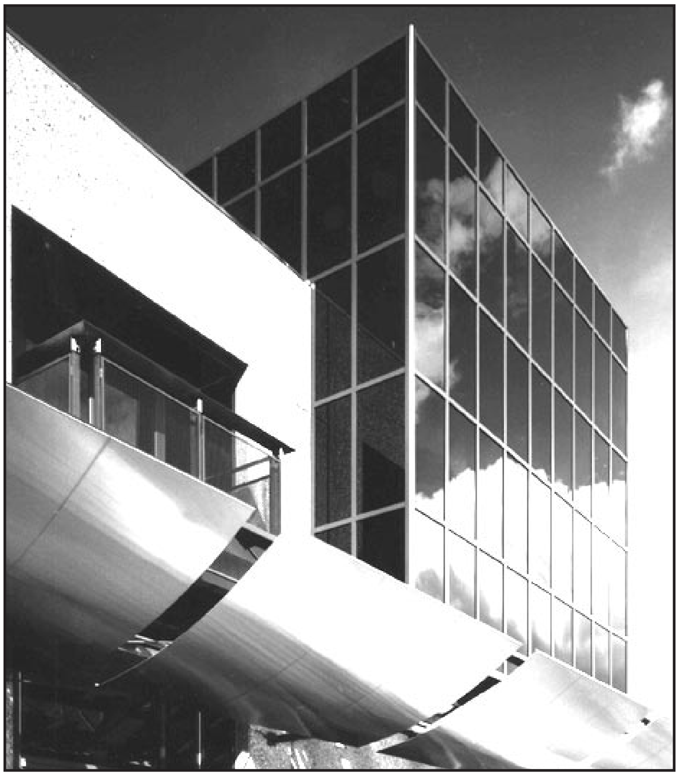

Fig. 5. PV curtain wall "cube" at APS facility in Fairfield, California. The BIPV system icludes amorphous silicon PV modules in standard curtain wall framing. The framing is at a 76cm x 152cm (2.5' x 5') spacing. Ten of the glazing units at the left center of the cube are tinted vision glass.

Fig. 6. Interior view of PV curtain wall at APS. For comparison, two of the PV panels to the left of the vision area are left unsealed, showing the relative transparency of the modules.

III. CONSTRUCTION MATERIAL CREDITS

The key to the economics of the highest-value BIPV systems is the material credit received for the replacement of conventional building materials. For curtain wall and sloped glazing, there exists a broad range of conventional glazing materials, construction methods and assemblies. The choice of a particular material for a project depends on many factors including solar control, aesthetics and construction budget. BIPV installations are most cost-effective in projects where high-end glazing materials are used.

Non-glass materials such as stone or metal panels are also used as building cladding in curtain walls. These materials can be more expensive than glass – indeed more expensive than PV modules – which can result in a PV cladding system which is cheaper than a conventional one. However, since these materials have significantly different aesthetic and material characteristics from glass and glass-based PVs, they are not considered to be directly replaceable in this study.

Glazing Materials

With the growing focus in the building community upon control of energy flow in building envelopes and with the increased use of glass as a featured architectural material, the glass industry has introduced an increasingly sophisticated line of products. Following is a list of single-pane glazing products, most of which can be replaced with a standard BIPV module under the right conditions:

<u>Transparent Glazing:</u>

- *Clear float glass*, the basic element of glass construction, is applicable where high visibility and clarity are required and thermal control and safety are not a priority.

- *Tempered glas*s is a treated glass product which provides resistance to breakage from wind and thermal loads. It is commonly found in entrances, storefronts and curtain walls (approximate cost premium over clear glass: 36%).

- *Tinted float glas*s is colored glass which controls light transmission while reducing solar heat gain. Green or blue tints allow more light and are often used in skylights and atria. Gray and bronze tints are used where reduced light transmission is desirable, as in office buildings or hotels (approximate cost premium over clear float glass: 43%).

- *Laminated glass* is manufactured by combining two or more layers of glass together with an adhesive interlayer. Laminating offers additional strength and sound control. Since it is less likely to break or shatter under loads, it is most suitable for sloped glazing and skylight applications (approximate cost premium over clear glass: 61%).

- *Reflective glass* has an applied reflective coating which controls light transmittance and reflectance to varying degrees while reducing solar heat gain. It is commonly found in applications similar to tinted glazing, but provides higher levels of performance and control (approximate cost premium over clear glass: 76%).

- *Low-emissivity (low-E)* glass has a high-performance, neutral-colored coating which maximizes visual light transmittance, provides good solar thermal performance and blocks UV transmission. It is applicable where energy performance and light transmittance are priorities (approximate cost premium over clear glass: 100%).

Semitransparent Glazing:

- *Fritted glass* is a specialty glazing material in which an opaque ceramic paint is silkscreened and fired onto glass. The pattern reduces heat gain by blocking direct radiation. It partly or completely obstructs views in or out and is often used as a design element. Fritted glass is found in many high-design or high-tech architectural projects which use glass extensively. Two examples of fritted glass construction: the United Terminal at O'Hare airport in Chicago and the Federal Judiciary Building in Washington (fig 7). (approximate cost premium over clear float glass: 120%).

Fig. 7. Example of fritted glass curtain wall at the Federal Judiciary Building in Washington, DC.

Opaque Glazing:

- *Spandrel glass* is used in curtain walls to cover areas between floors where no view or light transmission is required. Some spandrel glass is designed to match the appearance of reflective or tinted vision glass; in these cases the spandrel glass is made with similar or identical coatings, sometimes with a separate opaque layer behind. Other spandrel glass is back painted or fritted to produce a colored, opaque unit. {Approximate cost premium over clear float glass: 73%}

Chart 1 illustrates the relative costs of these glazing materials as compared to current photovoltaic technology costs.

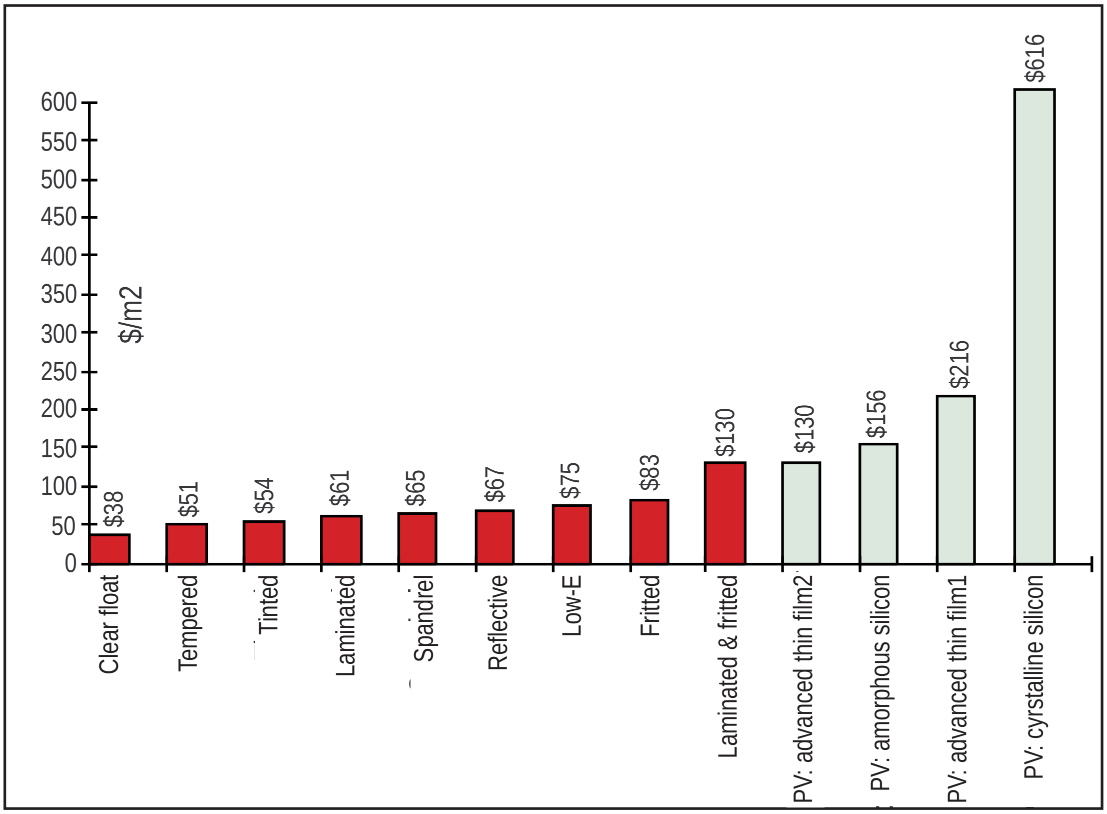

Chart 1: Typical glazing materials costs vs. typical photovoltaic module costs in $/m^2. "Advanced thin film2"=more aggressive prediction for CIS and CdTe technologies in the near term. (Glazing costs source: RS Means Inc.; PV costs source: Energy Photovoltaics Inc., Advanced Photovoltaic Systems, AD Little).

Insulating Glazing:

Due to their superior thermal performance, insulating units are used in more than 80% of all transparent building glazing.[1] These units are fabricated from two layers of glass separated by a spacer and sealed. The most common configuration is a 25mm (1”) thick unit consisting of two layers of 6mm (1/4”) glass separated by a 12mm (1/2”) air space. Many variations of the basic unit are possible, including triple glazing, gas-filled units, units with a thin heat-reflective plastic film in the airspace, and others. Any of the single pane glazing products discussed previously can be combined into an insulating unit. For overhead (atrium) applications, for example, the outer lite is often tinted, heat-strengthened glass while the inner lite is laminated for safety reasons.

Configuring PVs for Architectural Glazing

Glass-to-glass PV modules are fabricated in several different ways, depending on the PV material, encapsulation method, electrical connector detail, and other factors. For ease of integration into glazing systems, frameless laminated modules of a standard thickness (6mm for single glazing) are easiest to accommodate.

The following figures illustrate some of the most common PV module types and their method of integration into insulating units and into framing systems.

Crystalline Silicon Modules:

Crystalline and polycrystalline silicon PV modules (figs. 8, 9) are characterized by high reliability, good efficiency (12-15% cells, 10-12% modules), and costs in the range of $4-5/W$_p$.[2] As figure 9 shows, these modules are made up of individual cells laminated between two sheets of glass or one sheet of glass and another encapsulating film such as Tedlar.

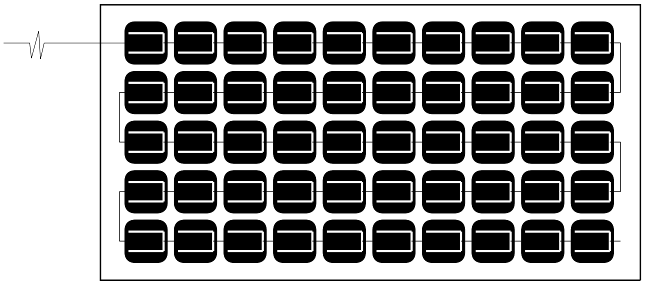

Fig. 8. Diagram of typical crystalline silicon glass-based PV module. Silicon wafers are encapsulated between two layers of glass and connected in series by electrical contacts.

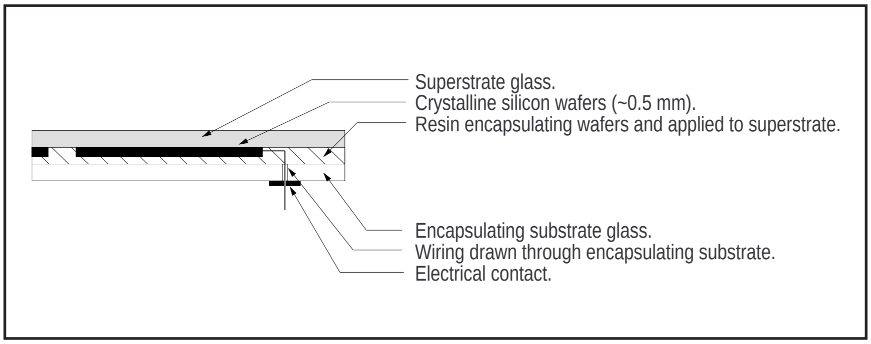

Fig. 9. Typical section detail of crystalline silicon PV module suitable for building integration (not to scale).

Thin Film Modules:

Thin film modules (fig. 10) include amorphous silicon, a technology which is presently available, and CIS (Copper Indium Diselenide) or CdTe (Cadmium Telluride), more advanced technologies which will be available in the near future. These are large-area monolithic devices with a single, uniform surface punctuated by thin scribe lines. They are either superstrate-based, where the PV film is applied to the bottom surface of the top glass (fig. 11), or substrate-based, where the surface is on the top of the bottom glass (fig. 12). Amorphous silicon and CdTe are superstrate-based modules while CIS modules are substrate-based. For architectural applications, there are advantages and disadvantages to both configurations.

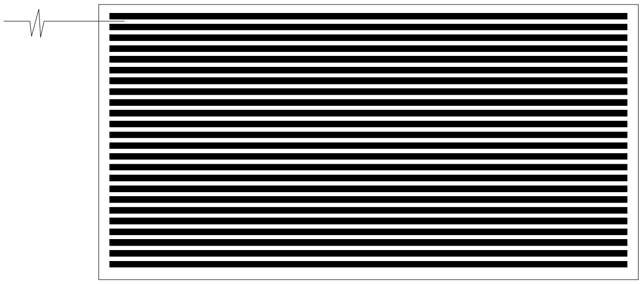

Fig. 10. Diagram of typical thin-film glass-based PV module. A thin film of photovoltaic material is deposited on a layer of glass and laser-scribed, creating a series of thin "cells" connected in series. A second layer of glass encapsulates the module.

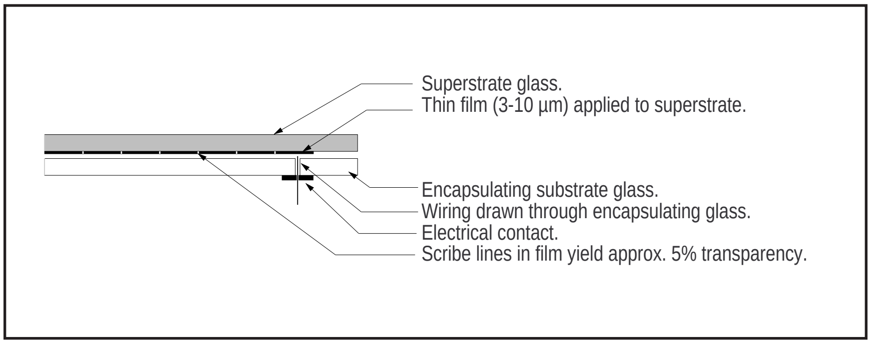

Fig. 11. Typical detailed section of a thin-film superstrate-type PV module (not to scale).

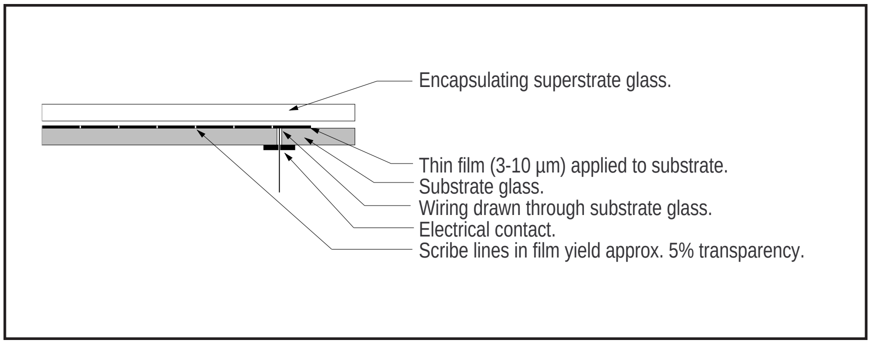

Fig. 12. Typical detailed section of a thin film substrate-type PV module (not to scale).

PVs as Glazing Material

PVs can replace conventional architectural glazing in a number of applications.

Opaque PV Glazing:
Any PV can replace spandrel glass, provided the size and visual quality of the module are compatible with the building design. A very close visual match is possible between existing thin-film amorphous PV modules and vision glazing (fig. 5).

Semi-transparent PV Glazing:
To date, no PV products have been developed which are sufficiently transparent to replace vision glass. However, there are many applications for semi-transparent glazing for which PVs are well suited. Skylights, atria, and greenhouse structures often use heavily tinted or patterned glass to minimize heat gain or control glare. Like patterned glass, most large-area thin-film modules are partly transparent as a result of thin lines scribed through the cell material. Single crystal or polycrystalline BIPV modules

usually consist of a grid of opaque PV cells, laminated between two sheets of clear glass. Light passes through the space between cells, and light transmission is easily controlled by varying the space between cells.

The transparency of thin-film BIPV modules can be controlled by etching additional patterns in the PV material by the same lasers that pattern the cells. This process requires a modification to the in-line lasers on the manufacturing line, or a separate laser station off-line, either being a significant capital investment on the part of the PV manufacturer. For either type of PV module, any significant penetration of the architectural market will demand some degree of design flexibility.

The highest-cost glazing that can reasonably be replaced by PVs is tinted, laminated glass with a fritted pattern. This type of glass is used in high-end buildings for atria and exterior curtain walls where safety issues require lamination and aesthetic and/or solar control issues justify the fritted pattern. The cost of this type of glazing is approximately \$130/m^2 (\$12/sf).[3] This number is used as the high-end material credit in the cost analysis.

Insulating PV Units:

Packaging thin film or crystalline modules into architectural insulating units will render the modules more thermally effective, and therefore more attractive to the building market. A PV module may be incorporated into insulated units either as the exterior glass element (fig. 13) or interior glass element (fig. 14). Either approach has certain advantages and disadvantages:

- *Exterior-lite* PV insulating units allow the PV unit direct exposure to the sun. However, since the air space behind the PV is not ventilated, the module operates at a higher temperature, and efficiency is reduced. Furthermore, running wiring from front to back of the sealed unit requires the penetration of the insulating unit seal. Failure of the seal leads to moisture penetration, causing window fog and possible short-circuiting. In sloped glazing applications, building codes require that the inner lite of an insulated unit be laminated. This increases the cost of the unit.

- *Interior-lite* PV insulating units will lose some efficiency due to reflective losses through the outer lite, but will run cooler. For code purposes, the laminated PV unit may replace the standard laminated inner lite, saving cost.

Cost projections for PV insulating units are more speculative than for PVs as single glazing. No standard PV insulating unit exists as a product today, and no prototypes have been built in the US. For the purpose of this report, the cost difference between a standard insulating unit and a PV insulating unit is assumed to be equal to the difference between the PV module and the standard glass lite it replaces in the unit. No additional cost is assumed for provision of wiring, because without actual production experience these costs are difficult to predict. The study assumes that wiring costs within an insulated PV module will not be significant.

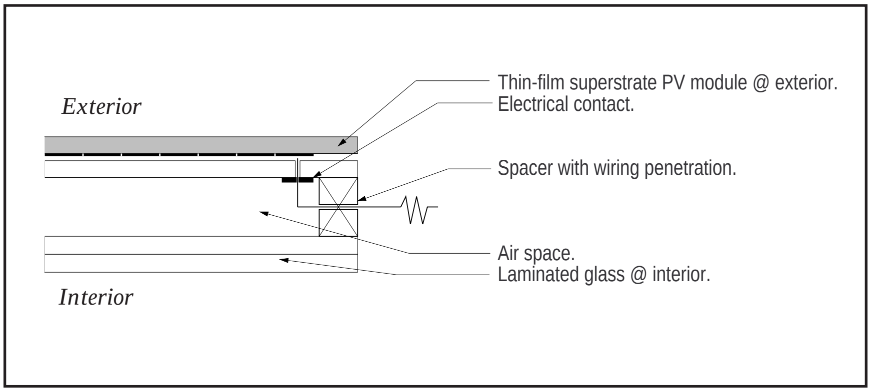

Fig. 13. Detailed section of PV insulating unit with PV as exterior lite (not to scale).

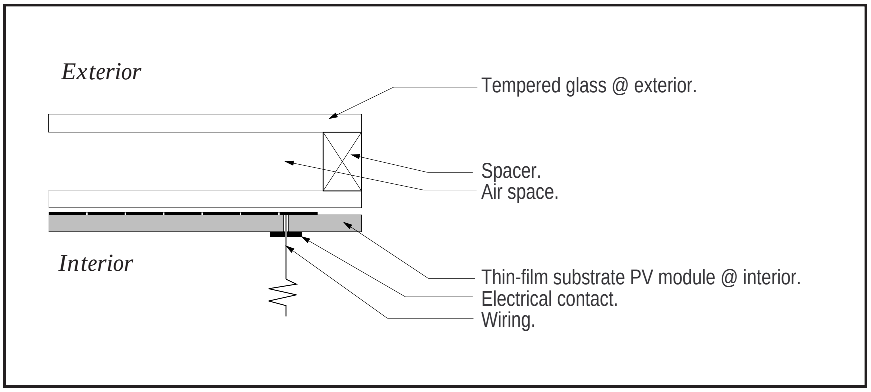

Fig. 14. Detailed section of PV insulating unit with PV as interior lite (not to scale).

IV ADDITIONAL BIPV CONSTRUCTION COSTS

Although BIPV installations offer a number of significant cost savings, there are additional costs and complexities to consider. Ideally, a BIPV module behaves exactly like a piece of architectural glazing as far as building structure and framing systems are concerned, and no additional costs are incurred for structure or installation labor. A BIPV module is also an electrical component, however, and consequently there are other factors which will add costs.

Glazing Construction Methods

Two basic glazing methods exist in conventional glazing construction.

- *Pressure-plate glazing* (fig. 15) consists of horizontal and / or vertical framing members that capture the glass in gaskets and are fastened by the pressure of exterior mullion caps. Details and installation methods vary with individual manufacturer.

- *Structural silicone glazing* (fig. 16), also known as flush-glazing, eliminates the need for a mullion cap by capturing and sealing the glass using a structurally adhesive silicone.

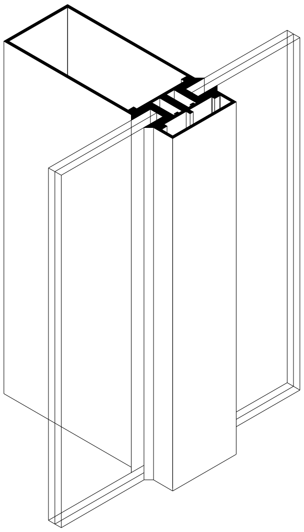

Fig. 15 Pressure plate framing.

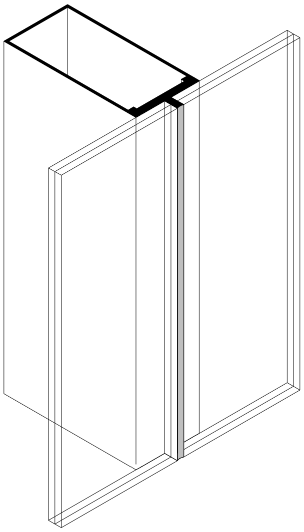

Fig. 16. Structural silicone framing.

PVs in Glazing Construction

Glazing Method:

Both pressure-plate and structural silicon glazing methods are suitable for BIPV applications. Pressure-plate glazing is the more common and less expensive of the two, but has the disadvantage of a projecting mullion cap which casts a shadow on the module. The shadow can be especially disruptive to thin film modules, where a thin shadow that completely covers one of the individual module cells can shut down the entire module. These effects are minimized by using shallow mullion caps and by making a small inactive region at the edge of the module.

In flush glazed systems, shadowing effects are eliminated, but other problems are introduced. The structural silicone sealant which seals the glass at the edge may react with the PV module laminate. In addition, flush-glazed modules are visible in their entirety. Since some PV modules have unfinished or different-colored edges, module edges may have to be painted or otherwise treated. Furthermore, wiring accommodation will be difficult to conceal.

Because there are fewer potential problems with pressure-plate construction, it is the method assumed in performance analyses in this study. Performance calculations, which are done on a per-square-meter basis, do not account for reduced efficiency due to inactive edge zones as discussed above. It is assumed that these effects are relatively insignificant.

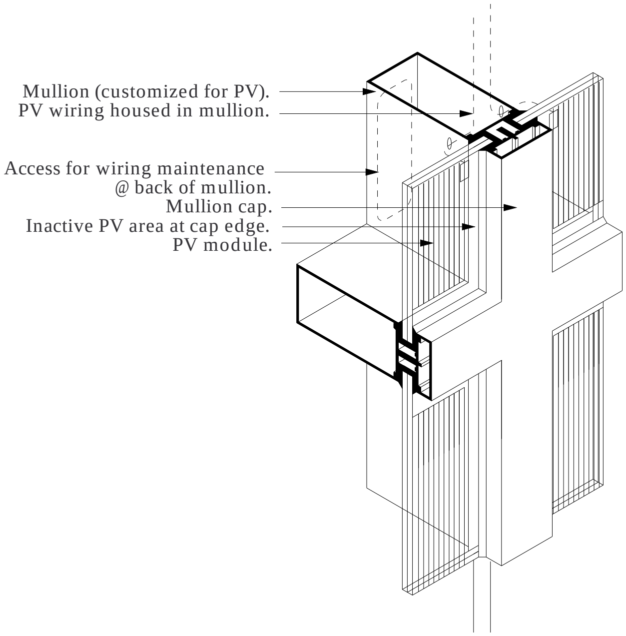

Fig. 17. BIPV glazing detail: single-glazed PV glazing in pressure plate framing.

Wiring:

Wiring may be accommodated by conventional conduit or inside the hollow framing elements if they have been appropriately customized. Figure 18 illustrates options for wiring insulating PV units in pressure plate framing. For insulating units, wiring from a superstrate module must penetrate the air space and seal in order to be concealed within the framing members. Substrate modules avoid any manipulation of the thermal seal, but a wiring cap may be required at the back electrical contact.

Inverters:

Most PV systems use DC wiring to an inverter; there are also small inverters under development ("AC modules") which allow AC wiring between PV modules. In an atrium, these inverters would be visible on the inner surface of the module unless they can be remotely located. This study assumes DC wiring to a large central inverter.

Ventilation:

Heat buildup behind PV modules causes reduced PV efficiency, creates thermal stress which may induce cracking, and increases heat gain into the building. This problem particularly affects curtain wall spandrel areas, which are normally covered by interior finishes. To minimize these problems, a curtain wall or atrium structure requires some degree of ventilation. Ventilation can be accomplished simply by exposing the back face of the panels, but this configuration transmits heat into the interior. An exposed system may be appropriate for spaces with little need for environmental control, such as greenhouses or solariums.

Spaces which require a greater degree of thermal control may justify ventilation. Some examples follow:

- *Convective ventilation* in the framing members is a method used in the APS curtain wall system (fig. 5, 6). Standard curtain walls framing is used to frame uninsulated PV modules. Insulating panels at the back of the framing form a thermally-sealed air space within the frame. This space is then vented to the roof via slots in the mullions.

- *Mechanical ventilation* is a more complex and expensive alternative. If properly designed, excess heat gain may be recovered and used elsewhere in the building via exhaust fans and ductwork.

In many cases, the extra expense of venting will not be justifiable, since the loss in PV efficiency due to heat gain is often negligible and high-end construction considered in this report usually includes sophisticated mechanical systems. In this study, no cost allowance is made for ventilation.

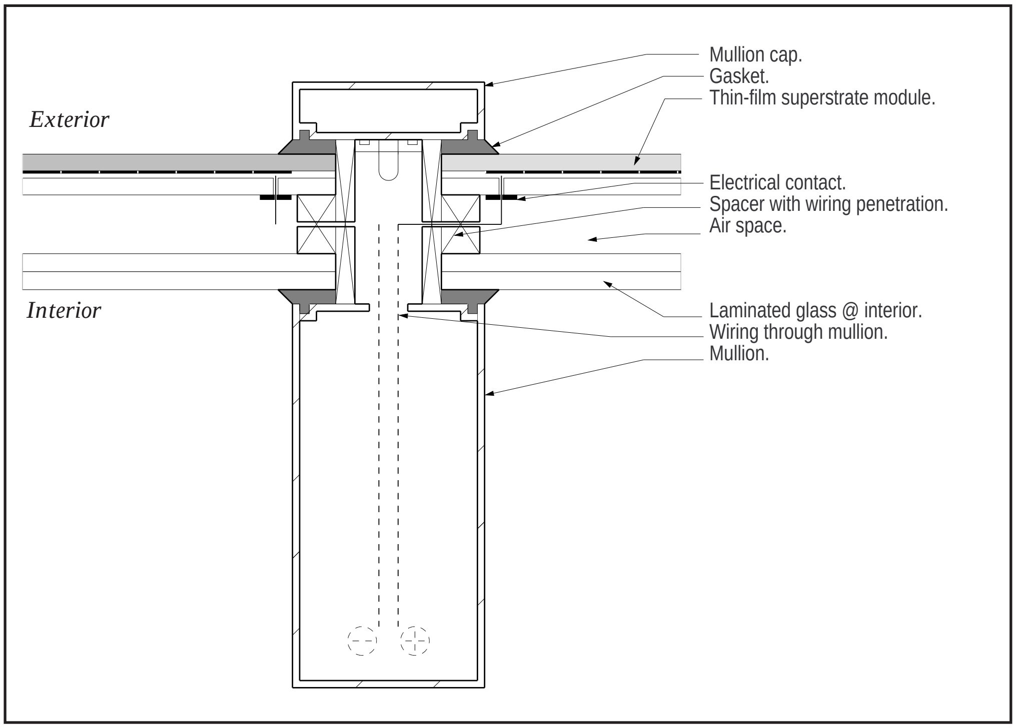

Fig. 18. Detailed section of exterior PV insulating unit in typical framing.

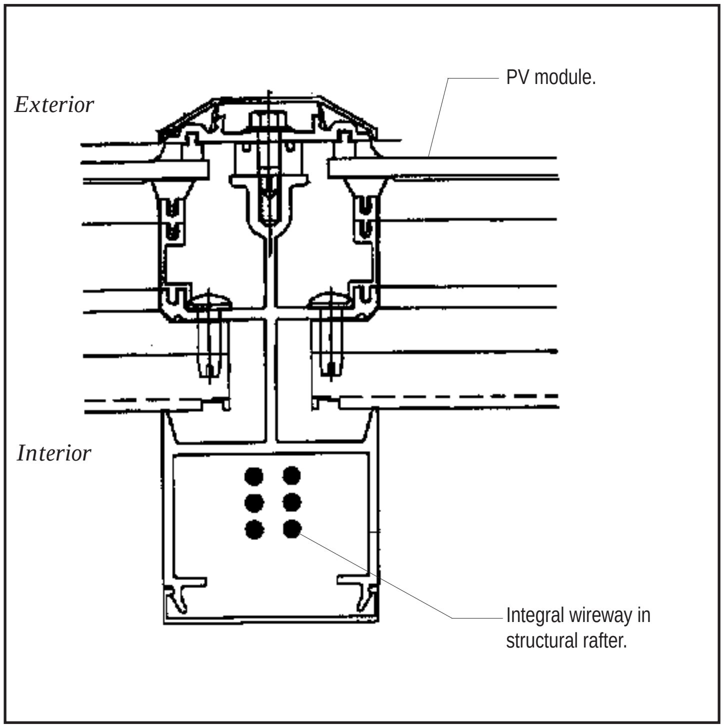

Fig. 19. Cross-section detail of PV curtain wall at BWI Air Terminal (Courtesy of Solar Design Associates).

Construction Codes and PVs

If a glass-to-glass PV module is considered the equal of other laminated glass products by code officials, there is no structural problem in replacing standard laminated glass with PVs. Preliminary projects have been constructed using laminated PVs, but there are no specific code provisions in US national or local codes governing the use of BIPV materials. Likewise, electrical interconnections between modules are typically governed by the interpretation of local code officials of standard electrical codes. No specific provision for BIPV products has yet been made.

The lack of clear code provisions and the rarity of built examples of BIPV systems will cause some code officials to take a conservative attitude toward such projects.

As an active energy source, PV glazing may offset the energy code calculations required for a building's mechanical and electrical loads. For large-scale installations, PVs may provide an opportunity for exemption from energy code regulations altogether.

The BIPV industry is still in its infancy. Until there is a greater body of built BIPV projects, each project will have to be evaluated by local code officials individually.

V. LOCATION

The cost-effectiveness of BIPV systems is as dependent on the value of avoided electricity as it is on insolation or climate. For this reason, locations were evaluated whose average commercial electric rates ranked within the top 15 of average US electricity prices.[4] Average electric rates were then multiplied by the PV output for a latitude-tilt, south-facing 10% efficient cell. The product was used to rank these locations by total PV value as follows:

Rank by Total PV $/m2/yr

Location	*Utility*	*Total PV kWh/m2/yr**	*Average ¢/kWh**	***Total PV $/m2/yr***	
Honolulu	**Hawaii Elec Light**	**202**	**16.99**	**$34.32**	<
Honolulu	Maui Electric	202	13.91	**$28.10**	
Tuscon	**Tuscon Electric Power**	**251**	**10.67**	**$26.78**	<
Los Angeles	**Southern California Edison**	**218**	**10.87**	**$23.70**	<
Honolulu	Hawaiian Electric	202	11.00	**$22.22**	
Phoenix	**Arizona PS**	**250**	**8.24**	**$20.60**	<
San Francisco	**PG&E**	**216**	**8.99**	**$19.42**	<
New York	**Long Island Lighting**	**151**	**12.78**	**$19.30**	<
Bangor	Bangor Hydroelectric	151	12.45	**$18.80**	
Boston	Commonwealth Electric	155	11.83	**$18.34**	
Newark	Jersey Central P&L	163	10.97	**$17.88**	
Philadelphia	Peco Energy	162	11.03	**$17.87**	
New York	Consilidated Edison	151	11.67	**$17.62**	
Concord	PS New Hampshire	150	11.64	**$17.46**	
Boston	W. Massachussetts Electric	150	10.85	**$16.28**	
Hartford	United Illum.	149	10.64	**$15.85**	
Buffalo	Niagara Mohawk & Power	141	10.67	**$15.04**	

Chart 2: Locations ranked by PV output and electric rates.

From this list, six top locations were evaluated in detail. Two of the Hawaiian locations were eliminated to avoid repetition. Detailed rate structures were obtained from each utility and are discussed later in this chapter.

Orientation

Chart 3 shows the effects of array slope and azimuth orientation PV power production for a sample city. South-facing arrays perform consistently better when their slope approaches local latitude. For more vertical tilts (e.g. curtain walls) a southwest (or southeast) orientation produces more power. West-biased curtain walls often provide power with a higher energy value, since many utilities charge higher rates in the afternoon. In any case, optimizing orientation for BIPV atria and curtain walls is dependent upon insolation levels and utility rate structure and will need to be evaluated on a case-by-case basis.

For consistency in the payback analysis, a south-facing orientation is used, with PV array tilts equal to local latitude for atriums and 90° for curtain walls. In addition, shadowing effects are not quantified. It is assumed that the building is located in an optimal environment.

Orientation and shadowing will not always be optimized for BIPV installations. As Figures 1, 2 and 3 illustrate, building integration means less flexibility in defining PV orientation. Site constraints will demand less-than-ideal solar conditions: PV arrays may be forced to face southwest, west or even somewhat north; neighboring buildings may cast shadows on PV curtain walls; PV atria may be periodically shaded by the building to which they are attached, since atria are sometimes several stories shorter than the rest of the building. Even so, PV arrays will perform successfully as a building skin provided that other positive variables affecting BIPV performance exist to offset any losses incurred in PV efficiency, such as high insolation levels, costly local utility rates and/or high material credit construction. Adverse effects may also be minimized by proper building design. However, building environments are difficult to predict. For photovoltaics to succeed in the building market, they must be adaptable to different building conditions. They must perform as a building material first and a PV device second.

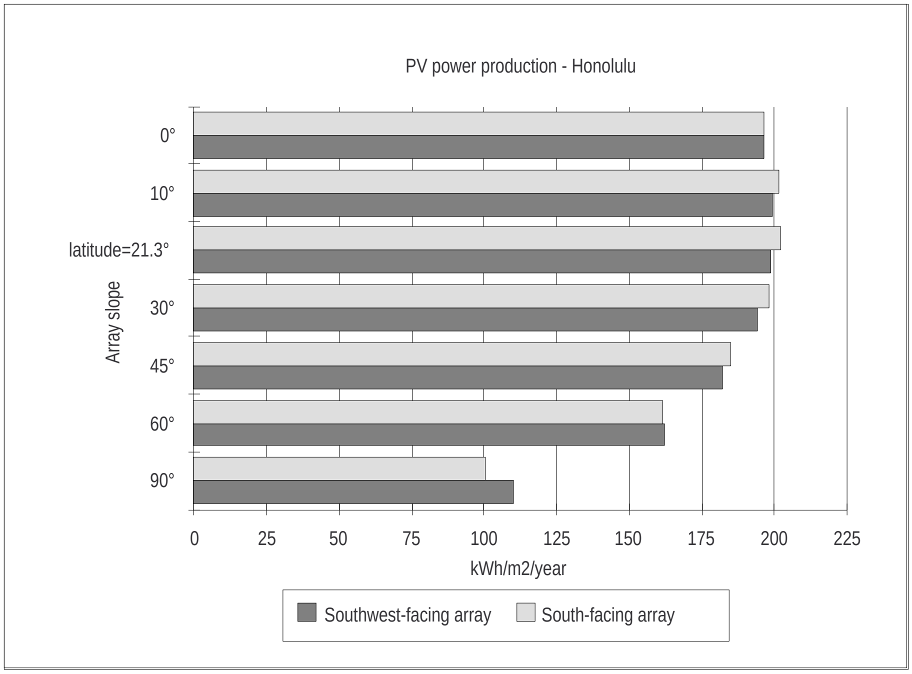

Chart 3: The effects of azimuth and orientation on PV output in Honolulu.

Utility Rates

For the six locations evaluated in detail, the actual value of PV electricity is determined and used as a basis for payback calculations. Utility rate data was collected in one of two ways: 1) from a database compiled by Casazza, Schultz & Associates for the Gas Research Institute, entitled Electric and Gas Rates for the Residential, Commercial and Industrial Sectors: 1994 or 2) from 1995 rate schedules acquired directly from the utility. In each location a rate was found which was applicable to a commercial customer with a peak demand between 300kW and 500kW. When there was more than one applicable rate, the rate that appeared to yield the best return based on maximum time-of-use energy rates was selected.

To obtain the most accurate value of avoided electricity, PV performance is modeled on an hourly, per-square-meter basis for each location using PV-F Chart© software. PV production for each hour of the day for each month is multiplied by the electric rate prevailing at that hour (taking into account time-of-use charges, seasonal variations, surcharges, energy cost adjustments and taxes) to get an hourly energy value of the PV power produced. The annual sum of these energy values is then added to the annual sum of monthly demand charges offset by the PV system. This final sum represents the total energy cost offset by the BIPV installation per year.

Demand Credit

Most commercial and many residential electric rates contain demand charges, whereby billing is based on the highest peak power used over a fixed interval (usually 15 minutes) during the billing period. There is usually one 15 minute period each month when electrical usage is high and the weather is cloudy, at which time the PV system will be producing about 20% of its full capacity. Accordingly, for each utility rate, any demand charges are reduced by 20% of the PV system capacity.

VI. PV TECHNOLOGY

Four different PV technologies are evaluated in the payback analysis. These technologies range from high-efficiency, high-cost/W modules to low-efficiency, low cost/W modules. PV1 and PV2 represent currently available technologies for near-term BIPV applications. PV3 cost and performance figures are assumed to be available in the next five years using any number of high-efficiency thin-film technologies under development.

PV4 is a more aggressive projection based on advanced thin film technologies. Recently, a number of reputable companies have issued near-term cost projections substantially lower than previously considered possible. PV4 reflects these lower costs. In some assessments, these costs could be available in five to ten years. Since substantial construction projects can take several years to plan, design and build, this aggressive projection for the year 2000 may be compatible with construction projects that are in the planning stages today.

PV1 Crystalline Silicon
(Assumes 140 W/m^2, \$4.40/W$_p$ module cost.[5]
PV2 Amorphous Silicon
(Assumes 52 W/m^2, \$3.00/W$_p$ module cost.[6]
PV3 High-efficiency thin-film
(Assumes 108 W/m^2, \$2.00/W$_p$ module cost.[7]
PV4 High-efficiency thin-film - projected
(Assumes 130 W/m^2, \$1.00/W$_p$ module cost.[8]

Figures 8-12 illustrate typical diagrams and details of glass-based crystalline silicon and thin-film modules.

VIII. PAYBACK

Building clients and utility organizations typically measure the value of renewable energy installations in terms of the time it takes to pay back the initial capital cost. Most commercial building owners and users in the US today are unwilling to consider investments beyond a 5-year payback. According to a study by Arthur D. Little, BIPV: Analysis and US Market Potential, "the threshold payback period required to initiate a significant market penetration is on the order of four to five years."[9] Furthermore, the study estimates that acceptable payback periods are somewhat shorter when viewed from the customer perspective and slightly longer from the utility perspective. Once BIPV payback periods reach acceptable levels, the BIPV industry should be able to penetrate a larger portion of the US commercial building market.

Charts 6-21 show payback results for PV atria and curtain walls in six US cities using four PV technologies. In each case, the total additional cost premium for a PV system is divided by the retail value of electricity avoided. Two sets of payback charts are provided, which illustrate two of the principal variables affecting payback periods: construction material credit and tax depreciation allowance. These variables are discussed in the following sections.

Summary of Cost Assumptions

Chart 4 outlines the various cost assumptions made concerning construction methods and material credits, wiring and power conditioning. The costs are given for each of the four PV technologies, and are expressed both in $\$/m^2$ and $\$/W_p$. Individual cost factors are defined, by line number, as follows:

1 PV modules:

As outlined in the previous chapter, industry-standard, present-day PV costs are used for crystalline and amorphous silicon technologies. Predictions are made for advanced thin-film technologies using prominent PV and utility industry sources.[10]

2 PV wiring:

These costs depend upon the size of the system, the methods used to connect the modules in series and the methods used for home runs to the inverter. For PV1, the allowance is equivalent to $\$0.25/W_p$. By comparison, the AD Little study, BIPV: Analysis and US Market Potential, assumes a range of $\$0.30$ - $\$0.20/W_p$ for similar systems.[11] Wiring costs decrease for PV4 because more efficient wiring techniques and product development (conduit built into framing extrusions, for example) will drive prices down.

	PV1: Crystal. Si, 1995		PV2: a-Si, 1995		PV3: CIS/CdTe, future1		PV4: CIS/CdTe, future2	
	W/m2 =	**140**	**W/m2 =**	**52**	**W/m2 =**	**108**	**W/m2 =**	**129**
	$/W =	**$4.40**	**$/W =**	**$3.00**	**$/W =**	**$2.00**	**$/W =**	**$1.00**
	($/m2)	($/W)	($/m2)	($/W)	($/m2)	($/W)	($/m2)	($/W)
PV modules	$615.72	$4.40	$155.01	$3.00	$215.29	$2.00	$129.17	$1.00
PV wiring	$34.88	$0.25	$34.88	$0.68	$34.88	$0.32	$12.92	$0.10
Other indirect	$55.97	$0.40	$20.67	$0.40	$43.06	$0.40	$51.67	$0.40
Power Conditioning	$111.95	$0.80	$41.33	$0.80	$86.11	$0.80	$38.75	$0.30
	$818.51	$5.85	$251.88	$4.88	$379.33	$3.52	$232.51	$1.80
Material credit: (Laminated/fritted glass)	($129.17)	($0.92)	($129.17)	($2.50)	($129.17)	($1.20)	($129.17)	($1.00)
Subtotal	$689.34	$4.93	$122.71	$2.38	$250.16	$2.32	$103.34	$0.80
Markup factor @ 15%	$103.40	$0.74	$18.41	$0.36	$37.52	$0.35	$15.50	$0.12
Tax credit @ 10%	($68.93)	($0.49)	($12.27)	($0.24)	($25.02)	($0.23)	($10.33)	($0.08)
Construction location factor (San Francisco)	$165.44	$1.18	$29.45	$0.57	$60.04	$0.56	$24.80	$0.19
Total system cost	**$889.25**	**$6.35**	**$158.30**	**$3.06**	**$322.71**	**$3.00**	**$133.30**	**$1.03**

Chart 4: Summary of PV system and construction cost assumptions for the payback analysis (sample location: San Francisco).

3 Other indirect:

These costs allow for miscellaneous PV system design and distribution costs such as engineering, permits, shipping, insurance and project management.[12]

4 Power conditioning:

Inverter and electrical equipment are included in these quantities. Estimates are relatively conservative and assume a 300-500 kW PV system size. As with wiring, the projected cost for PV4 assumes that improvements in the electrical equipment will bring prices down.

5 Material credit:

Glazing material costs considered in this report are equivalent to typical, present-day values used by the US building industry. For the payback analysis, the highest material credit is used: $129.17 for laminated, fritted glass.[13]

7 Markup factor:

A 15% distributor's markup is included.

8 Tax credit:

A 10% federal energy tax credit is given for the PV system.

9 Construction cost location factor:

Since construction costs vary greatly with location, a factor is applied to the complete system cost for each city evaluated. The factors, taken from Means Construction Cost Data, are as follows:[14]

City	*Location factor*
Honolulu	1.20
Tuscon	0.90
Los Angeles	1.12
Phoenix	0.90
San Francisco	1.24
New York	1.24

Payback Results

Payback as a function of construction material credit:

The payback periods for existing high efficiency technology (PV1) are considerably longer than for existing and future thin-film technologies (PV2-4). This is due partly to the high cost of modules, partly to the effects of construction material credit. Regardless of higher efficiency, PV1 applications suffer from higher material costs which are not significantly affected by construction material credits. Charts 6-13 illustrate the effects of construction material credits on payback.

PV2 and PV3 applications perform better, with payback periods between 10-20 years for atria and 15-30 years for curtain wall applications. PV2 performs as well as PV3 in this study despite a significantly lower efficiency and higher cost/watt, because its lower cost per area is offset to a greater extent by the construction material credit. Put another way, the cost of fritted glass is 83% the cost of PV2 per square meter; the same glass is only 60% the cost of PV3 per square meter and 21% the cost of PV1 (see chart 1).

Future thin-films (PV4) show payback periods under 5 years for PV atria and 10 years for PV curtain walls. The cost of PV4 is equal to the cost of fritted, laminated glass per square meter. Ultimately a thin-film PV is a very similar product to laminated architectural glass: both are coated with thin metallic films and encapsulated. A PV module has electrical connectors missing from architectural glazing, but fritted glass has the laborious and energy-intensive steps required to silkscreen and fire a ceramic pattern.

Chart 5 illustrates the progressive effects of increasing material credits on PV1 - PV3 in Los Angeles:

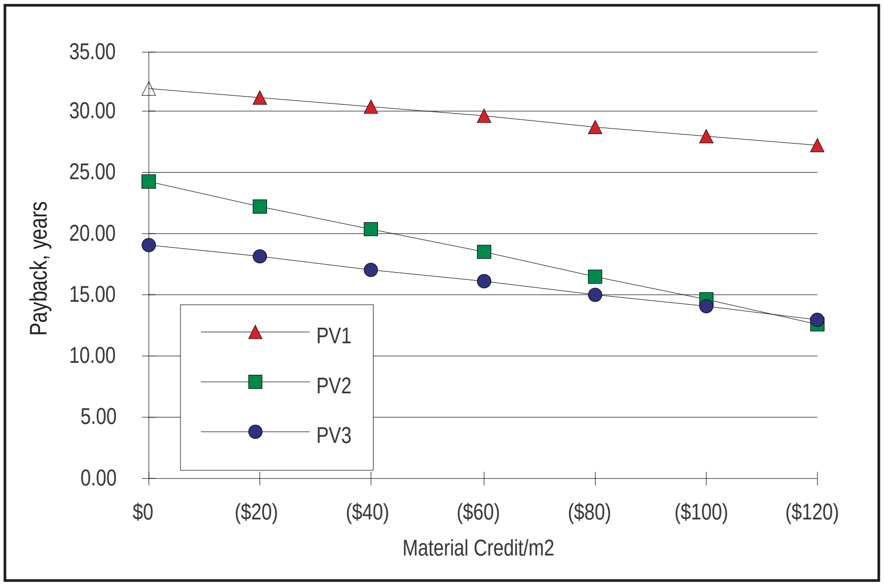

Chart 5: Material credit trend for PV atrium in Los Angeles.

Charts 6-13 illustrate the effects on payback of material credits for all locations. The material credit values range from \$67/m^2 for standard tinted, laminated glass to \$129/m^2 for fritted, laminated glass. Most other atrium glazings will fall within this range.

Payback for PV Atria:

Material credit comparison

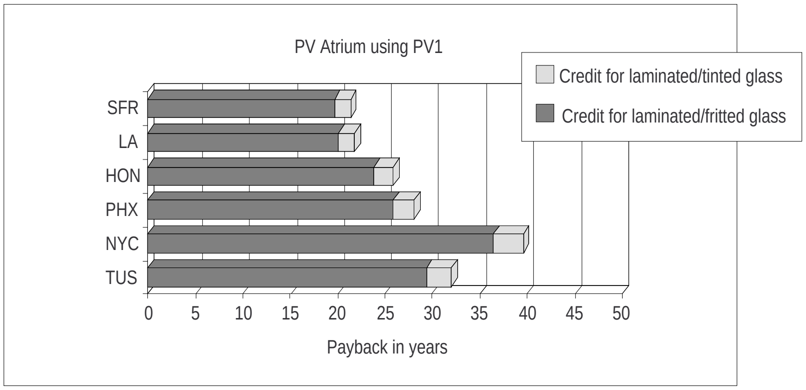

Chart 6:
Payback periods for BIPV atria using crystalline silicon modules (PV1).

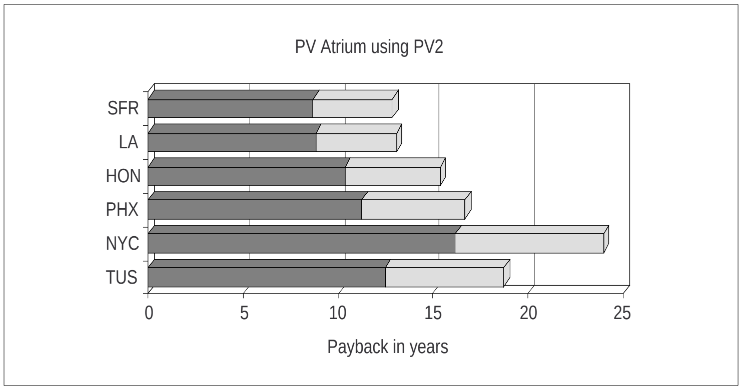

Chart 7:
Payback periods for BIPV atria using thin-film amorphous silicon modules (PV2).

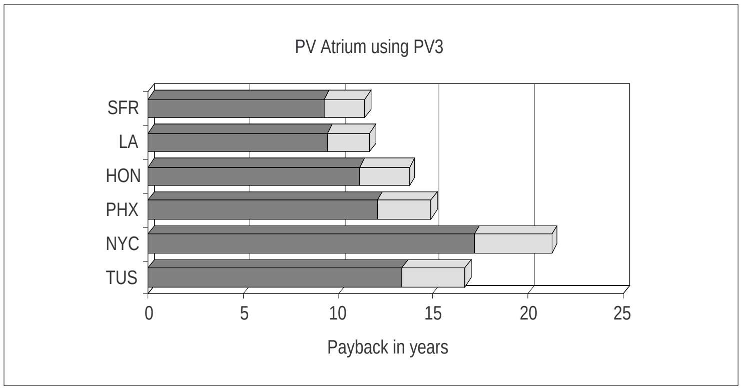

Chart 8:
Payback periods for BIPV atria using thin-film CIS modules (PV3).

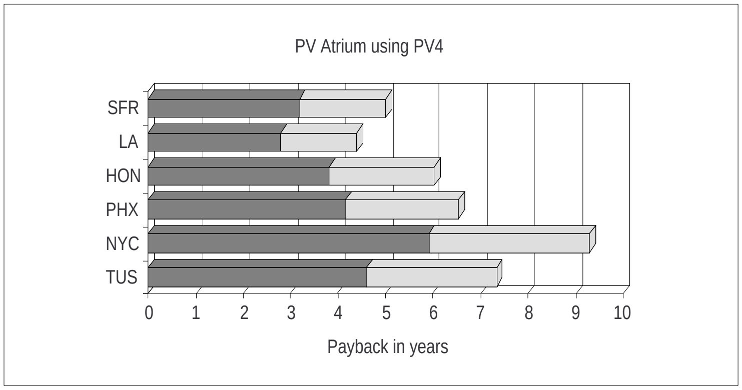

Chart 9:
Payback periods for BIPV atria using future thin-film technology (PV4).

*Analysis uses a 30% depreciation credit.

Payback for PV Curtain Walls:

Material credit comparison

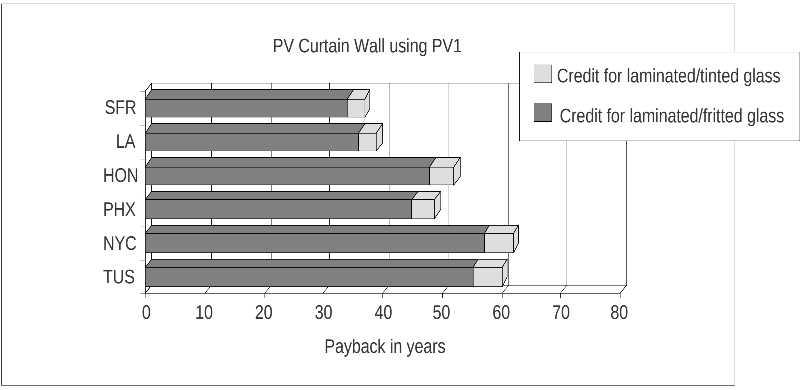

Chart 10:
Payback periods for BIPV curtain walls using crystalline silicon modules (PV1).

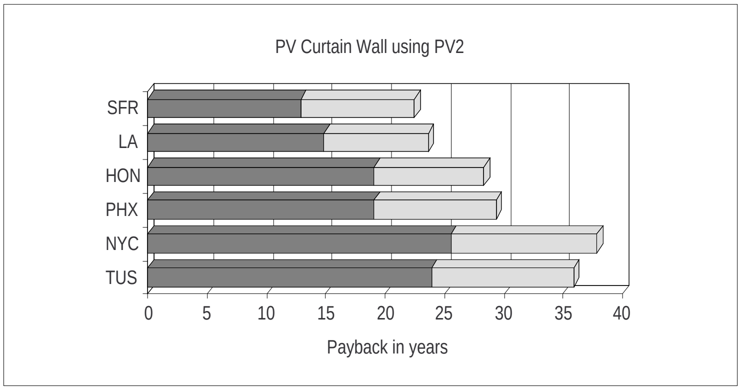

Chart 11:
Payback periods for BIPV curtain walls using thin-film amorphous silicon modules (PV2).

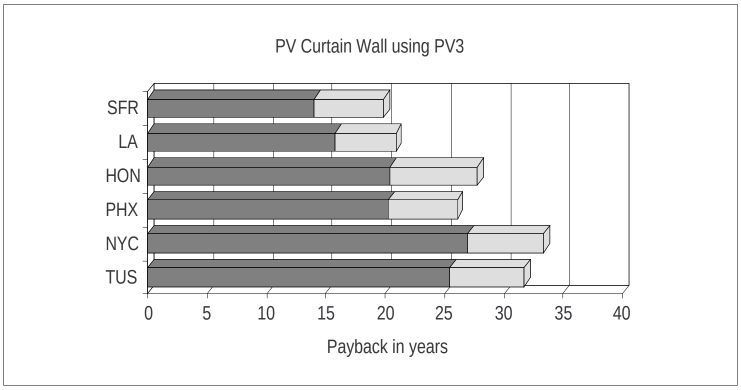

Chart 12:
Payback periods for BIPV curtain walls using thin-film CIS modules (PV3).

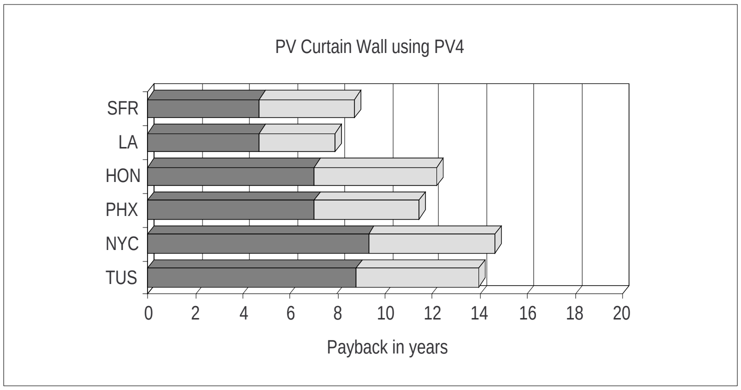

Chart 13:
Payback periods for BIPV curtain walls using future thin-film technology (PV4).

*Analysis uses a 30% depreciation credit.

Payback as a function of depreciation allowance:

In the United States, there are few incentives offered by municipalities or utilities for PV systems, as are available in many European countries. However, existing federal tax provisions can amount to a significant incentive for qualified PV system owners. The 10% Federal Energy Tax Credit has been factored into all the system costs evaluated. There is also a 5-year accelerated depreciation allowance for Alternative Energy Properties, including PVs. For businesses in the highest tax bracket, the value of the depreciation approaches 40%. In the following set of payback charts, the effects on payback of depreciation credits of 0% - 30% are illustrated using a material credit for fritted glass.

Payback for PV Atria:

Depreciation credit comparison

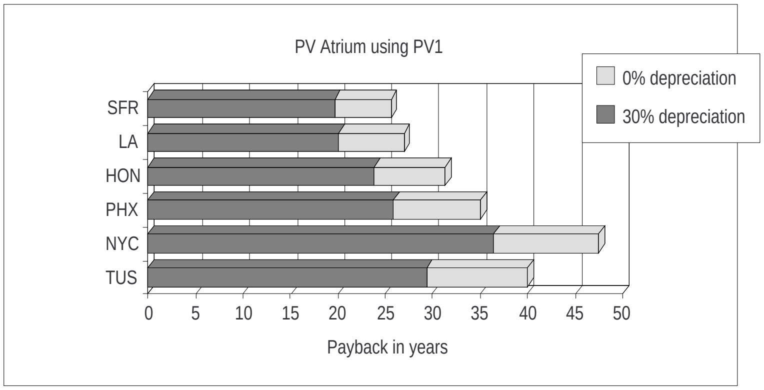

Chart 14:
Payback periods for BIPV atria using crystalline silicon modules (PV1).

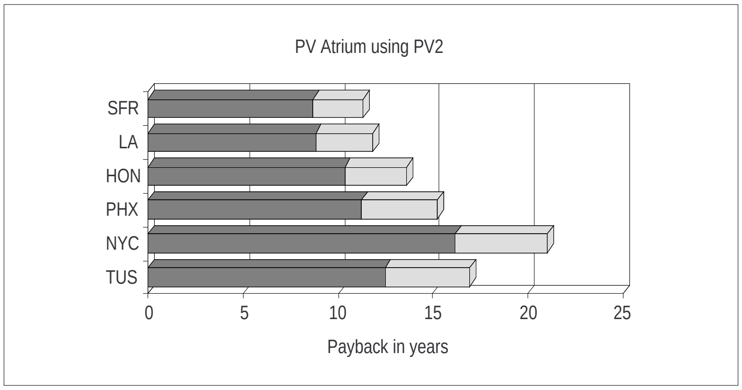

Chart 15:
Payback periods for BIPV atria using thin-film amorphous silicon modules (PV2).

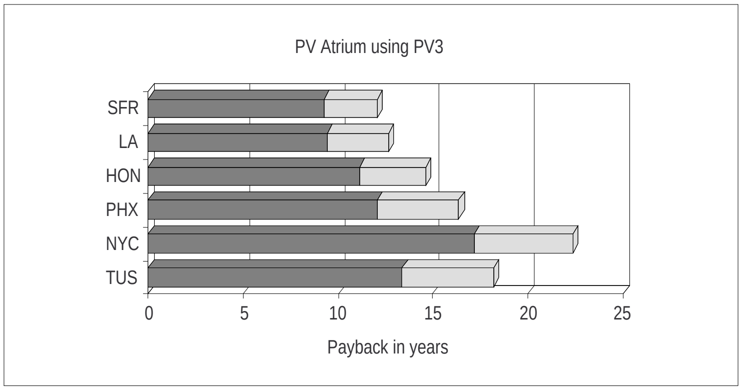

Chart 16:
Payback periods for BIPV atria using thin-film CIS modules (PV3).

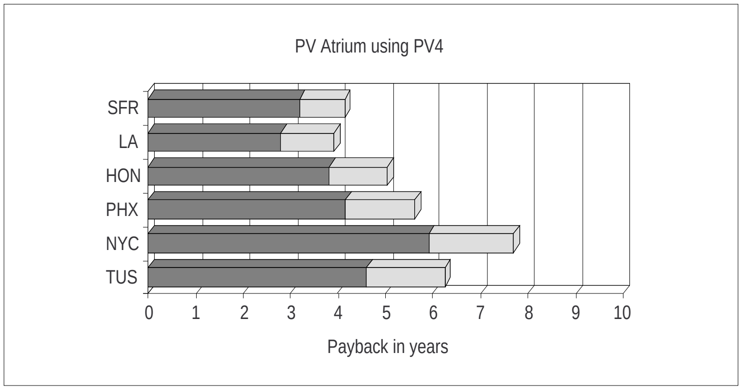

Chart 17:
Payback periods for BIPV atria using future thin-film technology (PV4).

*Analysis uses material credit for fritted glass.

Payback for PV Curtain Walls:

Depreciation credit comparison

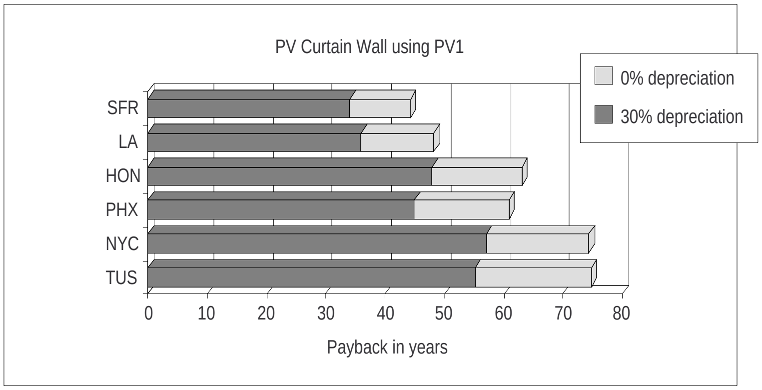

Chart 18:
Payback periods for BIPV curtain walls using crystalline silicon modules (PV1).

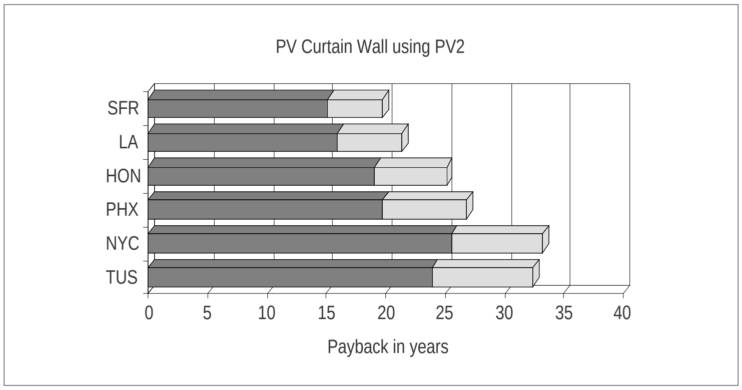

Chart 19:
Payback periods for BIPV curtain walls using thin-film amorphous silicon modules (PV2).

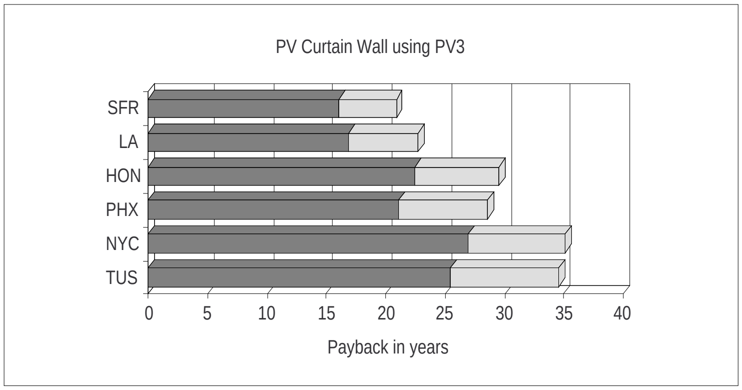

Chart 20:
Payback periods for BIPV curtain walls using thin-film CIS modules (PV3).

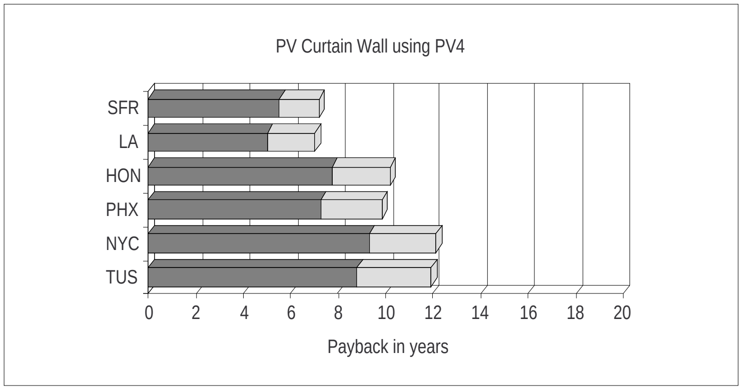

Chart 21:
Payback periods for BIPV curtain walls using future thin-film technology (PV4).

*Analysis uses material credit for fritted glass.

VIII. PAYBACK AND ARCHITECTURAL VALUE

Monetary payback is not the only criterion in selecting an architectural finish material, and often it is not a criterion at all. Traditional architectural finishes have no payback period per se, but are selected on the basis of intangible criteria – as much for aesthetic reasons as for perfomance and cost. A curtain wall, whether it be glass, stone, metal panel, or a mixture, is rarely the cheapest way to clad a building. No one evaluates the simple payback of an atrium or a curtain wall.

Since BIPVs produce electricity, the tendency is to evaluate them the same way as we evaluate equipment like energy-efficient chillers or lighting systems. In high-end curtain wall and atrium applications, however, BIPVs also function as high-end building materials. If PV manufacturers can deliver modules with appealing aesthetic qualities, the importance of financial payback will decrease. BIPV materials would then be judged with the same intangibles as other architectural cladding materials. BIPVs have clear appeal as part of a very high-tech design vocabulary, with the aesthetic qualities of fritted glass, and the considerable “green” value of PVs.

These intangible values will, in many cases, make the issue of payback recede to secondary importance.

IX. CONCLUSIONS

- With existing technologies, high-value BIPV atrium applications show payback periods under ten years in two out of six locations evaluated: San Francisco and Los Angeles. The average payback periods for the four PV technologies were:

PV1:	25.9 years
PV2:	11.3 years
PV3:	12.0 years
PV4:	4.1 years

  PV2 is an existing technology, and PV3 and PV4 may be available within one to five years. For the long-term investor, BIPV is economical in the right project now. When PV4 cost / performance levels are achieved, a broad market should exist for BIPV in many commercial buildings. Many inexpensive office and retail developments even with low construction budgets feature atria and other focused architectural features to distinguish themselves in a competitive market.

- Curtain walls in this analysis had approximately 70% longer paybacks than atria. Despite this, the curtain wall market should also be viable in the near future. The average payback figures for the six locations were:

PV1:	43.6 years
PV2:	19.2 years
PV3:	20.5 years
PV4:	6.9 years

  In some cases, curtain wall applications will perform relatively better. For consistency in comparision between atria and curtain walls, a true south orientation was used for all systems evaluated in this report, but in many cases a southwest orientation will perform better for curtain walls (see Chart 3, p.22), not only in total power produced but also in value of electricity offset, when time of use billing charges are in effect.

  With present technologies, San Francisco yielded a 12.9 year payback and Los Angeles 14.8 years. With PV4 criteria, all locations had payback periods under 10 years, and the California locations were under five years.

- The material credit and the depreciation tax allowance are both extremely important to the economics of BIPV systems. Of the two, the depreciation credit affects present day, high-cost per square meter technologies more than the material credit, since the tax credit is related to total system cost. Conversely, the material credit becomes relatively more important as PV costs per square meter decline. Both of these factors are not widely appreciated by the building and design communities at present.

- If PVs are seen to be architecturally competitive with high-end building products like fritted glazing, they can achieve the favorable economic scenarios in this report. In order to do so, manufacturers must offer these products at competitive prices, with all the performance, safety and aesthetic features of standard building products. This will mean a degree of flexibility in size, appearance and other specifications that no PV manufacturer has yet demonstrated.

- To achieve the most aggressive cost projections associated with PV4, the challenge to improve other balance-of-system components such as wiring systems and inverters will be as important as refinements to PV technology. Ultimately, as the cost of the PV module approaches the cost of standard glass, the incremental cost of a BIPV system will approach the cost of the wiring and inverters alone.

FOOTNOTES

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Solar Design Associates, Cambridge, MA.
Solarex, Frederick, MD.
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