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Building-Integrated Photovoltaics

Kiss Cathcart Anders Architects, P.C.

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by the Midwest Research Institute
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NREL Technical Monitor:
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'Building Integrated Photovoltaics' prepared by:
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Report cover:
Paving pattern depicting sun dial and photovoltaic effect, Fairfield, California; designed by KCA Architects, 1992.

I. Introduction

Public consciousness, market forces, and (to a small extent) government policy have promoted a trend toward the development of sustainable architecture in the United States. In the last twenty years, great improvements have been made in the energy efficiency of buildings. The gains already made are just a start to the process, however. Photovoltaics (solar electric cells or ‘PVs’) integrated into buildings can help to take building technology to the next step, by generating electricity while enhancing efficiency. At the same time, building integration will improve the economics of photovoltaics.

Do photovoltaics make sense as a building product? Recent trends in PV and building technologies imply that they will. First, PVs have become cheaper, although they are still not generally competitive with utility electricity. Second, buildings have become much more energy-efficient, and the incentives are great for further improvements. The integration of PVs into buildings could effectively decrease the cost of the PV system while transforming building skins from energy consumers to energy producers.

Photovoltaic modules are typically produced on glass or metal substrates similar to traditional building materials. Advances in production technologies have led to large size modules which approach the size of standard construction components. There are potentially several levels of symbiotic benefits between PVs and buildings: 1) to the extent that a PV product replaces a building material, the value of that material can be deducted from the cost of the PV system; 2) if a PV device is part of a building, the structure supporting it and the cost of the land it sits on are paid for, and 3) a PV building element, oriented to capture the most possible light, can also reduce cooling loads by its shading effect. The value of these subsidies may make PVs cost-effective in cases where they wouldn’t be otherwise.

Another benefit to the economics of building-integrated PVs lies in the ownership and use of the system. A traditional view of PV power generation is of large arrays in desert fields, owned by utilities who sell the power to their customers. Building-integrated PVs will likely be owned by the building owner, and the power they generate will in most cases be used within the building. Many buildings (particularly commercial ones) consume most of their power during the day, when electricity is most expensive. Any power generated by the PVs and used in the building saves the owner the peak cost of the equivalent utility electricity, while power sold back to the utility is usually sold at a much lower rate. The value of building-integrated PV power to a building’s owner is full retail; the value to a utility is wholesale.

II. Objective

This is a study of the issues and opportunities for building-integrated PV products, seen primarily from the perspective of the design community. Although some quantitative analysis is included, and limited interviews are used, the essence of the study is qualitative and subjective. It is intended as an aid to policy makers and members of the technical community in planning and setting priorities for further study and product development. It is important to remember that the success of a product in the building market is not only dependent upon its economic value; the diverse group of building owners, managers, regulators, designers, tenants and users must also find it practical, aesthetically appealing and safe.

The report is divided into 11 sections. A discussion of technical and planning considerations is followed by illustrative diagrams of different wall and roof assemblies representing a range of possible PV-integration schemes. Following the diagrams, several of these assemblies are then applied to a conceptual test building which is analyzed for PV performance. Finally, a discussion of mechanical/electrical building products incorporating PVs is followed by brief surveys of cost issues, market potential and code implications.

The scope of this report is such that most of the discussion does not go beyond stating the questions. A more detailed analysis will be necessary to establish the true costs and benefits PVs may provide to buildings, taking into account PV power revenue, construction costs, and "hidden" costs and benefits to building utility and marketability.

III. Considerations in Designing Building Envelopes for PVs

The following discussion attempts to identify pertinent issues to be considered when designing, producing, constructing and marketing building-integrated PVs. Central to the study of PV-building design is the conflict between PV solar considerations and contemporary building conventions. The primary goal in PV power systems layout is to maximize the amount of power generated via optimum array orientation, but this goal is tempered in the case of building design by considerations of construction costs, optimum building floor area, daylight control, thermal performance, and aesthetics. PV panels are usually oriented at a tilt equivalent to the local latitude in order to receive maximum solar radiation, while building walls are generally vertical for reasons of economy, efficiency and tradition.

In addition, building envelopes are often designed to deflect and minimize the amount of radiation falling on a building's surface, since cooling is usually the largest consumer of energy in a building. In contrast, photovoltaics need the most possible radiation in order to perform optimally.

The issues of building-integrated PV design are not exclusively technical. The balance between the issues of PV-building design and construction will vary greatly according to the circumstances of each project (climate, budget, client priorities, aesthetics, etc.).

A. SOLAR CONSIDERATIONS

Photovoltaic Panel Performance

Optimizing PV panel performance in building wall applications will usually require more complex detailing and therefore higher construction costs in order to accommodate optimal orientations to the sun. For wall applications, these complex configurations may take on a sloped or "sawtooth" profile (*see diags. E,F,G,H, pp. 16-19*) or the PVs may be applied independent of the building's skin as awnings or light-shelves (*diags. C,D, pp. 14-15)*. For roof applications, installations generally will require little compromise in solar orientation but may create structural or weatherproofing problems.

Passive Solar Performance:

PV panels may provide energy benefits beyond the electricity they generate by providing passive solar heating or cooling load reduction.

PV Awnings/Skylights:
Opaque PV panels installed as PV window awnings *(diag. C, p.14*) or partial PV skylight enclosures (*diags. K,L, pp. 21-22*) will shade interior spaces from direct sunlight while simultaneously harnessing power from the sun's rays. PV roof monitors could also reduce or eliminate the need for daytime electric lighting by providing indirect daylight.

PV Light Shelves:
PV light shelves (*diag. D, p.15)* can shield direct sun while providing diffuse, indirect light to interior spaces. The portion of these light shelves which are exposed to sunlight would be PVs; the portion in shade could be any reflective material. The panels' surface would bounce light onto the ceiling inside.

PV Windows:
Another PV device with some passive solar benefits is the semi-transparent photovoltaic panel, or PV window, designed to admit a specific amount of light and/or view to a space (*see diag. A, p. 12)*. Some thin-film PV devices are inherently semi-transparent if produced

with clear conductive coatings on glass substrates. Alternatively, opaque PV devices may be rendered effectively transparent by the creation of a pattern of clear areas where the opaque materials have been removed. It should be possible to incorporate semi-transparent PVs into insulating or high performance (low E) multi-pane glazing units.

With less active PV area, the solar performance of these semi-transmissive panels will be less than opaque PVs. But the passive benefits and vision area produced in some cases will outweigh the reduction in efficiency.

B. DESIGN CONSIDERATIONS

Representation

The vocabulary of "solar" (specifically, passive solar) design has not been widely accepted by architects. More often than not, designers view solar design as a limitation rather than an opportunity. Although it has been used in visionary projects, many architects and clients feel that solar architecture implies rigid design limitations regarding orientation, placement of windows, sloping roof elements, sun spaces and so on. Such design can also exact penalties in lifestyle by requiring occupants to operate insulating shades or pumps and restricting the placement of rugs or furniture on a thermal collector floor slab. Such projects may not function properly if all the prescribed procedures are not followed.

While PVs are perfectly compatible with projects of this kind, they should also be compatible with many other existing types of buildings not commonly associated with solar design (in particular, larger-scale, non-residential applications); PVs may even serve to create entirely new building types.

By virtue of their flexibility and (ultimately) their economy, PVs' solar performance will not necessarily dominate design criteria; human function, comfort and architectural quality will not have to be compromised. Designers will have the option of suppressing or expressing PV components, introducing an entirely new language to architectural expression and technology, providing new design opportunities for architects and engineers and new markets for manufacturers.

Aesthetics

In the long run, designers will need choice in the appearance and nature of PVs. Some variety of color, texture, reflectance, and transparency will be desirable. Flexible substrates such as sheet metal or fabric (*diag. Q, p. 26)* would open up large new markets. PV devices that mimic traditional building materials (such as clay roof tiles) may also increase their market.

Economy

The inherent flexibility of PVs compared to other types of solar collectors (wiring is inherently easier to run than plumbing), combined with anticipated low material cost (thin-film PVs on glass substrates are basically similar to coated architectural glass), raises the possibility that they can be used as a building material first, as a PV device second. Thus an architect desiring a monolithic appearance to a building may choose to clad all of a building's surfaces with PVs, even those that will never see the sun. If the economics permit, PVs can be used in any number of building component configurations and without an overriding demand for optimal orientation. If PV orientation is not perceived as a design restriction, architects will be much more open to their use.

Engineering

The mechanical and electrical systems required to maintain and operate a substantially-scaled building are often complex and can expend a tremendous amount of energy. PVs provide both additional benefits and additional levels of complexity to the engineer's task. PV buildings will challenge engineers to develop innovative solutions for integrating a building's support systems with PV-supplied power. Critical issues to consider for engineering systems integration will be, among others, safety, durability and economy.

Product Development

PV building-integrated systems offer a challenge among a multitude of trades and organizations in the building industry to develop new lines of PV-building packages for either retrofit or for large scale installations. Some of these possible smaller-scale product options are discussed in more detail in Section VI of this report.

C. SITE CONSIDERATIONS

Real Estate

Building floor area can be a precious commodity. In some cases, PV panel configurations will reduce the amount of occupiable perimeter floor area because the wall effectively 'cuts back' on floor area as the building gets taller (*diags. G,H, pp. 18-19)*. Any reduction in usable floor area needs to be considered when evaluating the life-cycle costs of a PV system.

High-Rise vs. Low-Rise

High rise structures are usually built in an urban environment where real estate costs are high and the surrounding landscape is dense. Shadows cast by other tall buildings reduce the performance of the panels. It may be that for certain high rise projects, only the upper stories will be clad with PVs. Or if a uniform appearance is desired, it may make sense to clad all of a tall building in PVs with only some areas active during the course of a day. These types of buildings may benefit from the control systems mentioned in Section F.

Litigation

PV building applications in a dense urban context also raise potential legal issues. Shadows cast by neighboring high rises upon PV walls could reduce revenues to owners and may induce them to claim legal rights to sunlight.

D. CLIMATIC CONSIDERATIONS

Locations and their Climates

Latitude, average cloudiness, average temperatures, precipitation, humidity, dust/dirt, wind loads, seismic conditions: all these issues will affect the economics of a PV-integrated building by virtue of how they are addressed in the envelope design. The methods for addressing these issues follow:

Insulation

Both mild and extreme climates require good insulating properties at the envelope. PV panels may be directly laminated with insulation or may be incorporated into multi-layer air- or gas-filled insulating units. Electrical connection design will also need to take into account thermal bridging.

Water

The envelope system must be designed to resist any water which may permeate the skin and potentially infiltrate not only the framework, but the photovoltaic panel interlayer. Electrical connections which penetrate the weather seal must also be designed to perform reliably. In climates where clear/cold days mean substantial and immediate temperature changes on building surfaces, the PV envelope system needs to resist or eliminate the moisture build-up that develops as hot panels are rapidly cooled when the sun sets.

Wind/Snow/Seismic Loads

PV substrates and framing members will need to be stiff and yet flexible enough to account for considerable deflections due to wind and/or snow loads.

Wind loads may be substantial for vertically-oriented curtain wall panels on both high rise buildings as well as low-rise structures in open-field landscapes. The taller the structure, the higher the wind loading upon the envelope. In addition, independent PV awning systems, light shelves and rooftop array configurations will require substantial bracing to resist the gusting and uplift which develops at a building's exterior surface. This latter issue is particularly important for independent arrays mounted on the roofs of high rise structures where wind velocities can be substantial and conventional bracing methods meant for field-mounted arrays may not be sufficient.

Horizontal roof configurations on skylights and rooftops must be structured to accommodate other types of loading such as snow and water. This issue will require different solutions depending upon the location of the building. In climates where snow accumulation is considerable, skylights and roof systems incorporating PVs may need to be designed at a slope sufficient to shed snow, which may be steeper than the optimal slope for solar gain.

In some cases, seismic design criteria may dominate. Any dynamic loads will have to be resisted by the building's structure, which may increase costs, especially in retrofit construction.

Lightning

The impact of lightning on PV building envelopes is another important environmental issue. PV structures will need to be grounded and circuited to prevent a possible power surge which may result in damage to the panels or a hazard to their occupants.

E. CONSTRUCTION CONSIDERATIONS

Installation

For both new construction and retrofit, the method of installation is important to the cost effectiveness of the system. For example, glazing installation from the interior does not require building exterior scaffolding. Interior glazing is a common method of contemporary curtain wall installation today, accommodated via splitting the mullion and muntin extrusions into separate elements which snap into place in the field.

Shop labor is usually cheaper and more precise than field labor. Whenever possible, panelized or prefabricated wall or roof sections will save money, especially for complex PV wall profiles. Prefabricated systems could also include some electrical balance of systems or PV-powered devices such as fans or lights.

It is important to recognize that the integrated nature of architectural applications of PV installations (curtain wall framing, glazing systems, PVs and electrical connections, etc.) will require the combined efforts of a number of different building trades and jurisdictions. Conventional construction sequences and responsibilities must be considered in the development of PV products, if they are to fit present construction industry practice.

Dimensions

The number of elements and amount of material in a building's envelope increases with the complexity of the wall or roof profile, with a corresponding impact on cost. For curtain walls systems, typical horizontal mullion spacing is in the neighborhood of 4'-0" between each member; vertical mullion spacing is typically between 5'-0" and 7'-0". Presently, no monolithic modules as large as 4'-0" by 5'-0" are produced. Yet PV panels smaller than these dimensions pose a marketing constraint for the building industry. If smaller panels are used, additional framing (and cost) will be required. Units large enough to fit standard construction modules can be fabricated from multiple smaller modules, but these assemblies will add to the cost of the system and may create an undesired aesthetic or weatherproofing problems.

Details

There are two basic curtain wall framing systems in common use: pressure plate and structural silicon glazing. In pressure plate systems, the glazing unit is mechanically held from the front by a plate with an extruded cover or 'cap'. Structural silicon glazing glues some or all of the glazing edges to the framing system, leaving no framing visible on the outside. In PV applications of pressure plate systems, the mullion cap depth must be kept to a minimum to avoid adverse shadowing on PV cells. Alternatively, flush application of a structural silicon seal between PV glazing units eliminates shadowing effects but increases weatherseal and durability problems for PV panel edges.

To minimize sealing problems, it may make sense to fabricate a double wall envelope, where the PV glazing is the external, unsealed layer and the inner layer is the weather tight enclosure.

F. MECHANICAL/ELECTRICAL CONSIDERATIONS

Ventilation of the Envelope

Exposure to sunlight heats PV panels considerably. Therefore in any PV window / wall or roof application, some measure of ventilation at the back of the panels may be required to shed additional heat loads to the building and to minimize overheating and thermal stresses in the modules. Higher module temperatures also reduce the device's efficiency. PVs may be incorporated into double-layer wall assemblies to either supply or extract hot air (*diag. E.4, p. 16)*. In most cases, natural convective ventilation in an air space within the wall or roof will be sufficient. Other options involve mechanical ventilation using louvers and fans to extract the hot air; these mechanisms could be powered by PVs (*fig. 5, p.41*). In either case, the hot air could be recycled into the building HVAC system when in a heating mode.

Electrical Issues

Methods for accommodating the electrical wiring in a PV envelope are dependent upon the placement and level of transmissivity of the panels and the complexity of the installation. PV windows, for example, will require that wiring be hidden from view and from touch. Future PV curtain walls may need to be customized to accommodate this wiring while making installation simple and efficient. When the back of the panels are covered with drywall or some other method of insulation, the wires leading out of the back of each panel are already hidden from view and may only need to be contained for code purposes.

Panel circuiting schemes may also affect the space requirements for wiring: if many panels are wired in series, voltages may increase to the point where different wire gauges or conduit types may be required.

In buildings with large PV surfaces subject to shadowing or where PVs are applied on walls of different orientations, it may be desirable to have control systems that can switch sections of panels in and out and / or combine together sections operating at partial capacity to maximize overall power production. Such a system could be based on a simple time-clock, or it could be flexibly controlled via a computer using light sensors. It should be possible to modify existing computer-based building control systems to carry out these functions.

G. MAINTENANCE CONSIDERATIONS

Cleaning

PV panel performance is highly dependent upon its ability to remain clean. Accessibility for frequent maintenance and cleaning of the panels from the exterior of the building must be considered as part of PV building design.

Building mangers may find that more frequent cleaning than normal is justified. This in turn may affect the provision for cleaning tracks or fasteners in curtain wall systems and may increase operating costs.

The cleaning frequency of a particular window system depends upon:
1) The climate. If the building is located in a dry and dusty environment, cleaning frequency might be increased in order to keep the panels dust-free. If the climate is wet, cleaning frequency may not need to increase.
2) Typical cleaning standards of the particular building. If the building's normal cleaning frequency is low, then a PV window / wall should significantly increase the operating costs of the building. The amount of increase to the operating costs for PV window / walls cannot be specifically determined unless the typical costs are known. Most high-rent commercial properties already keep their glass quite clean for reasons of appearance.

Maintenance

Electrical maintenance is another issue which may impact operating costs. Replacing a broken glazing unit will be more expensive if it is wired since it may require two separate building trades (glazing and electrical) for reinstallation. Furthermore, wiring within a building envelope may be subject to corrosion or mechanical breakage. Other components such as sensors, building control computers, inverters and batteries will also require maintenance.

H. SAFETY CONSIDERATIONS

Thermal stress

Different types of building materials expand at different rates when heated. This expansion and contraction must be accommodated within the framing members of the envelope. Thermal expansion of PVs is an important issue. PV windows / walls will expand at comparable rates to laminated glass or metal panels but will expand more than clear glass windows or stone spandrel panels.

Code requirements for tempered and/or laminated glass

As a new variation on a laminated glass panel, PVs as a building material must adhere to specific code requirements. When used as glazing units at or near floor level or as skylight / overhead glazing, PVs' structural strength and cohesiveness will need to be comparable to laminated, tempered or wire glass. Manufacturers will have to perform necessary testing and certifications.

J. ENVIRONMENTAL CONSIDERATIONS

An evaluation of the environmental benefits of PVs in buildings should not be restricted to a measurement of reduced need for conventional electricity. The full environmental cost of a product will include the following issues, among others:

Disposal of broken or replaced panels

Some PV devices may contain heavy metals or other materials which may complicate disposal of rejected or broken units. Others may be as innocuous as typical scrap glass or metal. As PV use increases in building applications, proper planning for disposal and/or potential recycling programs will need to be considered.

Hazardous, toxic and non-renewable materials used in panel production

Some PV devices are produced using toxic substances which may pose a local environmental threat at the production facility. Wastes must be neutralized and/or disposed of responsibly.

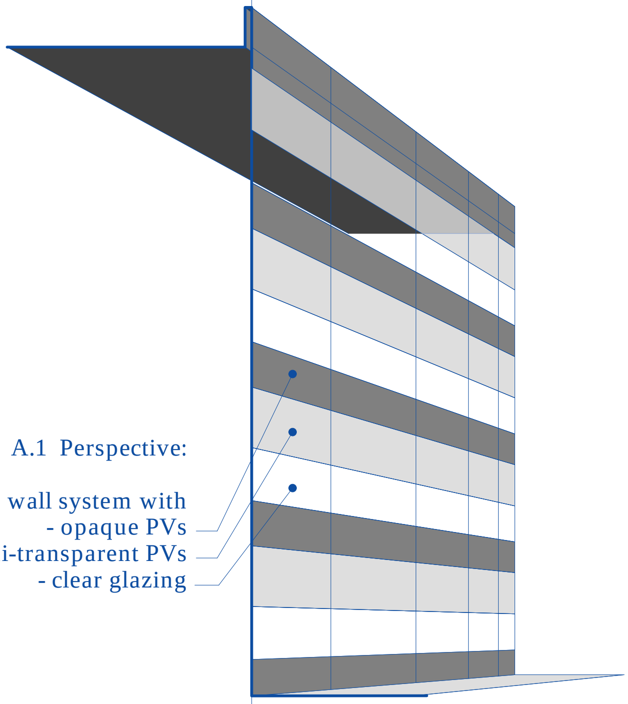
Energy consumed in panel manufacturing (embodied energy)

An analysis of the energy efficiency of PV devices should include the energy consumed in producing the product, including the PV module and additions and modifications for the building product. For example, if one to two kilowatt-hours are required to produce one watt of PV capacity, the PV panel will produce more energy than it took for the manufacturer to produce it within six to twelve months of its use.

IV. PV Building Envelope Diagrams

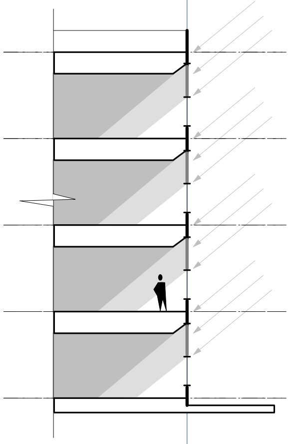
A. Vertical Curtain Wall

Characteristics:
- Standard, economical, accepted construction



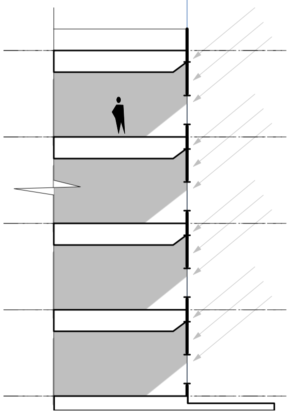
A.1 Perspective:

PV vertical curtain wall system with
- opaque PVs
- semi-transparent PVs
- clear glazing



A.2 Wall Section:

PV vertical curtain wall system with
- opaque PVs
- semi-transparent PVs
- clear glazing



A.3 Wall Section:

PV vertical curtain wall system with
- opaque PVs
- clear glazing

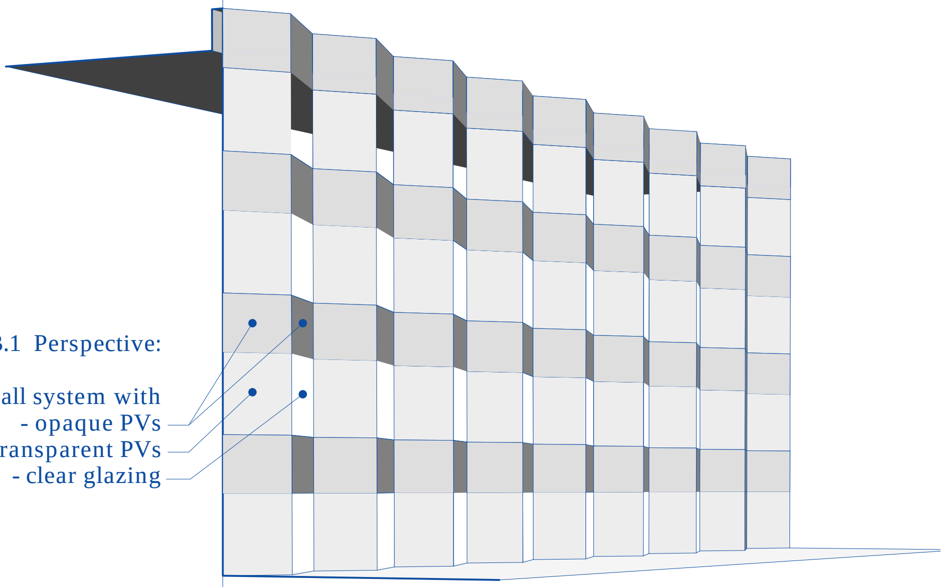
B. Sawtooth Vertical Curtain Wall

Characteristics:
- Minimal additional construction cost
- Good solar performance in certain orientations•

Creates multiple "corner" windows

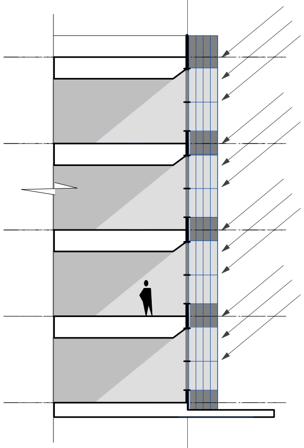
B.1 Perspective:

PV sawtooth vertical curtain wall system with
- opaque PVs
- semi-transparent PVs
- clear glazing



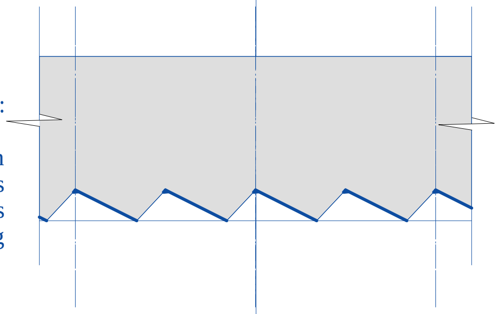
B.2 Wall Section:

V sawtooth vertical curtain wall system with
- opaque PVs
- semi-transparent PVs
- clear glazing



B.3 Floor Plan:

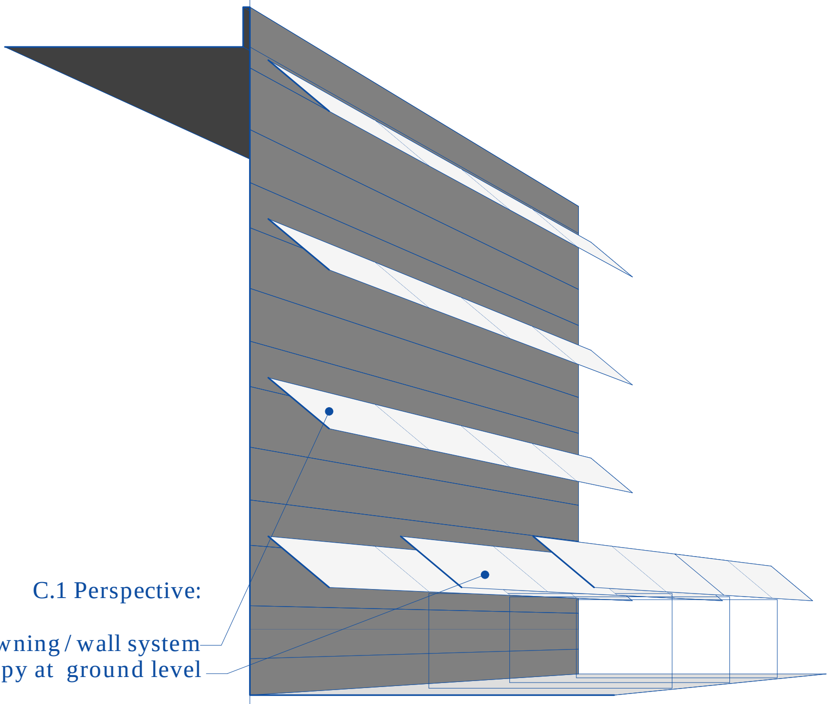
awtooth vertical curtain wall system with
- opaque PVs
- semi-transparent PVs
- clear glazing



C. Hybrid PV Awning Systems

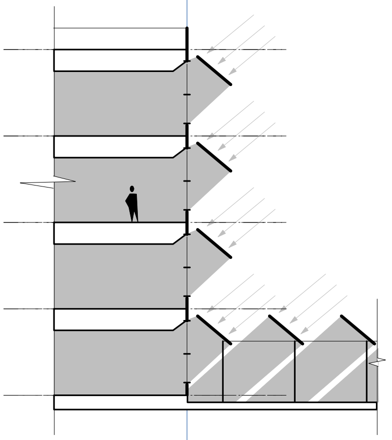
Characteristics:

- PVs independent of building skin
- New construction or retrofit
- Passive shading / daylight control benefits
- Moderate additional costs for structure
- Little danger of waterproofing complications
- Wiring must penetrate building skin



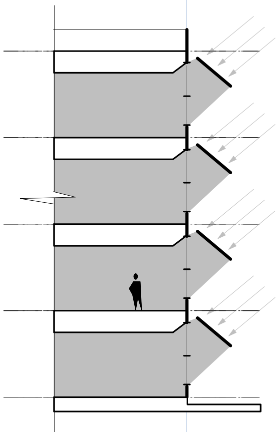
C.1 Perspective:

PV hybrid awning / wall system
Cna be extended into independent trellis / canopy at ground level



C.2 Wall Section:

PV hybrid awning / wall system with:
- opaque awnings attatched to vertical wall,
- awnings can be extended into independent trellis at ground level

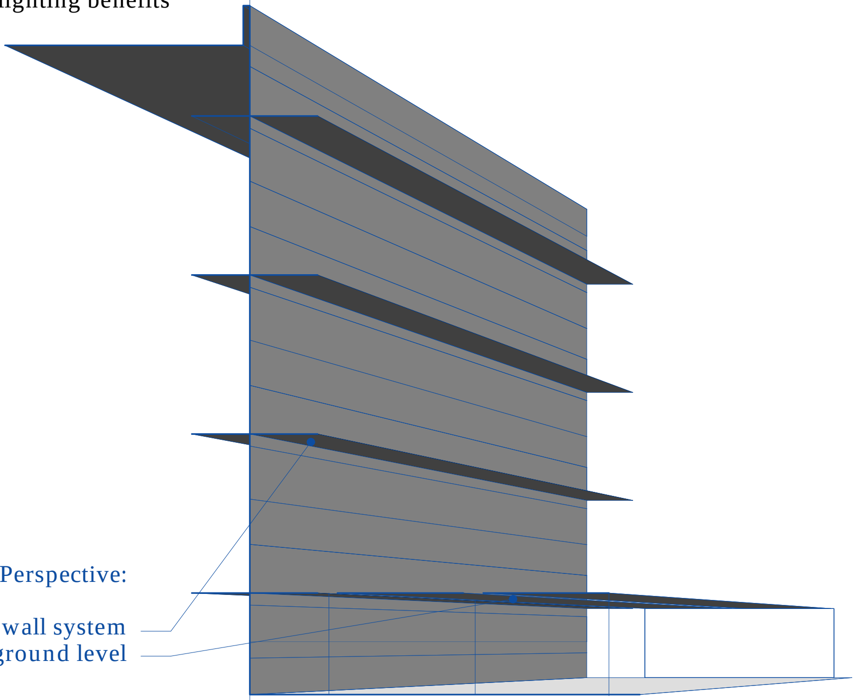


C.3 Wall Section:

PV hybrid awning / wall system with:
- opaque awnings attatched to vertical wall

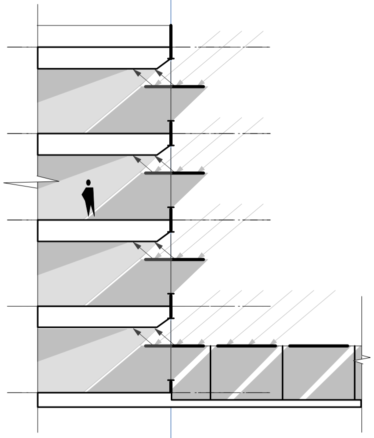
D. Hybrid PV Awning/Light Shelf Systems

Characteristics:
- PVs independent of building skin
- New construction or retrofit
- Passive shading / daylight control / daylighting benefits
- Potentially significant structural and weatherproofing costs



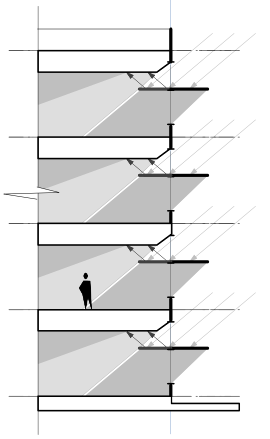
D.1 Perspective:

Hybrid PV light shelf / wall system
Can be extended into independent trellis at ground level



D.2 Wall Section:

Hybrid PV light shelf / wall system with:
- opaque PV light shelves attached to vertical wall
- horizontal PVs which can be extended into independent trellis at ground level

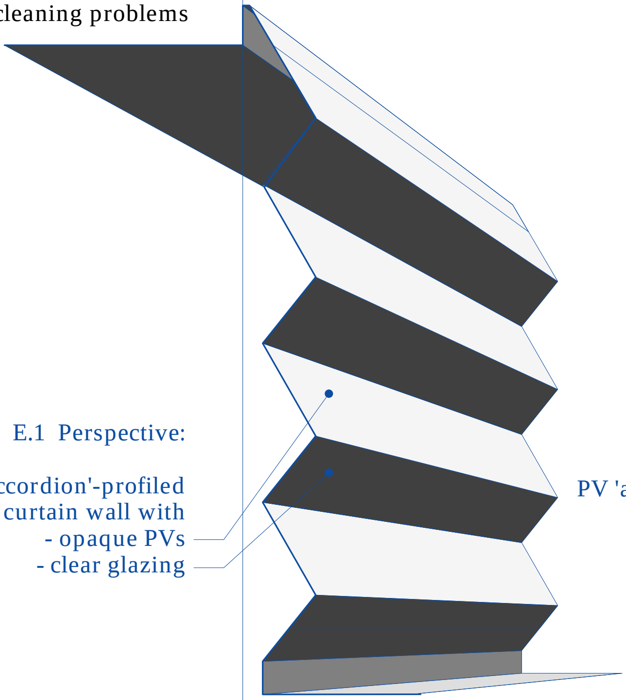


D.3 Wall Section:

Hybrid PV light shelf / wall system with:
- opaque PV light shelves attached to vertical wall

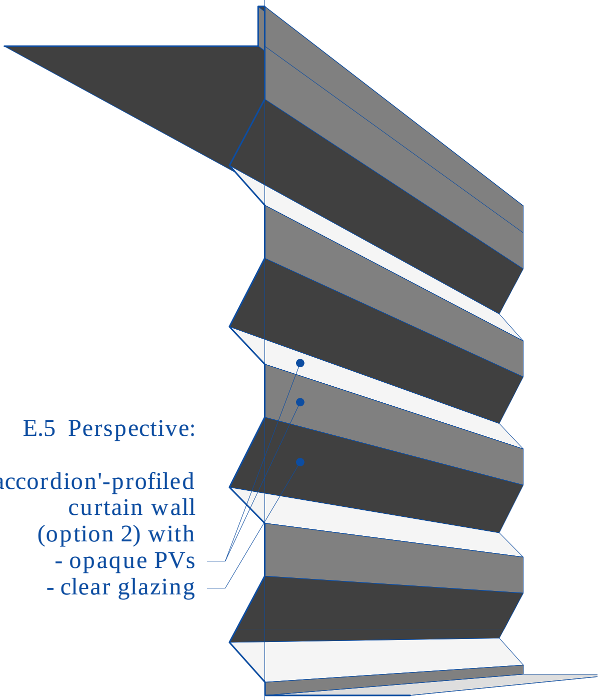
E. PV Accordion Curtain Wall

Characteristics:
- PVs as building skin
- Complex curtain wall construction
- Good PV efficiency
- Potential cleaning problems



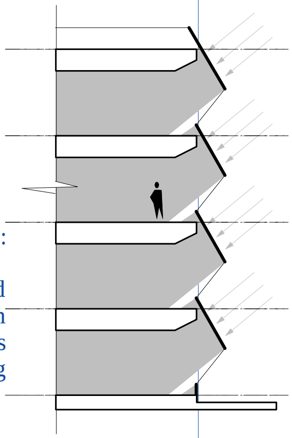
E.1 Perspective:

PV 'accordion'-profiled
curtain wall with
- opaque PVs
- clear glazing



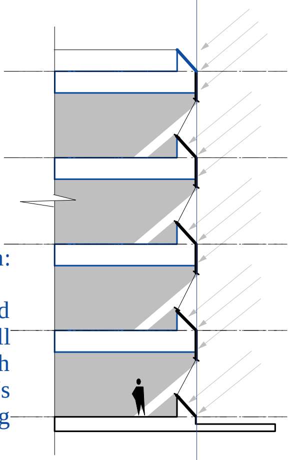
E.5 Perspective:

PV 'accordion'-profiled
curtain wall
(option 2) with
- opaque PVs
- clear glazing



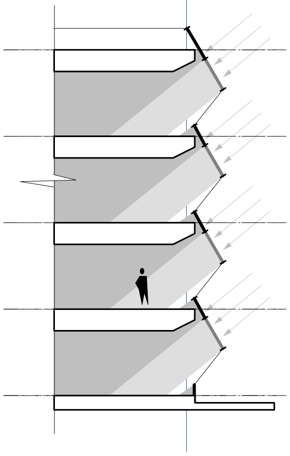
E.2 Wall Section:

V 'accordion'-profiled
curtain wall with
- opaque PVs
- clear glazing



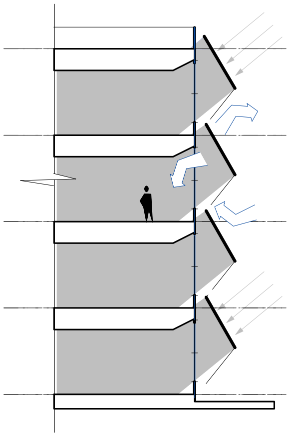
E.6 Wall Section:

PV 'accordion'-profiled
curtain wall
(option 2) with
- opaque PVs
- clear glazing



E.3 Wall Section:

V 'accordion'-profiled
curtain wall with
- opaque PVs
semi-transparent PVs
- clear glazing



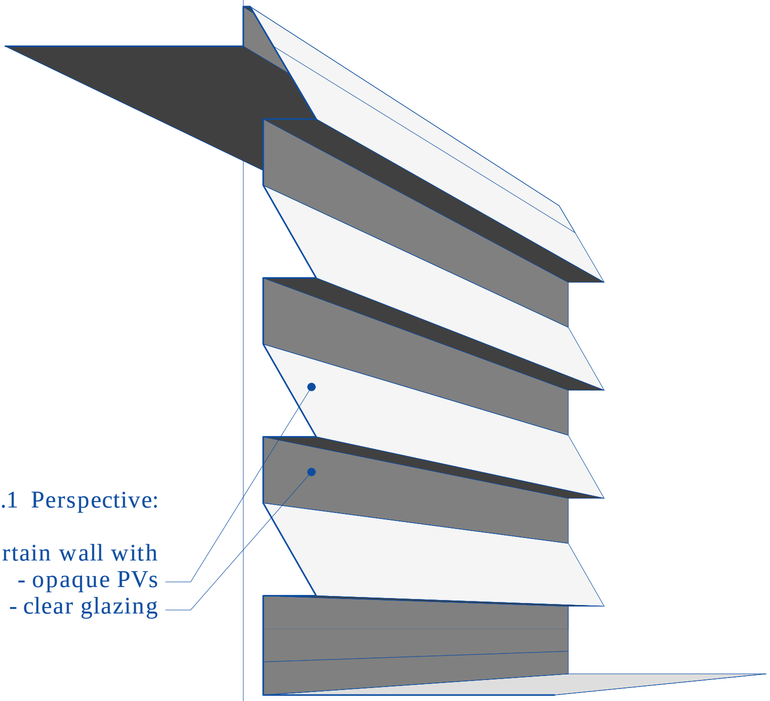
E.4 Wall Section:

PV 'accordion'-profiled
curtain wall with double wall system:
- inner layer as weather seal
- outer layer as active / passive solar source
  (opaque PVs)
- double wall providing PV-powered
  ventilation for thermal build-up from PVs

F. PV Sawtooth Curtain Wall

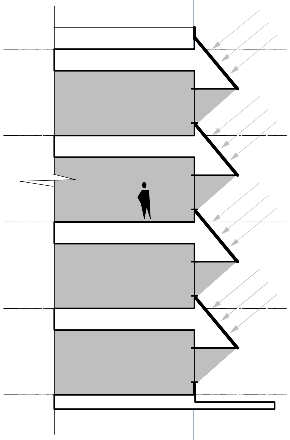
Characteristics:

- PVs as building skin
- Complex curtain wall construction
- Good PV efficiency
- Passive shading / daylight control
- Potential cleaning problems



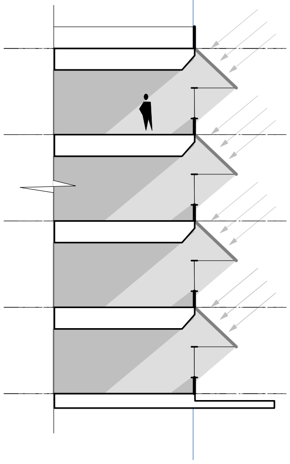
F.1 Perspective:

'Sawtooth' PV curtain wall with
- opaque PVs
- clear glazing



F.1 Wall Section:

'Sawtooth' PV curtain wall with
- opaque PVs
- clear glazing



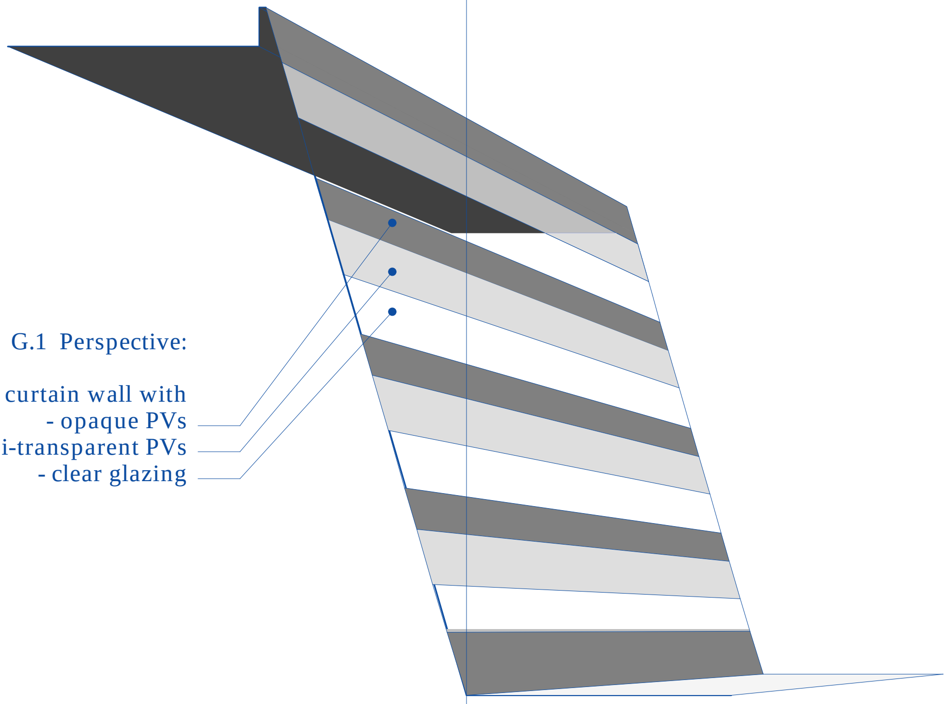
F.2 Wall Section:

'Sawtooth' PV curtain wall with
- opaque PVs
- semi-transparent PVs
- clear glazing

G. PV Sloping Curtain Wall

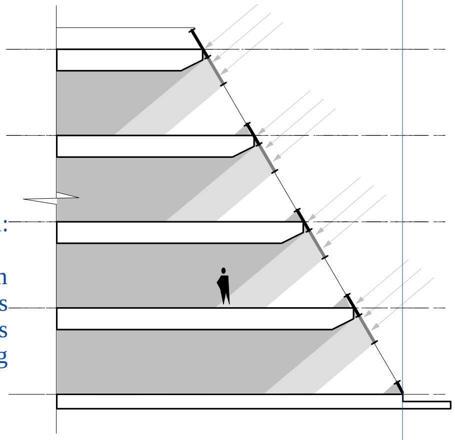
Characteristics:

- Good PV max efficiency
- Less efficient use of building footprint



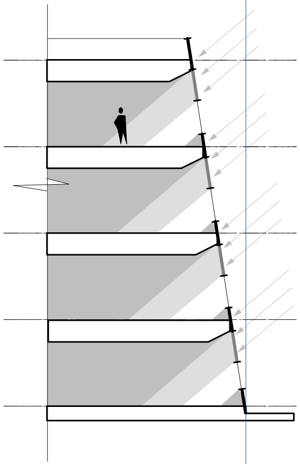
G.1 Perspective:

70° sloping PV curtain wall with
- opaque PVs
- semi-transparent PVs
- clear glazing



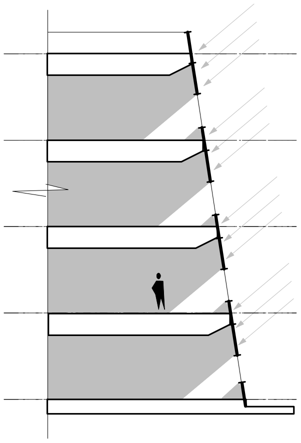
G.2 Wall Section:

60° sloping PV curtain wall with
- opaque PVs
- semi-transparent PVs
- clear glazing



G.3 Wall Section:

80° sloping PV curtain wall with
- opaque PVs
- semi-transparent PVs
- clear glazing



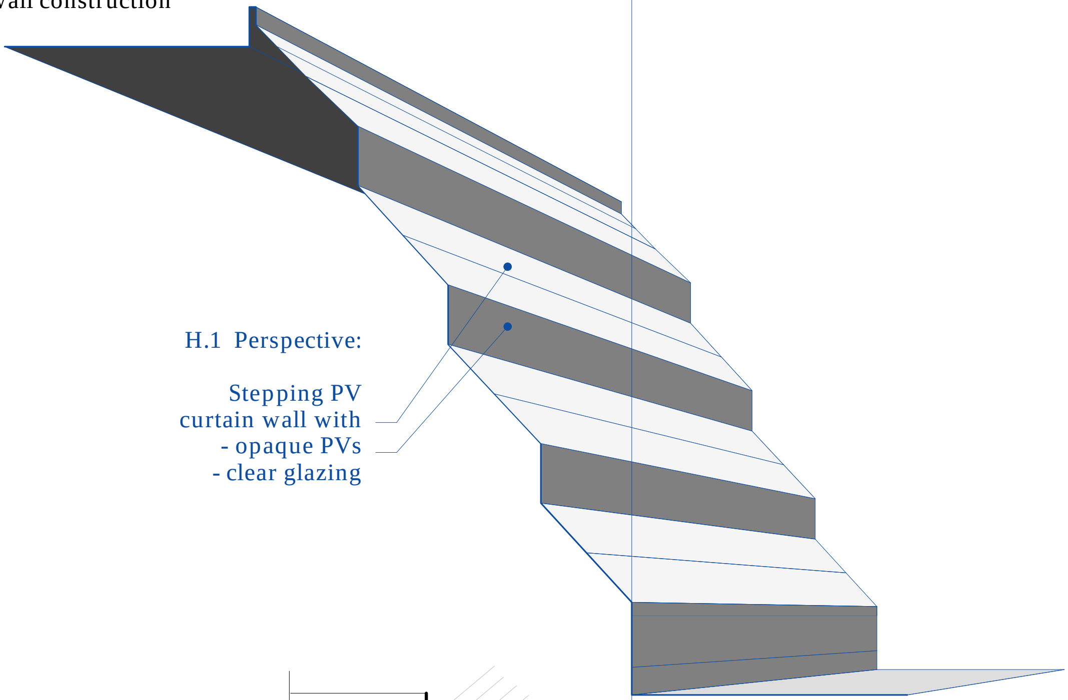
G.4 Wall Section:

80° sloping
PV curtain wall wit
- opaque PVs
- clear glazing

H. PV Sloping/Stepped Curtain Wall

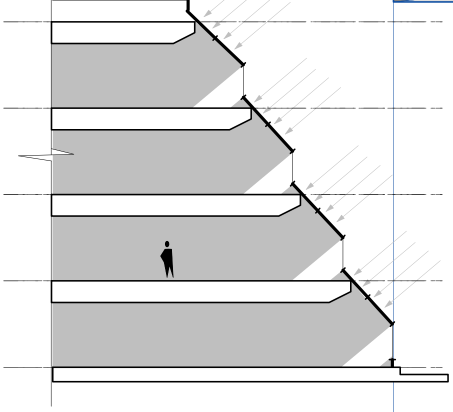
Characteristics:

- Good PV max efficiency
- Less efficient use of building footprint
- Complex curtain wall construction



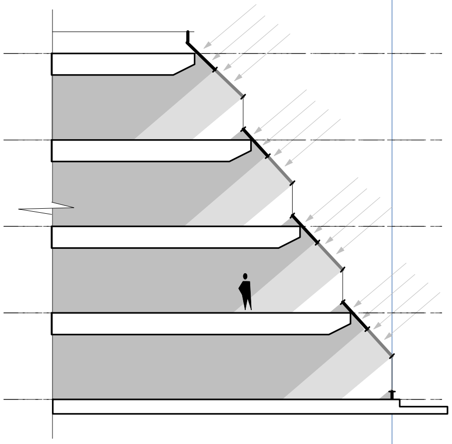
H.1 Perspective:

Stepping PV
curtain wall with
- opaque PVs
- clear glazing



H.2 Wall Section:

Stepping PV curtain wall with
- opaque PVs
- clear glazing



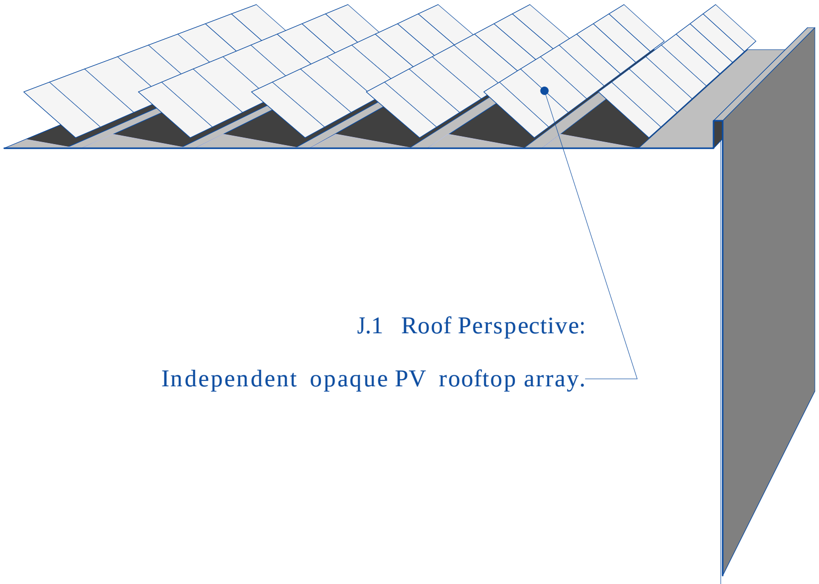
H.3 Wall Section:

Stepping PV curtain wall with
- opaque PVs
- semi-transparent PVs
- clear glazing

J. Independent PV Rooftop Array

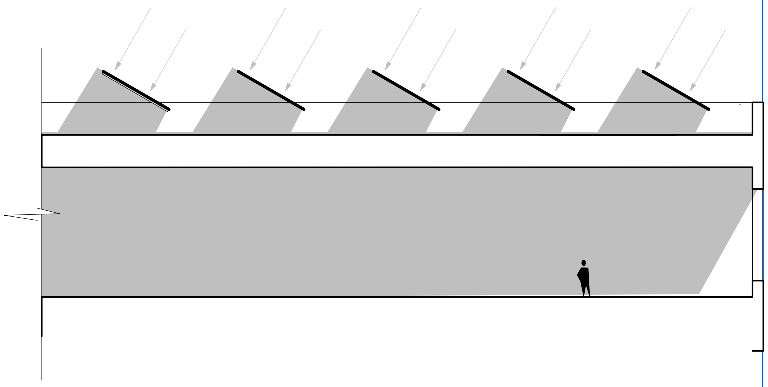
Characteristics:

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



J.1 Roof Perspective:

Independent opaque PV rooftop array.

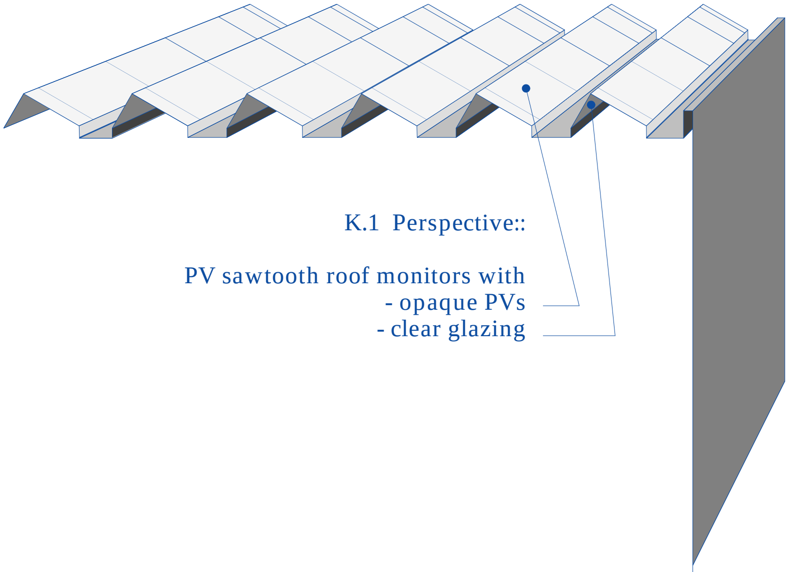


J.2 Roof Section:

Independent opaque PV rooftop array.

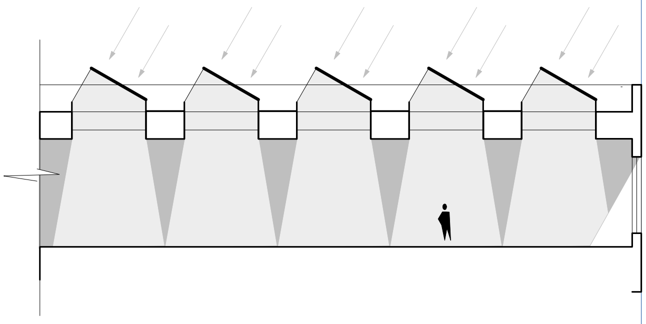
K. PV Sawtooth Roof Monitors

Characteristics:
- PV system as building skin
- Retrofit to exist. industrial buildings
- Good PV efficiency
- Good daylight benefits



K.1 Perspective::

PV sawtooth roof monitors with
- opaque PVs
- clear glazing



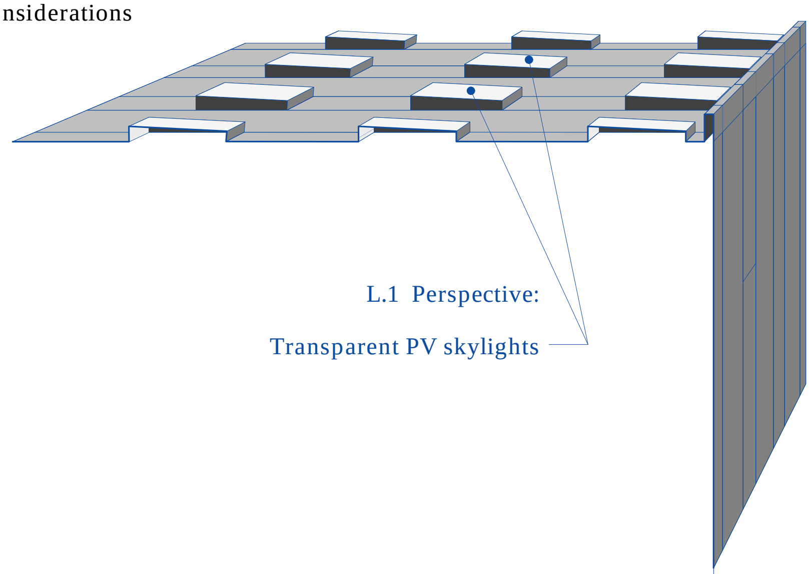
K.2 Roof Section:

PV sawtooth roof monitors with
- opaque PVs
- clear glazing

L. PV Skylights

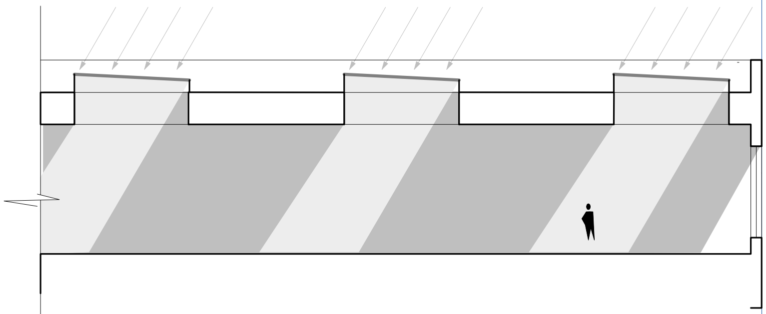
Characteristics:

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



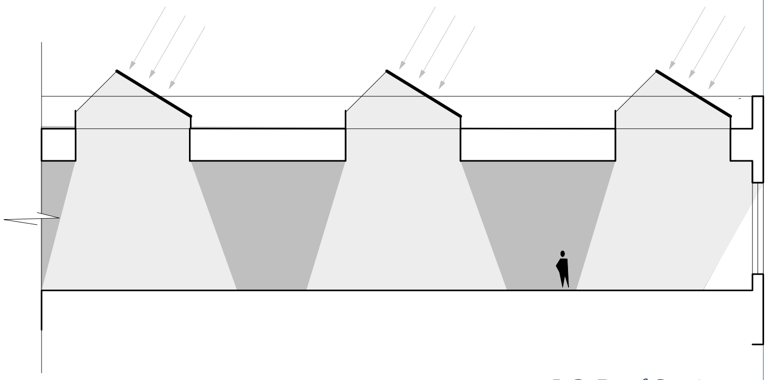
L.1 Perspective:

Transparent PV skylights



L.2 Roof Section:

Transparent PV skylights



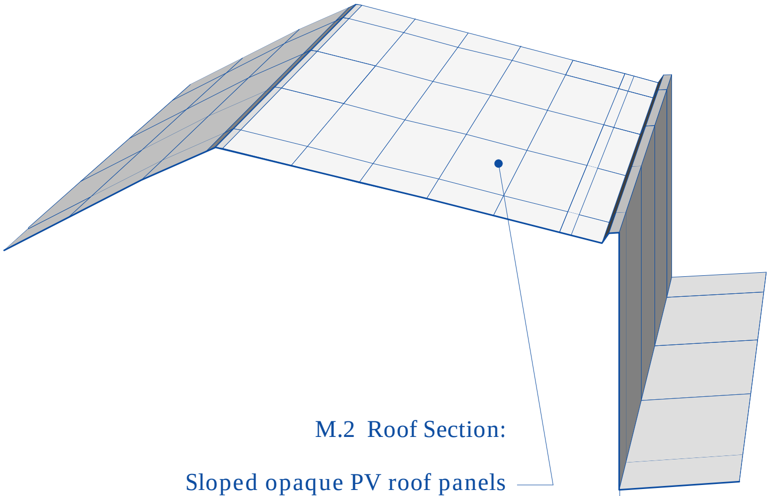
L.3 Roof Section:

Opaque PV skylights

M. PV Roof Panels

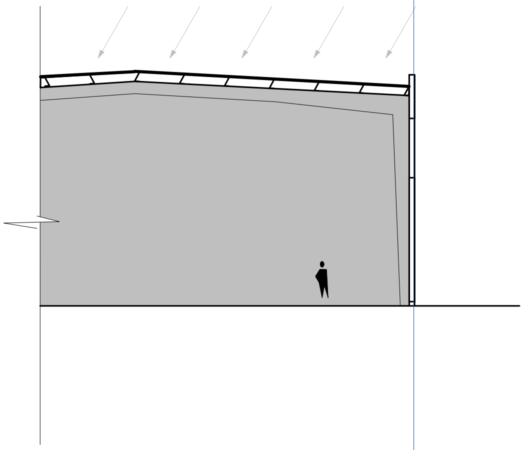
Characteristics:

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



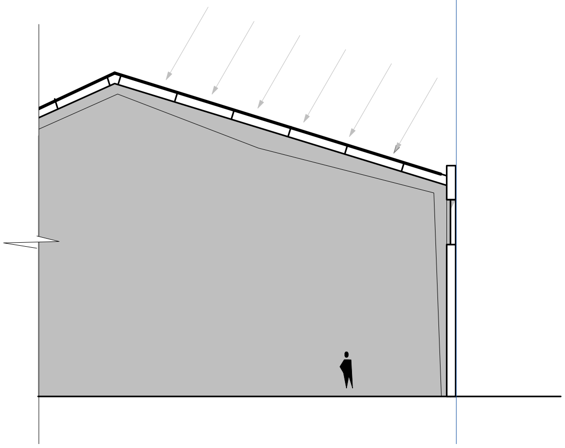
M.2 Roof Section:

Sloped opaque PV roof panels



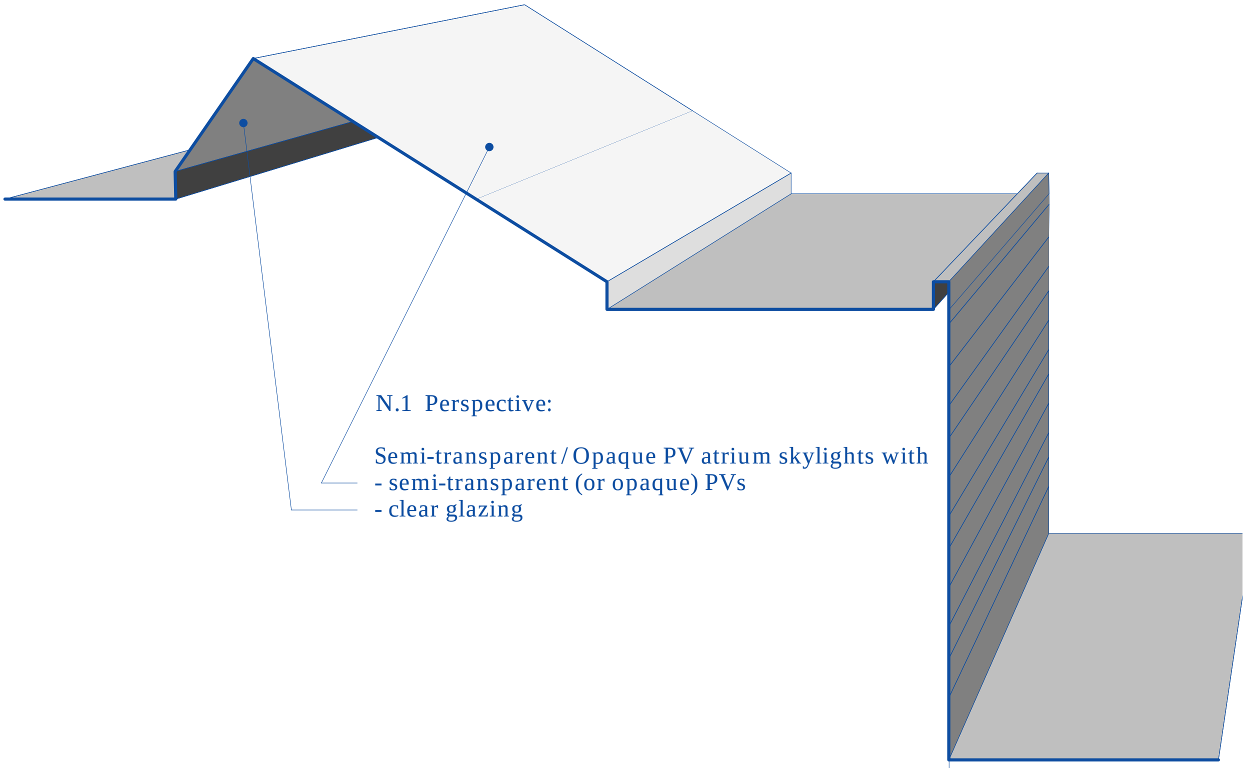
M.2 Roof Section:

Horizontal opaque PV roof panels



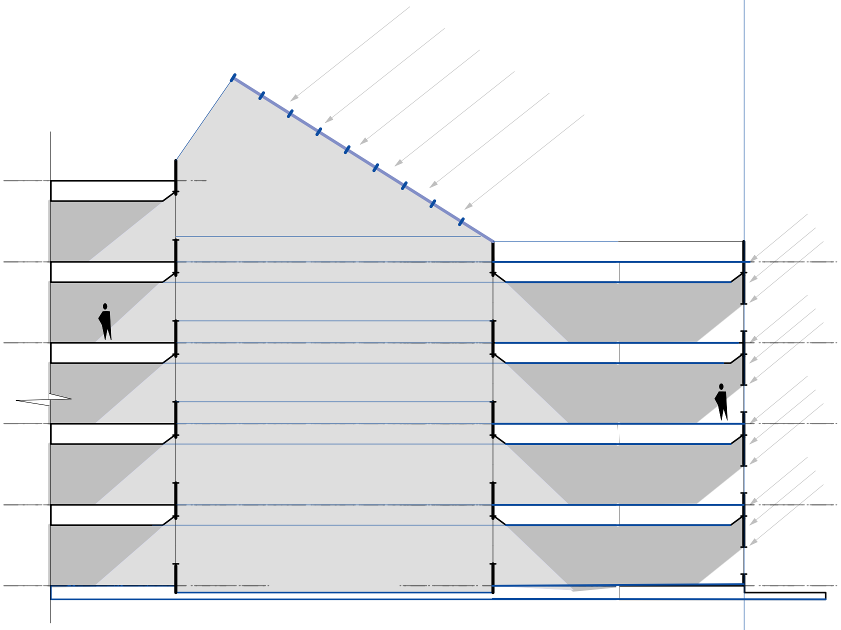
M.3 Roof Section:

Sloped opaque PV roof panels



N.1 Perspective:

Semi-transparent / Opaque PV atrium skylights with
- semi-transparent (or opaque) PVs
- clear glazing



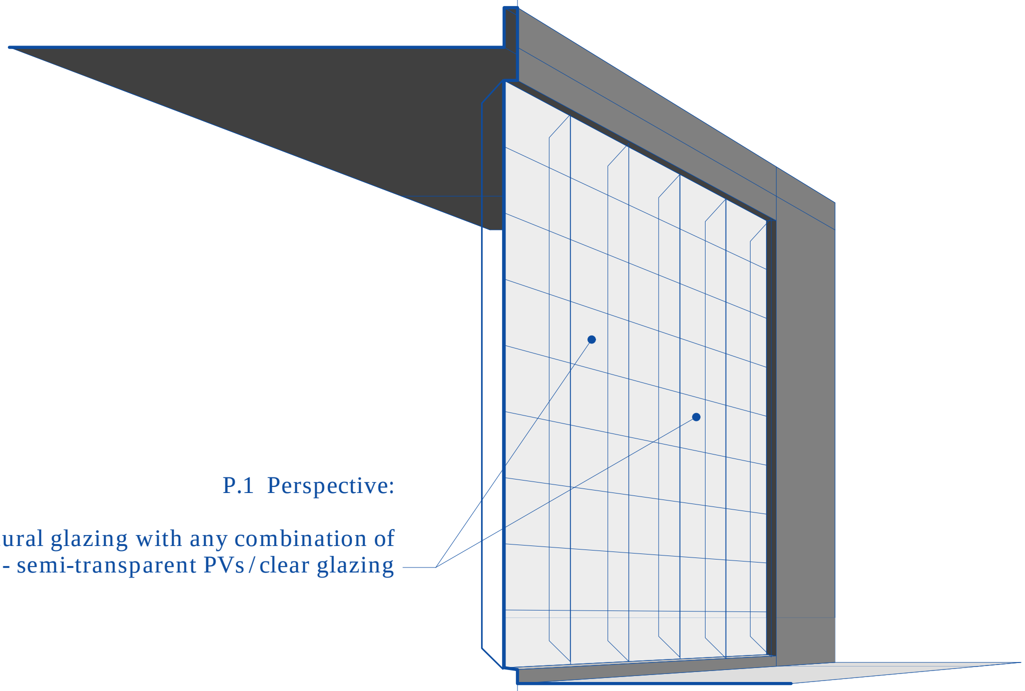
N.2 Roof / Wall Section:

Opaque & / or transparent PV atrium skylights with
- semi-transparent (or opaque) PVs
- clear glazing

P. PV Structural Glazing

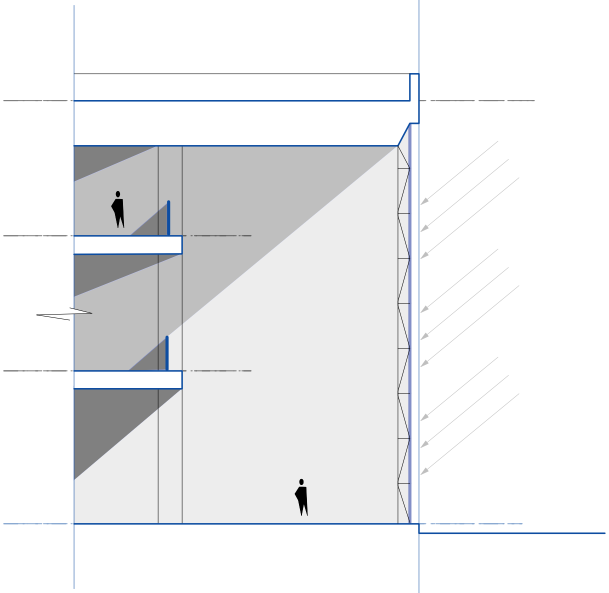
Characteristics:

- Standard, economical , accepted construction
- Difficult sealing problems for PV edges



P.1 Perspective:

Vertical PV structural glazing with any combination of
- semi-transparent PVs / clear glazing



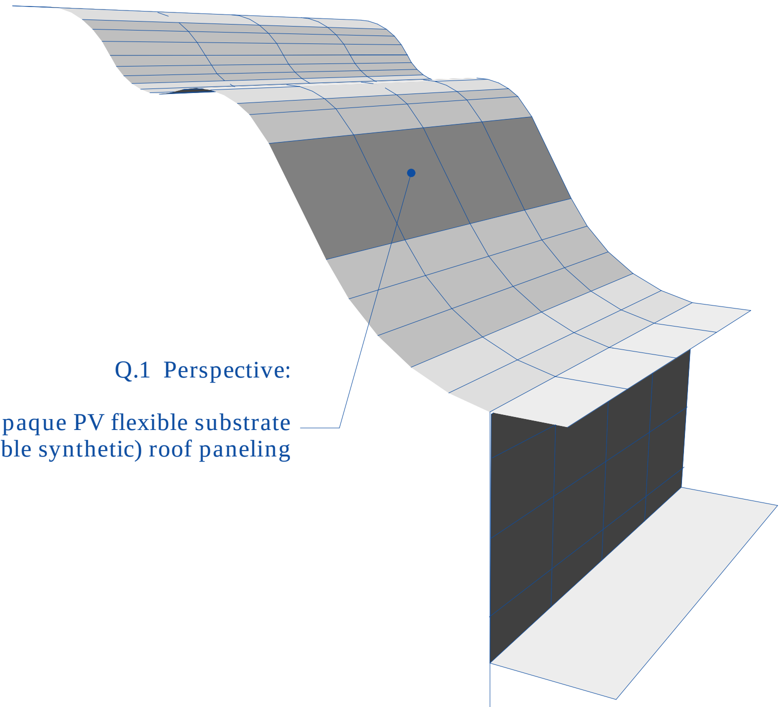
P.2 Wall Section:

Vertical PV structural glazing with any combination of
- semi-transparent PVs / clear glazing

Q. Flexible/ Metal PV Substrates

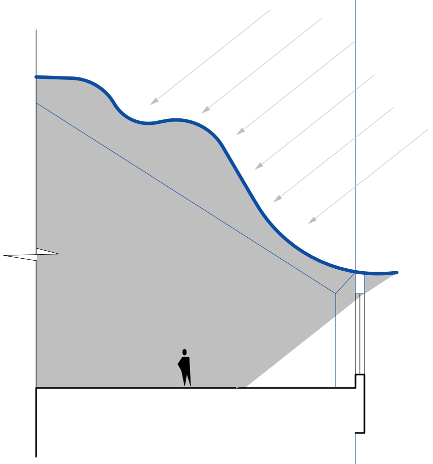
Characteristics:

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



Q.1 Perspective:

Opaque PV flexible substrate
(sheet metal or flexible synthetic) roof paneling



Q.2 Wall Section:

Opaque PV flexible substrate
(sheet metal or flexible synthetic) roof paneling

V. PV Performance Analyses

The following section presents a series of quantitative analyses performed to evaluate PV performance for some of the wall configurations diagrammed in the previous section. The purpose of these analyses is to begin to identify those building profiles and configurations which optimize PV performance, regardless of other considerations external to the solar benefits. Not surprisingly, the following results indicate that those configurations which produce optimum power are also the configurations which require more complex detailing and higher costs. The analyses attempt to contrast and compare which of these configurations offers the most solar benefits for different orientations, seasons and times of day.

The building dimensions, climatic conditions and PV technology assumptions for these analyses are outlined as follows:

A. ASSUMPTIONS AND PARAMETERS FOR THE ANALYSES

Photovoltaic Technology and Conditions:

This analysis does not attempt to evaluate any specific PV technologies. We have assumed devices similar to those available today, or new devices that might reasonably be developed in the next five years such as semi-transparent modules or modules on flexible substrates. Cell efficiencies used in the analyses are conservatively assumed to be 5%. Higher efficiency cells will improve all the analyses and could lead to different conclusions than those reached in this report.

Photovoltaic Performance Assumptions:	
Array reference efficiency:	*5%*
Base cell temperature (NOCT conditions):	*25ºC*
Operating reference temperature:	*63ºC*
*Temperature coefficient (*1000):*	*2.7 1/°C*

Photovoltaic Analysis Tool

The PV calculations presented in the following series of PV performance analyses were performed by F-Chart Software. This software package was designed by S.A. Klein and W.A. Beckman, © 1992, for the design and economic analysis of contemporary PV systems. The program calculates PV performance for free-standing arrays for different orientations, slopes and tracking configurations in major locations across the US. and Canada. F-Chart requires input for cell efficiency and temperature parameters as well as array size, location and orientation numbers. The results are generated in monthly or hourly kW-hr’s and efficiency percentages.

Test Case Building:

Some of the systems analyses discussed in this study are based upon a test case 40,000 square foot, four story suburban office building. The 10,000 square foot floor plate is 100' on a side, oriented due north-south-east-west. The square footprint is chosen not to optimize solar orientation, but rather for it's neutrality.

The building envelope is assumed to be built to good but not exceptional standards of energy efficiency. The climate is assumed to be similar to Southern California, with good insolation and high cooling requirements.

Test Building Assumptions:	
Floor plate dimensions:	*100' x 100'*
# stories	*4*
Floor-to-floor height:	*12'-0"*
Orientation:	*Due north-south-east-west*
Occupancy:	*Suburban office*
Location:	*Los Angeles*
Climate:	*Arid, hot*
Ambient temperatures:	*55º-70ºF, winter-summer*
Latitude:	*33.9º*
Ground Reflectance:	*0.20*

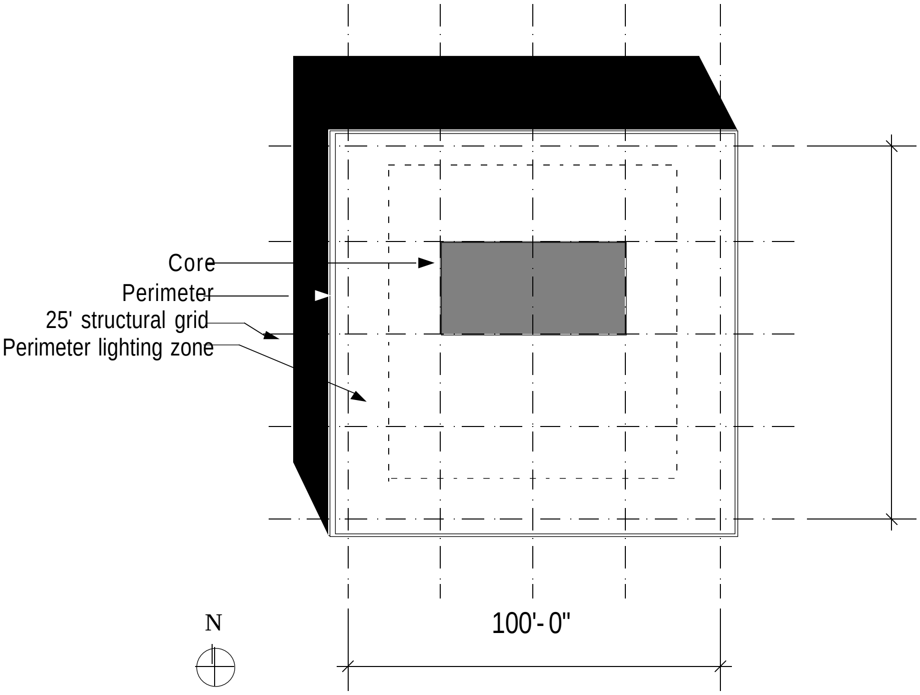


Fig. 1
Test Case Building Plan

B. PLANNING PROPORTION ANALYSIS

Charts 1 and 2 examine the effects which different building planning configurations have upon PV performance. The analysis assumes the theoretical four story test case building is completely clad in vertically oriented PV panels (*diag A, p. 12*) for the five planning configurations diagrammed below.

The F-Chart analysis was conducted for two cases: 1) for a building with a fixed 40,000 square foot total floor area (whose perimeter increases with narrower footprint) and 2) for a building with a fixed 19,200 square foot perimeter wall surface area (whose floor area decreases with narrower footprint).

Based solely upon the amount of photovoltaic power produced, the analysis indicates that for vertical PV panels a narrow building footprint oriented on the north-south axis, with the majority of PV panels on the east and west walls, generates the most power. But exclusive analysis of PV performance does not take into consideration the negative effects resulting from this orientation such as solar heat gain, morning / afternoon sun glare and less efficient floor planning options.

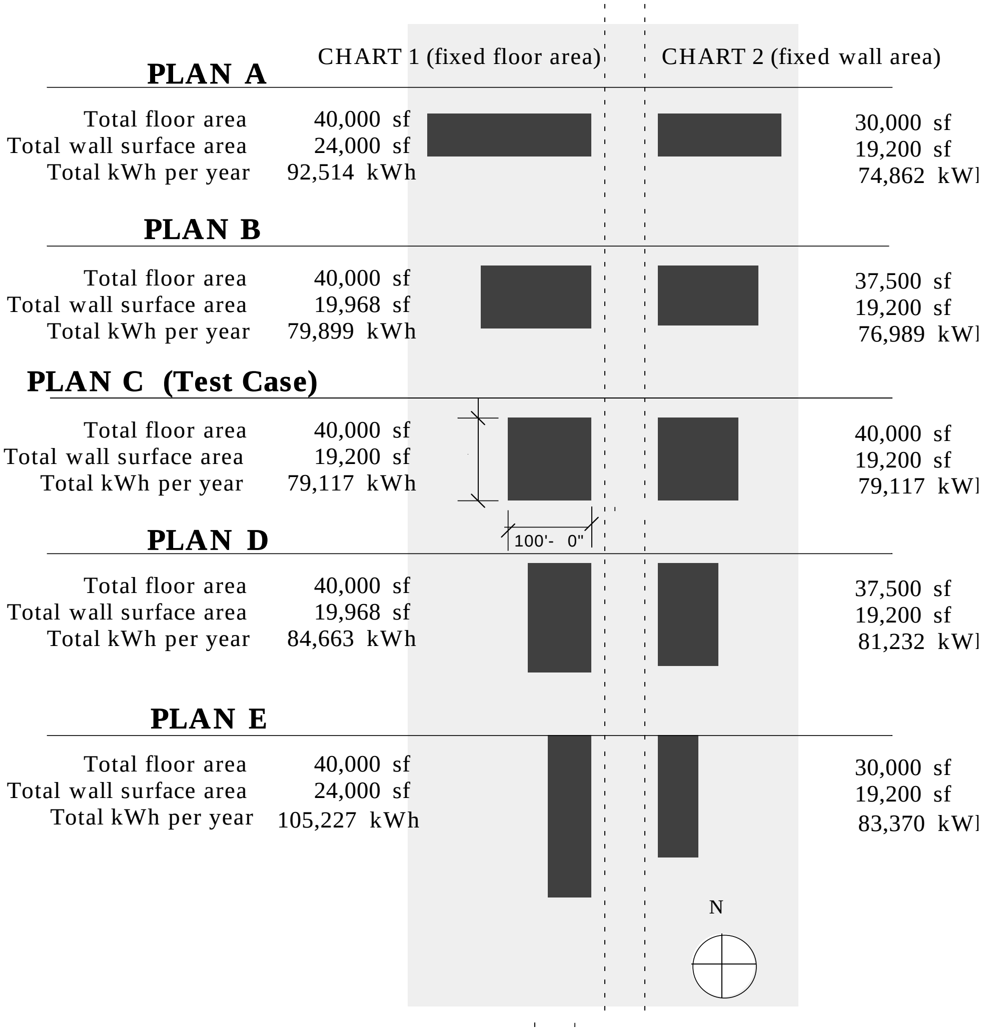


		CHART 1 (fixed floor area)	CHART 2 (fixed wall area)
PLAN A	Total floor area	40,000 sf	30,000 sf
	Total wall surface area	24,000 sf	19,200 sf
	Total kWh per year	92,514 kWh	74,862 kWh
PLAN B	Total floor area	40,000 sf	37,500 sf
	Total wall surface area	19,968 sf	19,200 sf
	Total kWh per year	79,899 kWh	76,989 kWh
PLAN C (Test Case)	Total floor area	40,000 sf	40,000 sf
	Total wall surface area	19,200 sf	19,200 sf
	Total kWh per year	79,117 kWh	79,117 kWh
PLAN D	Total floor area	40,000 sf	37,500 sf
	Total wall surface area	19,968 sf	19,200 sf
	Total kWh per year	84,663 kWh	81,232 kWh
PLAN E	Total floor area	40,000 sf	30,000 sf
	Total wall surface area	24,000 sf	19,200 sf
	Total kWh per year	105,227 kWh	83,370 kWh

Fig. 2:
Alternate planning configurations.

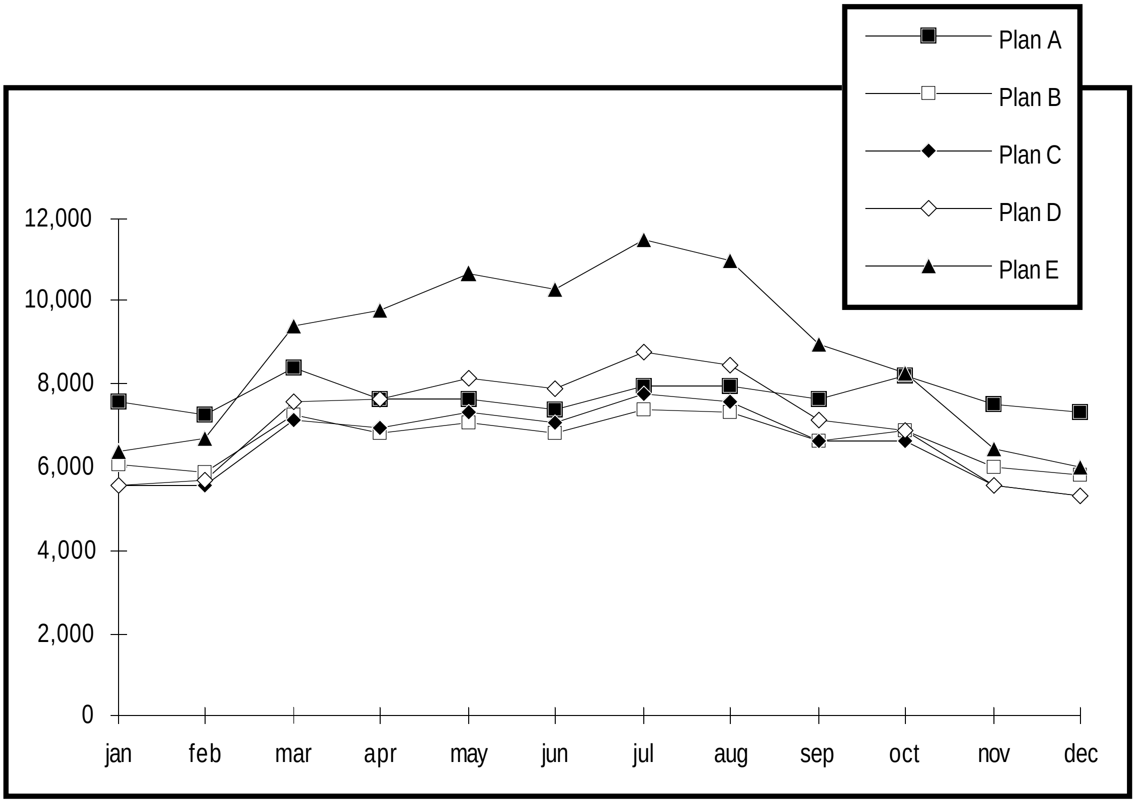


CHART 1: Monthly planning orientation effect on total building PV power production in kWh.
Fixed building floor area.

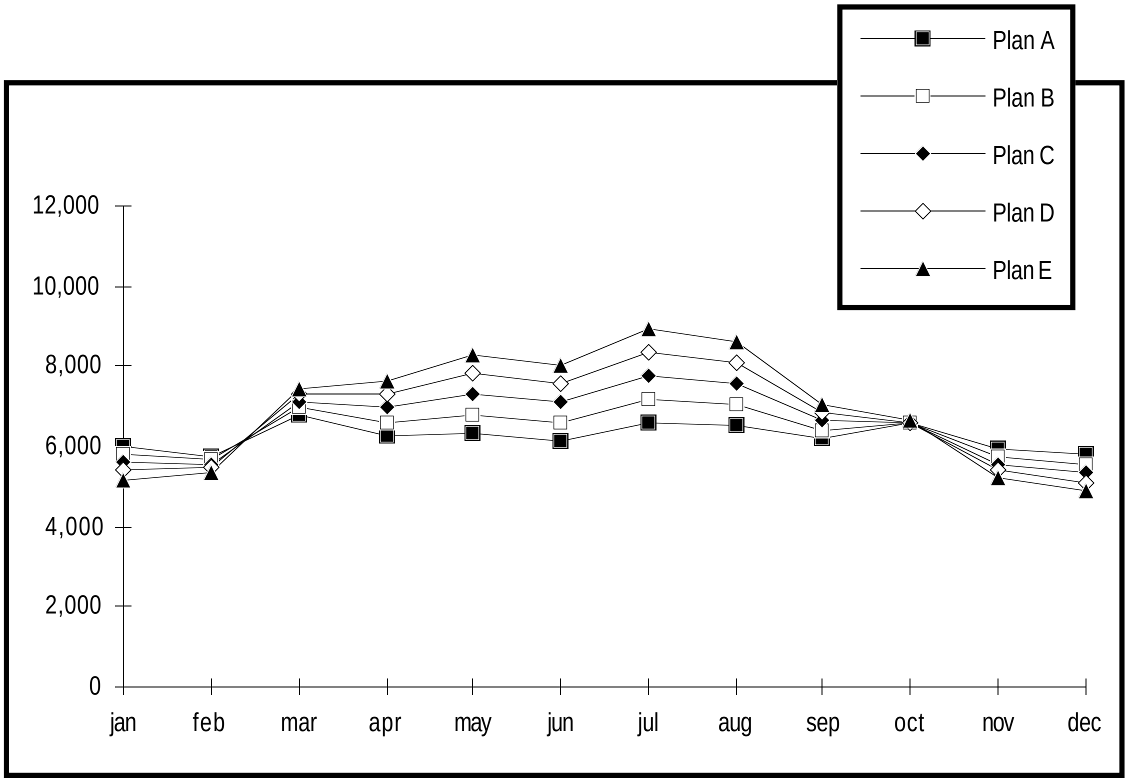


CHART 2: Monthly planning orientation effect on total building PV power production in kWh.
Fixed perimeter wall surface area.

C. WALL TILT ANALYSIS

Charts 3 and 4 on the following page present a comparison of the effects of tilting a south-facing curtain wall as a single plane from vertical to 40 degrees (*diag G, p. 18)*. The analysis assumes the four-story test case building with a 100 foot long wall with a 48 foot high south wall and 3000 square foot total PV area at the vertical orientation.

Chart 3 indicates the effect of tilt on PV power production while keeping the PV area fixed. Since floor-to floor heights in buildings are generally fixed early in the planning phase, tilting wall planes will generally mean the surface area of each wall component will increase as the wall is tilted in order to preserve the vertical dimension of each. As a result, tilting a building wall will usually mean increasing the collector area as well as its efficiency, as Chart 4 demonstrates. The PV wall surface area increases from 3000 square feet to approximately 4667 square feet at a 40 degree tilt.

This additional power capacity from tilting the wall plane must be measured against the various tangible and intangible costs of the tilted section. Construction costs will increase for a tilted curtain wall. More importantly, valuable building floor area will be reduced in the upper floors, as shown in the diagrams below. And perimeter zones will receive more direct sunlight and therefore require more daylight control during the middle hours of the day.

	CHART 3 (fixed PV area)	CHART 4 (increasing PV area)
90° vertical		
Total south wall PV area	3,000 sf	3,000 sf
Total lost floor area	0 sf	0 sf
Total kWh per year	15,433 kWh	15,433 kWh
80° tilt		
Total south wall PV area	3,000 sf	3,046 sf
Total lost floor area	1,290 sf	1,290 sf
Total kWh per year	18,444 kWh	18,728 kWh
70° tilt		
Total south wall PV area	3,000 sf	3,193 sf
Total lost floor area	2,650 sf	2,650 sf
Total kWh per year	21,184 kWh	22,544 kWh
60° tilt		
Total south wall PV area	3,000 sf	3,464 sf
Total lost floor area	5,407 sf	5,407 sf
Total kWh per year	23,445 kWh	27,077 kWh
50° tilt		
Total south wall PV area	3,000 sf	3,916 sf
Total lost floor area	6,120 sf	6,120 sf
Total kWh per year	25,098 kWh	32,815 kWh
40° tilt		
Total south wall PV area	3,000 sf	4,667 sf
Total lost floor area	8,690 sf	8.690 sf
Total kWh per year	26,146 kWh	40,676 kWh

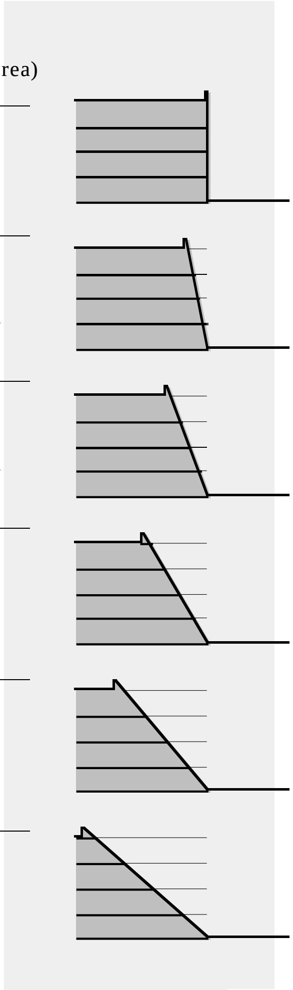


Fig. 3
Six wall tilt configurations.

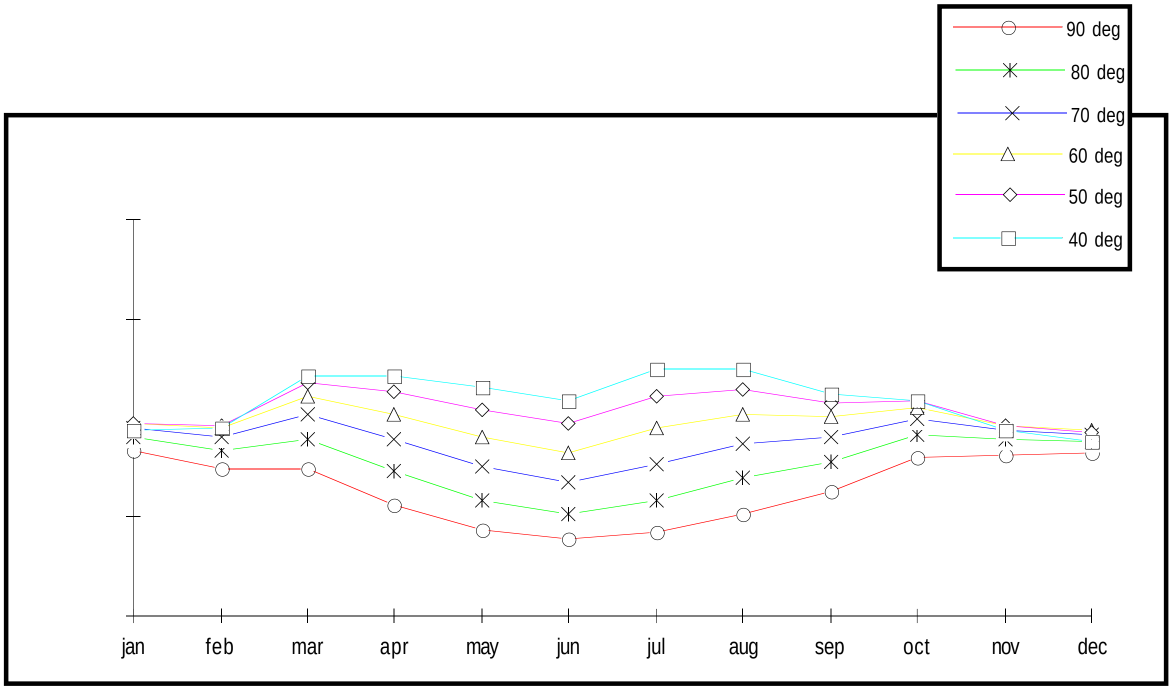


CHART 3: South facing PV curtain wall from vertical (90°) to 40° (types A1, G1).
Monthly power production in kWh, fixed wall surface area.

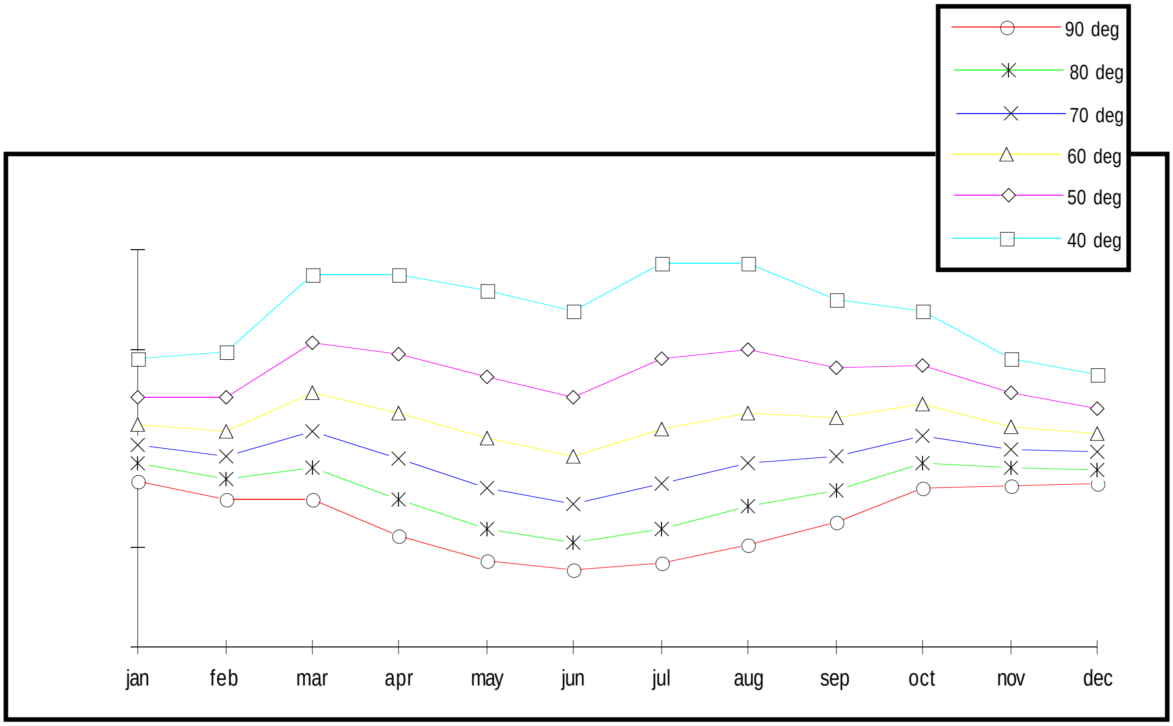


CHART 4: South facing PV curtain wall from vertical (90°) to 40° (types A1, G1).
Monthly power production in kWh, wall surface area increasing with tilt.

D. VERTICAL VS. TILTED WALL COMPARISON

The following Charts 5 and 6 indicate PV panel performance of a vertical curtain wall (*diag A, p. 12)* versus the PV performance of a 70 degree tilted wall (*diag G. p. 18)* on all four walls of the test case building. The analysis assumes the four-story test case building with 100 foot long, 48 foot high walls facing east, west, north and south and each wall with 3000 square foot total PV area at the vertical orientation.

These charts indicate the relative PV power performance at the four walls of the building. In both cases, southern orientations produce more power in the winter months while northern and eastern / western orientations behave in the opposite manner. For the vertical walls, southern orientations actually perform slightly worse than northern orientations in June when the altitude of the sun is at its highest. Although the general proportions remain the same, the tilted wall configuration improves the power performance of the southern and eastern / western walls over the entire year while the northern wall performance increases only in the summer months.

Clearly, titled orientations are optimum for PV efficiency, as these charts indicate, but not quantified are those considerations which affect other aspects of the building: Sloping the curtain wall impacts the effective floor area at the perimeter of the building, reduces the amount of building area per site area, and may cost more to construct.

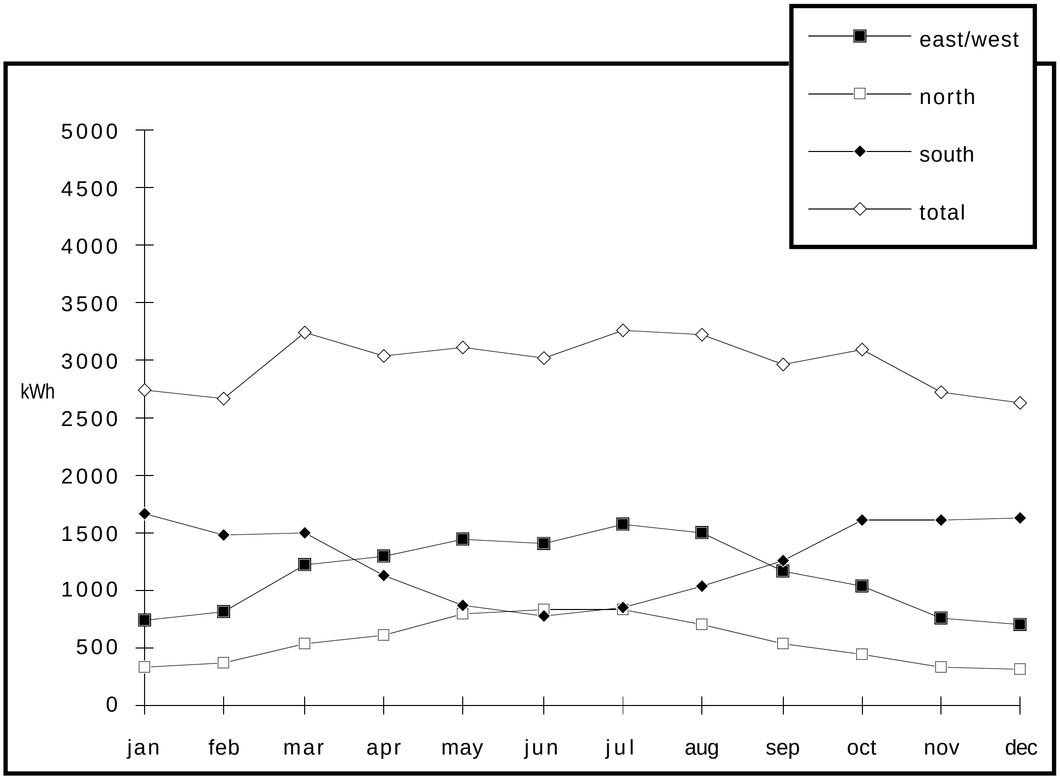


CHART 5: Vertical PV curtain wall (type A1).
Monthly power production in kWh for four polar orientations.

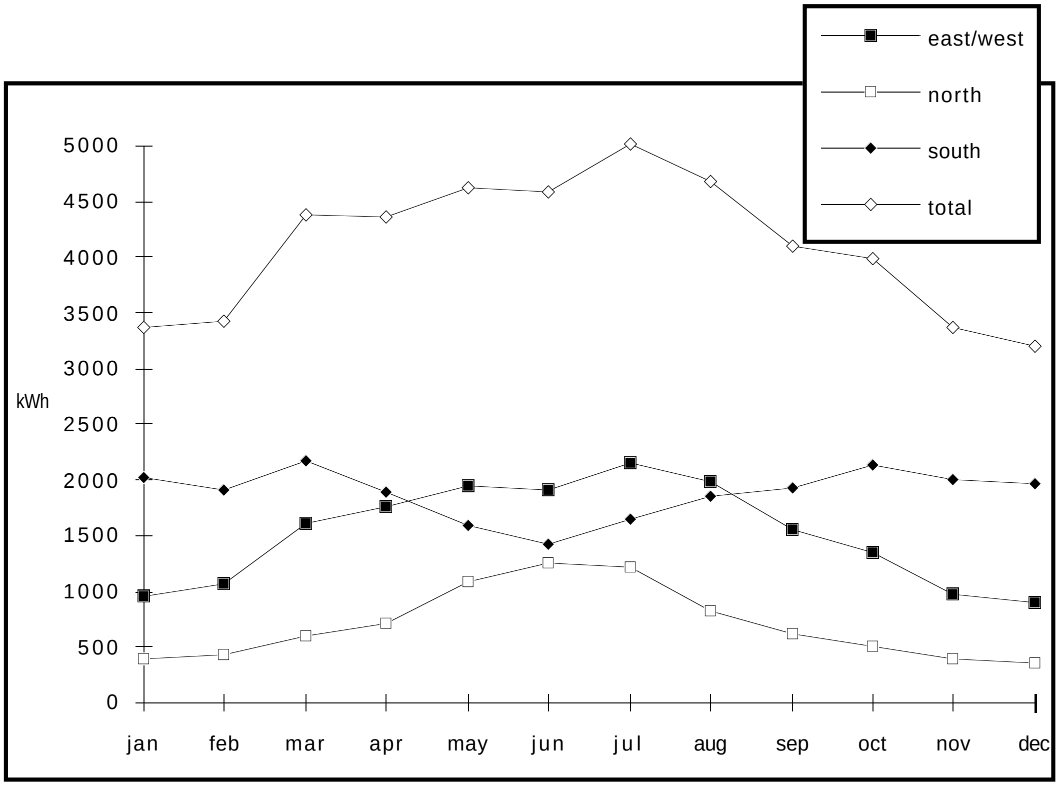


CHART 6: Tilted PV curtain wall (type G1 @ 70° tilt, with increasing surface area).
Monthly power production in kWh for four polar orientations.

E. SHADOWING EFFECTS OF SAWTOOTH WALL PROFILE

The following sets of graphs present an analysis of the sawtooth wall profile (*diags. E,F, pp. 16-17)*. This configuration increases individual PV panel performance without having some of the negative effects of the fully tilted wall section discussed previously. However, complexities of the profile introduce other issues, namely the self-shadowing which occurs as the sun's altitude increases. This analysis attempts to quantify the shadowing effects which impact the performance of the panels. It assumes a sawtooth wall profile (*diag. F, p. 17)* on all four walls of the test case building with tilted PV panels 6 feet long at a 60° slope to the horizontal.

Charts 7 through 9 present the hourly PV power produced, by month, on the south wall both with and without shadowing effects. The first chart indicates the unshadowed peak PV power production which drops slightly in the summer months. With shadowing effects, this power production is considerably reduced in the summer months as the sun gets higher and the percentage of sunlight falling on the panels decreases. This implies that south wall power will be most effective for supplying the buildings peak winter loads.

Charts 10 through 12 present the same analysis for the west wall. Without shadow considerations, PV performance is low in the morning and peaks in the afternoon hours. With shadowing effects, the west wall is considered in full shadow in the morning hours where the PV production is zero and shifts to peak power production after noon. Across the months, the afternoon power performance increases in the summertime. These same results are found for the morning hours of an eastern sawtooth wall, therefore implying that east / west wall PV performance coincides with a building's peak summer cooling loads.

Even with shadowing effects, overall sawtooth wall performance is quantitatively more effective than a simple vertical curtain wall. But other considerations temper this advantage. A sawtooth curtain wall's complex profile may cost as much as twice the amount required to construct a standard curtain wall and its particular image may not appeal to architects or owners involved in a building's design. Further design development by architects and engineers of new types of 'sawtooth' profiles and detailing is warranted.

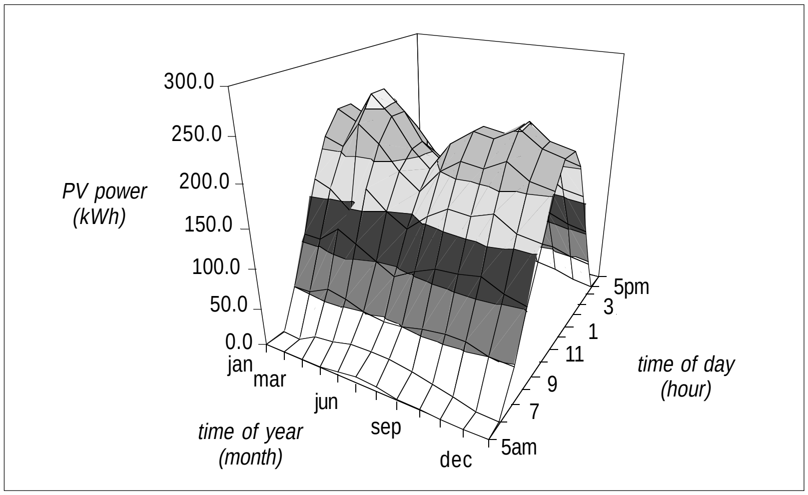


CHART 7: SOUTH-facing sawtooth PV wall (F.1): POWER OUTPUT W/O SHADOWING.
Power production in kWh, by month.

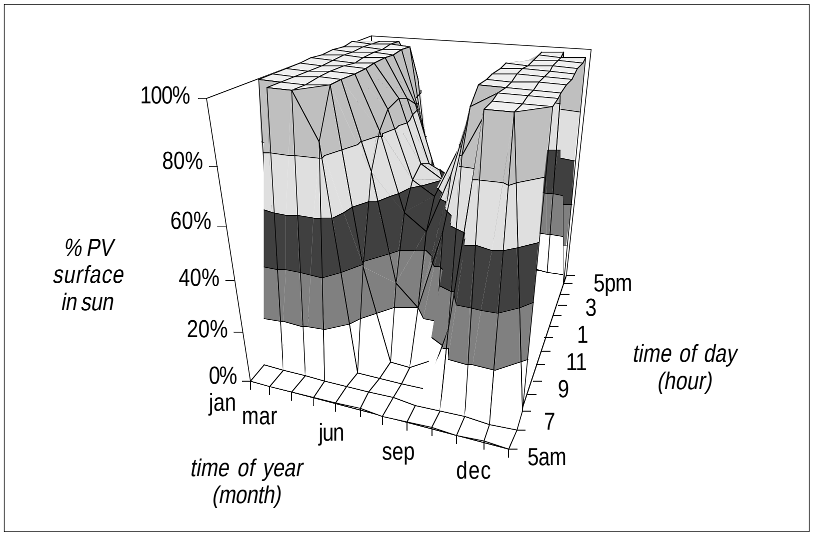


CHART 8: SOUTH-facing sawtooth PV wall (F1): SHADOWING EFFECTS.
Hourly percentage of PV panels not in shadow, by month.

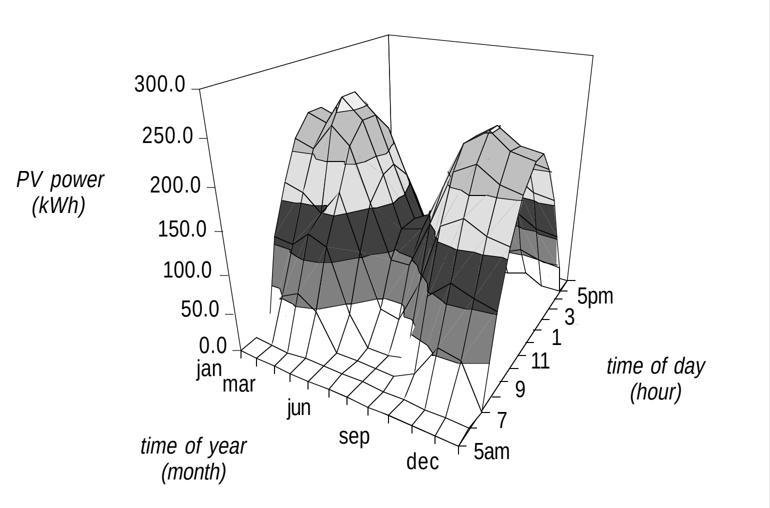


CHART 9: SOUTH-facing sawtooth PV wall (F.1): POWER OUTPUT WITH SHADOWING.
Cumulative power production per hour in kWh, by month.

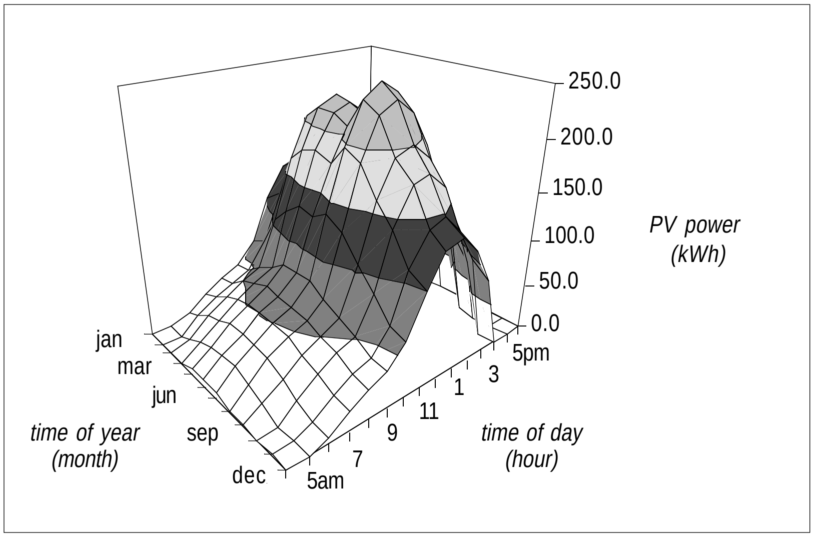


CHART 10: WEST-facing sawtooth PV wall (F.1): POWER OUTPUT W/O SHADOWING.
Power production in kWh, by month.

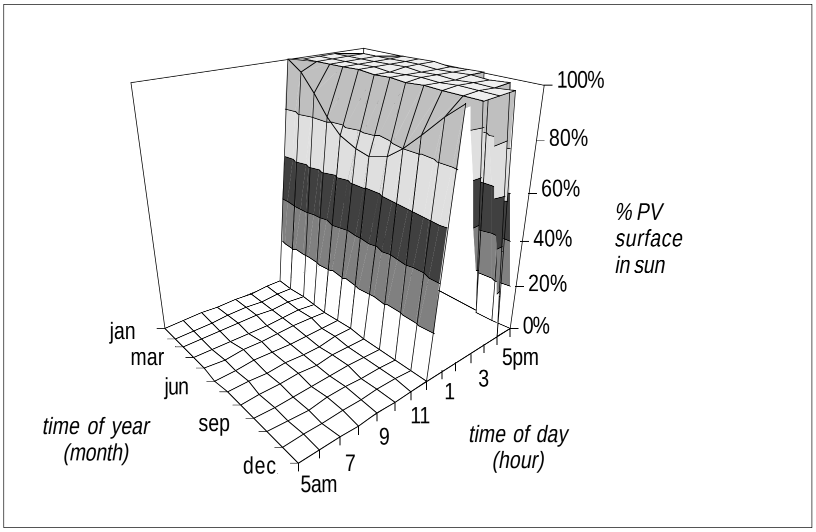


CHART 11: WEST-facing sawtooth PV wall (F1): SHADOWING EFFECTS.
Hourly percentage of PV panels not in shadow, by month.

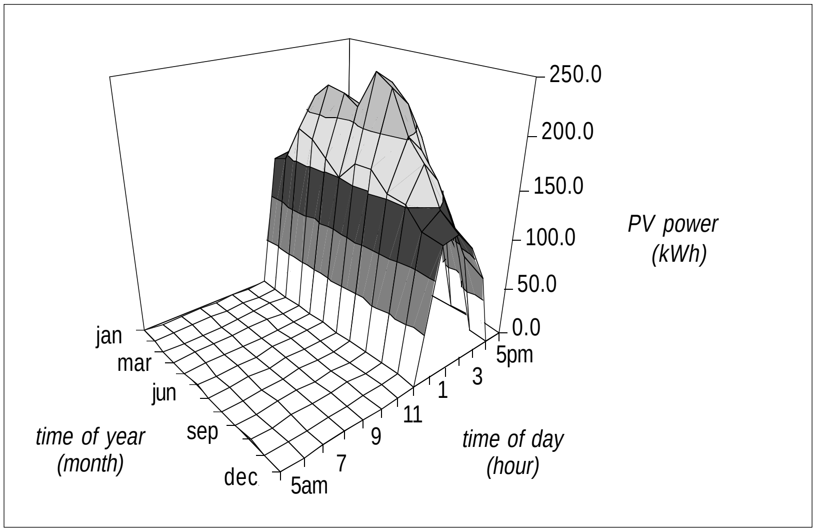


CHART 12: WEST-facing sawtooth PV wall (F.1): POWER OUTPUT WITH SHADOWING.
Power production in kWh, by month.

VI. PVs and Building Systems

A. PV IMPACT UPON BUILDING SYSTEMS

This section presents a brief discussion of building-integrated photovoltaics' impact upon a building's regulatory systems, focusing on the potential for PVs to provide data for controlling these systems.

The following graph shows a diagrammatic relationship between PV power and building loads. The PV power graph represents performance at midsummer for a south facing vertically oriented PV panel. The vertical scale of the PV curve is arbitrarily adjusted to be equal to the HVAC load curve, which is the largest load, in order to show a *proportional* relationship between the PV power provided and the corresponding electric loads requiring power. The load curves are all in approximate scale to each other.

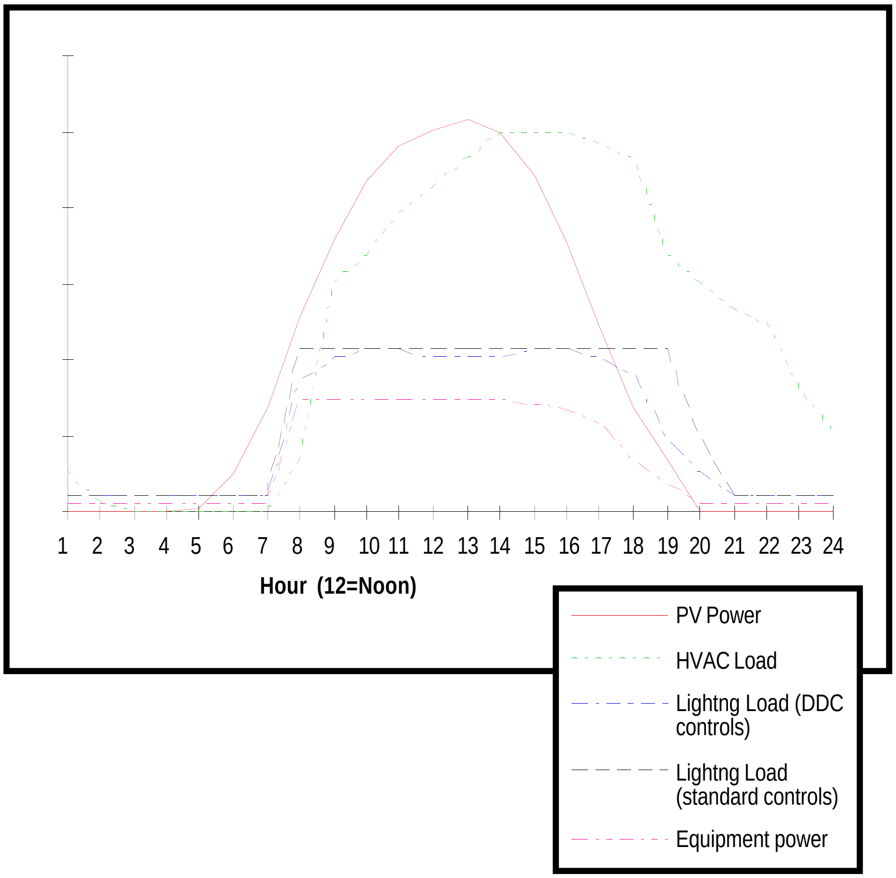


CHART 13: PV Power vs. Building Load

This chart raises a number of possibilities concerning non-residential building load profiles and how these loads may be supplied and controlled by PV power:

<u>*PV Power*</u>: Note the 2-3 hour lag with the HVAC load. Storage could be required in a stand-alone system to match the two.

<u>*Lighting (DDC controls)*</u>: This system assumes an intelligent lighting control system using

occupancy sensors and/or daylight sensors. Depending on the type of use, the lighting load profile could more closely match building activities. The building control system could use power data from PVs to adjust lighting levels.

Lighting (standard controls): assumed to be turned on by workers as they enter in the morning and off by cleaning crews at the end of the day. PV wall systems which improve daylight penetration (light shelves) will reduce the load curve in proportion to available daylight.

Equipment power: The equipment loads assume PCs and other medium-light duty office equipment which is switched on and off by individual workers at the beginning and end of the day.

B. PV-INTEGRATED BUILDING SUBSYSTEMS:

A great number of small scale products can be developed which integrate PVs into building HVAC, lighting or electrical systems. Building-integrated PV panels acting as building sensors for DDC systems offer an opportunity for the panels to play multiple roles in building performance: the panels provide both an envelope (transparent or opaque), they provide power for operating building systems, and they provide the data necessary to regulate those systems.

A few likely products are discussed in the following section:

PV-Powered Mechanical Daylighting Systems *(fig. 4)*

PVs are well suited to passive and active daylighting mechanisms. PV panels can power motorized blinds or electrochromic windows, providing active daylighting and thermal control during the peak hours of the day.

PV-Powered Ventilation Systems *(fig. 5)*

PVs provide the opportunity for creating a dynamic wall system for ventilation. This system can be self-powered to provide automatically-driven ventilation louvers for thermal control of the building’s perimeter zones as well as for ventilation within a double-wall envelope. Such a system could exhaust hot air in warmer months and direct it back into the building in the cooler months.

PV-Powered Emergency Lighting Systems *(fig. 6)*

PVs also offer the potential as a security and/or emergency device. A PV-emergency light package may be activated by battery-stored power during a power outage, or may be activated by a fire alarm system or by building system controls.

PV-Powered Security Systems *(fig, 7)*

PV-powered stand-alone motion detectors could provide security to the exterior or interior building perimeter. These systems would have the advantage of being independent of the power grid. They would also be easy to retrofit to existing buildings.

PV Building Product Diagrams

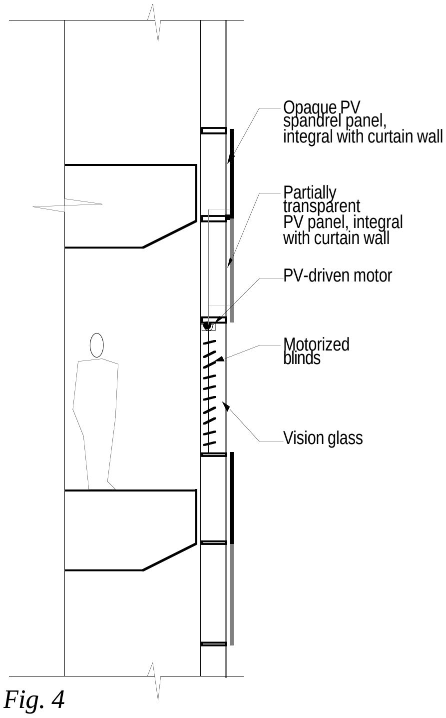


Fig. 4

PV-integrated window unit with PV-driven blinds

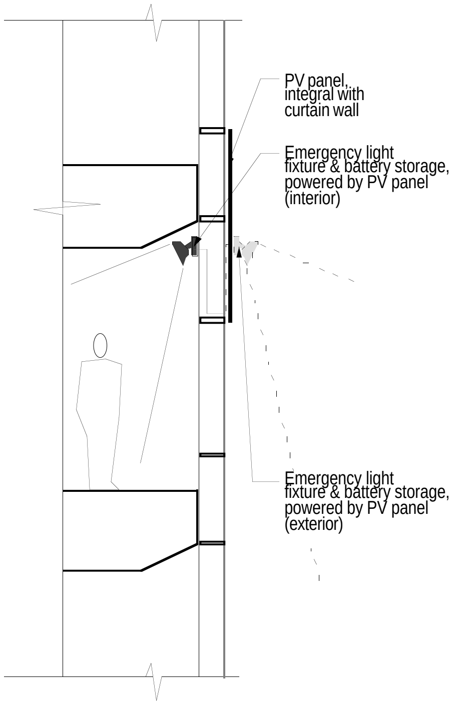


Fig. 6

PV-powered emergency lighting: interior and exterior applications

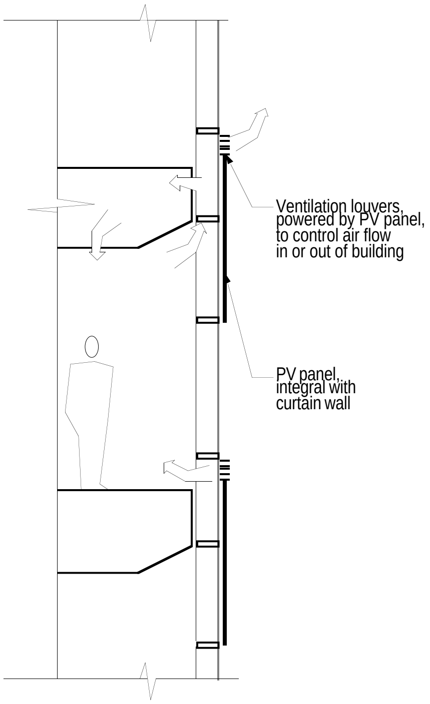


Fig. 5

PV-powered ventilation system: single curtain wall

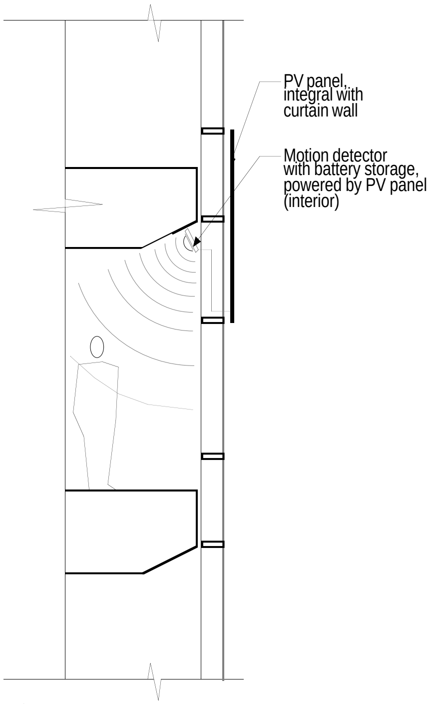


Fig. 7

PV-powered motion detector: lighting mechanism or security device, interior and exterior applications

VII. Cost Issues for PV Buildings

Historically, photovoltaics have not been a cost-effective source of power for general building applications. The ultimate life-cycle cost benefits could not compensate for the up-front expense of the device. As PV costs come down and energy costs rise, PVs will be cost-effective in increasingly large markets.

PV building applications may improve the economics of PVs by allowing some costs of the PV system to be shared by the building, i.e., the value of the traditional building materials the PV products replace. Despite these savings, PV building envelopes will cost more to purchase, design, install and maintain than standard contemporary building skins. These additional costs will have to be balanced against the tangible and intangible benefits provided.

To establish PV building system costs up-front, related existing building costs must be identified. Construction costs for a standard curtain wall, for instance, depend upon factors such as:

- type and quality of framing desired (structural silicon or pressure plate detailing, interior or exterior glazed, tubular or I-beam framing, etc.)
- desired thermal characteristics (thermal breaks, insulated glass etc.)
- type of glazing material used (tempered glass, laminated glass, stone spandrel panels, etc.)
- finish of the framing
- dimensions of the framing members and panels
- manufacturer’s flexibility (custom designs, specialty products)
- field installation vs. prefabrication
- location / climate
- geometry of the wall surface (number of individual elements)
- size of the building
- desired quality, tolerances and standards

Different combinations of these variables can yield overall costs ranging anywhere from $20 to $70 per square foot for material and installation of glazing and framing. In New York, a ‘standard’ glass curtain wall without any special properties, geometries or finishes can run anywhere between $20 and $35 per square foot while a granite curtain wall can cost between $50 and $60 per square foot. At a higher end, structural “all-glass” glazing systems, or planar glazing systems using steel plate fittings and glass mullions for lateral bracing (*diag. P, p.25)*, presently run between $80 and $125 per square foot.

A. INITIAL PV COSTS

The chart on the following page illustrates a rough cost analysis performed for five of the PV wall diagrams discussed in this report. Specific quantitative information has been deliberately omitted because of the multiple variables involved in establishing defined costs. Different building types, contractors, manufacturers, and real estate markets, etc. will lead to a wide range of possible costs up-front. Likewise, different building occupancies, utilities, locations, and energy markets will yield varying life-cycle costs. This chart does not attempt to make these predictions; it is meant only to show rough proportional relationships between initial building costs with and without PVs.

To establish a baseline, the “test case” standard 100 foot long 48 foot high vertical curtain wall was chosen, consisting of typical interior-glazing, tubular aluminum framing, pressure-plate detailing, insulated vision glass and glass spandrel panels. This standard is represented by the darkest bar for each of the five wall diagrams.

Additional costs for PV integration are quantified proportionally by the bars extending beyond the standard cost bar. PV module costs are assumed to be slightly more than those for typical high-end glass building products. Other additional costs estimated are extra wall area resulting from new geometries and allowances for customized construction (a rough estimate which varies with wall complexities).

Clearly, Chart 14 indicates that the full-wall slope and stepped configurations are the most costly. It is important to note that not quantified on this chart is the present value of income from the reduced usable floor area eliminated as the walls slope inward.

Aside from the allowance for reduced floor area, the more costly configurations involve slopes and / or more complex stepped or sawtooth geometries. Sloped walls require surplus material to maintain the same floor-to-floor height; stepped and sawtooth configurations require more parts and therefore more intensive labor for installation.

Not surprisingly, the less costly configurations involve vertical flush curtain walls and awnings retrofitted to the wall. These configurations simply require additional costs for the PV material and relatively minor construction complexities.

It is important to note that this analysis pertains to present-day construction technology. As PVs become common in the building industry, costs for PVs and related materials will decrease. Likewise, standardized construction techniques and prefabricated elements will bring down the custom construction contingency costs factored into this analysis.

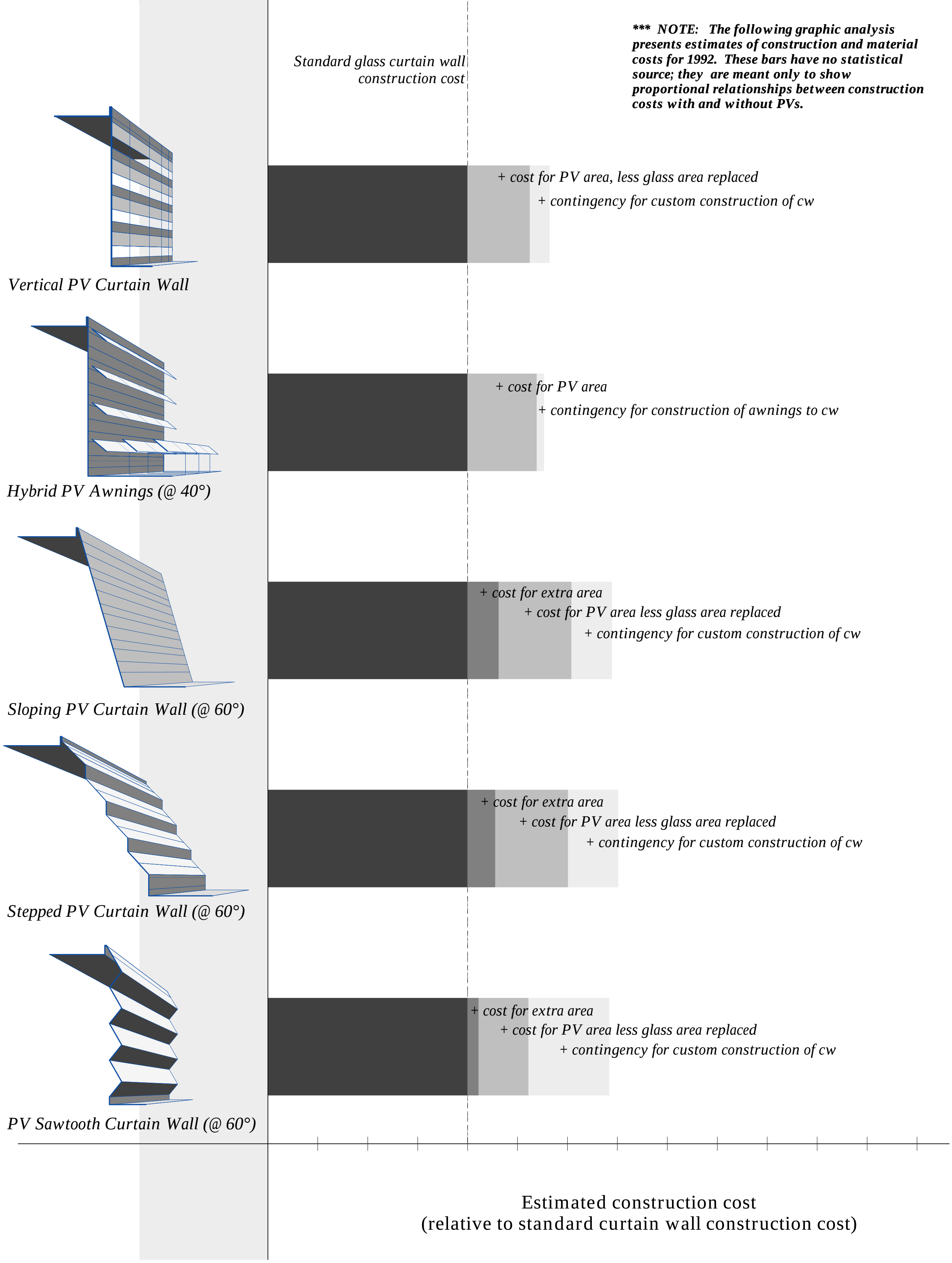
Costs Not Quantified:

Not quantified are estimates in the change of costs of building floor area; i.e. with a sloped or stepped wall, there will be less floor area for a given footprint compared to a vertical curtain wall. The savings in floor area construction will be offset to some degree by more complex building structure.

Also not quantified is an allowance for the electrical balance of systems required to support the PV system; i.e. wiring, control systems, inverters, etc.

ESTIMATED COSTS FOR PV WALL CONSTRUCTION

Chart 14



****** NOTE: The following graphic analysis presents estimates of construction and material costs for 1992. These bars have no statistical source; they are meant only to show proportional relationships between construction costs with and without PVs.***

B. PV POWER PERFORMANCE VS. COST

Chart 15 and the accompanying data below illustrate seasonal and annual PV power generated in ideal conditions for the five wall configurations. The numbers were derived from the PV F-chart software calculations described in Section V. The analysis assumes the 100 foot long, 48 foot high south wall of the four-story test case building. For consistency, the shadow considerations discussed previously were eliminated.

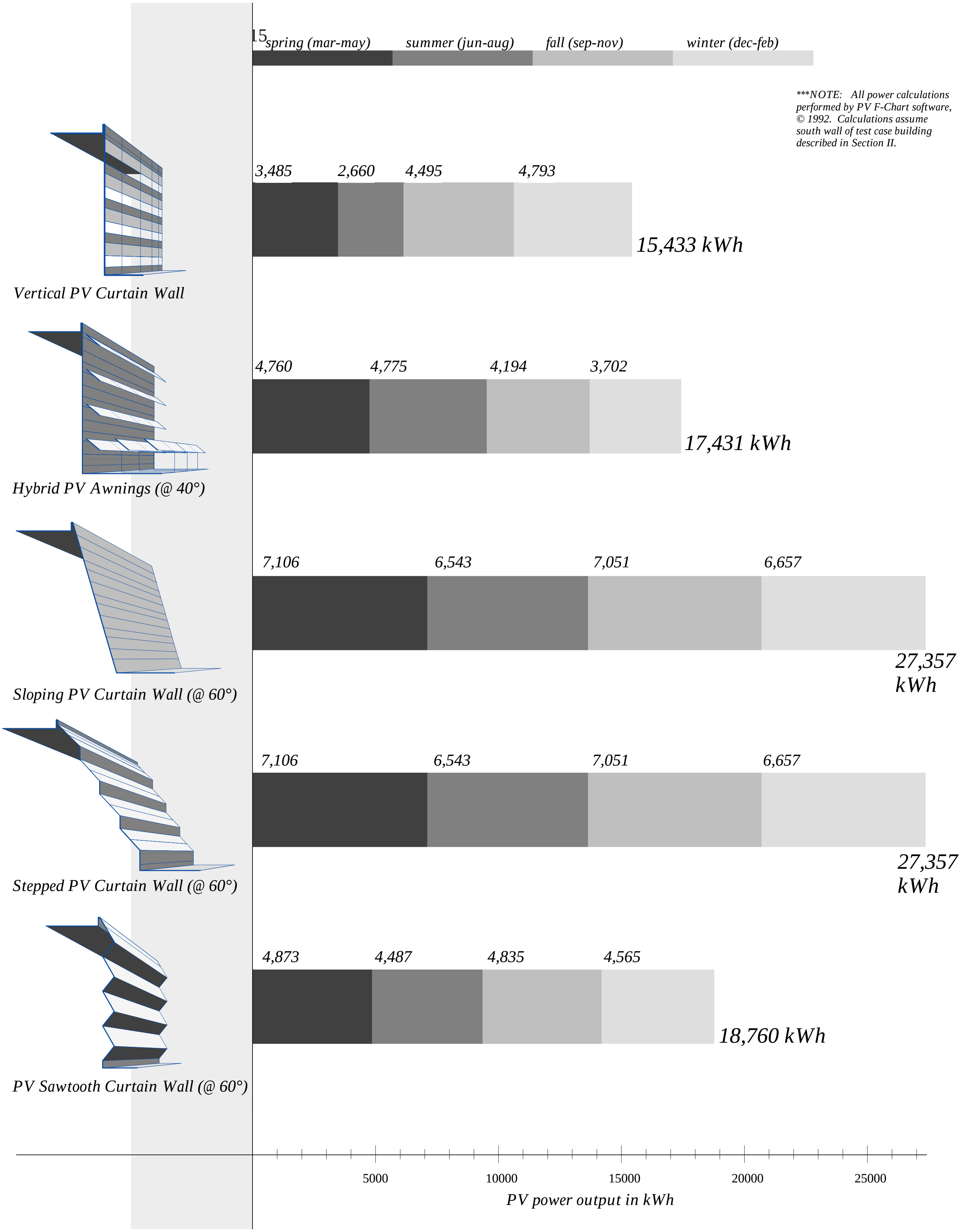
While the sloped and stepped configurations are the most costly , this analysis shows that they also generate the most power. This is due to the relative amount of PV area gained as the wall surface stretches back as well as the optimum panel orientation. Not quantified for these stepped configurations is the present value of the lost income from the reduced floor area.

PV POWER GENERATED FOR 5 DIFFERENT CURTAIN WALL OPTIONS

Test Case Building: *100' long, 48' high south facing wall*
Amorphous silicon panels, 5% efficiency,
.0027 temp. coefficient, 25°C cell temp., 63°C array reference temp.

	vertical cw power output in kWh	**cw awnings power output in kWh**	**sloping cw power output in kWh**	**stepped cw power output in kWh**	**sawtooth power output in kWh**
	(3000sf, 90°)	(2000sf, 40°)	(3500sf, 60°)	(3500sf, 60°)	(2400sf, 60°)
dec	1,637	1,182	2,182	2,182	1,496
jan	1,672	1,246	2,272	2,272	1,558
feb	1,485	1,274	2,204	2,204	1,511
winter	4,793	3,702	6,657	6,657	4,565
mar	1,493	1,611	2,598	2,598	1,781
apr	1,123	1,612	2,389	2,389	1,638
may	868	1,537	2,120	2,120	1,453
spring	3,485	4,760	7,106	7,106	4,873
jun	779	1,453	1,937	1,937	1,328
jul	846	1,661	2,226	2,226	1,526
aug	1,035	1,661	2,380	2,380	1,632
summer	2,660	4,775	6,543	6,543	4,487
sep	1,265	1,498	2,341	2,341	1,605
oct	1,610	1,449	2,464	2,464	1,690
nov	1,621	1,248	2,246	2,246	1,540
fall	4,495	4,194	7,051	7,051	4,835
year	15,433	17,431	27,358	27,358	18,759

B. SEASONAL PV POWER GENERATION FOR 5 SOUTH FACING CURTAIN WALL CONFIGURATIONS



****NOTE: All power calculations performed by PV F-Chart software, © 1992. Calculations assume south wall of test case building described in Section II.*

VIII. The Market for PV Buildings

PV building activity within the US

The PV building applications discussed in context of this report are primarily targeted for the US commercial building market. Commercial (non-residential) window construction totaled some 250 million square feet of vision area in the United States in 1990*. This construction includes curtain wall, storefront and architectural windows; its volume has in recent years been generally split between new construction and remodeling of existing structures. If 10% of this market was PVs at 4 W/sf, this would represent approximately 100 mW/year of PV capacity.

Aside from the non-residential market for curtain walls, storefront and architectural windows, total US glass demand also includes new and remodeling residential applications, double glazing installations, opaque spandrel panels, etc. In 1989, the total glass demand in the US amounted to approximately 2.56 billion square feet (excluding specialty and automotive applications). 1.84 billion of this amount accounts for residential applications; 725 million represents the non-residential demand**. These statistics give an idea of the substantial volumes which exist in the glass building market, both for residential and non-residential applications.

With new construction facing a soft economy in the past few years, remodeling and retrofit window applications have reached substantial volumes Statistics indicate that over 60 percent of all non-residential buildings in America are over 30 years of age**. The upgrading of these older structures often predominates when new construction is inappropriate or unfeasible. The introduction of PVs into the building industry may be helped by the development of PV products such as retrofit windows, awnings, light shelves , skylights or roof-mounted PV arrays for application in remodeling.

The key to successful, large-scale PV integration is to introduce photovoltaics early into the design process and incorporate them as building components from the start. The integrated PV envelope systems and building product packages illustrated in this report will enjoy larger-scale US applications as new construction begins to grow again in the coming years and as PV costs are lowered.

PV building activity outside of the US

The market for PV buildings in Europe and Japan, while still in it's infancy, is more advanced at present than that in the United States. Government subsidies, higher energy costs, better standards of energy efficiency, and a high level of public awareness of the issues have created an environment in which some of the products mentioned in this report have already been realized. Switzerland and Germany, for instance, have demonstrated a number of large-scale PV wall and roof applications on prototypical buildings. Japan has also devoted considerable research to the development of PV building products.

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* *'Industry Statistical Review and Forecast' by the American Architectural Manufacturers Assoc..*

** *'Forecasting Foresight' by R. Cunningham, Glass Magazine , May 1989.*

IX. Questions and Concerns from the Building Community

It is important to recognize that the complexity of the building-integrated PV installations and systems will require the combined efforts of a number of different building trades and product manufacturers. This study presents an informal list of questions and concerns raised during interviews with members of the building community concerning PV building integration.

A. ARCHITECTS

How can PVs be incorporated into essential building components, such as windows, roof tiles and curtain walls?
Will there be any choice in color or finish of the panels?
Will PVs be developed on a flexible substrate such as sheet metal?
Will transparent PVs be developed that have acceptable visual qualities and are available in a range of transmissivities?
How do PVs tie into a building's electrical and mechanical systems?
Where does one turn for information on detailing, specifying, estimating PVs?

B. ENGINEERS

Safety and liability: PVs would be one of few systems that are both in the realm of the Architect and Electrical Engineer; who will be responsible for their design and specification?
With DC power potentially running in a grid throughout a building's skin and weather barrier, what are the chances for short circuits?
How much power can realistically be supplied by building-integrated PVs?

C. DEVELOPERS

Is there a marketing advantage to an energy-producing building? If so, will it be a passing fad?
Are there specific amenities that can be selling points:
Semi-integrated PV systems, such as parking arrays that shade cars in hot weather?
What tax incentives are there to construct with PVs?
What other financial incentives are there, including utility rebates?

D. OWNERS

What are the effects on operating costs?
What is the payback period / life cycle costs?
What tax incentives are there to construct with PVs?
What about demand charges? Energy displacement?
What are the safety and liability issues?

E. FACILITIES MANAGERS

Are the systems reliable?
Do they unduly increase the complexity of the building control system?
How much maintenance is required for PV installations?

F. BUILDING PRODUCTS MANUFACTURERS

What are the available sizes of the panels?
Is there flexibility in size, color, etc. for custom installations?
What are the structural properties of the modules?
What is their weatherseal quality?
How much do the modules weigh?
What are the thermal characteristics?

What are the code requirements?
How much do they cost to produce?
What is their rate of production?
Are there any particular mounting/framing requirements for the panels?
What are the edges of the panels like? Do they need special edging or support?
What is the present rate of change within the PV industry (is there a potential for obsolescence)?

G. BUILDING CONTRACTORS

How should the building trades be coordinated for PV construction and installation? Whose territory is this?
What are the PVs' availability and lead time?
What support exists for installation information?

X. Regulatory Issues for PV Buildings

A. EXISTING CODES AND REGULATIONS

There exist numerous national and state building agencies with energy conservation standards and model energy codes outlined to set minimum energy requirements for the design of buildings. These codes and regulations are meant to ensure that all new building construction is designed with a concern for minimizing the amount of energy required to operate and occupy a building during its lifetime. As an active energy source (PV-supplied power) and / or a passive energy source (daylight and thermal control), PVs may offset the energy calculations for a building's mechanical and electrical loads. As physical building elements, they fall under the same thermal and weathering requirements of a typical building envelope and must meet specific criteria regarding thermal transmittance and air infiltration.

The primary building systems with which these regulations are concerned are the exterior envelope and the systems and equipment associated with the mechanical, water-heating, energy distribution, equipment and lighting systems. To achieve compliance with required design criteria, the designers may choose from a range of guidelines and performance models (some more quantitative than others) to calculate energy performance levels.

The two primary energy codes presiding at the national level are discussed below. These standards were developed by the building community as a direct response to the national energy crisis which seized this country some twenty years ago. While appropriately conservative, the earlier models were restrictive, encouraging minimal glazing and less surface area. As architecture and building systems and have become more and more complex and comprehensive, these documents have experienced extensive review and revisions to accommodate the innovations in both building envelope design and the systems which operate within them. Their scope and methodology will certainly continue to change in the future.

ASHRAE Standard 90.1

Developed by:
American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. (ASHRAE)
Illuminating Engineering Society, (IES)
American National Standards Institute (ANSI)
United States Department of Energy (DOE)

This document, originally published in 1975 as ASHRAE / IES Standard 90-75, represents the national building community's first attempt to address the American energy crisis of the 1970's with a comprehensive national energy standard. It has since undergone extensive review and several revisions in the past two decades with its most recent version, Standard 90.1, offering a more flexible design approach to allow for more interaction and exchange between the different building system components. Two alternative compliance approaches are available with this standard: the system / component and the building-cost budget method.

The system/ component method offers the building designer flexibility in the design of the building envelope and lighting systems via a series of compliance calculations measured against the heating and cooling performance of the envelope. This method has a significant impact on PV-integrated envelope systems design because it measures the efficient thermal performance of the individual envelope elements. This thermal performance may be offset by the passive and active energy benefits provided by the PVs.

Perhaps more conducive to large-scale PV-integrated building design is *the building-cost budget method* which establishes compliance via calculated energy costs measured against a comparable, prototypical building. A building is in compliance when the total calculated annual energy costs for the proposed building do not exceed the annual energy costs of the comparable prototype. This method is appropriate for photovoltaic building systems because it encourages energy-efficient design strategies like active solar systems and passive daylight control. With the building-cost budget method, energy savings provided by the photovoltaic panels and their efficient integration into an envelope system may allow for higher levels of energy to be used for other building systems in other areas.

Model Energy Code

Developed by:
Council of American Building Officials (CABO)
Building Officials and Code Administrators International, Inc. (BOCA)
International Conference of Building Officials (ICBO)
National Conference of States on Building Codes and Standards (NCSBS)
Southern Building Code Congress International, Inc., (SBCCI)
United States Department of Energy (DOE)

The Model Energy Code was developed in 1977 with collaboration from the national building organizations listed above, its content based largely upon the ASHRAE Standard 90-75 (an earlier version of Standard 90.1). Like the ASHRAE Standard, its intent is to establish guidelines for building design which encourage innovative techniques for energy conservation in the building envelope and its mechanical and electrical systems. Like ASHRAE, the code provides alternative methods for compliance. The alternatives consist of two primary compliance paths: a systems approach for the entire building and a component performance approach for the different elements within the building. A third alternative applies to smaller, residential-scale buildings and is not considered in the context of this report.

The *systems analysis method* for building design establishes compliance by comparing total annual energy usage with a comparable prototypical building sharing the same function, floor area, and environmental conditions. This total annual comparison method is similar to Standard 90.1 although instead of an estimated annual energy cost, the code requires calculated loads via a one-year simulation of the operation of the building and its service systems. This is then measured against a “standard design”.

Important to note in the systems analysis method is a unique component which outlines provisions for what it terms “nondepletable energy sources”. This includes, among other phenomena, solar radiation and natural daylighting. The code allows for any “nondepletable energy” utilized in the building to be excluded from the total energy calculations. In the case of PV-integrated buildings, this would include both PV-supplied power and the passive solar energy savings provided by shading or windows with insulating blinds. More importantly, the code concludes that buildings which derive over 30% of their annual thermal requirements or over 50% of their total energy requirements from these “nondepletable sources” are exempt from performing any calculations at all and need only present documentation verifying the percentage of annual energy provided.

The *component performance approach* requires more detailed calculations for the performance of the individual building elements and systems. The components are divided into sections for envelope requirements, mechanical systems, service water heating, and electrical power and lighting. These sections establish criteria for specific factors such as thermal resistance and air-infiltration of building envelopes or illumination levels and reflectance factors of lighting systems. This approach is appropriate for a highly specific analysis of individual systems, but not for overall building performance. For photovoltaics, this approach may be necessary for localized retrofit PV applications at the building envelope but for larger-scale PV building applications, the systems method will address the energy benefits associated with photovoltaics.

B. CODE IMPACT ON PV BUILDING SYSTEMS

PV-integrated systems offer yet a new dimension to the existing standards and regulations:

- As an active energy source (PV-supplied power) and / or a passive energy source (daylight and thermal control), they may offset the energy calculations for a building's mechanical and electrical loads
- As a physical building element, they fall under the same thermal and weathering requirements of a typical building envelope and must meet specific criteria regarding thermal transmittance and air and water infiltration.
- For large-scale PV building installations, photovoltaics provide an opportunity for potential exemption from these regulations altogether.

XI. Conclusions

This study suggests that photovoltaics can be a viable building material and that, despite some compromises in efficiency, photovoltaics as a building material can also be a viable source of power. A PV building skin will do more than keep out the weather and modulate heat and light transmission; it will produce energy (and therefore revenue) instead of consuming and losing energy. As an active element of the building, it will be dynamically linked to other systems in ways we cannot fully anticipate.

Some significant points the study has raised are:

- PV efficiency will not always be the overriding consideration in PV building design.
- Installations and technologies such as PV awnings or lightshelves or semi-transparent modules can offer both passive and active solar benefits.
- In addition to supplying power, PV skins must provide a proper weatherseal, modulate thermal transmission and have the structural capacity to withstand the stresses inherent in a building's envelope.
- PVs might act as both a power and data source for supplying and controlling a building's regulatory systems.
- PV building products might include discrete building packages such as PV-powered daylighting mechanisms or ventilation systems.
- The costs for PVs in buildings will usually be more than those for standard envelope construction.
- Development of photovoltaics in the building industry will require the combined efforts of multiple interests in the building community, including architects, engineers, developers, contractors, manufacturers, property owners, real estate brokers, government organizations, corporate sponsors, etc.

The final success of PV-building applications depends on the answers to a number of issues beyond the scope of this study. Questions involving cost, aesthetics, safety and reliability require quantitative answers:

- What will the true costs be, tangible and intangible, of integrated PV-building products?
- What benefits, economic and environmental, tangible and intangible, will PV building products bring to the public and the building community?
- What incentives can or should the public and private sectors provide to develop and install these systems?
- Will factors other than cost influence their acceptance: aesthetics, liability, their environmental appeal, the security and independence their power provides?

Further study of the costs and benefits of PV-integrated building skins and products is warranted. Given the great potential PVs have to benefit the design and construction industries while simultaneously improving the environment and energy security, it is in the interest of both the public and private sectors to promote the technology in every reasonable way.

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