PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2004; **12**:395–408 (DOI: 10.1002/pip.554)

Special Issue

Photovoltaics in an Architectural Context

Henk Kaan[1]*,† and Tjerk Reijenga[2]
[1]*ECN Energy Research Centre of the Netherlands, P.O. Box 1, 1755 ZG Petten, The Netherlands*
[2]*BEAR Architects, The Netherlands*

In well-populated areas, such as western Europe, PV is often integrated into the building envelope. Despite the fact that there are many examples showing that PV can be an aesthetically neutral or visually attractive element in architecture, many BIPV systems display few architectural qualities. But if well applied, PV can increase a building's character and value. Within Task 7 of the IEA PVPS programme a team of experts with an architectural background studied which key requirements needed to be complied with (design criteria for good-quality PV projects) in order to produce successful PV integration. These criteria are discussed in the article.

PV is not automatically considered an indispensable material in architectural terms. This is why, no matter how well it is integrated, PV remains an 'added' element. Architects can take this as their starting point and can use one of the design approaches that are presented in the article. These criteria for incorporating PV in the building design and the design criteria for good-quality PV projects are important to architects and architectural critics in determining why a BIPV project, be it their own design or that of a colleague, is or is not aesthetically pleasing. This offers learning opportunities and reasons for follow-up or improvement options. Architects who apply PV in a well-thought-out way can make their clients very happy, and thereby contribute to a greater acceptance of PV technology. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: building-integrated PV; architecture; BIPV design criteria; architectural integration of PV

INTRODUCTION

The governments of many western countries recognize the importance of PV (photovoltaic solar energy) and underline this by frequently providing financial support for PV systems. Both the scientific and industrial sectors are working hard to improve the production process, primarily to make PV less expensive. The western world and Japan are familiar with buildings in which PV has been applied in an innovative fashion. It is therefore all the more remarkable that the vast majority of architects and property developers do not have sufficient knowledge of PV systems. This article tries to improve this knowledge by indicating when to consider integrating PV into a building, and should also help structure any discussion of architectural integrity by raising the argument above the usual level that simply considers 'beautiful or ugly'.

* Correspondence to: Dr. Henk Kaan, ECN Energy Research Centre of the Netherlands, P.O. Box 1, 1755 ZG Petten, The Netherlands.
†E-mail: kaan@ecn.nl

 Received 1 March 2004

PV AND THE BUILT ENVIRONMENT

Around 40% of the energy consumption in western countries is used by the built environment, in some form or another, with electricity taking an increasingly larger role. Generating electricity from renewable sources is therefore becoming increasingly important, and PV can play a prominent role in this. In contrast to wind energy, biomass and hydropower, PV is extremely well suited to the built environment. In well-populated areas, such as western Europe, PV is often integrated into the building envelope. This avoids having to use a separate mounting construction for the PV modules and overcomes the physical lack of space. It also ensures that the electricity generator is very close to the user. If high-quality sustainable energy is to be encouraged then PV is the obvious solution, at least as far as the built environment is concerned (Figure 1).

PV, ARCHITECT AND CLIENT

However, the number of building-integrated PV (BIPV) systems remains limited. Despite the fact that there are many examples showing that PV can be an aesthetically neutral or visually attractive element in architecture[1]—many of the examples can be found on the Internet database compiled by Task 7 of the International Energy Agency's (IEA) Photovoltaic Power Systems (PVPS) programme[2] and show that buildings and PV systems can form an excellent combination—many BIPV systems display few architectural qualities. Besides the fact that many architects have never thought about using PV as a means of architectural expression and have therefore never produced good solutions for architectural integration of PV, inexperience and lack of PV knowledge by clients, mean that architects often draw the short straw when it comes to discussing PV with clients, consultants and/or installers. When it comes to costs, maximizing revenues and implementation/technical requirements, the architect often has no convincing argument for combining the architectural and aesthetic qualities with the possibilities offered by PV systems.

Property developers and institutional investors often see a building as a means of generating a certain, precalculated, return on their investment. These principals build for the rental market or for anonymous house buyers. They feel that a building should be as neutral as possible, both architecturally as well as operationally. In order to encourage these clients to consider applying PV the architect will need to present it as neutrally as possible, with regard to aesthetics and costs. This is certainly not impossible, as PV is a good alternative for existing exterior façade materials, such as those used for office buildings. PV also has most of the physical building characteristics of conventional façade materials, so that the building engineering remains fundamentally the same. Since conventional façade materials are generally not cheap, PV can often also represent a financially competitive alternative.

Figure 1. Interior of the conservatory in Building 42 at ECN in Petten, Netherlands, with PV system integrated into the transparent roof. Design: BEAR Architects, Gouda, Netherlands

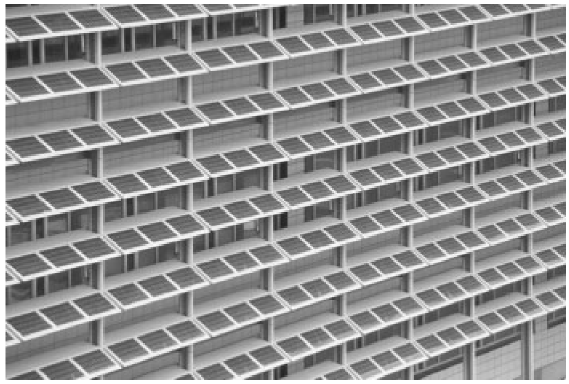

Figure 2. South façade of Building 31, the renovated laboratory at ECN in Petten, Netherlands. The curtain of vertical blinds includes a 35 kWp PV system. Design: BEAR Architects, Gouda, Netherlands

PV AND RENOVATION

PV plays an important role in renovating buildings as it increases the building's value, both aesthetically and energetically. A well-thought-out solution can make less successful or boring façades look visually more attractive. A good example is ECN's Building 31, which was redesigned by BEAR Architects. The original 1963 laboratory was completed renovated in 1999, during which the heavy prefabricated concrete façades were replaced by wooden skeleton framework façades that included ceramic elements. A curtain of vertical blinds was placed along the south façade as sun protection, with four blinds per floor containing PV modules (Figure 2). The roof was fitted with a 'parasol' of PV modules. These constructions (roof and vertical blinds) have reduced the coding demands of the building so much that a cooling installation is no longer necessary. The improved insulation, sun protection and PV system, which supplies 90% of the building's electricity needs, have resulted in the building's energy consumption being reduced by 75%. Integrating the PV system into the external sun protection means that the extra costs are only slightly higher than the costs of individual modules and inverters, while the aesthetic qualities of the building, and therefore its character, are greatly improved.

PRIVATE CLIENTS

In contrast to property developers and institutional investors, private clients often have specific ideas about how they want their building to look, often reflecting the type of work and attitude of the principal/user. Therefore private clients should realize that PV sends a very clear message. If well applied, PV can increase a building's character and value. Although Bequerel discovered photovoltaic principles as far back as 1839, PV still has a 'high-tech' image and is therefore ideally suited for buildings with an untraditional character.

PV's second important symbolic function lies in the way it highlights the autonomy of the building—and its user. By expressing their individuality users show a clear wish to be less dependent on the energy supplier. This autonomy can be taken to extremes, such as the Energieautarkes Haus in Freiburg (Figure 3). This experimental building—which was occupied for several years as part of the experiment—is completely autonomous as far as energy is concerned. The energy concept is determined by excellent thermal insulation, optimum use of thermal solar energy and by incorporating PV to generate electricity. If not used immediately, the electricity generated by the PV system is partially stored in batteries and partially used to convert water into hydrogen and oxygen. Fuel cells ensure that the hydrogen is used to generate electricity as and when required. The hydrogen is also used for cooking and heating via catalytic burners.[3,4]

Figure 3. The Energieautarkes Haus in Freiburg, Germany, has a rounded façade that allows maximum solar entry. A semi-integrated PV system is visible on the roof

ARCHITECTURAL INTEGRATION: CRITERIA FOR GOOD PV ARCHITECTURE

Architects are not only confronted with the question of whether or not to incorporate PV into their designs and what the building's physical, mechanical, electrotechnical, financial and organizational conditions will be; they are primarily concerned with the question of how to incorporate PV into the aesthetic aspects. The large numbers of architecturally unsatisfactory solutions clearly show that many architects are still struggling with this problem.

The IEA PVPS programme defined a specific task entitled Photovoltaics in the Built Environment (Task 7). The experts who collaborated on this project from the various participating countries all have an architectural background (10 team members, including the authors of this article). The team studied which key requirements needed to be complied with (design criteria for good-quality PV projects) in order to produce successful PV integration. The Delphi approach allowed a small group of experts to formulate a number of (not too subjective) criteria whereby integration of PV in buildings could be architecturally classified and evaluated. The criteria can be used as a guideline for both the designer and the architectural critic.

The team of experts gave their written, anonymous, but motivated evaluations of approximately 50 BIPV projects.[2] The assessment criteria used were then collected, classified and compressed, i.e., similar, or nearly similar, criteria were combined. The projects were then evaluated on the basis of these defined criteria, and the results announced. In many cases the experts agreed immediately, although other projects generated a certain amount of discussion. Arguments based on background information, such as 'maintenance and operational problems' were not allowed to play any part in the discussion of aesthetic qualities, although they may well be valid in labelling a project as not of good quality. After all, a BIPV project still has to meet technical quality criteria (e.g., technical aspects of modules, cabling and inverters) as well as architectural quality criteria.

The following aesthetic criteria were finally accepted as being vital to a successful BIPV project.

Natural integration of the PV system

This means that the PV system seems to form a logical part of the structure (Figures 4 and 5) and adds the finishing touch to the building. The PV system does not have to be that obvious. In renovation situations the result should look as though the PV system was there before the building was renovated.

The PV system is architecturally pleasing, within the context of the building

The design must be architecturally pleasing (Figures 6 and 7). The building should look attractive and the PV system should not noticeably improve the design. This is a very subjective issue, but there is no doubt that some buildings are considered more pleasing than others.

Figure 4. Fire station in Houten, Netherlands. Transparent panels have been fitted into the curved roof. Design: Philippe Samyn & Partners, Brussels, Belgium

Figure 5. Toilet/shower facilities on a campsite near Poitiers, France with the PV system completely integrated into the roof

Figure 6. Indoor corridor at the environmental information centre known as De Kleine Aarde in Boxtel, Netherlands. As a result of the special lighting, the PV system contributes to the attractive interior. Design: BEAR Architects, Gouda, Netherlands

Figure 7. Façade with sun protection that includes a PV system. Fitting the integrated system of vertical blinds livens up the building and makes it visually attractive. Design: ABZ Architects, Netherlands

Good composition of colours and materials

The colour and texture of the PV system should be consistent with the other construction materials (Figures 8 and 9).

The PV system fits the gridula, or visual pattern of the grid (is in harmony with the building and, as a whole, forms a good composition)

The dimensions of the PV system should match the dimensions of the building (Figures 10 and 11). This will determine the dimensions of the modules and the building grid lines used. (Grid = modular system of lines and dimensions used to structure the building.)

The PV system matches the context of the building (contextuality)

The appearance of the building, as a whole, should be consistent with the PV system used (Figures 12 and 13). In a historic building, a tile-type system will look better than large modules, if the PV system cannot be placed out of sight. A high-tech PV system, however, would look better on a high-tech building.

Figure 8. Horse stables in Bern, Switzerland. This historic building includes PV slates that, together with the standard roofing slates, harmonize with the old building. Colour and texture blend well together

Figure 9. Apartments in the 1·3 MW project in Amersfoort Nieuwland, Netherlands. The façade consists of three blocks of colour, so that the block with blue solar panels harmonizes with the adjacent brick-coloured blocks. Design: Studio Z, Rotterdam, Netherlands

Figure 10. 'Solar Cube' at the Discovery Science Museum in Santa Anna, Los Angeles, USA. Design: Steven Strong, Solar Design Association, Harvard, USA

Figure 11. Modehuis Kaiser, Freiburg, Germany. A more open façade was added when the building was renovated. The huge amount of glass is protected by a glazed sun protection that includes PV cells. The system exactly fits the size and shape of the windows that it covers

Figure 12. Roof outline of the UBS bank in Suglio, Switzerland. The detachable PV console modules form a total concept with the 'high-tech' image of the roof outline

Figure 13. Houoh High School in Houoh, Japan, with a roof covering that consists of roofing tile modules. This type of PV system blends well with the traditional Japanese slate-type roof

The system, and its integration, are well engineered

This does not refer to the waterproofing or reliability of the construction, but to the elegance of the details (Figures 14 and 15). Did the designer pay attention to detail? Has the amount of material been minimized? These considerations will determine the influence of the working details.

The application of PV has led to innovative designs

PV systems have been used in many ways, but there are still countless new ways to be developed. This is all the more reason to consider this criterion, in addition to the other considerations (Figures 16 and 17).

HOW CAN PV BE INCORPORATED INTO THE BUILDING DESIGN?

The aforementioned criteria partially apply to all construction materials and building components. The fact that most of these criteria are automatically applied to traditional materials, but are explicitly formulated and discussed only for PV, stems from the fact that PV is not automatically considered an indispensable material in architectural terms. It is not seen in the same light as windows, roof coverings, load-bearing constructions and

Figure 14. Sustainable office in Doxford, near Sunderland, UK with a finely detailed southern façade. Design: Studio E Architects, London, UK

Figure 15. Children's Museum, Rome, Italy, with a PV system integrated into the sun protection that is particularly well detailed. Design: Abbate & Vigevano Architectura, Rome, Italy

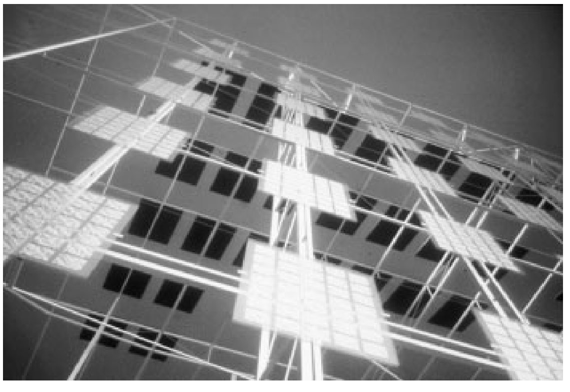

Figure 16. Renovating an office building for the Ministry of Economic Affairs in The Hague, Netherlands. The façade is fitted with a curtain of transparent PV modules that contain grey cells. Design: Babet Galis, Delft, Netherlands

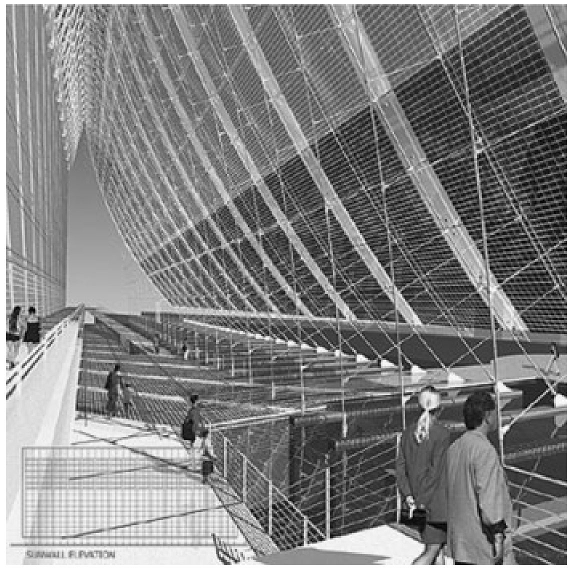

Figure 17. Renovation of the Department of Energy (DOE) in Washington, USA. The building was renovated with a special PV tent structure. Design: Solomon Cordwell Buenz & Associates, Chicago, USA

Table I. Overview of the criteria for good PV architecture, as defined by Task 7 of the IEA PVPS programme

Natural integration of the PV system
The PV system is architecturally pleasing, within the context of the building
Good composition of colours and materials
The PV system fits the gridula, is in harmony with the building and, together, forms a good composition
The PV system matches the context of the building (contextuality)
The system, and its integration, are well engineered
The application of PV has led to an innovative design

façades. Buildings without windows are generally unacceptable, and buildings without load-bearing constructions are absolutely impossible. But this cannot be said for PV systems. This is why, no matter how well it is integrated, PV remains an ‘added’ element. Architects can take this as their starting point and can use one of the following design approaches.

PV is applied invisibly

The PV system is incorporated invisibly and is therefore not architecturally ‘disturbing’, Figure 18. The PV system harmonizes with the total project. The National Research Home Park (Figure 19) is a good example, where the architect has tried to integrate PV modules into the design invisibly. This solution was chosen because the entire project concerned ‘historic’ architecture. A modern high-tech material would not be appropriate for this architectural style.

PV is added to the design

The PV system is added to the design (Figure 20). Building integration is not really used here, but this does not necessarily mean that architectural integration is also lacking. The ‘added’ PV system is not always visible (Figure 21).

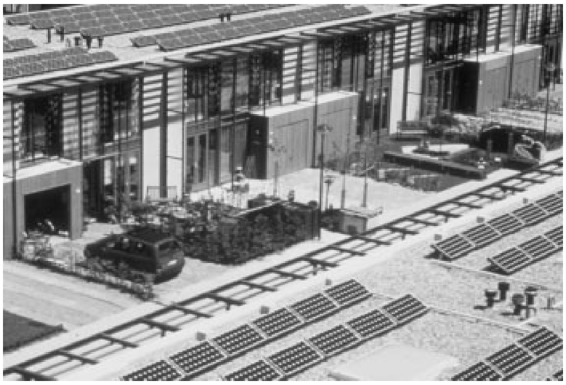

Figure 18. Modern homes in the 1·3 MW Nieuwland project in Amersfoort, Netherlands. PV systems are mounted on the flat roofs, where they cannot be seen from the street. Design: Babet Galis, Delft, Netherlands

Figure 19. Historic-style homes in the National Research Home Park in Bowie, Maryland, USA

Figure 20. Solar Energy Institute at the University of Madrid, Spain. The PV system was added to the building at a later date and is also used as permanent sun protection

Figure 21. Homes in the 1·3 MW project in Amersfoort Nieuwland, Netherlands. The PV systems have been visibly added. The architect has accentuated this by selecting a white roofing foil. Design: Duinker & Van der Torre, Amsterdam, Netherlands

The PV system adds to the architectural image

The PV system has been integrated beautifully into the total design of the building, without changing the project's image (Figure 22). In other words, the contextual integration is very good (Figure 23).

The PV system determines the architectural image

The PV system has been integrated into the design in a remarkable and beautiful way, and plays an important role in the total image of the building (Figure 24).

The PV system leads to new architectural concepts

Use of PV modules, possibly in combination with other types of solar energy, leads to new designs (Figure 25) and new architecture (Figure 26). The integration of PV modules has been considered at a conceptual level, which gives the project extra value.

The IEA BIPV experts have classified these categories according to the increasing extent of architectural integration. However, a project does not necessarily have to be of a lesser quality just because the PV modules are not visible. A visible PV system is not always appropriate, especially for renovation projects with historic architectural styles. The challenge for architects, however, is to integrate PV modules into buildings properly. PV modules are a new building material that offers new design options. Applying PV modules in architecture

Figure 22. The Swiss Institute EMPA has integrated PV systems into the façade and combined them with movable sun protection. Design: Theo Hotz, Zürich, Switzerland

Figure 23. The edge of the roof on this office building is fitted with a glass overhang to protect the façade, which mostly consists of transparent glass modules. Design: BEAR Architects, Gouda, Netherlands

Figure 24. These houses, in the 5 MW_p project in Langedijk, Netherlands, all have a large roof that is completely covered in PV modules, without drainage perforations, which emphasises the roof. Design: BEAR Architects, Gouda, Netherlands

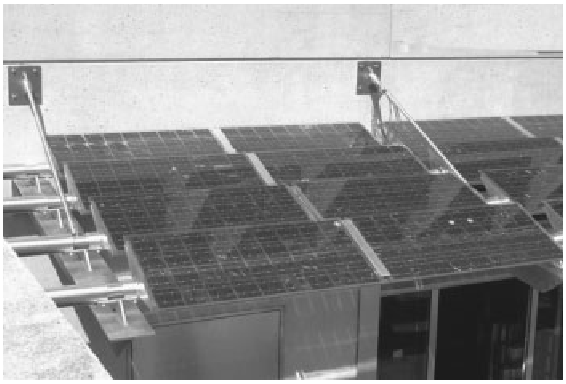

Figure 25. A sunshade for a shop window in Lausanne, Switzerland, which gives the fairly boring shopping centre a new and high-tech image

Figure 26. Zero-energy homes in Etten-Leur, Netherlands. The roofs are fitted with a steel construction that fits over the houses, so that the direction of the PV modules does not depend on the orientation of the homes. Design: BEAR Architects, Gouda, Netherlands

Table II. Types of PV integration, listed according to the increasing amount of architectural value

PV is applied invisibly
PV is added to the design
The PV system adds to the architectural image
The PV system determines the architectural image
The PV system leads to new architectural concepts

should therefore lead to innovative new designs. In some of the selected projects, the design was based on this principle.

FINAL COMMENTS

This article has no scientific pretensions. Architecture, although often supplying subjects for scientific studies, is not in itself a scientific discipline. The authors hope this article will help readers who are not confronted with architectural design criteria on a daily basis to understand the architectural value of the BIPV examples shown here.

The criteria presented here are important to architects and architectural critics in determining why a BIPV project, be it their own design or that of a colleague, is not aesthetically pleasing. This offers learning opportunities and reasons for follow-up or improvement options. Architects who apply PV in a well-thought-out way can make their clients very happy, and thereby contribute to a greater acceptance of PV technology.[5]

REFERENCES

1. Hagemann IB. *Gebäudeintegrierte Photovoltaik: Architektonische Integration der Photovoltaik im Gebäudehülle* (Architectural Integration of Photovoltaics in Building Envelopes). Rudolf Müller: Köln, 2002.
2. IEA Photovoltaic Power Systems Programme. www.pvdatabase.com
3. Voss K. *Experimentelle und theoretische Analyse des thermischen Gebäudeverhaltens für das Energieautarke Solarhaus* (Experimental and theoretical analysis of the thermal consequences of the building shape, Energieautarke Solar House). Fraunhofer IRB Verlag: Freiburg, 1996.
4. Stahl W, Goetzberger A, Voss K. *Das Energieautarke Solarhaus: Mit der Sonne wohnen* (The Energieautarke Solar House: Living with the Sun). C. F. Müller: Heidelberg, 1997.
5. Van Mierlo B. *Sociale monitoring van PV-projecten: Een evaluatie van de rol van pilotprojecten bij de introductie van zonnecellen in de woningbouw* (Social monitoring of PV projects. An evaluation of the role that pilot projects play in introducing solar cells into residential buildings). IVAM Environmental Research: Amsterdam, 2000; 39.

