Development of Bi-functional Photovoltaic Modules for Building Integration. “BIMODE”

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2. Table of Contents

3. Abstract

In the BIMODE-Project, designers, architects and scientists were working closely together for the first time to enhance the aesthetic appearance of PV-modules. A range of designs was proposed using solar cells in different colours and shapes on mono- and multi-crystalline wafers. Six prototypes were produced: A triangular module containing multi-crystalline triangular laser grooved buried grid (LGBG) cells of dark blue, steel blue, gold and magenta colour. For these cells a novel gridline pattern and interconnection method were developed to make cell interconnection without the use of busbars. A rectangular module consisting of square and rectangular multi-crystalline LGBG cells in the colours magenta and pale gold. The rectangular cells enhance the striped appearance of the module. Three rhombic modules with mono-crystalline hexagonal LGBG cells of dark blue, steel blue and pale gold colour. The three modules give a strong three dimensional impression of a cube when placed together. A hexagonal module with mono-crystalline hexagonal cells of green colour and a sinusoidal bus bar pattern. The green cells were produced using screen-printing technology. The prototypes have module efficiencies between 6.3 and 12.1%.

4. Partnership

Partner	Address	Contact Person
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TFM	Pol. Ind. Pla d’en Coll, c/ Gaia 5, 08110 Montcada (Barcelona), Spain	O Aceves
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5. Objectives

The objective of the project was to develop a range of building facade photovoltaic modules which contribute useful electrical power to the building and have an enhanced visual appearance and are therefore bi-functional. The enhanced visual appeal is generated by combining high efficiency multi- and mono-crystalline silicon solar cells of different colours with various sizes and textures into a facade element. A team of creative designers at the Kunsthochschule für Medien in Cologne reviewed the visual properties of the available colours and textures of crystalline silicon solar cells and proposed visually attractive prototypes which were to be produced by the other partners. It is important that the proposed prototypes should not just be artistically interesting but should also be fully functional within the building envelope and acceptable to architects. To fulfil this role, Ove Arup was to obtain feedback from the building design community and make recommendations on the prototypes to be produced. The fabrication of prototypes was the responsibility of the wafer producing and solar cell developing partners (Bayer, BP Solar and AIOU). It was essential that the prototypes are fully functional as photovoltaic electricity generators and therefore a minimum module efficiency was required. The technical target was for at least one prototype to demonstrate, at the end of the project, 8% module efficiency at standard test conditions, while still being visually attractive. However it is well known that significant power losses can occur in a multiple solar cell array if the cells within the array do not have nearly identical electrical properties particularly at short circuit conditions. This is not likely to be the case where cells have different colours and textures and hence different reflectivities. It is therefore essential to model the behaviour of mismatched cells to understand how the cells can be combined by series and parallel connection to obtain the desired final module efficiency. This work was to be carried out by the IES.

An additional objective of the project was to stimulate the architectural community into a greater awareness and acceptance of photovoltaic modules integrated into buildings. While a few internationally renowned architects have led the way there is still reluctance among the general profession. One of the perceived disadvantages of photovoltaic is its lack of visual appeal while buildings appear black or dark blue. The purpose of this project is to show that photovoltaic panels can be so visually interesting as to regarded as works of art and enhance the value and attractiveness of buildings in the same way that sculptures, fountains and murals presently do. The artistic appeal creates added value and diminishes objections to lack of cost competitiveness in photovoltaic systems when compared with utility supplied electricity from fossil fuels.

The objective was therefore to produce a bifunctional module of 8% efficiency of high visual appeal and artistic merit which should lead to a stimulation of the market for building integrated photovoltaics.

6. Technical Description

The years 1996 and 1997 have seen unprecedented rapid growth in the world PV market with nearly 40% growth in 1997. This growth has slowed dramatically towards the end of 1998 but some very positive factors have emerged and will be effective in the coming years. In particular the European White Paper on Renewable energy sets challenging targets for the integration of PV into buildings in Europe. The Protocols from the Kyoto Conference on Climate Change have set demanding targets requiring greater use of renewables in developed countries. The new government in Germany is progressing legislation for a feed-in law and has started a 100 000 roof programme. On the international market Japan has announced a new initiative to extend its world leading PV domestic programme to include industrial premises. In the USA more substance has been given to the president's 1 million roof proposal in which building integration is a significant part. Additionally major companies are wishing to show a "green " image and one way of doing this is too use photovoltaics on corporate buildings. In the UK the climate change consortium of banks and insurance companies is committing to install photovoltaic systems on the buildings of its members. The Ford and Mercedes Benz companies have installed PV on their factories and BP Amoco has announced a programme of introducing photovoltaics onto 200 service stations.

The above factors set a background of demand which is particularly relevant and favourable for the outcome of this project. There is likely to be a growing demand for building integrated photovoltaic both in Europe and the world market. However it has been noted that architects are generally resistant to photovoltaic integration because of its lack of visual appeal. Therefore it can be easily imagined that the supplier which can meet architects aspirations for high visual appeal PV modules can command a good share of a rapidly growing market.

6.1 Technical Status

6.1.1 Task 1 Design of Aesthetically Pleasing Modules.

Initial samples of cells different colours and crystalline grain structure were made available to KHM together with initial input from the architectural community on the problems of solar PV buildings and in particular their lack of visual appeal. Analysis of previous creative use of colour suggested that the designs should be based on the basic symmetrical shapes of triangle, rectangle, hexagon and circle. The principal colours of steel blue, magenta and gold were given prominence but cells that in blue/green and grey were also identified as need for the full designs to be realised.

Schematic designs were presented to the community of architects by Ove Arup and feedback was obtained on the concepts. Clear preferences were expressed. In particular, the final module shape should be of the same symmetry as the component cells. Also little support was found for modules containing circular cells despite popularity of the aesthetic appeal of the designs within the consortium.

The selection of the prototypes was made at a working group meeting in Vienna in July 1998. It was agreed to produce four prototypes, one more than the minimum of the contract. These are shown in Figure 6-1 and Figure 6-2 below and are:-

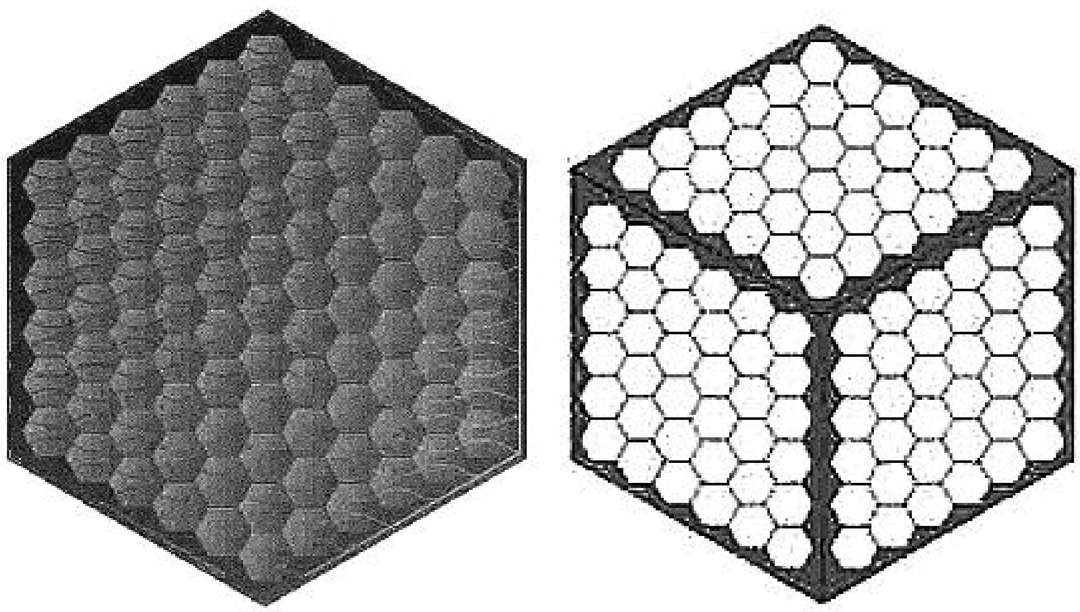

Figure 6-1: Design proposals with mono-crystalline hexagonal cells: On the left a hexagonal module with blue green cells and a sinusoidal form of busbars. On the right there are three rhombic modules, which give the impression of a three dimensional cube when put together.

1. A hexagonal module based on screen printed blue-green hexagonal cells with sinusoidal bus bars.
2. A composite panel formed of three rhomboic laminates (with 60° and 120° corners) each of different LGBG coloured cells to give the three dimensional effect of a cube.
3. A rectangular module formed of rectangular blue-grey and magenta square LGBG cells.
4. A triangular module formed out of triangular dark blue, steel blue, gold and magenta multicrystalline LGBG solar cells.

A demonstration of how the BIMODE concept might be applied to a real building was carried out at KHM and can be seen in chapter 9.

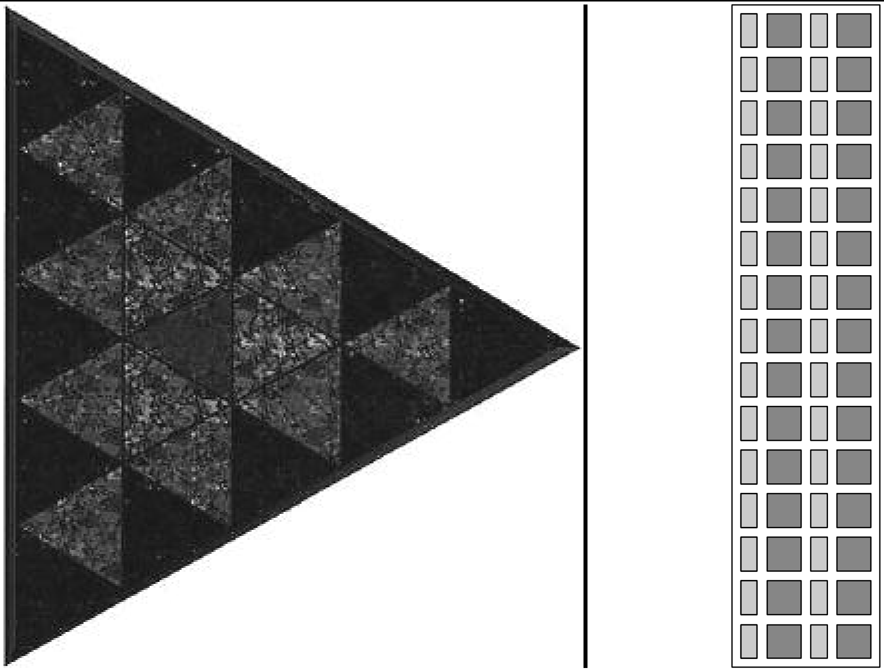

Figure 6-2: Prototypes with multi-crystalline solar cells: On the left there is a triangular module with differently coloured triangular cells and on the right there is a sketch of a very long rectangular module with square and rectangular cells.

6.1.2 Task 2, Supply of Multicrystalline Wafers

Due to the high optical appeal of multicrystalline Silicon it is best suited for facade applications.

But some particular boundary conditions have to be fulfilled simultaneously:

- Homogeneous grain size, preferentially big.
- Homogeneous electronic quality.
- Good sawing quality (no visual kerfs).
- Good optical surface quality (clean).
- Low production costs (at a mass production level).
- Meeting all these requirements has been Bayer's task of this project.

Grain structure distribution analysis was performed using computer simulations. Also the electrical activity and dislocation density had to be tailored. Specific items are: specific resistivity distribution in mc-Si, efficiencies and local characterisation of mc-Si, dislocation density distribution in mc-Si wafers and ingots and numerical simulation and experiment.

Different cleaning and etching procedures for mc-Si wafers were also investigated. The results of this task can be summarized as follows:

The Bayer - SOPLIN process is well suited for the production of homogeneous multicrystalline wafers for building integration in optical as well as in electronic aspects.

Multicrystalline Silicon wafers with different grain size aided by numerical simulation can be produced reproducible (grain size tailoring).

Dislocations: the most efficiency-relevant defects in multicrystalline Silicon (mc-Si) can be reduced by about 50% with the aid of numerical simulation. It proved to be a valuable process tool to meet the requirements of a large-scale high production rate fabrication of multicrystalline Silicon wafers.

A low dislocation density distribution is leading to high solar cell efficiencies being in good quantitative agreement with experiments.

A water washable cutting slurry is highly desirable to improve cleaning quality and reduce costs.

6.1.3 Task 3, Development of Solar Cells

6.1.3.1 LGBG Cells

In the previous JOULE project EUROFACADE (JOU2-CT94-0395) work focused exclusively on the development of monocrystalline coloured cells by the LGBG process. Subsequent feedback from prospective customers was that multicrystalline solar cells were much preferred for their visual appearance in building applications. Initial work determined the process conditions to achieve the correct ARC thickness for the main colours of steel, blue, magenta and gold on mono and multicrystalline wafers. After shaping the cells to the appropriate size the cells were measured and used to fabricate the prototypes.

6.1.3.2 Screen printed Solar cells.

Detailed calculations were made of expected electrical and shading losses for 16 different front grid metallisation patterns, including losses in the emitter for silicon solar cells. It was found that when a cell with standard H pattern attains an efficiency of 13.8% under 1 sun conditions, the same cell will show an efficiency of at least 13.0% with the worst performing of the artistically designed front contact patterns and will have around 13.5% efficiency for most of the patterns. Test cells have been made with the artistic bus bars but comparison between result and theory has been inconclusive due to shunting of the cells.

To progress the direct metallisation to the grain boundaries of multicrystalline wafers to improve appearance and cell efficiency an ink jet printer has been fitted to an x-y plotter table. An optical pattern recognition programme identifies the grain boundaries and appears capable of controlling the print head to deposit metal paste onto the grain boundaries with an accuracy of 25 µm.

The preferred prototype for screen printed cells are hexagonal monocrystalline with blue-green colour and sinsusoidal bus bars. The blue green colour requires a very thick anti-reflection coating which could not be fired through in the production equipment within the parameters of the normal production process. Therefore it was decided to fire the contacts first and then deposit the anti-reflection coating to the required colour with PECVD silicon nitride. Subsequently the silicon nitride on the bus bars had to be removed to allow tabbing of the cells.

6.1.3.3 Novel interconnection methods.

In addition to the modified bus-bars produced by screen printing the possibility of removing bus bars entirely must be considered. The visual appearance particularly for LGBG cells where the grid lines are almost invisible, would be enhanced if the cell interconnection were made to pads on the cell edges. The triangular cells required for the prototypes are of low area and it should be possible to connect these cells using an edge interconnect with limited series resistance losses. On the triangular cells the distances between fingers had to be tailored in order to minimize series resistance losses. This was done by computer simulation. Edge interconnects have been developed.

6.1.4 Task 4, Modelling of the solar cell array

The modelling must take into account the distribution in the cell I/V parameters, the different cell spectral responses and the thermal properties of the laminate. The SPICE device simulation programme has been used to model an array of diodes of different characteristics based on a current generator two diode representation of a solar cell with series and parallel resistances. Initial simulations have been made with real and typical test data prior to formulation of the prototype designs. Current mismatches between the present coloured solar cells are within acceptable limits but series and parallel connections will be required if cells of different area are to be connected in the same laminate. Spectral response variations also appear to be within acceptable limits.

The developed programme has been used to test three of the prototypes. The 91 cell hexagon module presents no problems as the cells are identical and the rhomboic modules are similar. In the rectangular module strings of cells in different sizes have been connected in parallel. The triangular module with four cell colours presented the greatest challenge. Five configurations were modelled. In the worst case of two series strings power losses could be ~5% while in the best case of five parallel strings the loss was less than 0.5%. In the actual triangular prototype all cells are connected in series. The loss for this configuration was estimated to be as small as 3%. The reason for this results is due to different encapsulation gains for differently coloured cells. Though the currents of the bare cells are very different, this is levelled out after encapsulation.

Task 5, Facade Module Fabrication

All prototypes have been constructed. The electrical performance is summarised in the following table.

Table 6-1: Electrical performance of prototype modules under standard test conditions.

Module	Isc [A]	Voc [V]	FF	Pmax [W]	Module-Eff [%]
"Triangular"	**1.49**	**14.55**	**0.62**	**13.4**	**6.3**
"Striped"	**6.05**	**17.37**	**0.63**	**66.1**	**7.6**
"Hexagonal"	**2.98**	**46.07**	**0.62**	**86.0**	**6.7**
"Cube (dark blue)"	**3.04**	**21.95**	**0.78**	**52.1**	**12.1**
"Cube (steel blue)"	**2.72**	**21.77**	**0.79**	**46.6**	**10.8**
"Cube (titanium)"	**2.67**	**21.94**	**0.77**	**45.2**	**10.5**

It can clearly be seen that three of the prototypes are in excess of the project target of 8%.

7. Results and Conclusions

The BIMODE project was very successful. For the first time artists and architects had a major input into the design of PV modules for building integration. All the designs and not only the prototypes have a very high level of visual appeal and can be regarded as works of art. At the same time the prototypes are photovoltaically functional. Therefore the prototypes are the realisation of the philosphy which was especially developed within the project and was behind all the designs: “form follows energy”.

Ove Arup, the seminar held in Cologne and the extensive press coverage guaranteed a constant feedback from the architectural community. In general this feedback was very positive. It was also used for further refinements of the designs at the end of the project.

Architects prefer the appearance of large grain multicrystalline Silicon wafers for building integration. This is a clear outcome of the project. Bayer delivered such wafers and did a great deal of research into tailoring their production process towards larger grain sizes. Simulations showed that this can be achieved maintaining the production throughput and the wafer quality and therefore maintaining low wafer costs.

A lot of research had to be done on the cell level in order to accommodate the design whishes of the group at KHM. Novel grid structures had to be developed and tested for both screen printing and laser grooved buried grid technologies. A completely new interconnection design was successfully developed and incorporated into the triangular module. With this new interconnection bus bars could be removed completely from the cell surface. This was one major demand of the architectural community.
On the screen printing technology a completely different approach was used. Here the bus bars were designed in a way to show a special pattern when cells are assembled into modules. This new technology was successfully incorporated into the hexagonal prototype module.
On the idea of directly connecting to the grain boundaries on multicrystalline wafers significant progress was made. However a lot more work needs to be done to develop this technology further if it is to be applied in volume production.

8. Exploitation Plans and Anticipated Benefits

The consortium consists of a materials producer, a solar cell manufacturer, a facade designer, architects and building consultants. The results were disseminated in a seminar in Cologne in June 1999 and active discussions will take place to develop projects using BIMODE concept modules. These prototype modules will form the basis of a new range of products for building integration which will give designers a greater freedom to specify the use of photovoltaics in a way which enhances the functionality and appearance of buildings. Such a product has considerable commercial advantages over PV building facades which to this point in time are purely functional with their lack of aesthetic appeal. All partners are committed to a full commercialisation given significant market demand.

9. Photographs

On the following pages there are a number of photographs showing the protoype modules and possible applications, which illustrate the potential of the developed prototypes.

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9.1 Applications

Design for renewal of St. Gertrude Church, Cologne:

Prof. Jürgen Claus developed together with Jörg-Paul Janka a design proposal in which the triangular prototype is choosen to form expressive patterns on the concrete wall of a church. St.Gertrude Church (1960-66) in central Cologne is an example of Gottfried Böhm's "phantastically exuberant sixties architecture". Built in an extremely difficult site facing the railway lines, the church is based on asymmetrical, concrete structures -"a powerfully expressed claim to art rather than dry functional thinking, excess rather than economy" (W.Pehnt).

The church was choosen to integrate BIMODE modules, as it needs a great deal of renewal. Two alternatives with different variations have been designed for the southern part of the asymmetrical polygon and the tower. Pictures of the modules integrated into the facade and the tower can be seen in Figure 9-1.

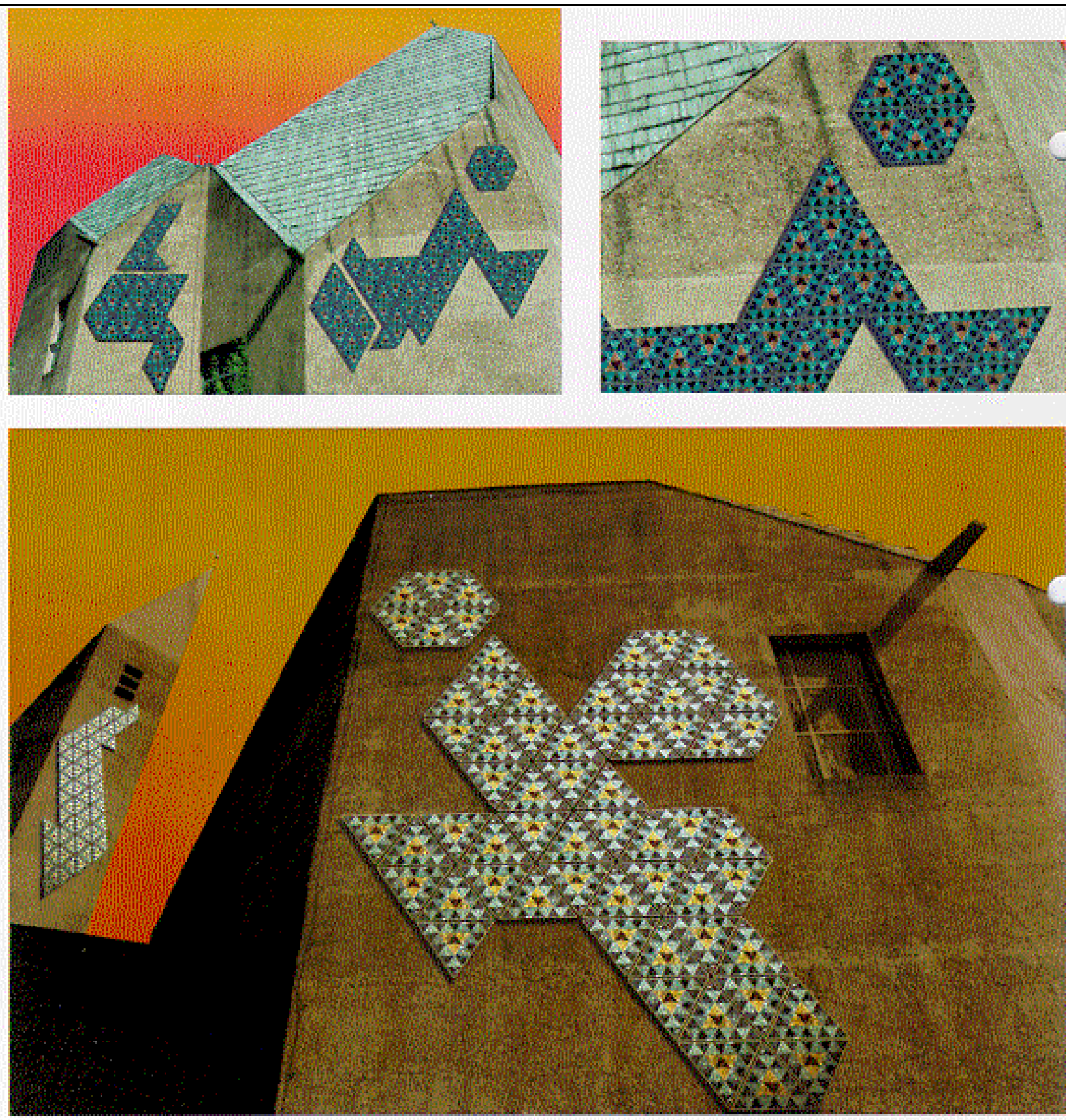

Figure 9-1: Possible Renovation of St. Gertrude Church in Cologne using the triangular prototype.

As an example for this Jürgen Claus and Jörg-Paul Janka developed on the basis of an historic photography a simulation of Bruno Taut's glass pavillon from 1914 in Cologne with the triangular solar modules integrated in the glass dome (see Figure 9-2). The module has been produced as a laminate with black Tedlar background cover sheet

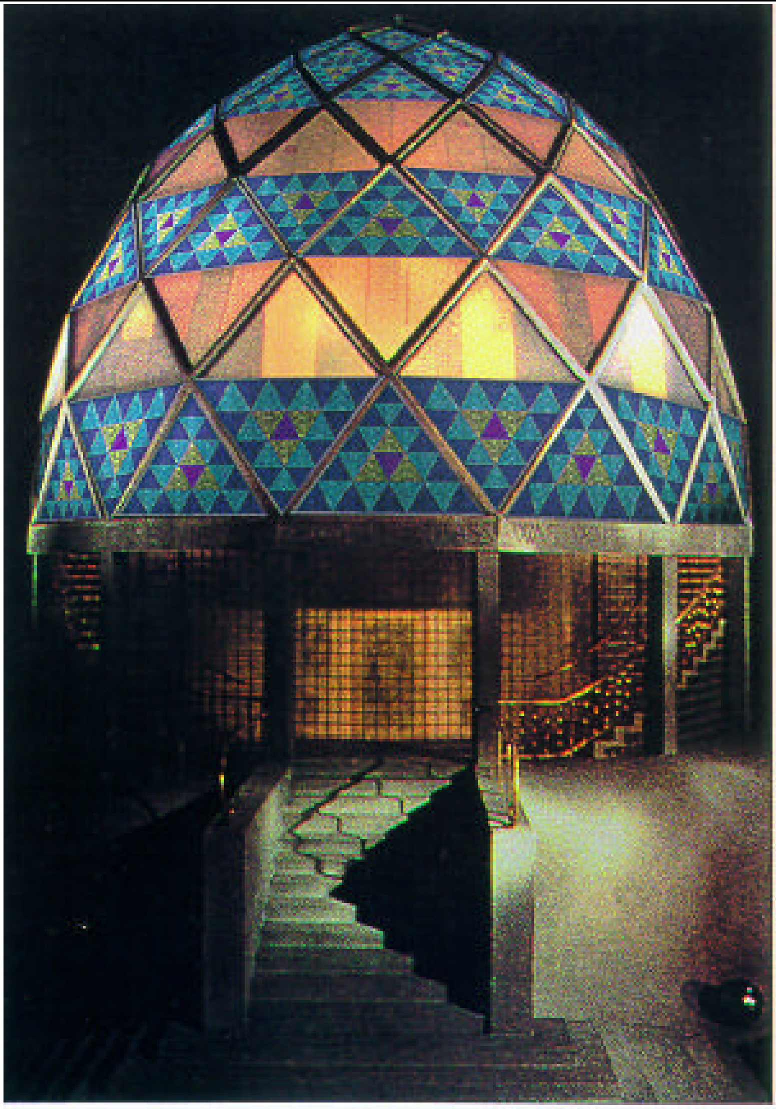

Figure 9-2: Animation of Bruno Taut's Glass Pavillion with the triangular prototype covering the dome.

Jörg-Paul Janka as the 3-D expert of KHM-group developed a 3-D CAD-model of the Mannesmann-multi-storey car park in Düsseldorf. The model was used for a computer-animation showing buildings with integrated striped modules in the colours blue and green. This integration is an example for the renewing of old infrastructures and industrial buildings. Huge areas of concrete walls could be used for the production of solar energy and could get a much more attractive visual appearance with this type of reconstruction (see Figure 9-3) .

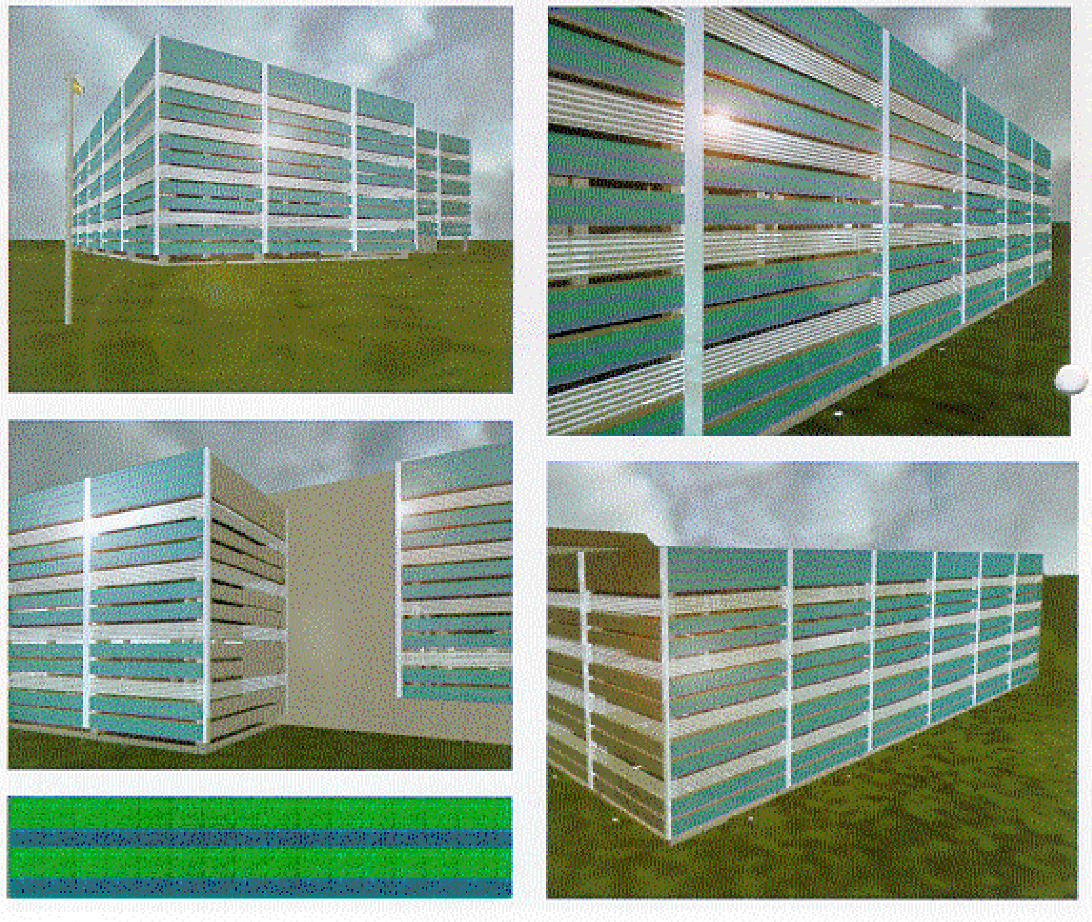

Figure 9-3: Computer animation of a possible renovation of the Mannesmann multi storey car park in Düsseldorf.

Integration of PV in Glass-art:
Jürgen Claus worked together with the glass-manufacturer 'Oidtmann' in Linnich. The idea was to integrate glass art, glass-painting and coloured PV-modules. A glass window in the traditional stained glass technology has been designed by Prof. Jürgen Claus with figurativ ornaments showing crystals and spirals. Small solar modules with backside panels made from coloured glass fit into the overall design of the window. The solar cells are assembled using standard interconnection. One of the PV-glass-art windows can be seen in Figure 9-4. Two parts of the window, including 18 dark blue monocrystalline LGBG cells have been produced. The glass studio of Dr. Oidtmann produced the stained glass window, the engineer Wolfgang Krug the solar modules as well as an amperemeter to count energy production.

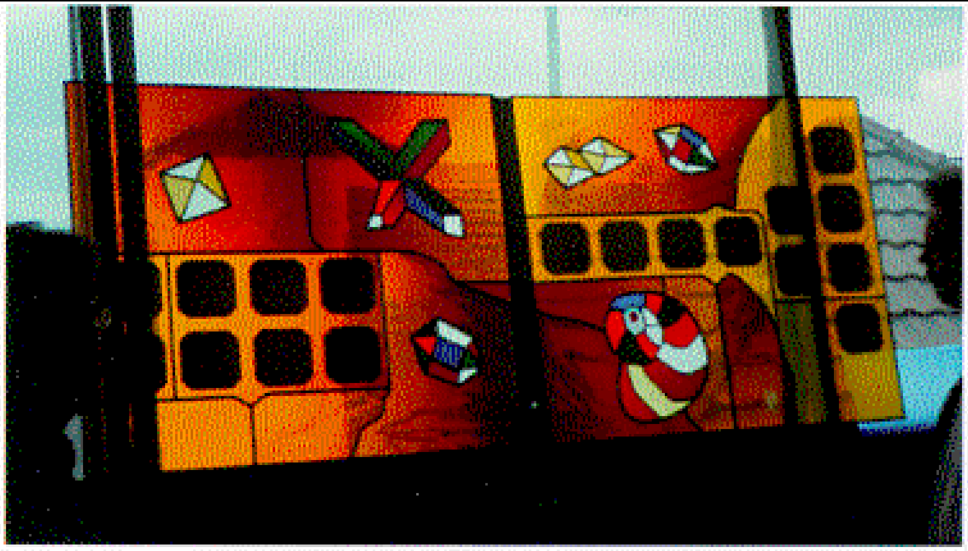

Figure 9-4: Example of PV incorporated into glass art.

Hellmuth Costard chose a different technical solution and worked together with a glass-artist manufacturing fused glasses. In this technology coloured glasses are superimposed to a huger sheet of glass, the glass is heated to the melting-point and the glasses are fused together. The fusing technology seemed to be interesting for PV as such a fused pane of glass could be immediate part of a solar module in the function of a front or backside sheet. Several different designs with stripes and grids of coloured glasses have been carried out. Two examples can be seen in Figure 9-5. The areas where cells should be incorporated have been uncovered by

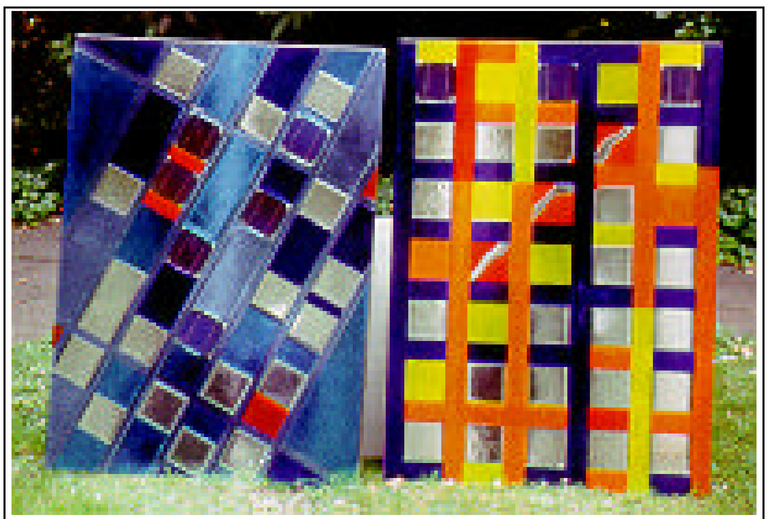

Figure 9-5: Combination of fused glass technology and PV technology.

fused glasses, i.e. they are clear. As a back side Hellmuth Costard chose a mirror. The mirror reflects the light through the areas of coloured glass, that way they look very bright and shiny. Dark blue monocrystalline standard solar cells have been used for the modules. The intention was to produce a colourful PV-glass-facade or -window element without the need of coloured solar cells wich are less efficient and more expensive than dark blue standard cells. Also the problems of shaded areas or areas around disturbing parts of facades, could be cladded with smaller fused glass elements more easily than with PV-modules.