DESIGN INNOVATION FROM PV-MODULE TO BUILDING ENVELOPE:
ARCHITECTURAL LAYERING AND NON APPARENT REPETITION

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ABSTRACT: This paper documents the study of Photovoltaic integration in the building’s envelope using architectural analysis and design strategies. The research is based on the latest PV technology and commonly applied façade technologies from the building industry. Whilst the architect’s primary objective is to deliver the ‘results’ of architectural planning, the goal of the research is to propel sustainable energy generation in building envelopes to the forefront of integral design thinking leading to exciting new architectural applications.

We focus on two UNStudio projects to illustrate the range of design aspects relevant to the aesthetic integration of PV in façade design. One project is the performative integration of architectural PV panels on the building scale with an office building façade design for a major PV supplier. The second project is on a PV module scale and refers to the initial results of EU funded research into aesthetical and cost efficient PV modules for the European market. This project is in cooperation with partners from the Construct-PV consortium.

We would like to share our vision on designing and integrating PV in architectural building envelopes. This paper provides an insight into design research that combines clear technological constraints with soft design decisions and creative solutions.

Keywords: Building Integrated PV (BIPV), PV Module, Solar architecture

1 INTRODUCTION

As an architectural design practice, UNStudio often accepts requests from the market to provide bespoke design solutions in the field of PV architecture. Although our main objective is to provide aesthetical and performance driven designs, we are sensitive to the requirements set by clients, contractors and end-users as far as costs are concerned. We understand the competitive market conditions both in the PV and the building industries, and try to use this understanding to add an architectural design premium and associated branding value by applying well-considered design interventions, adaptations and additions using the latest PV products.

Recently we have been involved in fundamental research to provide Building Integrated Photo Voltaic (BIPV) solutions, using the strict cost constraints referred to above. This has forced us, together with partners from the Construct-PV European research consortium, to dissect and reinterpret the latest PV technology into separate architectural layers and to use our design knowledge to navigate the strict cost requirements using strategies of cataloguing and modularization. With these tools we aim to maintain our ambition to deliver exciting, new interpretations in framing, cell placement, cell and module colours, patterns and material finishes in various combinations.

This approach of layering a finite number of design effects can result in seemingly infinite layered effects and a design feel associated with bespoke custom-made design solutions. In reality the base geometries actually resemble those of catalogued families of elements, with the advantage of the inherent cost-effective manufacturing properties of modular elements.
2 BACKGROUND

2.1 Possibilities of Building Integrated Photovoltaics

The harvesting of solar radiation for electricity generation with PV cells has been around for a good part of the 20th century. The evolution of PV technology has moved from the high tech applications of early communication satellites to an increasing array of functions and applications that today range from solar powered cars to solar powered buildings. Since the early 1980’s onwards PV technology has been adapted for installation on buildings resulting in Building Integrated Photo Voltaic (BIPV) systems.

The first prototype installations were developed for stand-alone buildings that were not linked to the electricity grid and that relied on PV as their sole energy source. These systems were loosely integrated and used the technology available -such as basic aluminium framing- and were mounted separately on the building’s roof. From these initial prototypes the BIPV modules developed further to cover a range of applications for roofs, facades and external devices such as shading and canopies.

BIPV systems have two objectives. The primary objective is, of course, to generate electricity. The secondary objective is to ensure that the module is a functionally integrated element in the building’s envelope. This means that at least one of the building’s physical properties, for example, waterproofing, insulation or shading should be met by the BIPV module. A less strict classification of integration of PV is the principle of BAPV (Building Applied Photo Voltaics) where PV is applied as an additional layer to an existing building or as a replacement module in a retro fit building.

Over the years the integration of PV has become more common in regular building stock resulting in the standardization and industrialization of the technology in a range of designs from “add-ons” to more sophisticated integrations. Although the market offers a range of BIPV solutions that are based on standard modular building products, many of the applications are still custom made and need adaptation to the specific requirements of an architectural design during the building process.

Because of these limitations and the resulting additional cost associated with BIPV, the main possibilities for the technology lie in new building designs and in major renovations.

Although the costs associated with BIPV are generally higher than regular PV systems, the promise of this principle is that, in the future, building envelope surfaces could power almost 50% of our daily energy needs in buildings. This estimate is based on the available building envelope surfaces and the possible electricity generation capacity that can be supplied. With this large future market in mind the possibilities of offering architectural PV façade products to clad these surfaces is potentially huge. Both for architects and PV manufacturers this is something to keep in mind.

2.1 Competitive sectors: the PV industry

The Photovoltaics industry is a competitive business sector in the current economically turbulent times. The market has been growing at over 30 percent per year since 2006 and growth continues. At the same time, a large-scale consolidation and industrialization of PV technology is taking place. The production of PV panels has been industrialized to the extent that - especially in the range of cheaper modules - the prices of PV installations have fallen dramatically from ±4.2 €/W in 2000 to ±0.65 €/W in 2014. This means that the margins for producing modules are minimal at best in the current market. This offers serious challenges but also chances for new products, business models and reinvented roles for major players in the industry to capitalize on their existing technology.

At the cheaper end of the spectrum it is difficult to compete. Manufacturers recognize the need to search for further technical integration and sophisticated products that can offer a higher profit margin. One of these added-value technologies could be the BIPV modules. The further integration of functionality can result in the value of combining building cladding materials and electricity generation capabilities in one single priced product. Furthermore, building materials have a strong aesthetical requirement since they represent the visual component of the building’s envelope. This factor makes the argument for a quality product stronger than in the general case of industrialized modules used for electricity generation in a typical solar park.

2.2 Competitive sectors: the building industry

A similar trend can be identified in the building industry. Because of fierce competition the margins in more traditional projects are minimal. One strategy here is to diversify into new and more advanced project types.

One of the services that can be offered by building companies is the implementation of energy-saving measures in new and existing projects. Companies providing these services such as Energy Service Companies (ESCO) provide services ranging from energy conservation to retrofitting and power generation. The PV module is a product that aligns with this strategy and has the potential to contribute to the positive energy balance of energy use in buildings.

It is clear that the interests of the PV industry and the building industry converge in the Building Integrated Photo Voltaic products. However, apart from the financial side of the equation while making a BIPV product the aesthetics need to be further defined in order to be attractive for use in the building industry. Also the need for further standardization and certification of these building products is a clear need and demand in the existing market

To justify the higher price of a designed BIPV module, the advantages in terms of added aesthetic quality in relation to electricity production need to be evident. In terms of priority the financial component will - in most cases - have a higher priority than the aesthetical component. In which case the baseline for investments by building owners or investors in BIPV-modules will be a (subsidiized) price of electricity from PV, which is competitive with market prices of electricity...
from fossil fuel powered or other conventional energy plants. This sets high standards for additional quality through design, standardization of modules, production and the efficient installation and maintenance of the PV-system.

2.3 Regulatory trends: sustainable goals
Economic arguments are not the only reason for choosing PV. Solar power will be a necessary and inevitable solution in the race to reduce the world’s carbon emissions. Already governments and regulators are setting higher targets for permitted carbon emissions to reduce the reliance on carbon fuels.

In the road map for moving to a low carbon economy in 2050, the EU sets out a cost-effective pathway to reduce carbon emissions by 40%. This includes major sectors such as power generation, industry, transport and buildings and construction. Although the emphasis is on reducing carbon emissions carefully without damaging economic growth, the trend is clear. With our current knowledge about global warming, carbon emissions and energy dependence it is likely that these regulations will be more strictly enforced by regulators in the coming years.

The government and local municipalities in particular are developing strategies to implement these goals. They can be seen as being amongst the early adopters of these principles. The road that they are paving will be followed by companies and individuals either motivated by the money that can be earned from tariffs or in reaction to the toughening of regulations. Solar power, together with hydro and wind power, is one of the truly renewable alternatives to fossil fuel.

The trend is that more economic modules will become available and generation costs will decline possibly by as much as 50% by 2020. The institutional drive for renewable sources, together with the financial incentives such as tax rebates and feed-in-tariffs will add to the impetus behind this development.

From the point of view of regulation in the building industry it is clear that BIPV products will be used more often and become better known. This includes availability of knowledge within the building sector and among planners and suppliers, but also the number of products that are certified for direct application in the building process. These factors make it clear that BIPV as a building element is here to stay, and will evolve further to a generally accepted cladding material with added value and functionality.

3 APPROACH

3.1 Integral research
UNStudio favours an integral approach to architecture; a non-hierarchical, complex, generative and integral research and design process that takes into account all aspects of architecture including a range of sustainable parameters. The shifting fields of architecture, efficient use of natural resources and energy production have led us to reinterpret the possibilities provided by the solar industry and to design bespoke architectural PV modules.

Our research is based on existing and proven PV products that can be procured in the market, and can be used as the basis for either regular PV installations or can provide the basis for sophisticatedly integrated BIPV envelope modules.

3.2 Architectural scale levels
From an architectural point of view a design can be understood and approached at various levels of scale. Examples of architectural design can range from urban master plans to the design of a door handle. The design task at hand can involve the development of a complete Photovoltaic building façade, or on a more detailed level the design of cell placements, the finishing for the module frame or cell wiring of a facade BIVP module.

The departure point of this research is a thorough analysis and an understanding of the technical product that forms the basis for Building Integrated Photovoltaics: the PV module. The research structure has been designed and organized together with the Construct-PV consortium, in a way that makes it possible to study the basic product at different levels of scale and to see what architectural effects can be achieved. Within these scale levels design parameters are identified and linked to technical options to give an overview of the design possibilities. This is followed by a classification of the available design parameters in a catalogue of options.

In a successful design working with design elements at different levels of scale should result in a holistic and integrated solution which is aesthetically pleasing and economically viable. For example, the design of a southward oriented building volume can be designed with complementing façade module geometry. The overall irradiation of the building can be translated to a system of modules that allow external shading from solar radiation while, at the same time, permitting daylight entry and unimpeded views of the surrounding landscape from inside the building.
A large range of design parameters emerge from site specific parameters. These can influence the technical design choices available in the design of building integrated PV and the integration of PV elements into facades. The parameters identified on the various architectural levels of scale provide the starting point of design concepts and these solutions can be evaluated both separately and in relation with each other in 3D software environments. In this iterative design process it is also possible to allow verification of manufacturing possibilities with the help of PV manufacturers and builders. In this integrated process, the goal is to come to a cost-effective re-crafting and reorganization of the separate design elements into a layered and richly crafted premium architectural design.

3.3 Layered effects

In addition to aesthetic requirements, the technical requirements set by the industrialized production process in terms of manufacturing are used to verify the direction of the design solutions. Because of the cost sensitive nature of the PV industry the range of options is limited by the way production lines currently being used in the industry are organized. In the production of glass-glass PV modules, for example, a fixed number of manufacturing steps are involved in developing the end product. Apart from traditional steps such as connecting cells, encapsulation and final assembly, other layers of architectural finishing can be considered and introduced in pre-fabricated elements such as the glass panels.

Figure 3: Diagram layered effects in PV module

Examples here include colour coating layers, fritting or silk screen effects on the glass surface, gloss level coating and textured glass which can be introduced without disrupting the basic layering setup of the module production line. A short list of design parameters that can be addressed when enhancing the layering include:

- glass surface finishing
- cell colours
- cell form and placing
- back panel colour
- silkscreen, gloss, frit finishing
- module framing

Given these factors, the aesthetical choice of applying a range of designs and materials becomes a question of finding a balance between cost and effect. For example, designs with adapted cell placements might offer possibilities in terms of patterns or transparency but it needs to be taken into account that any loss of coverage in cell surface has a negative effect on electricity production in relation to the standard module. This can have considerable impact on the overall cost of the panel as well as an adverse effect on the economic value of the PV module. Such a design choice needs to be carefully considered in relation to the desired aesthetic effect. A similar effect in reduced output will occur in the choice of certain cell colours. The range of colours needs to be carefully considered in terms of standard market availability, aesthetical quality and electricity output.

A different layering example with a more beneficial design result would be the colouring of the glass back panel. This would have a relatively minor impact on PV capabilities and the price of the module, while adding a strong visual component. In planning the production of the module the colour can be added to the back layer of the module in a way that fits the demands of the architectural design. By applying the colour during the production process or ordering a pre-coloured pane of glass directly from the glass supplier, this step can be easily integrated into the production process.

Figure 4: Layering enhancement example: back colouring

As a final step the PV module leaving the production line can be further adapted architecturally by being mounted within the façade element. These façade elements can range from curtain wall elements, to window frames or externally mounted façade panels.

4 APPLICATION OF EFFECTS:

4.1 Examples of layering and modularization

Using the architectural layering and modularization approach as a design tool, the application and adaptation of the described effects to specific requests from clients, local site conditions and performance requirements can begin. For a detailed understanding of the application of the described design effects, two case studies have been chosen. These provide an in depth description of architectural designs that show how PV technology has been taken and applied pushing the boundaries of the technological solutions currently available and furthering the integration of PV into practices commonly used in the building industry:

- Construct-PV: Aesthetic and cost-effective BIPV
- Hanwha: Performative BIPV Façade design

4.2 Construct-PV

These examples are on different levels of scale. The first – Construct-PV – is on the architectural scale of designing an innovative glass-glass BIPV module. Construct-PV is a European research project in which UNStudio is part of a consortium that includes universities, contractors, consultants, manufacturers and research institutes concerned with investigating a generic module that can be customized with a catalogue of
aesthetic and cost efficient choices that will result in a
catalogue of layered PV modules.

The base product is the latest Multi Wire Glass-Glass
PV module from Swiss manufacturer Meyer Burger. This
high-end PV panel was used as a tabula rasa for further
design research focusing on the creation of a new PV
product. The goal is to use the new design insights from
this product to improve future PV production lines that
will be introduced by Meyer Burger. This equipment is
aimed at European or other manufacturers to establish
local production of customized BIPV products.

Additionally the projects partners contributed to the
broad information-base. The knowledge was derived
from the research capacity of the following consortium
partners: Züblin, Germany
D’Appolonia, Italy
Fraunhofer-ISE, Germany
NTUA, Greece
AMS, Greece
SUPSI, Switzerland
ENEA, Italy
TU Dresden, Germany
Meyer Burger, Switzerland
Tegola Canadese, Italy

In this research a design catalogue with aesthetic and
cost effective choices for the application of PV modules
in the opaque parts of the building façade is being
developed. The aim is to bring these choices to the
European market in a product that allows different
layering choices in design, colour and finishing. Using
market research in combination with technical and design
research, the generic PV module is converted into a range
of design choices for different consumer needs in the
various countries of the European Union.

The research will run until 2016. Currently, the initial
design solutions are being produced in test samples. A
good example of these initial results is the setup of a
range of base colours in the architectural NCS system
that enables a first adaptation to architectural colour
requirements for facades. The colour range and intensity
within these base choices is limited by cell efficiency,
and the chosen colour ranges comprise red, blue, green,
aubergine and anthracite and are in the darker colour
range. Gradients and colour transitions become a
possibility with these colour options and can add
vibrancy and decoration to the façade.

A selection of these design options will be combined
with other design layers and assembled in two mock-ups.
One mock-up will specifically deal with the integration
of PV in the façade; the other will focus on a solution for
PV roof integration. These two life scale models will be
tested at small-scale demonstration sites in Stuttgart,
Germany, and in Lugano, Switzerland, before being
evaluated, improved and produced for large-scale
installation on the envelope of two existing buildings.

The following images are studies of material
eamples, cell placements and pattern designs undertaken
for the Construct-PV research. The studies focus on
layering using different cell designs, back panel
colouring and glass finishing creating different plays of
repetition and enhancing pattern effects:

Figure 6: Patterns enhancing the geometrical repetition

Figure 7: Softening patterns and natural propagation

4.2 Hanwha Headquarter

The second project is a façade design for a retro-fit
office building in South Korea. The brief for this
assignment called for a remodelling of the existing
headquarters of Hanwha, one of the leading
environmental and PV technology manufactures in the
world. The aspiration was to integrate PV-cells from the
product portfolio of the client, within the technical
constraints of an existing building retro-fit. UNStudio’s
design in cooperation with ARUP (sustainability and
façade consultant), Loos and van Vliet (landscape
designer) and AgLicht (lighting designer) was selected as
the winning entry in an invited competition.

The design of the façade for Hanwha in Seoul, South-
Korea is based on a responsive facade system with
integrated renewable energy sources. The proposed
façade addresses the desire to make one of these sources,
in this case PV, an integral part of building design. This
lead UNStudio to a performative envelope design which
takes into account the specifics of the program behind the
façade geometry in combination with the harvesting of
solar radiation. The base product supplied by the client
for the building is a Qcells PV module which required
adding a separate formal design layer to convert it into an
architectural façade element and enable it to become part
of the overall architectural vision.
The existing façade was made up of a basic curtain wall system organized in horizontal bands of opaque panelling and single layers of dark glass. In the remodelling this is replaced by a contemporary façade solution with clear insulated glass and aluminium façade modular framing elements. This frames both the PV panels in the opaque area of the façade and the clear glazing in the transparent areas of the façade making a clear differentiation and enabling both views outward to the surrounding environment and the entry of natural light.

The BIPV modules are 3-dimensionally modelled with the correct rotation and directionality façade panels to harvest energy from the sun. PV cells are placed on the opaque panels in the zones with optimal irradiance.

**Figure 8:** Hanwha. PV integration in framing module

UNStudio’s concept for the project results in taking the designed modular setup and applying it to a retro-fit façade design that respects external factors such as solar radiation and the surrounding city environment. The indoor climate is controlled by matching the interior program with the exterior of the façade.

The office program, together with public functions in the building provides the main basis for façade expression. By naturally propagating the placement of the façade panels according to solar radiation and shading a variety of program-related openings are created. The result is a seemingly random composition within the façade elevation using a cost-efficient solution with a limited set of standardized modules.

**Figure 9:** Propagation of PV modules in the façade

The surrounding situation is analysed and measured, using these values from the site as well as climate and building program distribution to inform the design decisions. The analysis of the building volume, together with the surrounding buildings, presents a hierarchy of areas of shading and irradiation on the Hanwha building.

This results in a tailored-design solution providing a synergy between modular repetition and a unique rhythm of the façade, while maintaining an aesthetically pleasing overall effect and a high quality energy producing façade.
5 CONCLUSIONS:

5.1 The qualities of architectural PV integration

Although these projects are quite different in character, in distinct requirements they follow a similar logic. Variation and modularization play an important role in both projects in order to maintain the balance between the aesthetics of variation and the economics of repetition. The innovation is to be found in new forms of design-driven integration of existing PV technology into façades through the use of architectural design strategies. This includes solar radiation analysis, mapping of local influences, the strengthening - through the design - of relations with the surrounding context and ensuring the optimization of functionality and aesthetics.

In this case both projects are still in the early phases of completion but the outlook for successfully designing and building physical representations of the design research is good. In the not too distant future the graphical representation in the form of diagrams, impressions, design drawings and mock-up photos of the design process will be built. And the projects involved will be complemented with a built design in full 1:1 scale.

The improvement of BIPV design modules will continue to develop as understanding of the material involved and the degree of integration increases, and slowly such common place materials as architectural glass, bricks and metal panelling will be replaced. The world is on the verge of non-subsidized application of BIPV envelope elements and this will mean a conversion to a self-sustaining building energy environment. Hopefully this will result in a strong aesthetical component, with façade modules allowing design flexibility and reflecting the surrounding environment, local influences and colours.

REFERENCES


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