Architectural integration of light-transmissive photovoltaic systems
An analysis at the cell and laminate level

Robert Baum*

Ph.D. Candidate, Department of Architecture, The University of Tokyo, Japan

Abstract

This paper is a study of light-transmissive photovoltaic systems (LTPV) and the state of the art of their architectural integration into buildings. Findings indicate a number of innovative solutions that extend the possibilities for building integration in an architectural and aesthetically pleasing way.

Keywords: BIPV; light-transmissive; architecturally integrated; key design parameters; PV innovation

1. Introduction

As the advantages of renewable energy generation are becoming more and more attractive to architects as well as investors, the spread of knowledge about photovoltaics (PV) and how they can be integrated technically, economically and aesthetically into the architectural design of buildings is one of the key issues to their wide-spread adoption [1]. Light-transmissive photovoltaics (LTPV) have due to their material and aesthetic similarity with conventional building materials like glazing many head start advantages over opaque PV. They are rather easily integrable into the planning and construction process [2], the field of potential application in overhead glazings and curtain walls is extremely wide [3], and their impact on saving energy is higher [4]. Advantages of light-transmissive PV are not limited over opaque PV, but can be found over conventional glazing as well. Beside the added function of direct renewable energy generation, they also have a clear advantage in terms of daylight control [5], sun protection and reducing heat gains [6]. However, many authors see, beside technical and economical issues, especially the lack in aesthetic quality [7] and design versatility [2] as a main barrier to the widespread cultural and social acceptance of PV in the built environment [8, 9].

This paper explores, based on built architecture, the design parameters of light-transmissive PV on the solar cell and laminate level. The scope of this paper is to show, how architects and engineers together with the PV industry have done and can influence the appearance of PV, a knowledge useful for future PV applications in architecture.

2. Methodology

From a corpus of more than 500 buildings with light-transmissive PV, that were realised within the last 20 years, 35 were selected (Tab.1) for further analysis of the design parameters. These are then illustrated with computer generated renderings based on a given spatial geometry (Fig.1: A), to visually compare the design parameters.

3. PV Technology

Depending on focus, solar cells can be divided into different groups. A common classification based on PV technology and manufacturing process is in crystalline silicon cells and thin-film cells.

crystalline silicon (Tab.1: cs1-27, cstf1+2) The production of crystalline silicon cells, mono- or polycrystalline, is split into the manufacturing of standard wafers (growing or casting of the silicon and

---

* Contact Author: Robert Baum, Ph.D. Candidate,

Department of Architecture, Graduate School of Engineering,
The University of Tokyo,
7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-8656 Japan
Tel / Fax: +81-3-5841-6174
e-mail: robertbaum@hotmail.com

(The publisher will insert here: received, accepted)

sawing into wafers) and the solar cell process (texturing, diffusion and metallisation).

For module production, multiple crystalline silicon cells are electrically connected in linear cell strings, and a number of side by side cell strings are encapsulated in a lamination process between front and back sheets of glass or film for protection and stability.

thin-film (Tab.1: cstf1+2, tf1-6) Thin-film PV uses photoactive materials like amorphous silicon (tf1-4), copper indium (gallium) selenide (CIS/CIGS; tf5), or sensitised dyes (DSC; tf6). Nanometre thin layers of the photoactive material and the electrically conductive transparent layers are deposited onto a glass or film substrate and scribed by lasers into individual cells. The resulting thin-film sheets of monolithic series-interconnected cells are less restricted in size and generally much larger than crystalline silicon cells.

id (*1)	name	location	Year (*2)	architect, designer, artist, engineer or pv company	rated power [kWp] (*3)	building type (*4)	PV integration (*5)	cells/laminate; feature (*1)
cs1	Brundtland Centre	Toftlund, Denmark	1995	KHR AS arkitekter	14.25	office building	sawtooth atrium roof + canopy	round cells, oblique grid
cs2	Tsukuba OSL	Tsukuba, Japan	2001	Nihon Sekkei	10.5	research facility	ver curtain-wall	round cells, rectangular grid
cs3	Solarcafé "Sonnenzeit"	Kirchzarten, Germany	1999	Roland Rombach	1	café	inclined roof	semi-transparent crystalline cells
cs4	Community centre Ludesch	Ludesch, Austria	2005	Hermann Kaufmann	18.05	community centre	courtyard canopy with sawtooth roof	semi-transparent crystalline cells
cs5	Trade School Center	Munich, Germany	2007	Bauer Kurz Stockburger + Partner	n.a.	education, other	noise barrier	bifacial
cs6	Opera House	Oslo, Norway	2007	Snøhetta	35	opera house	facade	cells in horizontal stripes
cs7	Daito University Itabashi Campus, Building No. 3	Tokyo, Japan	2003	Ben Nakamura and Yamamoto Hori Architects	30	university	flat roof + ver curtain-wall	cells in vertical stripes, laminate pattern
cs8	Solar Office Doxford International	Tyne and Wear, UK	1998	Studio E Architects	73	office building	inclined curtain-wall	non-rectangular,irregularly striped laminates
cs9	OLV Hospital	Aalst, Belgium	2007	VK STUDIO	46	hospital	inclined curtain-wall	varied string spacing
cs10	Solar Development at Schlierberg	Freiburg, Germany	2005	Rolf Disch	n.a.	residential, multi-family	roof with overhang	dense spacing
cs11	Akademie Mont-Cenis	Herne, Germany	1999	Jourda & Perraudin + HHS	1,000	education, other	flat roof; ver curtain-wall	varied cell spacing for a cloud like roof pattern
cs12	Recreation centre Vestervang	Copenhagen, Denmark	2002	Entasis	n.a.	recreation centre	facade	laminate with PV centre piece
cs13	GreenPix, Xicui Entertainment Center	Beijing, China	2008	Simone Giostra & Partners	79	entertainment centre with cinema, restaurant	façade, media wall	varied regular cell densities, multimedia
cs14	McDonald's Cycle Center	Chicago, IL, USA	2004	Muller & Muller	7.84	bicycle station	roof	chequerboard pattern
cs15	Kankakee Community College	Kankakee, IL, USA	2007	Legat Architects	42	education, other	ver curtain-wall	dotted cell arrangement
cs16	Madrid-2 La Vaguada	Madrid, Spain	2007	ErtexSolar	10.148 (100.388)	commercial and leisure centre	overhang	trapezoidal laminates
cs17	The Core at the Eden Project	Cornwall, UK	2005	Nicholas Grimshaw & Partners	30.47	education centre	overhang	rhombic laminates
cs18	California Academy of Sciences building	San Francisco, CA, USA	2008	Renzo Piano Building Workshop	172	museum	overhang on four sides	rectangular laminates, trapezoidal at the corners
cs19	Solarsail	Münsingen, Switzerland	1999	Halle 58 Architekten	8.2	solar art project	inclined freeform installation	rectangular and non-rectangular laminates
cs20	True North/Lux Nova	Vancouver, Canada	2008	Sarah Hall (artist), Clive Grout (architect)	0.4	ventilation tower for underground library	ver curtain-wall	artistic pattern, dichroic glass
cs21	Hotel Industrial	Paris, France	2008	Emmanuel Saadi, Jean-Louis Rey, François da Silva	94	office building	ver curtain-wall	varied irregular cell densities, stone imitation
cs22	Marrakech Ménara Airport	Marrakech, Morocco	2008	E2A Architecture	55.44	airport terminal	skylight	Arabic pattern, rotated cells / strings
cs23	Christian Kindergarden Ulmenstreet	Dresden, Germany	2003	Reiter & Rentzsch	1.1	kindergarten	windows	unequal cell spacing, colourful stripes
cs24	Fujipream Kohto Factory	Hyogo, Japan	2003		21.66	factory	curved roof	bent glass
cs25	SBIC East Head Office Building	Tokyo, Japan	1998	Nihon Sekkei	29.7	office building	eaves, louvres	dummy cells
cs26	Sun Monument "Greeting to the Sun"	Zadar, Croatia	2008	Nikola Bašić	15	NBST, urban media installation	pavement	laminates with curved edges, cut cells
cs26	Blue Sapphire, AquaCity	Poprad, Slovakia	2007	ARCHSTUDIO Kučera & Rubáš	24.5	swimming pool	facade	screen prints
cstf1	"Solar Decathlon" entry of TU Darmstadt	Washington DC, USA	2007	Technical University Darmstadt, Prof. Hegger	11.4	PV experimental building	flat roof; façade, hor louvres	cs + tf, semi-transparent crystalline cells
cstf2	Sant Celoni Kindergarden	Sant Celoni, Spain	2008	Torsten Masseck	11.5	kindergarten	inclined curtain-wall	cs + tf, coloured glass
tf1	Kanazawa Bus Terminal	Kanazawa, Japan	2005	TODEC Inc., Taiyo Kogyo Corp.	110	bus station	canopy	
tf2	Schott Iberica	Barcelona, Spain	2006 (2001)	Torsten Masseck	1.35	office building	ver curtain-wall	coloured glass + screen printing
tf3	Solar Information Plate at Castello San Giorgio	La Spezia, Italy	2004	PVACCEPT Designteam UdK	0.35	NBST, information plate	at a wall	screen printing in front of PV
tf4	Kulturhaus Milbertshofen	Munich, Germany	2005	RPM-Architekten	4.7	community centre	ver curtain-wall	tf cells combined in larger glass panels
tf5	Würth Holding Headquarters	Chur, Switzerland	2002	D. Jüngling + A. Hagmann	3.7	office building	skylight	CIS, wider scribing lines to achieve 50%
tf6	Houses of the Future	Sydney, Australia	2004	Innovarchi	n.a.	prototype residential	facade	DSC

(*1) cs – crystalline silicon solar cells, tf – thin-film solar cells, cstf – crystalline silicon and thin-film solar cells used in the same building.
(*2) if two years are given, completion of PV installation and completion of the building (year in brackets) didn't happen the same year.
(*3) rated power of light-transmissive PV installation, (rated power in brackets indicates and additional opaque PV installation); n.a. - non available
(*4) NBST – non-building structure
(*5) ver – vertical, hor – horizontal

Tab.1.

4. Translucency and transparency

For both technologies, crystalline silicon as well as thin-film, opaque solar cells account for the lion's share of production. To achieve translucence there are two common ways.

'light-through' Increasing the distance between opaque cells, so that light can pass through the resulting gap, is a relatively easy way for crystalline silicon cells. However, as views are still obstructed by the opaque cells, this type of semi-transparent PV is often called 'light-through'. The shadow plays, or interplays of light and shadow cast by opaque cells and transmitted light, are a strong characteristic (Fig.1: B).

'see-through' A different approach is to make the solar cell itself light-transmissive. This involves milling, etching or scribing grooves or holes in the millimetre or micrometre range, which results in a much more uniform translucency. As views are less obstructed this type of semi-transparent PV is often called 'see-through' (Fig.1: C). The method is commonly applied to thin-film cells, but 'see-through' crystalline cells are available as well.

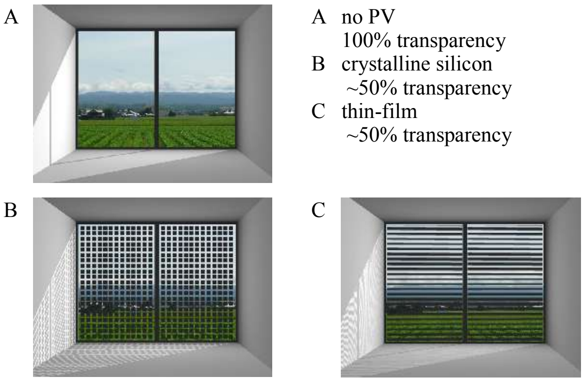


Fig.1. Comparison of technologies.

5. Analysis of crystalline silicon PV

shape Crystalline silicon cells are standardised and independent of the manufacturer usually round, pseudo-square with rounded edges, or square (Fig.2). Round cells and pseudo-square cells are from monocrystalline silicon. The round shape is a feature of the ingot and the crystal growth process, for pseudo-square cells the ingot gets trimmed on four sides before it is sawn into wafers. Square cells are mainly polycrystalline cells, where the ingots are cast in blocks, but are produced from monocrystalline silicon as well. The diameter of the ingot has to be the same or near the diagonal length of the square, e.g. a Ø 220 mm ingot for a 156 mm square cell.

Round cells were common in the early days of PV (cs1, cs2). However, pseudo-square and square cells became standard due to more space efficient arranging possibilities in opaque applications, with round cells hardly used any more. Other shapes, like triangular or hexagonal cells are sometimes proposed in the literature, e.g. the BIMODE international research project [10, 11], but built examples were not found.

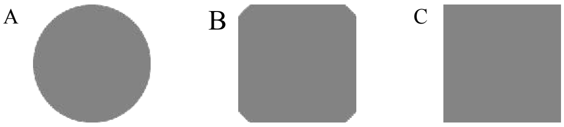


Fig.2. Shapes of crystalline silicon cells.

size Crystalline silicon cells have a side length or diameter of 100, 125 or 150~156 mm, equal to the industry standard of 4, 5 or 6 inches (Fig.3).

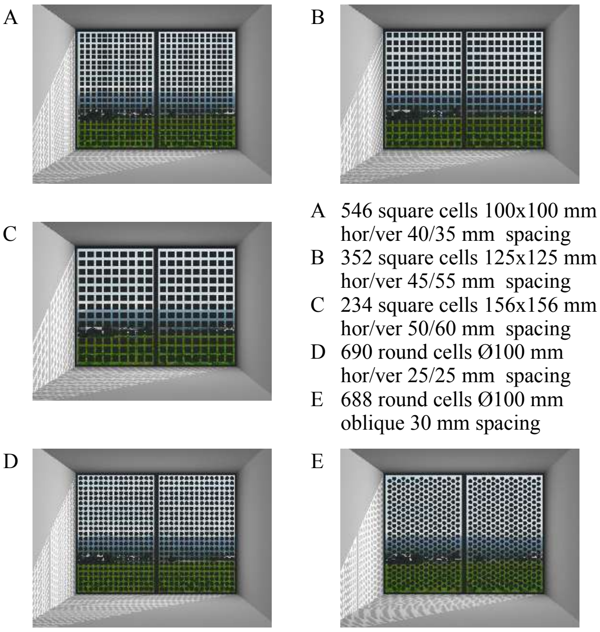
Fig.3. Sizes of crystalline silicon cells.

special cells Beside the standard cells, some manufacturers are producing special cells like semi-transparent crystalline silicon cells (cs3, cs4, cstf1), or bifacial cells with two photoactive sides (cs5).

colour In the case of standard cells, front and back side have a different colour, as only the front side has an anti-reflective coating. An exception are bifacial cells, with an anti-reflective coating on both sides. Although the most common colours are dark blueish or blackish (darker colours trap more light), a limited range of other colours, like greyish, reddish, greenish, brownish or yellowish are available as well. The reason is a thinner anti-reflective coating, and as an effect of the brighter colour more light is reflected, which slightly reduces the cell's efficiency.

5.1 Standard patterns for crystalline silicon PV

The most common arrangement of the cells is in a rectangular grid with equal spacing between the cells. A comparison of the different cell sizes with an equal distribution of 50% cells and 50% gaps for translucency is shown in Fig.4. This clearly illustrates that with larger cells much less are required, which reduces the amount of electrical connections, but reinforces view obstructions. Round cells are arranged either in a rectangular grid (Fig.4: D; cs2), or oblique grid (Fig.4: E; cs1).



A 546 square cells 100x100 mm hor/ver 40/35 mm spacing
B 352 square cells 125x125 mm hor/ver 45/55 mm spacing
C 234 square cells 156x156 mm hor/ver 50/60 mm spacing
D 690 round cells Ø100 mm hor/ver 25/25 mm spacing
E 688 round cells Ø100 mm oblique 30 mm spacing

Fig.4. Square and round crystalline silicon cells.

5.2 Variations for crystalline silicon PV

As the individual cells are interconnected in linear strings, the easiest variation is to change the spacing between the strings (Fig.5), a design with either horizontally (cs6) or vertically (cs7) homogeneous stripes. Strings can have variable spacing within a laminate (cs8), as was also suggested by Pellegrino et al. [12], but for a large façade or skylight it might be sufficient to combine differently string-spaced laminates (cs9).

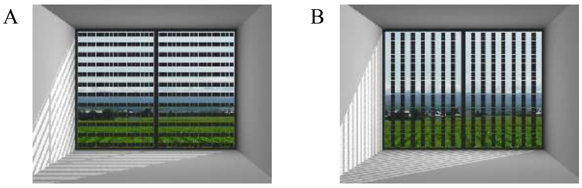


Fig.5. Variation of wider cell spacing in one direction.

The more common variation is an equal spacing in both directions, the distance between the cells being equal or similar to the distance between the strings, to achieve a uniform appearance (Fig.6).

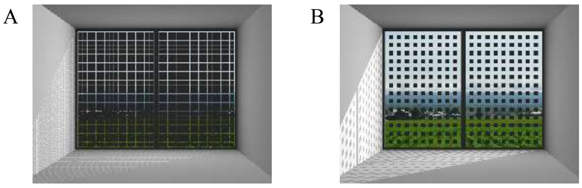


Fig.6. Variation of equal cell spacing in two directions.

A very dense spacing is used for shading and to limit unwanted heat gains (cs10). A wide spacing on the contrary permits more light to enter the building, views to the outside and desired heat gains (cs11).

Both functional requirements can be combined in the same PV laminate (Fig.7), similar to windows in a wall, like the centre (cs12) and frame (cs13) variation.

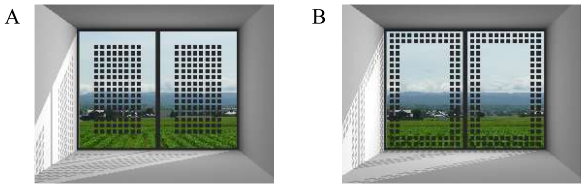


Fig.7. Centre/frame variation.

The arrangement of cells side by side is not an imperative, Fig.8 shows alternating cell position. The dense pattern is known as chequerboard (cs14), but with a wide spacing the appearance changes to dotted spots of cells (cs15).

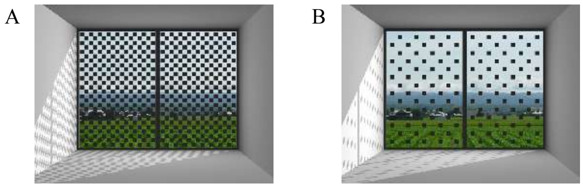
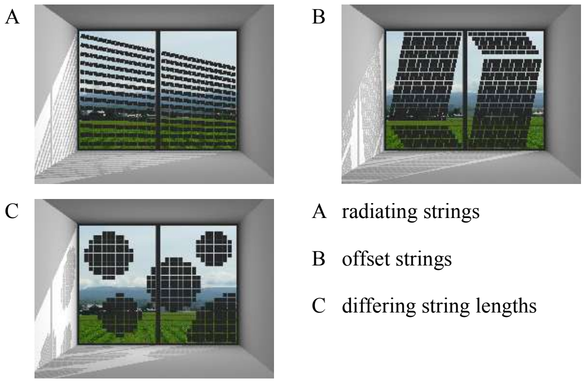


Fig.8. Chequerboard.

So far all patterns were ideal for rectangular laminates, but sometimes the architecture requires the use of non-rectangular laminates.



A radiating strings

B offset strings

C differing string lengths

Fig.9. String variation for non-rectangular panel shapes.

Radiating strings follow the widening of trapezoidal shapes (Fig.9: A; cs16), offset strings follow the oblique angles of parallelogram shapes (Fig.9: B; cs17), and differing string lengths can be used for basically any shape, best suited for laminates with curved or inclined edges (Fig.9: C; cs18, cs19). Non-rectangular shaped laminates are used in canopies (cs16), sunshades (cs17), or at building corners (cs18).

Partial non-uniform gaps (Fig.10) break with the strict linear graphic quality (cs20) and overlay the purely technical photovoltaic imagery with references from other fields, like this imitation of a stone texture (cs21), reminiscent of early low-resolution monochrome computer graphics.

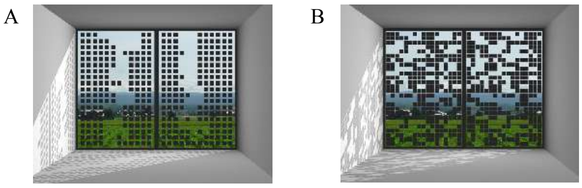


Fig.10. Non-uniform gaps.

Traditional patterns can be taken as an inspiration for PV as well [13], an example being Oriental patterns (cs22), for which the cells were rotated in relation to the laminate edges (Fig.11).

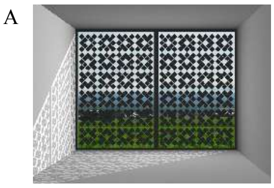


Fig.11. Rotation of whole pattern.

Even the grid-like arrangement of the cells within a string, an assumption that all patterns discussed so far followed, is questionable and can be manipulated (Fig.12; cs23).

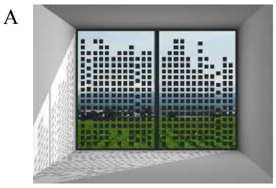


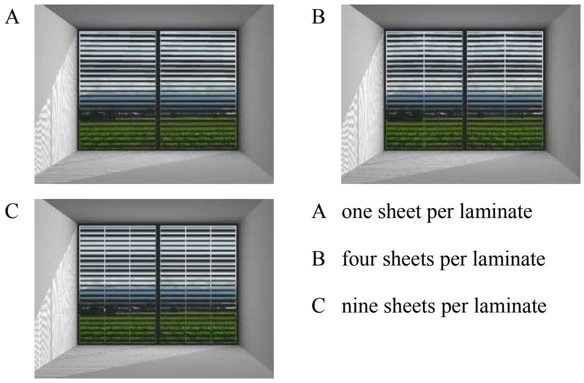
Fig.12. Varied cell distance within strings.

Finally, the strong linear arrangement of the cells in strings seems to be fixed due to the interconnection with bus bars front to rear of the next cell. Scognamiglio et al. [14] suggested to make this more flexible for alternative PV patterns, but built examples were not found. However, the current development of rear-contact cells may provide an opportunity for an elegant new interconnection technology [15].

6. Analysis of thin-film PV

translucency To achieve translucency, either the scribing lines, usually each 1~3 cm, are widened during the structuring process, or the cells are patterned with tiny holes in regular intervals. The former approach results in a homogeneous small scale zebra effect, the latter yields an even more uniform transparency. With both methods virtually any percentage for light-transmission is possible, the built examples have 5% (tf1), 10% (tf2), and 50% (tf3).

The finer the light-transmitting pattern and the higher the percentage, the more the thin-film PV will be similar to the appearance of standard glass. It must be noted that these percentages refer to the absolute light-transmission based on the percentage of light-transmitting holes in relation to opaque areas. But more important is the perceived visible light-transmission (VLT) by the human eye: *"a measured VLT of 10% is usually perceived as a VLT of 45% while a measure of 60% will be perceived as a 82% VLT"* [16], which of course applies to crystalline silicon PV as well. In the case of DSC, the photoactive dye itself can be transparent [17].



A one sheet per laminate

B four sheets per laminate

C nine sheets per laminate

Fig.13. Differently sized thin-film sheets.

size As mentioned before, thin-film PV sheets are generally much larger than the wafer based crystalline silicon cells and usually in the range of 0.5~0.6 x 0.9~1.2 m^2, with maximum dimensions of 2.4 x 2.6 m^2 for CIS [18]. However, the available sizes depend on the specification of each manufacturer's production line. Similar to crystalline silicon PV, smaller thin-film sheets can be and often are combined in larger size PV laminates (Fig.13; tf2).

colour The front side colour of thin-film sheets from amorphous silicon tends to be blueish, reddish or brownish black, whereas CIS/CIGS sheets are blueish, greenish or greyish black. With DSC a wide range of colours, even multi-colours are possible, but the red dye has been the commercially viable one so far. The back side colour depends on the colour of the back contact layer. When a transparent conductive layer is used, front and back are similar in colour as mentioned above. Non-transparent, but semi-transparently patterned layers are for instance silver.

7. Analysis of PV independent variations

Some variations are in principal independent of the PV technology, like the use of coloured (tf3) or bent glass (cs24), dummy cells at shaded areas (cs25), inactive cut cells to fill non-rectangular patterns (cs26), screen prints behind the PV layer (cs27) or in front (tf4), media installations (cs13, cs26) and art (cs20, cs23).

Furthermore, both technologies can be combined in the same building (cstf1), or even side by side, e.g. at the same façade (cstf2).

8. Discussion and outlook

Regardless the technology a variety of different designs are achievable. However, it becomes clear, that both technologies provide different opportunities, for influencing the level of transparency, for daylighting, and for the provision of visible connection between inside and outside. Whereas light-transmissive thin-film PV is a rather unobtrusive architectural material very similar to tinted glass, light-transmissive crystalline silicon PV has a strong visual impact and requires much more attention during the design and planning stage. However, severe restrictions may yield surprising opportunities. The analysis has shown, that the manufacturer independent standardisation of crystalline silicon cells provides architects and engineers in collaboration with PV companies the tools for experimentation and innovation. The result is an astonishing variety in key design parameters, summarised for crystalline silicon PV in Tab.2, and for thin-film PV in Tab.3.

It is not only the active PV technology itself, that an architectural light-transmissive PV element can be made of, but the combination with non-PV elements

(Tab.2, 3: No.9) provides more opportunities and is independent of the used PV technology. In fact, such additions can bridge between the different technologies, between PV technology and architecture, and finally between PV technology and widespread social and cultural acceptance. When several laminates are grouped to cover larger areas, façades or skylights, the number of combination possibilities starts to explode.

No.	Design parameter	Comment
1	PV technology	c-si, mc-si
2	Cell shape	Fig.2
3	Cell size	Fig.3, 4
4	Cell colour	limited range
5a	Cell spacing between strings	Fig.5, 6, 8
5b	Cell spacing within a string	Fig. 6, 8, 12
6	String length	Fig.9:C, 10-12
7	String position	Fig.4, 7, 9
8	String orientation	Fig.9:A, 11
9	non-PV elements	dummy cells, screen prints,
10	laminate	coloured interlayers, art glass or film, bent glass

Tab.2: Design parameters for crystalline silicon PV laminates

No.	Design parameter	Comment
1	PV technology	a-si, CIS/CIGS, DSC
2	Sheet shape	usually rectangular
3	Sheet size	manufacturer dependent
4	Sheet colour	limited range
5	'see-through' pattern	manufacturer dependent
6	'see-through' transparency	manufacturer dependent
7	Sheet position	variable
8	Sheet orientation	variable
9	non-PV elements	dummy cells, screen prints,
10	laminate	coloured interlayers, art glass or film, bent glass

Tab.3. Design parameters for thin-film PV laminates

9. Conclusions

The integration of PV technology into glass laminates has created a modern and superior architectural element and building material. In this paper the design parameters of light-transmissive photovoltaic systems (LTPV) on the solar cell and laminate level were analysed, with findings indicating a number of innovative solutions that extend the possibilities for building integration of photovoltaic systems in an architectural and aesthetically pleasing way.

References

1) Schoen, T.J.N. (2000) *Building with photovoltaics - the challenge for Task 7 of the PV Power Systems Program: IEA PVPS Task 7.*

2) Medio, S. (2010) Photovoltaic design integration at Battery Park City, New York. *The Second International Conference on Sustainable Architecture and Urban Development.*

3) Stamenic, L. (2004) Developments with BIPV Systems in Canada. *Asian Journal on Energy and Environment, 5*(4), 349-365.

4) Wong, P.W., Shimoda, Y., Nonaka. M., Inoue, M. & Nizuno, M. (2008) Semi-transparent PV: Thermal performance, power generation, daylight modelling and energy saving potential in residential application. *Renewable Energy 33* (2008), 1024-1036.

5) Riedel, A. (2010) Creating electricity, letting light through. *PV Magazine 01* (2010), 71-73.

6) Li, D.H.W, Lam, T.N.T. & Cheung, K.L. (2009) Energy and cost studies of semi-transparent photovoltaic skylight. *Energy Conversion and Management 50*(8), 1981-1990.

7) Wall, M., Windeleff, J. & Lien, A.G. (2008) *Solar Energy and Architecture, Annex Plan.* IEA-SHC Task 41.

8) Farkas, K., Andresen, I. & Hestnes, A.G. (2009) Architectural Integration of Photovoltaic Cells: Overview of Materials and Products From an Architectural Point of View. *The 3rd CIB Conference on Smart and Sustainable Environments Conference.*

9) Mercaldo, L.V., Addonizio, M.L., Della Noce, M., Veneri, P.D., Scognamiglio, A. & Privato, C. (2009) Thin film silicon photovoltaics: Architectural perspectives and technological issues. *Applied Energy 86* (2010), 1836-1844.

10) Claus, J. (2001) Solar Aesthetics and Urban Design Proposals for artistic BIPV. In Eurosolar (Ed.) *The City - A Solar Power Station: The State of the Art of Solar Building and Ecological Urban Planning.* Bonn: EUROSOLAR, 353-355.

11) Bruton, T.M. & Patterson, M.H. (undated) *Development of Bifunctional Photovoltaic Modules for Building Integration BIMODE.*

12) Pellegrino, M., Flaminio, G., Leanza, G., Privato, C. & Scognamiglio, A. (2002) Aesthetical Appeal of BIPV or Electrical Performance. *PV in Europe – From PV Technology to Energy Solutions,* 1109-1112.

13) Baum, R. & Liotta, S.-J. (2011) Culturally Inspired Patterns for Photovoltaics. *The 2nd Asian Conference on Arts and Humanities,* 284-302.

14) Scognamiglio, A., Graditi, G., Pascarella, F. & Privato, C. (2006) Boogie-Woogie, a photovoltaic glass-glass module “dancing” with the building. *The 21st European Photovoltaic Solar Energy Conference,* 2853-2856.

15) Sinke, W. (2008) *Stringing it out: Innovative solar module assembly technology.* Renewable Energy World.com

16) 3M. (2011) *Glossary of Words: Visible Light Transmission (VLT).*

17) Takeda, Y., Kato, N. & Toyoda, T. (2009) *Advances in monolithic series-interconnected solar-cell development.* SPIE Newsroom. DOI: 10.1117/2.1200903.1581

18) Würth Solar GmbH & Co. KG. (undated) *Architecture live: GeneCIS modules integrated into building architecture.*