Studies on light-transmissive photovoltaics (LTPV): patterns of integration into architectural design

（　透光性の太陽光発電モジュールについての研究：
建築デザインへの展開の類型化　）

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２０１２年３月２日

Thesis

submitted in partial fulfilment of the requirements

for the degree of

Doctor of Engineering in Architecture

The University of Tokyo

Graduate School of Engineering

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Tokyo

2 March 2012

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List of Abbreviations and Symbols

a-Si	amorphous silicon, a semiconductor for thin-film PV
a-Si:H	hydrogenated amorphous silicon, a semiconductor for thin-film PV
BAPV	building-added or building-applied or building-attached photovoltaic
BCSC	buried contact solar cell, a kind a crystalline silicon solar cell
BIPV	building-integrated photovoltaic
BJ	back-junction solar cell, a kind a crystalline silicon solar cell
BOS	balance of system
BSF	back-surface field
BST	building structure
CdS	cadmium sulphide, a semiconductor for thin-film PV
CdTe	cadmium telluride, a semiconductor for thin-film PV
CIGS / CIS	copper indium (gallium) (di)selenide; $CuIn_xGa_{(1-x)}Se_2$, a semiconductor for thin-film PV
CS	crystalline silicon, both mono- and multi-crystalline
c-Si	mono- or single-crystalline silicon
DSC	dye-sensitised solar cell, a semiconductor for thin-film PV
EFG	edge defined film-fed growth, a mc-Si manufacturing process
EPBT	energy pay back time
EROI	energy return on energy investment
EVA	ethylene vinyl acetate, a polymer used as laminant for encapsulation
EWT	emitter wrap-through solar cell, a kind a crystalline silicon solar cell
GaAs	gallium arsenide, a semiconductor of thin-film PV
GaInNAs	gallium indium nitrogen arsenide, a semiconductor for thin-film PV
GaInP	gallium indium phosphide, a semiconductor for thin-film PV
HOE	holographic optical elements
IBC	interdigitated back-contact solar cell, a kind a crystalline silicon solar cell
kWh	kilowatt hours
kWh/kWp	kilowatt hours generated per kilowatt peak installed
kWp	kilowatt peak
LTPV	light-transmissive photovoltaic
mc-Si	multi-crystalline (or poly-crystalline) silicon
MWT	contact wrap-through or metallisation wrap-through solar cell, a kind a crystalline silicon solar cell
n.a.	non-available or non-applicable
NBS	non-building structure
nc-Si	nano-crystalline silicon, a semiconductor for thin-film PV
OPV	organic photovoltaic, a semiconductor for thin-film PV
PEC	photoelectrochemical
PV	photovoltaic
PVB	polyvinyl butyral, a polymer used as laminant for encapsulation

PVF	polyvinyl fluoride, also known as Tedlar®, a polymer used as backsheet
PV/T	photovoltaic and thermal hybrid solar collectors
RGS	ribbon growth on substrate, a mc-Si manufacturing process
ROI	return on investment
Si	silicon
SiO_2	silicon dioxide
TCO	transparent conductive oxide
TF	thin-film
TiO_2	titanium dioxide
US DoE	United States Department of Energy
VLT	visible light-transmission

1 Introduction

Due to various reasons, to keep pace with a worldwide rising energy demand, to counter the limitation of fossil fuels, and to reduce greenhouse gas emissions which are considered to be a major source of climate change, many governments support the introduction of distributed power generation from renewable energy resources with generous support schemes like direct subsidies, tax rebates or feed-in-tariffs. Power generation with solar photovoltaic panels (PV) is one of these technologies, and due to the virtually infinite amount and scale of available solar energy a very attractive source of renewable energy.

> *"Today, PV provides 0.1% of total global electricity generation. However, . . . PV is projected to provide 5% of global electricity consumption in 2030, rising to 11% in 2050."* [1]

As the advantages of renewable energy power generation are becoming more and more attractive to investors in the building sector as well, the spread of knowledge about PV and how it can be integrated into the architectural design of buildings is one of the key issues to their wide-spread adoption.

1.1 Research background

Within the last years many books about PV in buildings - (Weller et al., 2010; Lüling, 2009; Roberts and Guariento, 2009; Scognamiglio et al., 2009; Gevorkian, 2008; DGS, 2008; Nelli, 2007; Nelli, 2006; Prasad and Snow, 2005; Hagemann, 2002; Rexroth, 2002; Thomas, 2001; Eiffert and Kiss, 2000; NREL, 1997; Sick and Erge, 1996; Humm and Toggweiler, 1993), or solar and more recently zero energy architecture including PV examples (Guzowski, 2010; Schneider, 1996) were published. On average they include 15-20 case studies, an exception being Hagemann (2002) and Nelli (2006) with more than 100 projects each. A summary of the reference literature is - Tab.1 - and a more detailed table of the case study projects using light-transmissive PV published in the reference books is included in - Appendix A.

[1] IEA (2010a) p.5

Tab.1: Reference literature with BIPV and LTPV case studies

	Weller, et al., 2010	Guzowski, 2010	Lüling, 2009	Roberts & Guariento, 2009	Scognamiglio, et al., 2009	Nelli, 2007	Nelli, 2006	Prasad & Snow, 2005	Hagemann, 2002	Thomas, 2001	Eiffert & Kiss, 2000	NREL, 1997	Schneider, 1996	Sick & Erge, 1996	Humm & Toggweiler, 1993
389 BIPV case studies	8	10	34	14	11	44	157	22	129	8	16	52	20	20	43
131 with light-transmissive PV	4	5	13	8	2	39	69	12	58	3	6	4	3	3	10

Even though opaque PV modules are contributing by far the lion's share in terms of module production, it is interesting to see that about one third of the BIPV case studies in the studied literature are using light-transmissive photovoltaic (LTPV) laminates, mostly bespoke solutions. This raises the question, whether LTPV are more appropriate for building integration than opaque PV, even though they are an absolute niche product for the manufacturers. In contrast to the importance that LTPV have as case study examples, their special features are hardly dealt with, at best in a brief section about transparency. An analysis with the main focus on LTPV, that addresses the issue of a comparative analysis of built examples based on a comprehensive corpus, is lacking.

To address LTPV separate from opaque PV is based on its translucent or semi-transparent properties and qualities. The ability to change the degree of light-transmittance, for illumination or shading, for allowing or preventing views, for letting in desired or blocking undesired heat loads, while fulfilling the basic function of PV as power generator, plus the aesthetic qualities of rich shadow plays, colour and texture, all in one building and architectural element, elevates its flexibility beyond opaque PV. Furthermore, 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 LTPV 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]

2 Medio (2010)
3 Stamenic (2004)
4 Wong et al. (2008)
5 Riedel (2010)
6 Li et al. (2009)

1.2 Objectives

The analysis of PV in buildings has commonly been based on opaque PV due to the overwhelming market share. My thesis is, that certain issues, only recently noticeable or noticeable only when looking from the point of LTPV, are showing the limitation of this approach. This study is meant to fill the gap, the lack of research into LTPV as an architectural element.

I. It provides an overview of PV technology and terminology as well as a historical introduction to PV and LTPV in architecture,
II. establishes key design parameters for LTPV based on a comparative analysis of built examples,
III. illustrates potential for manufacturing and architectural integration of LTPV.

1.3 Methodology and structure of the study

The study consists of six main chapters, that systematically provide the general basis of discussion on PV in architecture and subsequently lead to the analysis of LTPV examples.

1. **Introduction**
   The first chapter gives an overview of research background, objectives, study structure and research methodology.

The following two chapters address the first objective (I.):

2. **Photovoltaics: terminology, technology and energy**
   The second chapter gives an overview on the PV market, a detailed introduction to the terminology relevant for architecture, an overview of different PV technologies and their material characteristics, as well as an analysis of the energy balance of PV.
3. **Architecture and PV**
   The third chapter gives an introductory overview of the historical development of PV and first applications in space and on earth. A number of buildings and projects, that introduced the pioneering technology into the field of architecture, are introduced and compared. Challenges that had to be overcome are outlined.

To fulfil the second objective (II.), a corpus of 610 realised LTPV projects from the last two decades was compiled. This means about four to five times more built examples than the case studies published in the books about PV in buildings - Tab.1. From this full corpus 116 projects were selected for a comparative analysis, to establish and verify key design parameters for LTPV. The following two chapters address the second objective:

4. **Corpus of LTPV examples**

   The fourth chapter briefly introduces the corpus of light-transmissive PV projects, that constitutes the basis for the subsequent analysis of built examples. The full corpus is included in - Appendix B - and the selected corpus in - Appendix C - of this study.

5. **Six-Level-Matrix for analysis**

   The fifth chapter gives justification for the establishment of an extended analytical method named the Six-Level-Matrix. Based on this classification the characteristic features and key design parameters at each level are compared and enriched with examples from the corpus of LTPV projects.

To fulfil the third objective (III.), findings of the Six-Level-Matrix are summarised at each level within chapter 5. Discrepancies between available products and applications are outlined. Tendencies for a lack or rich availability of customisable solutions are mentioned.

6. **Alternative patterns for PV and LTPV**

   Based on the findings, alternative patterns for PV and LTPV are suggested in this chapter.

Finally, the study is concluded in the last chapter.

7. **Conclusion**

The thesis is completed by three appendices:

Appendix A

The first appendix provides an overview of LTPV examples in the reference literature.

Appendix B

The second appendix lists the complete corpus of built LTPV examples, that was compiled for this research.

Appendix C

The third appendix forms an important part of the thesis and introduces the corpus of selected LTPV examples, that provide the basis for the comparative analysis in chapter - 5. Six-Level-Matrix for analysis - of the main part of the study. Each example is presented with a project sheet including general information, technical data, images and an analytical part based on the Six-Level-Matrix with detailed data, descriptions and graphical icons.

2 Photovoltaics: terminology, technology and energy

2.1 BIPV market

According to an analysis by Frost & Sullivan, *"the European BIPV market in 2007 was estimated at €143 million with a total installed capacity of 25.7 MW for the commercial, residential, industrial and public markets combined".*[7] According to a forecast by research firm NanoMarkets, *"the BIPV market will make up about US $800 million in 2011, exceed US $4 billion in global revenues by 2013 and surpass US $8 billion in 2015".*[8] And finally, a market forecast by PikeResearch expects the *"combined BIPV/BAPV market to grow from 215 MW in 2009 (about 3% of the overall solar market) to 2,385 MW in 2016 (about 7% of the overall market) at a compound annual growth rate (CAGR) of 41%. Should conditions prove ideal, we believe BIPV/BAPV installations could reach as high 3,475 MW in 2016".*[9] Especially the cost advantage of BIPV against conventional PV is a driving force for their more rapid dissemination.

2.2 PV terminology for architecture

2.2.1 BIPV

When speaking about photovoltaic and buildings, than one acronym immediately sticks out - BIPV - short for building-integrated photovoltaic. However, to truly nail down it's meaning is a rather troublesome undertaking. The major problem with this term seems to circulate around the issue of integration: when can a PV system be considered as 'building integrated'? The following analysis will point out some inconclusive usages of the acronym, but, to say this already at the start, without arriving at an ultimate definition. However, it is hoped that the readers of this study will get an understanding for the variety of meanings.

Some of the first comprehensive studies addressing the issue of building integration of PV were done in the 1990s. Three subsequent reports were produced by a team led by Gregory Kiss. The first report[10] is a qualitative study with diagrams of the building envelope illustrating the impact of different types of integration on solar exposure, spatial impacts on plan, section and elevation, and includes some rough analyses on performance and cost. The second report[11] quantitatively evaluated five case studies of roof integration, and the third re-

7 Carella (2009)
8 Kho (2009)
9 Cavanaugh and Wheelock (2010)
10 Kiss Cathcart Anders Architects (1993)
11 Kiss, Kinkead and Raman (1995)

port[12] evaluated different types of integration based on a payback analysis. In the first report the term 'building-integrated PVs' (without the full acronym yet) was understood as *"potentially several levels of symbiotic benefits between PVs and buildings",*[13] mutually beneficial in terms of material, structural, spatial, energetic, and even the social issue of ownership. At the time of the third report, the authors clearly distinguished between building-mounted and building-integrated, both in comparison to field-mounted PV systems, and shifted the focus much stronger to the material and structural or economic issues. Furthermore, the acronym BIPV appears well established as an attribute to PV-related nouns like 'application', 'industry', 'installation', 'material', 'module', 'payback period', 'performance', 'product', 'project' and 'system', but furthermore to more building related nouns like 'atrium', 'construction cost', 'curtain wall', 'glazing detail' and 'roof', which distinguishes the use of BIPV from simply PV. As an exact definition of BIPV is not given, it is not exactly clear whether building-mounted installations are included or ultimately excluded. The closest to a definition is: *"Any building surface that intercepts the sun . . . can deliver the multiple benefits of BIPV: producing energy while performing other architectural functions . . . . BIPV systems may be built as part of new construction, or retrofit to existing buildings".*[14] [underline added] Multi-functional performance is the key, however, the meaning of *"other architectural functions"* was left ambiguously open and may include physical, social as well as symbolic or aesthetic *"functions"*. As such, building-mounted PV systems could be included in the acronym as long as they perform other architectural functions.

Frantzis et al., during the intermediate period of the previously introduced reports, defined BIPV for their study *"as two types of applications: 1) where the PV modules are an integral part of the building, often serving as the exterior weathering skin, and 2) the PV modules are mounted on the existing building exterior"*[15] [underlines added], clearly including building-mounted PV systems. This definition can be found mirrored in a recent report by the IEA: *"the term building-integrated PV systems is used to indicate both retrofit systems mounted on top of the existing building structure and fully integrated systems replacing roof tiles and façade elements"*[16] [underlines added], and appears to be a viable one when analysing the economic market potential of building-related PV products, as both reports do.

Weller et al., in one of the most recent books about PV and architecture, take a closer look at the issue of integration on the level of construction and conclude: *"we basically distin-*

12 Kiss and Kinkead (1995)
13 Kiss Cathcart Anders Architects (1993) p.1
14 Kiss and Kinkead (1995) p.4
15 Frantzis et al. (1994)
16 IEA (2010a) p.8

guish between three different concepts for the integration of solar energy systems: Addition, Substitution, Integration".[17] Here integration is only achieved when PV becomes the building envelope and performs all its local functions. A partial replacement, like the outer weather-proof cladding without the underlying structure, is termed substitution. This kind of 'integration' principle favours multi-functional, composite elements with a strong focus on maximising traditional attributes of building performance like *"weather proofing, thermal insulation, sunshading and sound insulation"* and freely accepts a lower performance of the PV system: *"However, as the degree of integration of the PV element in a warm (single-leaf) façade increases, so the module temperature increases, too, which reduces the conversion efficiency of the cells employed".*[18]

In terms of constructional integration in relation to the draining layer, Krippner and Herzog went a step further and distinguished five positions: *"on top"* as with rear-ventilated rainscreen cladding, *"on"* without rear-ventilation, *"within"* as part of the draining layer, *"between"* draining layer and inner surface of the wall, and *"interior"* as part of the interior design without direct connection to the building envelope.[19] This five level approach views the position of the PV system relative to the draining layer, but allows for a deeper spatial penetration, a possibility not considered well by the previous approaches.

A distinction in relation to time was done by Cavanaugh and Wheelock: *"BIPV tiles, panels, shingles or modules <u>replace</u> common building materials, are aesthetically appealing, and are completely integrated into the structure of a rooftop or building envelope. BAPV tiles, panels, shingles or modules are integrated or installed in a rooftop or a building <u>after initial construction</u>; these must also be architecturally and aesthetically appealing – not just solar modules mounted on an available and conveniently oriented rooftop"* [20] [underlines added]. BIPV here refers to building-integrated and BAPV to building-applied PV.[21] When comparing this with Frantzis et al.'s definition then it becomes obvious that here BIPV is used in a stricter sense, and even stricter than in Kiss and Kinkead's analysis, as both BIPV / BAPV are clearly distinguished from building-mounted PV systems.

17 Weller et al. (2010) p.49
18 Weller et al. (2010) p.49
19 Krippner and Herzog (2001) p.243
20 Cavanaugh and Wheelock (2010)
21 The acronym BAPV is not widely used in the literature studied, but may stand for building-applied or building-added or building-attached PV. Its usage is equally different from author to author, ranging from simply being the keyword for building-mounted PV (interestingly enough, an acronym BMPV was never suggested) in opposition to BIPV, to the clearly defined meaning by Cavanaugh and Wheelock (2010) in very close relation to BIPV. However, as the usage of BAPV is very sporadic, it is not analysed any further.

As stated at the beginning of this section, a final definition of the ultimate meaning of BIPV can not be given. It obviously depends on the context of each study and each author's intention, and this general confusion requires the boundary to be clearly stated. However, there is something similar to a conclusion that can be drawn after this short analysis. When the author focuses mainly on aspects of integration, such as physical or functional integration of the PV system, he ends up with a very narrow meaning. When the author is more interested in PV systems in buildings in general, then the meaning is much broader. Probably the broadest view was taken by Task 7 of the IEA PVPS programme, considering the *"integration of PV systems into the built environment (BIPV). . . . other than classified as 'ground based arrays'"*.[22] The view taken extends even beyond buildings, as it considers non-building structures as well, see section 2.2.5 NBS - non-building structures for more information.

2.2.2 PV in buildings

Initial research on the advantages to merge photovoltaic with buildings, to find answers to the question 'why PV in buildings / why BIPV?', was conducted by Task 16 of the IEA SHC Programme.[23] According to them, PV in buildings:

"[1] does not require any extra land area and can be utilized also in densely populated areas,

[2] does not require any additional infrastructure installations,

[3] can provide electricity during peak times and thus reduce the utility's peak delivery requirements,

[4] may reduce transmission and distribution losses,

[5] may cover all or a significant part of the electricity consumption of the corresponding building,

[6] may replace conventional building materials and thus serve a dual role which enhances pay back considerations,

[7] can provide an improved aesthetic appearance in an innovative way,

[8] can be integrated with the maintenance, control and operation of the other installations and systems in the building,

[9] can provide reduced planning costs".[24]

[22] This quote is part of the objective of Task 7 "Photovoltaic power systems in the built environment" of the IEA Photovoltaic Power Systens (PVPS) programme that operated from 1997 to 2001. It is written down in the foreword to each report, e.g. the first report by van Mierlo and Oudshoff (1999).

[23] Task 16 "Photovoltaics in Buildings" within the IEA Solar Heating and Cooling Programme (SHC) operated from 1990 to 1995.

[24] Sick and Erge (1996) p.6

As this report was written more than 15 years ago, the authors are vague in their statements by using modal verbs 'can', and 'may' from their third statement on, anticipating a widespread penetration of PV systems into the built environment. Not all of the stated reasons are exclusive to PV in buildings alone, like the third statement also applies to ground-mounted systems. The point of view taken by this report clearly is from the side of the PV system rather than from the building side, as becomes obvious with the ninth and last statement.

Despite the fact that the integration of PV into a dense urban environment under mostly not 100% ideal conditions has many drawbacks. When looking at it from the point of the building and building owner, however, such drawbacks are usually countered by gains somewhere else. Some further advantages can be added to the list, as PV in buildings:

➔ can help in reducing a building's, and furthermore a city's environmental footprint, when compared to forms of electricity generation from fossil fuel,

➔ are nowadays a marketing advantage as a 'green' building, as also recognised by green building standards (however, it is hoped for that such issues will become a matter of course rather than staying exceptions, resulting in an increasingly weaker 'advantage' over time),

➔ is the only building material (if it is used as one) that, by generating electricity, can individually pay back some of their investment cost, or ideally even generate a positive income, a unique return on investment (ROI), enhancing financial resilience of a building investment in the medium term,[25]

➔ are a shift in the ownership of electricity generation, away from utilities, a shift towards decentralised generation and ownership.[26]

2.2.3 PV as multi-functional building element

Multi-functional performance as the key for the success of PV in buildings was already mentioned, but what are the multi-functions that PV systems can perform? Bendel analysed factual and possible functions that PV can or could perform, when integrated accordingly: *"Witterungsschutz [1. weather proofing]. . . . Wärmedämmung [2. thermal insulation]. . . . Abschattung [3. sunshading]. . . . Sicherheit [4. security]. . . . Schalldämmung [5. sound*

[25] For financial viability in economic terms, the erection and maintenance cost of a building is set against the achievable rental income it produces during its lifetime, in other words, if there is no tenant, no rent will be achieved and the cost-performance will suffer greatly. A building that generates electricity from abundantly and freely available renewable resources, on the other hand, even if there is no tenant it may continue to generate some sort of income.

[26] The social issue of ownership, as also mentioned in the report by Kiss Cathcart Anders Architects (1993) - see 2.2.1 BIPV - is heavily advocated by EUROSOLAR (European Association for Renewable Energy).

insulation]. . . . Elektromagnetische Schirmdämpfung [6. electromagnetic shielding]. . . . Ästhetik / Design [7. aesthetic / design]. . . . Elektromagnetische Energiewandlung [8. electromagnetic energy conversion]. . . . Thermische Energiewandlung [9. thermal energy conversion]. . . . Photovoltaische Energiewandlung [10. photovoltaic energy conversion]".[27]

Roughly these functions can be separated into two main groups. On one hand some are **passive**, traditional architecture and building related functions, like weather proofing, thermal insulation, sunshading (and light-transmission), security, sound insulation, aesthetic / design and thermal energy conversion, which are mainly defined by the solar cell encapsulation materials like glass, metal sheets or membranes, and equal to traditional building materials. On the other hand some are new **active** functions, that become available because of encapsulated solar cells, like electromagnetic shielding, electromagnetic and photovoltaic energy conversion, a list which can be extended easily: switchable visibility by electrochromic ability,[28] electroluminescent ability, integrated LED lighting[29] or display features,[30] etc. Such electrical properties are by no means unique to photovoltaic, but as partly or fully self-powered inherent building material properties they are unique. Photovoltaic is another stepping stone, like electric lighting has been as explained by Banham,[31] that will extend the meaning of an architectural building material towards ephemeral phenomena.

2.2.4 PV in architecture

Kiss and Kinkead, as mentioned before, spoke of *"BIPV: producing energy while performing other architectural functions",*[32] pointing to the importance of considering architectural issues. Apart from solving technical and economical issues hindering the dissemination of PV in the built environment, a number of research projects were initiated to specifically, among others, address issues of architectural and aesthetic quality. Just to mention a few, the project BIMODE (1997-1999) that developed novel cell and module designs - see section 2.4 Characteristics of crystalline silicon PV, the Task 7 and more precisely Subtask 1 of the IEA PVPS programme (1997-2001) that documented high-quality case-studies, or Task 3.1 of the PV-NORD programme (2001-2004) that documented case studies in Northern Europe.

The non-technical issue of architectural quality and aesthetics is a rather difficult one, as it is often subjective or even contradictory: *"Architecturally integrated PV adds one more di-*

27 Bendel (2002)
28 Deb (2000); Santa-Nokki, Kallioinen and Korppi-Tommola (2007)
29 Lüling (2009) pp.45-50
30 The Japanese company MSK (now the Chinese Suntech) made protoype developments of LED laminated PV Glass and PV that functioned as projection screen.
31 Banham (1969)
32 Kiss and Kinkead (1995) p.4

mension to BiPV: Aesthetics or architectural quality . . . Architectural integration may either be in harmony with the architecture of the building as such or in contrast to or in dialogue with this" [33] [underlines added]. A good solution in one case might be a bad solution in the next case. However, architectural quality is not only about aesthetics. Aesthetics, or the appreciation of beauty, has been one of the three pillars of architectural history and theory since Vitruvius and his trinity of *firmitas, utilitas, venustas* (firmness, usefulness beauty): *"If firmitas (construction) is absent, we have scenography, not architecture. If utilitas (function) is absent, we have a sculpture, not architecture. And without venustas (aesthetics), we merely have a building. But each of these three requirements to a building must be optimised and must interact with the others to result in a building of architectural quality".* [34]

As a follow up of the outcome of IEA SHC Task 16 - see 2.2.2 PV in buildings - and to answer the next question 'how to do BIPV?', IEA PVPS Task 7 did initial research under the objective of enhancing the architectural quality of PV systems in the built environment by setting up seven architectural criteria to be used for qualitative evaluation: *"1. Naturally integrated . . . 2. Architecturally pleasing . . . 3. Good composition . . . 4. Grid, harmony and composition . . . 5. Contextuality . . . 6. Well-engineered . . . 7. Innovative new design".* [35] The criteria were condensed after collecting and analysing over 300 built projects, which are published in an internet database.[36] Some selected case studies were published as Task 7's final report.[37]

The importance of an aesthetic appearance as an integral requirement for the success of PV in buildings is also recognised by Cavanaugh and Wheelock in their recent report and market forecast: *"BIPV . . . are aesthetically appealing, and are completely integrated . . . BAPV . . . must also be architecturally and aesthetically appealing – not just solar modules mounted on an available and conveniently oriented rooftop".* [38] However, the use of 'BIPV products', that provide better integrated and multi-functional solutions, does not lead automatically to satisfactory aesthetic solutions. Even be-

33 Svensson and Wittchen (2004) p.56 - This report titled *"Aesthetics of PV building integration"* is the final report of Task 3.1 of the PV-NORD programme.

34 Ibid. p.9

35 Schoen et al. (2000); a slightly different wording was published by Kaan and Reijenga (2004)

36 The database is accessable at <http://www.pvdatabase.org>. It now includes building projects and BIPV products collected by Task 7 as well as urban projects collected by Task 10 of the IEA PVPS programme. The original address <http://www.pvdatabase.com> is no longer in use.

37 The final report is published as book, see Prasad and Snow (2005)

38 Cavanaugh and Wheelock (2010)

spoke solutions can be aesthetically disturbing, illustrated by a detailed description of a case study project by Svensson and Wittchen: *"The big panels on the wall are finally very poorly integrated with the architecture. Holmen and Grynnan may serve as a good example of how to, and how not to, adapt PV cells to an existing building",*[39] and: *"It is obvious that greater interest must be taken to the visual appearance of the PV panels if they are to achieve the status of an attractive building material".*[40]

That the search for guidelines and architectural quality criteria isn't over, may be best understood by the inauguration of a further research project, Task 41 of the IEA SHC titled 'Solar Energy and Architecture' in 2009.[41] But sometimes one has to look outside established domains to look for surprisingly pleasing results, as the next section will illustrate.

2.2.5 NBS - non-building structures

As mentioned earlier - see 2.2.1 BIPV, it was the IEA PVPS Task 7, that expanded the view on BIPV beyond buildings, the meaning of the acronym's initial word, into the built environment. As such, non-building structures like urban street equipment, barriers, shelters, kiosks, single and multi 'aerial' structures are included.[42]

Looking for built examples, that used PV in an innovative way, can reveal many among non-building structures. Non-building examples with innovative adaptation of PV often precede examples in buildings. In fact, this shouldn't come as a surprise at all, as it is rather the rule than the exception. Crystalline silicon cells were successfully used in satellites first, amorphous silicon TF cells in calculators, semi-transparent TF cells in car roofs, OPV cells in bus shelters.

In general, the building sector isn't the easiest test bed for any new technology. The introduction of new building products requires certification, an often tedious, time consuming and expensive process. As such, the building industry is often rather conservative.

Some examples of integration into non-building structures (NBS) as well as building structures (BST) are illustrated in Tab.2.

[39] Svensson and Wittchen (2004) p.20
[40] Ibid. p.21
[41] 'Solar Energy and Architecture' (undated); Wall, Windeleff and Lien (2008)
[42] Andersson, Romero and Johanesson (2001); Romero, Johanesson and Andersson (2005)

Tab.2: PV features in non-building (NBS) and building structures (BST)
see Appendix C for further information on each project

(a) bent laminates

Fig.1: NBS - Solar Catamaran, 1999 - cs14
Credit: © Tilla Goldberg

Fig.2: BST - Gemini House, 2001 - cs27
Credit: © City of Weiz

(b) PV as part of a media installation

Fig.3: NBS - Sun Monument, 2008 - cs60
Credit: © ertex solar

Fig.4: BST - GreenPix, 2008 - cs68
Credit: © Zhou Ruogu Architecture Photography

(c) PV in trapezoidal and/or parallelogram shaped panels with offset cell-strings

Fig.5: NBS - CCM 'The Brain', 2005 - cs44
Credit: © ertex solar

Fig.6: BST - The Core, 2005 - cs46
Credit: © Eden Project

(d) PV with bifacial cells

Fig.7: NBS - SBB noise barrier, 2008
Credit: © Scheuten

Fig.8: BST - BSZ Riesstrasse, 2007 - cs54
Credit: © Schüco International KG

(e) PV panels with inclined and/or curved edges

Fig.9: NBS - Solarsail, 1999 - cs10
Credit: © Halle 58 Architekten

Fig.10: BST - OLV Hospital, 2009 - cs78
Credit: © Sapa Building System

2.2.6 Solar cell, string or sheet, laminate, panel or module, array, system

A - **solar cell** - is the heart, the basic direct current generating 'unit' of any PV system. As the electricity generated by one single solar cell is limited, a number of equally sized cells are interconnected in cell-groups. Equally sized for the reason, that smaller cells would constrain the current, similarly to a narrow passage in a river or water pipe. The name of this kind of cell-group is - **string** - in the case of crystalline silicon cells, derived from the interconnection process called 'stringing'. In the case of thin-film cells, the term 'string' is not used because the interconnection of cells is monolithic and happens during cell production. As such TF 'cells' are different from CS cells, as they are almost never separate as individual cells. For lab research single cells in a size of a couple of cm^2 are convenient, however, at mass-production level large-area submodules made of dozens or hundreds of small cells are 'standard'. As such, the terminology of 'a thin-film solar cell' is often confusingly used as a singular when actually speaking about a number of monolithic series-interconnected cells. Interestingly, a proper term to describe TF appropriately at this processing stage has not yet evolved, but the term 'submodule' is most widely used. A kind of elementary definition was given by Emery: *"A module consists of several encapsulated, environmentally protected, and electrically interconnected cells. . . . A submodule or minimodule is an unencapsulated module".*[43] When speaking about PV only, this definition might suffice, as mostly each submodule is encapsulated separately. To describe TF in BIPV products and LTPV application, however, this definition is unsatisfactory, as often more than one submodule is encapsulated to form a larger, properly sized building element. In this study, the term - **thin-film sheet** - or simply - **sheet** - is used instead as a neutral term in contrast to the subordinate connotation of submodule.

To isolate the electrically conductive areas from the environment and protect the solar cells, they are encapsulated mostly in glass or film. In the case of crystalline silicon cells, usually a number of cell-strings are encapsulated together, in the case of thin-film cells, it is one or many single sheets. Such encapsulated composites are often called - **laminate** - due to the widely used process of lamination. As a next step, a junction box for external electric connection and sometimes an aluminium frame is added, and the whole is called solar - **panel** - or - **module**. In the literature these two terms are often used interchangeably. A number of panels / modules are connected to form a solar - **array**. All necessary additional cabling, a battery for DC application or an inverter for AC application and any other control electronic devices, are the so called - **electrical BOS** - (Balance of System) components. Any required

[43] Emery (2003) p.713

mounting material, structure or fixing parts are the - **mechanical BOS** - components. The solar array with both types of BOS components together constitutes a - **PV system**.

2.2.7 Translucency and transparency - 'light-through' and 'see-through'

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, as mentioned before. However, when the focus is less on technology, but more on building integration, a different classification seems to be required. Opaque modules have been the 'standard' so far and continue to be in terms of number of produced modules or kWp installed. When speaking about building-integration, however, opaque modules and panels are just one group of BIPV products. The other group, unique still to BIPV, are light-transmissive PV panels. Whereas opaque PV modules and panels are either added to the building or function as a replacement for non-PV, standard roofing and façade cladding materials, light-transmissive PV panels can be just added elements too, but more often they replace glazings in skylights, façades, awnings or sunshades. Light-transmissive PV has, in contrast to opaque PV, the additional purpose of modulating light penetration, both in terms of permitting desired amounts of natural light or views and preventing undesired heat loads or views. The classification proposed is based on the visual quality of the transmitted light.

There are two common and widely established ways to achieve light transmission in a PV panel. 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 obstructed by the relatively large opaque cells, this kind of translucent PV panels are often called - **light-through**. The shadow plays, or interplays of light and shadow cast by opaque cells and transmitted light, are a strong characteristic.

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 kind of semi-transparent PV panels are often called - **see-through**. The method is commonly applied to thin-film cells, but 'see-through' crystalline cells are available as well.

Even though the first LTPV examples in buildings date back at least to the early 1980s - see 3.2.5 LTPV enters the stage - and clearly belong to the 'light-through' type, it wasn't until the end of the eighties that the latter term emerges. The development of a novel 'see-through' type of TF solar cells was reported by Nakano et al., working at the Japanese company Sanyo:

"Many microscopic holes are spaced uniformly on the active area [of an a-Si solar cell]. *Thus, a part of incident light can pass naturally through this submodule".*[44] Previously available types of semi-transparent a-Si solar cells absorbed the short-wave part of the visible light spectrum, thus transmitting a reddish light. The main feature of this novel technology was the transmission of light in the full visible colour spectrum.[45] The first commercial application of 'see-through' type solar cells was for a car sunroof of a Mazda Sentia and marketed since 1991.[46]

Shortly after, a semi-transparent crystalline silicon cell was suggested by Willeke and Fath, a patent filed in 1993[47] and published in 1994.[48] Its development became part of the BIMODE project - see 2.4 Characteristics of crystalline silicon PV, which led to production of the POWER (POlycrystalline silicon Wafer Engineering Result) cell in 1999. Grinding thin trenches on front and 90° rotated on rear side resulted in more than 20,000 tiny holes for a 10% light-transmittance.[49] The first LTPV project with such cells is the **Solarcafe 'Sonnenzeit'** in Kirchzarten, Germany - Appendix C: cs13 - and built the same year. However, the original POWER-cells aren't produced any more. The current 'semi-transparent' monocrystalline silicon cells by the manufacturer Sunways have 64 (8x8) square holes of 5x5 mm^2 each for a combined 10% light-transmittance as well[50] - see Fig.22.

Even though the two approaches, for thin-film PV and crystalline silicon PV, are different in PV technology as well as the treatment that leads to semi-transparency, both can be seen as achieving a similar result. Furthermore, the recent development of DSC and OPV solar cells, that use colourful and transparent dyes or organic polymers, are rather similar in their selective absorption and transmission of coloured light to the pre-'see-through', early type of semi-transparent a-Si solar cell as described above. Therefore, and especially with the focus on LTPV application in architecture, I'm going to use a less-technology specific, thus wider and different definition for a 'see-through' LTPV product than was described by Nakano et al. for the 'see-through' a-Si solar cell. The focus will be less on the natural spectrum of transmitted light, but on the absence of view obstructions caused by large opaque areas. As such, 'light-through' and 'see-through' will be the two types of LTPV with opposing tendencies. The 'light-through' type of LTPV has significant view obstructions, whereas the 'see-through' type has less-significant view obstructions.

44 Nakano et al. (1988) p.127; see also Kishi et al. (1987)
45 Takeoka et al. (1993) pp.243-245
46 Ibid. pp.250-251; Yagi, Tanaka and Nakano (2004) p.217; Tanaka et al. (1988) p.61
47 Fath, Nussbaumer and Burkhardt (2002); Willeke and Fath (1998)
48 Willeke and Fath (1994)
49 Nussbaumer (2001); Fath, Nussbaumer and Burkhardt (2002)
50 'Datasheet Sunways Solar Cells Mono 125 (AH81-E)' (2011)

Some manufacturers have developed unique, proprietary approaches to achieve transparency, not by the use of novel photoactive materials but with unique manufacturing processes that result in novel products, like 'Sphelar Glass' by Kyosemi Corporation,[51] made with spherical solar cells - see also 2.4.4 Special cells, the 'Photovoltaic Glass Unit' by Pythagoras Solar,[52] or the 'Sliver cell' by ANU-CSES.[53] However, built examples that use these novel products were not found within the corpus of LTPV projects.

2.2.8 Kilowatt peak and kilowatt hour

Two metrics that are important in evaluating the electricity generating capacity of a PV system are watt peak (Wp) or kilowatt peak (kWp) and kilowatt hours (kWh). Watt peak and kilowatt peak are metrics of each solar cell or panel, a nominal power that is achieved under standardised laboratory conditions of 1 sun and air mass 1.5. This measure is given by each cell and module manufacturer, and it provides a basis for comparison of different manufacturers.

However, more interesting than the abstract unit kWp is the common unit kWh. According to BMU one kilowatt hour of electricity is enough to: *"Make 70 cups of coffee, Watch seven hours of TV, Iron 15 shirts, Listen to CDs for 40 hours, Power a 300-litre fridge for two days, Bake one yeast cake [or] Wash a machine full of laundry".*[54] In Japan, according to the Architectural Institute of Japan's 2006 report *Energy Consumption for Residential Buildings in Japan*, the average electricity demand is 12.2 kWh/day,[55] which can be calculated to an annual demand of 4453 kWh.

The usable electricity in kWh that can be generated from a PV system of 1 kWp capacity can be calculated. Such a calculation depends on many variables, **global factors** like direct and indirect insolation values or temperature, **exposure factors** of the PV array like orientation and inclination, sun-tracking and shading, **technology specific factors** like direct and low-light performance or temperature dependency, as well as **system design factors**, like module efficiency, module temperature, inverter efficiency, etc. As most of these factors can be individually influenced and may vary daily or even from one second to the other, like shading by clouds, long term statistical values are used in calculating a theoretical performance of kilowatt hours per kilowatt peak (kWh/kWp) by considering certain standard conditions. According to the CASBEE-H(DH) 2007 manual, an idealised South facing PV system

51 'Presentation of Sphelar: See-through BIPV Sphelar Glass' (2010); Taira (2007)
52 'The Sun Rises on Green Building Innovation' (2010)
53 'Sliver® Cells' (undated)
54 'Questions and Answers: Energy Efficiency Tips for Domestic and Electrical Appliances' (2007)
55 IBEC (2008) p.107

with a 30° angle of inclination in Tokyo can generate 986 kWh per kWp capacity,[56] which means, that the annual average electricity demand of the previously mentioned three-member household can be generated by a 4.5 kWp PV system. If the PV panels are installed in less ideal positions, in East or West direction or at different inclination, the capacity must be larger to accommodate for less kWh/kWp.

2.3 PV technologies

2.3.1 Crystalline Silicon PV

The development of photovoltaics is strongly related to the development of semiconductors made of crystalline silicon, or simply speaking to the development of crystalline silicon solar cells. The first modern solar cell with an efficiency of around 6% was developed by Daryl M. Chapin, Calvin S. Fuller and Gerald L. Pearson at the Bell Laboratories, officially announced on April 25, 1954, and published the same year.[57] It possessed already the basic features of today's' crystalline silicon cells - a dopant diffused p-n-junction.[58]

Crystalline silicon is still the most widely researched, manufactured and applied semiconductor in the photovoltaic industry. One of the reasons may be that silicon is one of the most common elements in the universe, and one of the most abundant elements on earth. Known in its oxidized form as silica (SiO_2: silicon dioxide), it is a natural constituent of quartz, sand and stone, and widely used in glass, ceramics and cement. The crystalline form of silicon (Si) is used in modern day semiconductor devices, like transistors and computer chips as a principal component. The production of crystalline silicon PV cells benefited immensely from developments in the electronics industry, as some technologies required for mass-producing silicon-wafers were used to produce slices for solar cells as well. Furthermore, in contrast to the very high-purity levels required by the microelectronic industry for electronic-grade silicon, the demands for solar-grade silicon are less stringent. As such the PV industry could procure scrap material at lower cost from the electronics industry.

Two approaches of producing crystalline silicon for solar cells are dominant. High-purity silicon can be crystallised and grown by the Czochralski process, named after the Polish scientist Jan Czochralski (1885-1953), who invented the process,[59] resulting in round **single-**

56 Calculated from primary energy equivalent (unit: GJ) to secondary energy equivalent (unit: kWh) by the given formula: 1 GJ = 1/9.83 MWh = 101.7 kWh in IBEC (2008, p.109). As an overall system performance is not given, it is difficult to compare this value.
57 Chapin et al. (1954); Perlin (2004)
58 Green (2001a)
59 Czochralski (1918)

crystalline or mono-crystalline ingots. The second most commonly applied method is casting **multi-crystalline** (or poly-crystalline)[60] silicon in blocks.

The production of crystalline silicon cells, single- and multi-crystalline, is split into the manufacturing of crystalline slices (growing or casting of the silicon and sawing into slices) and the solar cell process (texturing, diffusion and metallisation). For module production, multiple crystalline silicon cells are electrically interconnected in linear cell strings, and a number of side by side strings are encapsulated in a lamination process between front and back sheets of glass, film or polycarbonate for protection and stability.

The production and purification of silicon is a very high-temperature and energy-intensive process. Additionally, as the next manufacturing step, mechanical slicing of the ingot or cast block, results in an immense waste of raw material, a number of alternative processes to pull multi-crystalline silicon ribbon cells from the molten silicon were suggested and researched: most prominently the EFG (Edge defined Film-fed Growth) ribbon crystalline growth process already developed in the early 1970s,[61] the String Ribbon process,[62] or the RGS (Ribbon Growth on Substrate) process.[63] However, none of these alternative processes has succeeded in outpacing the efficiency increases and price reductions of the standard processes.

But crystalline silicon, the so called 'first generation' of solar cells, is not the only semiconductor in use today. In fact, it doesn't absorb light very well due to its indirect band gap (1.12 eV @ 300 K) and requires a certain cell thickness of a few hundred micrometres or additional measures to increase efficiency. Coupled with the energy-intensive process of crystallisation and wasteful mechanical processing steps, it inheres some serious disadvantages. To overcome these disadvantages and fuelled by the promise of huge cost saving potentials was the driving force behind the search for alternative semiconductors.

2.3.2 Thin-film PV

The so called 'second generation' or thin-film semiconductors are made of direct band gap materials, which absorb light much more efficiently. As such, a very thin layer, often less than a micrometre of the photo-active material is sufficient. The most common thin-film semicon-

60 Even though the term poly-crystalline is widely used in the literature, according to the 'Würz Energy Glossary : Multi-crystalline solar cell' (undated) this is questionable: *"Actually, the description "poly" in connection with silicon crystals is wrong: "Poly" really means "many of the same", but these solar cells are made up of differently sized crystallites. "Multi" means "many and varied" and this – as described above – is the case with solar cells. The manufacturers nevertheless usually write "polycrystalline" and even renowned scientists use this term."*

61 Ciszek (1972)

62 Hanoka (2001)

63 Lange and Schwirtlich (1990)

ductors in use today are amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium (gallium) (di)selenide (CIS/CIGS), gallium arsenide (GaAs), dye-sensitised solar cells (DSC), and organic photovoltaic (OPV). As only a very thin layer of the photo-active semiconductor is required, a totally different manufacturing process is necessary. Whereas the production of modules made of crystalline silicon cells is split into cell production and module production, in the case of thin-film PV it often is an in-line multi-process. Nanometre thin layers of the photoactive material and the electrically conductive transparent layers are deposited in subsequent steps onto a glass or film substrate or superstrate. The resulting thin-film sheet or submodule, often similar to the final module, consists of monolithic series-interconnected cells.

With crystalline silicon the cell size is predetermined by the established methods of fabricating silicon slices, which require the adaptation of the later following solar cell processing steps, like the application of a fine front side finger grid and bus bars for electron transport. In the case of thin-film the cell size is less predetermined. Large-area deposition of the photoactive and conductive material depending only on the size of the sub-/superstrate and the manufacturing equipment, with intermediate and subsequent laser ablating or mechanical scribing for cell isolation, allows to choose a more ideal cell size, which is often in the range of 1 cm wide and a manufacturer dependent length up to the full width of the sub-/superstrate.

2.3.2.1 Amorphous Silicon (a-Si)

Amorphous silicon (a-Si), and hydrogenated amorphous silicon (a-Si:H), is the non-crystalline 'second generation' relative of the 'first generation' crystalline silicon. It has a more favourable band gap (1.7 eV @ 300 K) and thus a much higher light absorption coefficient than crystalline silicon. The fabrication of the first amorphous silicon p-i-n-junction solar cell with a conversion efficiency of 1.1% was reported by David E. Carlson and Christopher R. Wronski of RCA Laboratories in 1976.[64]

Unfortunately, even today after many years of research the efficiency of lab-cells is just above 10% for a-Si and even with triple-junction amorphous and nano-crystalline silicon (a-Si/nc-Si/nc-Si) thin film cells it stands at 12.4%, both values way below the efficiency of crystalline silicon cells and modules.[65] However, the biggest competitors arise among other thin-film technologies with similar product characteristics, but higher efficiencies and/or lower production costs.

[64] Carlson and Wronski (1976)
[65] Green et al. (2011) pp. 566-567

2.3.2.2 Cadmium Telluride (CdTe)

Cadmium telluride (CdTe) has an almost ideal band gap of 1.44 eV (@300 K, direct) which made it a preferred candidate for research already in the 1950s.[66] However, in contrast to the abundantly available and non-toxic silicon, cadmium (Cd) and tellurium (Te) are both toxic, which has raised discussions on the wide spread use in solar panels. Furthermore, tellurium is one of the rarest elements on Earth, which raises questions of the security of its future supply. To form the p-n-junction, a very thin layer of cadmium sulphide (CdS) is added on top of the cadmium telluride layer. Despite all the draw-backs in terms of the use of toxic and rare materials, CdTe-based PV modules have become the commercially most successful thin-film PV technology on the market, mainly driven by the rise and success of the American company First Solar.[67] First Solar is not only one of the largest PV cell and solar module manufacturers in the world today, but also the only thin-film company in the top ten list of solar module producers.[68] CdTe lab cells have achieved efficiencies of more than 16%.[69] Despite the recent success of CdTe, built examples were not found within the corpus of LTPV projects.

2.3.2.3 Copper Indium (Gallium) (di)Selenide (CIS / CIGS)

Copper indium (gallium) (di)selenide (CIS / CIGS, or more precisely $CuIn_xGa_{(1-x)}Se_2$) has set the efficiency benchmark at around 20% for a low-cost thin-film technology to date.[70] Even though it has been researched at least since the 1970s, its importance as a commercially available PV technology has grown only recently, mainly due to high efficiencies, the use of non-toxic materials, at the promise of low manufacturing costs. To form the p-n-junction, a thin cadmium sulphide (CdS) layer is often applied, but cadmium-free CIGS cells with lower efficiencies are available as well.

2.3.2.4 Gallium Arsenide (GaAs)

Gallium arsenide (GaAs) has also an almost ideal band gap of 1.43 eV (@300 K, direct) and the first cells were progressively developed in the 1960s, as their better temperature stability and stronger resistance to radiation when compared to the initially used silicon cells increases

[66] Jenny and Bube (1954)

[67] The success of First Solar makes it a well presented case, however, that CdTe technology is not an automatically successful business strategy is best illustrated by the failure of BP Solar's CdTe activities named 'Apollo', that started with R&D in 1986 but were eventually abandoned in 2002. Manufacturing facility at that time was the former **APS Fairfield factory** - see Appendix C: tf1 - bought by BP Solar in 1996. Also in 2002 BP Solar abandoned it's a-Si 'Millenia' activities after an even longer period that started in 1977. For more information on both activities see Braun and Skinner (2007).

[68] Jäger-Waldau (2011) p. 26

[69] Green et al. (2011) p. 566

[70] Green et al. (2011) pp. 566-567

their longevity in the harsh environment of space application.[71] GaAs is one of the most efficient single-junction PV semiconductors to date with a record efficiency of more than 28%,[72] very close to the theoretical limit on the maximum possible efficiency of single-junction solar cells, the Shockley-Queisser limit.[73] By stacking single-junction cells with different band gaps, the efficiency can be raised above this limit, and the first heterojunction cells (AlGaAs/GaAs) were developed by a Russian team at the A.F. Ioffe Physico-Technical Institute led by Zhores I. Alferov in 1970.[74] According to Andreev, in 1986 such a solar array of 70 m^2 was used to power the Russian space station MIR.[75] But GaAs based semiconductors are not only developed for space application. They are ideal for concentrator applications on earth due to their relative insensitivity to heat. However, the high efficiency comes with a very high cost, seen less appropriate for standard BIPV installations. Due to its arsenic content GaAs is classified as a toxic and carcinogenic material. Built examples were not found within the corpus of LTPV projects.

2.3.2.5 Dye-sensitised solar cells (DSC)

The dye-sensitised solar cell was developed by Michael Grätzel and Brian O'Regan at the EPFL Lausanne in 1991.[76] DSC, also called photoelectrochemical (PEC) or Grätzel cells, absorb light in organic dye molecules that are coated on top and adsorbed into an optically transparent, porous film of titanium dioxide (TiO_2). DSC are hybrid organic/inorganic solar cells. Efficiencies of around 11% are achieved,[77] but major challenges to a wide-spread application are leakage and encapsulation problems caused by liquid electrolytes,[78] long term cell stability,[79] and upscaling issues significant for industrialised fabrication on the module level.[80] The company that has promoted industrialised fabrication the most to date is the Australian company Dyesol, that installed some of their products in BIPV showcase applications: at the temporary **Houses of the Future - Timber House** - see Appendix C: tf8 - and a test installation at the **CSIRO Energy Centre** - see Appendix C: cstf6. A further test installation is

71 Andreev (2003) p.354
72 Green et al. (2011) p. 566
73 The energy conversion efficiency is fundamentally limited by thermodynamics and depending on sunlight concentration between 31% and 41% for single-junction solar cells, see Shockley and Queisser (1961).
74 Alferov et al (1971)
75 Andreev (2003) p.354
76 O'Regan and Grätzel (1991)
77 Green et al. (2011) pp. 566-567
78 A progress review on the electrolytes was reported by Wu et al. (2008)
79 Grätzel (2003)
80 Hinsch et al. (2011) reported the worldwide first fully up-scaled fabrication of a 60x100 cm^2 module prototype.

the **Toyota Dream House 'PAPI'** - see Appendix B: 746 - with DSC cells made by the Japanese company Aisin Seiki.[81]

2.3.2.6 Organic photovoltaic (OPV)

The development of purely organic or polymer solar cells goes back to the 1950s but received a major push after the breakthrough of Ching W. Tang, published in 1986, who achieved about 1% efficiency.[82] The company recognised as being the leader to date in manufacturing commercially available OPV products is the American company Konarka, who also promotes application of their products for BIPV.[83] A primary large scale application are the **SFMTA Bus Shelters** - see Appendix C: tf15 - of which 300 will be equipped with PV.

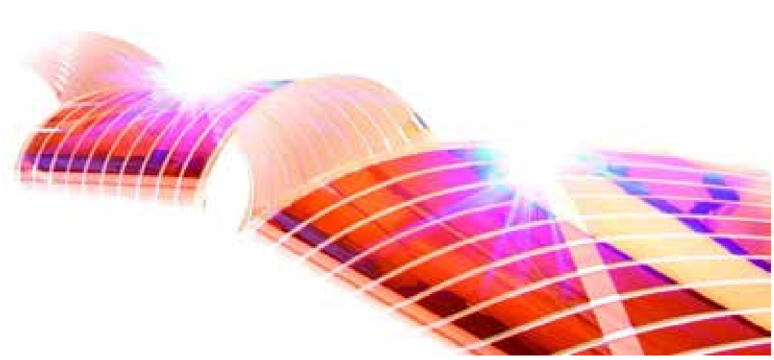


Fig.11: Transparent Konarka Power Plastic®
Credit: © George Disario

2.3.3 Third generation

After the success of the first and second generation of solar technology, the world is eagerly awaiting the emergence of the third generation. In fact, some companies that want to push their emerging technologies into the market, like Dyesol or Konarka, boldly market their products as third generation technologies. Interestingly enough, many of their advertised features, like thin photoactive layers, lightweight products, flexible substrates, as well as easy manufacturing with little material demand at low cost are already features that were promised by the second generation of thin-film technologies. This raises the question, what exactly defines the third generation of solar technology?

According to Martin Green, who coined the generation metaphor, a third generation technology is a high-performance and low-cost technology to fill the gap between the Shockley-Queisser-limit for a single junction cell and the Carnot limit on the conversion of sunlight to

81 Higuchi and Kato (2006)
82 Tang (1986); Spanggaard and Krebs (2004)
83 Konarka Technologies, Inc. <http://www.konarka.com/>

electricity of 95%.[84] Some of these 'third generation' high-performance approaches, like tandem cells, multi-junction cells, hot carrier cells, or multiband cells, are described and analysed in detail by Green,[85] and Brown and Wu.[86] Multi-junction cells are the technology leaders in terms of achieving maximum efficiencies, and the record stands at 43.5% under 418 suns concentration achieved by a 0.3124 cm^2 triple-junction cell (GaInP/GaAs/GaInNAs) in March 2011.[87] Such lab cells are extremely expensive, however, multi-junction technology has been applied at the consumer market level as well. Double- or triple-junction amorphous silicon cells produced by different manufacturers are more and more entering the market, however, the efficiency increases might be significant when compared to single-junction amorphous silicon cells, but are still in the range of 12~13% at most.

The challenge in the development of third generation solar technology continues to be the challenge to fulfil both promises, high-performance AND low-cost at the same time.

2.3.4 Comparison of best lab efficiencies

The following - Tab.3 - lists the highest conversion efficiencies of laboratory test cells according to Green et al.[88] As such cells are not commercially available, a comparison like this has only informative character, but it shows the potential of each technology. Efficiencies of commercially available modules are generally about 10-30% lower.

Tab.3: Confirmed terrestrial cell and submodule efficiencies
measured under the global AM1.5 spectrum (1000W/m^2) at 25°C
Source: Green et al. (2011) p.566

technology	efficiency
monocrystalline silicon	25.0 %
multicrystalline silicon	20.4 %
a-Si	10.1 %
a-Si/nc-Si (heterojunction)	cell: 11.9 % / submodule: 11.7 %
a-Si/nc-Si/nc-Si (triplejunction)	12.4 %
CdTe	cell: 16.7 %
CIGS	cell: 19.6 % / submodule: 16.7 %
GaAs (thin-film)	28.1 %
GaAs (multicrystalline)	18.4 %
GaInP/GaAs/Ge (multijunction)	32.0 %
DSC	cell: 10.9 % / submodule: 9.9 %
OPV	cell: 8.3 % / submodule: 3.5 %

84 Green (2001b)
85 Green (2003)
86 Brown and Wu (2009)
87 Green et al. (2011) p.568
88 Ibid. p.566

2.4 Characteristics of crystalline silicon PV

2.4.1 Shape

Crystalline silicon cells are standardised and independent of the manufacturer usually round, pseudo-square with rounded edges, or square - Fig.12. Round cells and pseudo-square cells are from monocrystalline silicon. The round shape is a feature of the ingot and the crystal growth process by pulling and rotating. For pseudo-square cells the ingot gets trimmed on four sides before it is sawn into slices. Square cells are mainly multicrystalline cells, where the molten silicon is cast in blocks, but are produced from monocrystalline silicon as well. In the case of multicrystalline ribbon cells, either full-size square shapes,[89] but also half-size rectangular shapes are available.[90] Round cells were common in the early days of PV. 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. Apart from these standard shapes, other shapes were proposed in the literature and are sometimes even manufactured and used in opaque modules. Before describing a number of different approaches it must be noted, that the use of such 'alternatively-shaped' cells in light-transmissive PV applications was not found within the corpus of built examples, except the few design proposals that are described in this section.

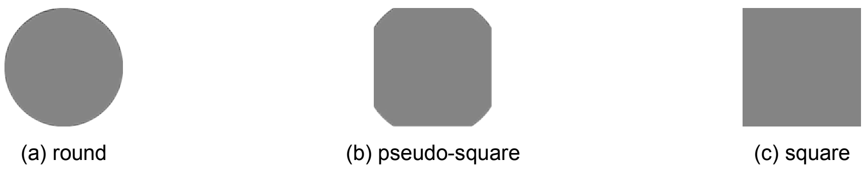


Fig.12: Shapes of crystalline silicon cells

Hexagonal shapes can be cut from round ingots more efficiently, reducing the waste of material while increasing module packing ratio when compared to round or pseudo-square cells. Examples are Sensor Technology's Sensagon cell from 1977[91] and Sanyo's HD (Honeycomb Design) cells and modules produced since 2009.[92] But not only higher material or packing efficiency are starting points for alternative shapes. Combining high efficiency cells with enhanced visual appearance were the two objectives for the 1997-1999 international research project **BIMODE (Bi-functional modules)**.[93] The outcome were proposals for triangular and

[89] 'Datasheet SCHOTT Solar EFG-Solar Cell 125 mm x 125 mm' (2005)
[90] 'Datasheet evergreensolar ES-E Series' (2011)
[91] Jones and Chitre (1977)
[92] Sanyo Electric Co., Ltd. (2009a); 'Datasheet Sanyo HIT-H250E01' (2010)
[93] Tölle and Bruton (1999); Schneider (2002)

hexagonal cells and modules, as well as simulations of architectural integration, most prominent Jürgen Claus and Jörg Paul Janka's design proposal for Gottfried Böhm's St. Gertrude Church from 1966 and Bruno Taut's glass pavilion from 1914.[94] Cueva and Markvart proposed triangular light-transmissive BIPV modules with triangular cells.[95] But how to manufacture triangular cells? Most easily is to cut round, square or hexagonal full-size cells diagonally into two half-size, four quarter-size[96] or even more equally sized smaller pieces. Hagemann did a graphical analysis of the variety of industrially manufactured opaque modules with cut cells.[97] However, these are niche products.

2.4.2 Size

Crystalline silicon cells today have a standard side length or diameter of 100~103 mm, 125 mm or 150~156 mm, equal to the industry standard of 4, 5 or 6 inches - Fig.13, but can be cut into smaller pieces as described above. Less common are cells with a side length or diameter of 114 mm[98] or 135 mm[99] or other dimensions. Smaller round cells of 1, 2 or 3 inches were used in the pioneering years of PV and in the early installations on solar electric buildings, see 3.2 Solar electricity and buildings, part I - the pioneering years for some examples.

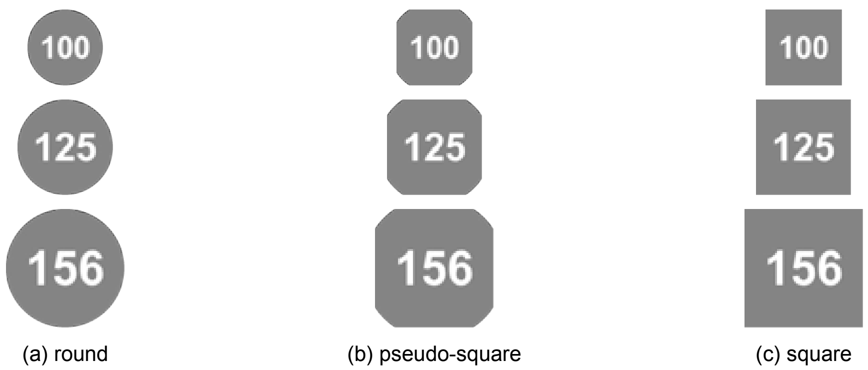


Fig.13: Sizes of crystalline silicon cells, scale 1:100

The exact size and shape of monocrystalline pseudo-square cells depends not only on the cutting width, but also on the diameter of the ingot, resulting in more or less pronounced

[94] Claus (2001); 'Solarkunst - Realisierungen' (undated)
[95] 'Announcement - Results of the Design Competition: Photovoltaic Products for the Built Environment' (2000) p.2; Markvart and Castañer (2003) p.740
[96] 'Datasheet PowerQuant PQ-2xx-PS2' (2010)
[97] Hagemann (2002) pp. 189-198
[98] According to the 'BP Solar : History' (undated): *"Solarex introduces the "Mega" cell: 114 mm x 114 mm in 1987."*
[99] 'Datasheet Webel Solar W 1600 Series' (undated)

rounded corners. Common sizes are Ø 125, Ø 135 or Ø 144 mm for a 100x100 mm pseudo-square cell, Ø 150 or Ø 165 mm for a 125x125 mm pseudo-square cell, and Ø 195 or Ø 210 mm for a 156x156 mm pseudo-square cell. If the diameter of the ingot is the same or near the diagonal length of a square, e.g. a Ø 220 mm ingot for a 156x156 mm cell,[100] than the shape of the monocrystalline silicon cell is almost square. The advantage is a higher achievable module efficiency for opaque modules due to less redundant areas, but it also results in a lot of material loss after trimming and is therefore rarely done.

2.4.3 Front and back side colour and pattern

A typical feature of crystalline silicon cells has been a shiny blueish front side and matt grey rear side. The blueish colour results from texturing the surface and applying a coating to reduce the reflection of light. The more light is 'trapped' and not reflected, the better will be the efficiency of the solar cell. Silicon itself has a silver colour, but with an anti-reflective coating, this changes to blue or even black and increases efficiency by around 30% relative.[101] In terms of minimising reflection losses, a colour close to black is desired, as almost all light will be trapped and hardly any reflected. Blue or dark-blue was the highest achievable for a long time with only little light reflected, but has been improved to 'truly' black cells available today. Cells in other colours, like greyish, reddish, greenish, brownish or yellowish, can be achieved by adjusting the thickness of the anti-reflective coating. Such colour cells are offered by some manufacturers, like Sunways, Gintech and Lof Solar - Fig.14.[102]

Decreases in efficiency are in the range of 1~2 % absolute for most of the colours,[103] but can be as high as 6% absolute in the case of a highly reflective silver cell, which illustrates the effectiveness of the anti-reflective coating in a standard blue, dark-blue or black cell. However, an embedding gain, resulting from light-trapping in the front side glass or film, is often expected for such highly reflective cells.[104]

[100] 'Datasheet Q-Cells Q6LMXP3' (2011)

[101] When comparing Sunways 'Silver' cell - Fig.14(c) - with the same manufacturers standard cell - Fig.14(a). A difference of 6% absolut equals 32~39% relative efficiency.

[102] The efficiency ranges are taken from the manufacturers' datasheets and catalogues. For further information see 'Datasheet Sunways Solar Cells Multi 156 (CA50-L)' (2011), 'Datasheet Sunways Solar Cells multicrystalline 156, coloured, 3 busbar' (2009), 'Datasheet GINTECH GIN156M 6"Multicrystalline Silicon Solar Cell Phoenix Series' (2011) and 'High Efficiency Color PV Expert' (2010) pp.7-8.

[103] A comparable dark blue solar cell by Gintech Energy Corporation, see 'Douro Series' (2011), has an efficiency range of 15.6~17.6 % or 1~2 % absolut higher efficiency than the colour cells of the same manufacturer.

[104] 'Datasheet Sunways Solar Cells multicrystalline 156, coloured, 3 busbar' (2009) p.2

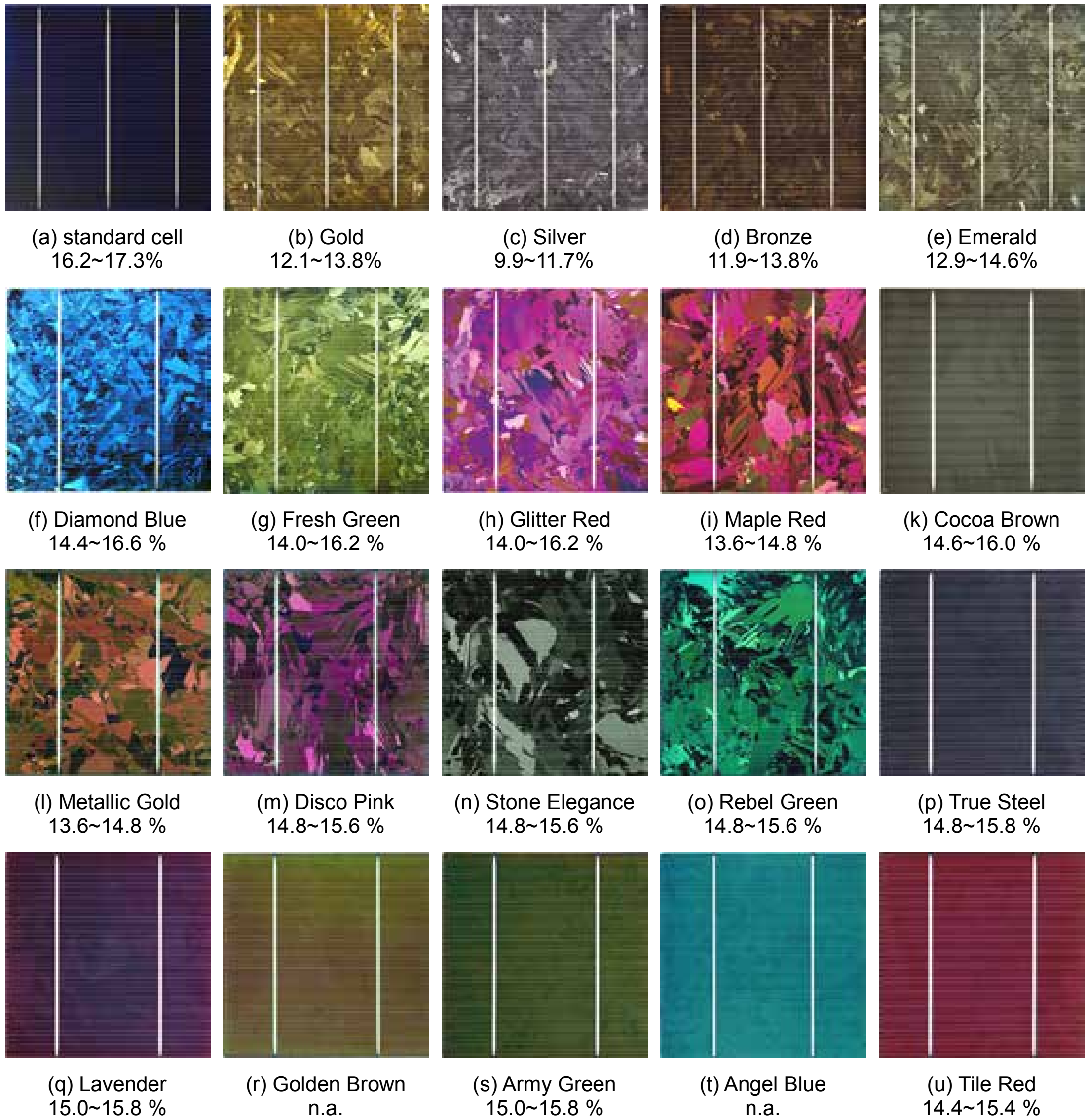


Fig.14 (a) to (t): Colour variations of mc-Si cells and efficiency range
(a) to (e) Credit: © SUNWAYS
(f) to (k) 'Phoenix Series', Credit: © GINTECH
(l) to (o) 'Marble Series', Credit: © LOF SOLAR
(p) to (u) 'Classic Series', Credit: © LOF SOLAR

Even multi-coloured cells, the combination of two or more colours on one cell, and engravings are possible - Fig.15.[105]

[105] 'High Efficiency Color PV Expert' (2010) p.13; 'Color Design Solar Cell' (undated); SoonEnergy Inc. (2011)

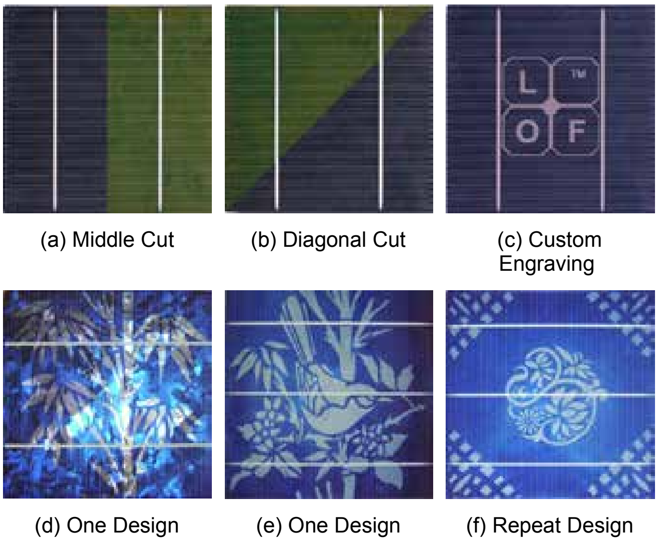


Fig.15 (a) to (f): Custom design solar cells
(a) to (c) Credit: © LOF SOLAR
(d) to (f) Credit: © SOONENERGY

The colour of the **rear side** - Fig.16(b) - is usually a matt grey, an aluminium back-surface field (BSF). In contrast to the sun-exposed front side, the rear is in shadow and not intended to collect any sunlight. The purpose of the BSF is to efficiently collect free charge carriers and to reflect any light that passed through the cell back into the silicon. Therefore a layer of aluminium paste is applied to the rear by either screen printing or evaporation and sintered into the silicon.

On the **front side**, however, such a full area contact is less desirable, as sun-light must reach the silicon. A fine grid of 0.1 mm or less thin and about 3 mm spaced metal contact fingers is applied to collect free charge carriers, and perpendicular, 2 mm wide and linear busbars carry them to the next cell. This is the most common pattern with two, three or even four parallel busbars and known as **H-pattern** - Fig.16(a). Problems with this kind of patterns arise from two sides, one is efficiency and the other aesthetics.

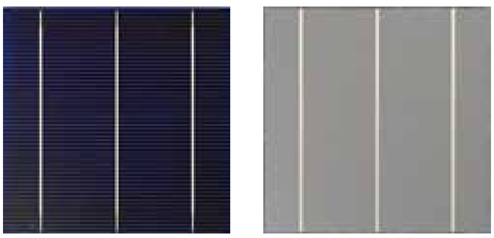


Fig.16 (a) and (b): front and rear side of an H-pattern cell with 3 bus bars
Credit: © SUNWAYS

Let's elaborate on the latter first. The reflectivity and pattern of the finger-grid, and even more of the thick busbars can be seen as disturbing for building integration. An easy countermeasure is to 'darken' the fingers and bus bars. Radike and Summhammer, however, suggested alternative and more artistic front contact patterns in 'X', 'L', 'T', 'U', 'Sinus', 'Braid', 'Ellipse', 'Delhi', 'Drops', 'Crack', 'Fissure', 'Vhex' or 'Art-Deco' shape - Fig.17.[106] Some calculated reductions in efficiency of 0.71% absolute for the 'worst' pattern in comparison to an H-pattern standard cell were reported. A novelty in their approach is the consideration of combinatorial variety of differently front-contacted cells on the module level of 4x8 or 6x11 cells - Fig.18. Resulting from the research are diagonally patterned 'Diagon' cells and commercially available individually patterned modules - Fig.19.[107]

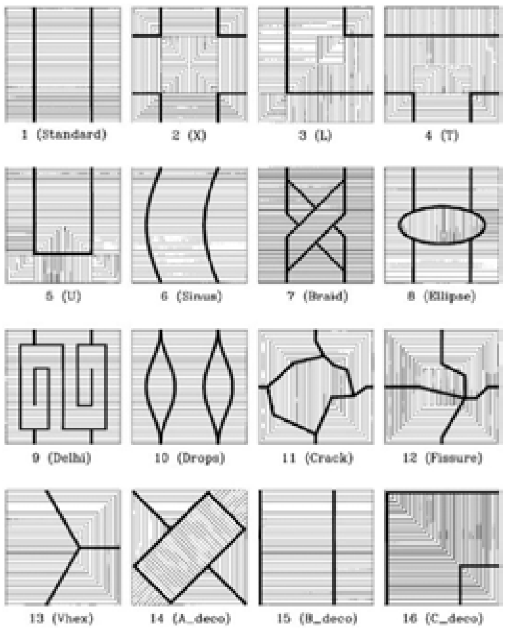


Fig.17: Radike and Summhammer (1999)'s alternative front metallisation patterns
Credit: © John Wiley & Sons, Ltd.

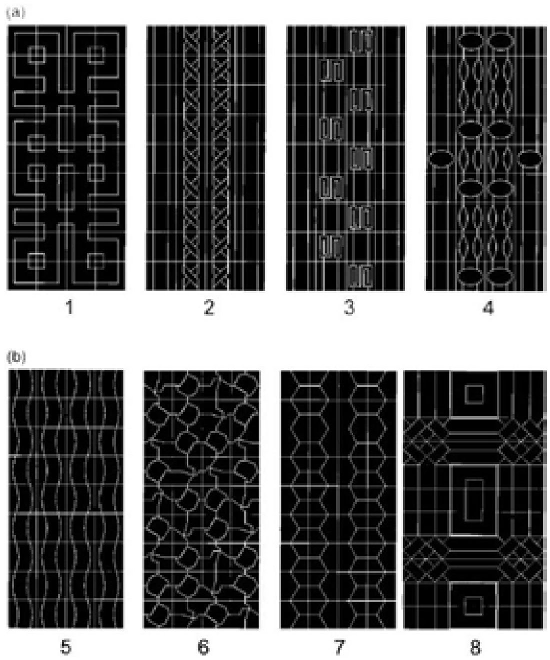


Fig.18: Radike and Summhammer (1999)'s examples of modules
Credit: © John Wiley & Sons, Ltd.

Fig.19 (a): 'Diagon' cell; (b), (c) and (d): Modules using 'Diagon' cells
Credit: © PowerQuant Photovoltaik GmbH

[106] Radike and Summhammer (1999)

[107] As interesting as these cells are, built examples in LTPV application don't exist yet, as confirmed by Johann Summhammer, one of the researchers and owner of the company PowerQuant, that offers opaque modules with 'Diagon' cells - personal communication, October, 15, 2011. However, opaque modules are available, see 'Datasheet PowerQuant PQ-120D' (undated).

The other problem, a loss in efficiency, is inherent to the H-pattern. To maximise free charge carrier transport, a dense finger and busbar grid would be desirable. However, each finger and even more each busbar is a 'shaded' area and does not contribute to the generation of electricity. To maximise the sun-exposed area would require the removal of the front contacts. As these two opposing requirements strongly collide, a fine adjustment to balance them is essential. A lot of research has been directed into this area, resulting in innovative, applied approaches like buried contacts with ultra-thin finger lines,[108] or novel research approaches like front contacts along multicrystalline grain lines.[109]

A fundamentally different approach are back contact cells, where the front contacts are moved to the back side of the cell resulting in both positive and negative contacts to be on the same side. This has a double advantage killing two birds with one stone. Shading losses are reduced even further resulting in higher cell efficiencies, and co-planar interconnection allows for a closer cell spacing ideal for opaque modules and easier manufacturing. An aesthetically desired side effect is either the complete absence of any finger grid on the front side as in the case of the interdigitated back-contact (IBC) or back-junction (BJ) solar cell, or interesting new front side patterns with the emitter wrap-through (EWT) solar cell and contact wrap-through or metallisation wrap-through (MWT) solar cell.[110]

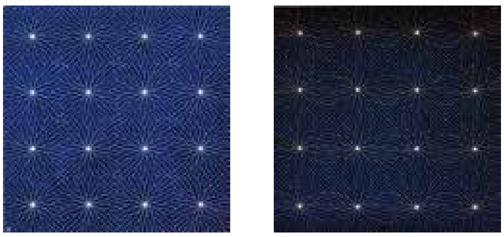


Fig.20 (a) and (b): Sunweb MWT cells
Credit: © Solland Solar

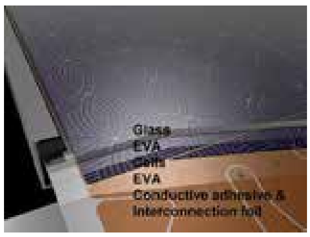


Fig.21: ECN MWT cell
Credit: © ECN

2.4.4 Special cells

Beside the standard cells, some manufacturers produce special cells like 'semi-transparent' crystalline silicon cells - Fig.22,[111] or bifacial cells with two photoactive sides, or proprietary HIT (Heterojunction with Intrinsic Thin layer) cells[112] - simply said a hybrid of a monocrys-

[108] Whereas the finger-grid 'lies' horizontally on the standard cell, it is vertically 'sunken' into a buried contact solar cell (BCSC), invented by Wenham and Green (1988) at the University of New South Wales, Australia.
[109] Ebner et al. (2003)
[110] Smith and Gee (2000); Van Kerschaver and Beaucarne (2006)
[111] see also 2.2.7 Translucency and transparency - 'light-through' and 'see-through'
[112] 'SANYO HIT Technology' (undated)

talline silicon cell coated with thin layers of amorphous silicon, or tiny spherical cells with a diameter of 1 mm each - Fig.23.[113]

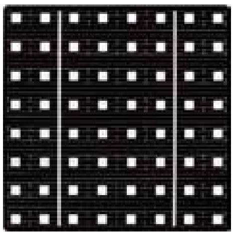


Fig.22: Sunways' semi-transparent cell
Credit: © SUNWAYS

Fig.23: Clean Venture 21's spherical cells
Credit: © Robert Baum

2.5 Characteristics of thin-film PV

2.5.1 Size

As mentioned before, even though thin-film cells are generally much smaller, monolithic 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 large dimensions of e.g. 2.4 x 2.6 m^2 for a-Si as manufactured by Signet Solar[114] or CIGS as manufactured by Würth Solar.[115] However, the available sizes strongly depend on the specification of each manufacturer's production line. Large sizes may have an advantage in processing speed, but have a great disadvantage in terms of handling and ultimately application variability. Similar to crystalline silicon PV, smaller thin-film sheets can be and often are combined in larger size PV laminates.

2.5.2 Colour

The front side colour of thin-film sheets from amorphous silicon tends to be reddish or brownish, more intense in the early days of TF - see Fig.39(b), but darker nowadays, whereas CIGS or CdTe sheets are blueish, greenish or greyish black. With DSC and OPV a wide range of colours, even multi-colours are possible. A colour-neutral dye isn't in sight yet, which means that any light falling through such a solar panel or any view will be like looking through coloured sunglasses. According to Grätzel, a ruthenium and iodine based red dye showed *"the best photovoltaic performance both in terms of conversion yield and long-term stability".*[116] As such, most DSC/OPV based products use a red dye, as can be seen at the **House of the Future - Timber House** - Appendix C: tf8. However, this might change, as a

[113] For more information see website of Clean Venture 21 Corp. <http://www.cv21.co.jp/en/index.php>
[114] 'Data sheet signet solar Thin film solar module' (undated)
[115] 'Architecture live: GeneCIS modules integrated into building architecture' (2009)
[116] Grätzel (2003) p.148

group under the leadership of Grätzel has just recently found a better performing porphyrin and cobalt based green dye.[117]

To illustrate the design potential of DSC, Sony has produced a highly sophisticated prototype, a solar powered lantern called 'Hana-Akari' or 'Flower-Light'[118] with opaque and semi-transparent areas in the most common dye colours red, orange, yellow and green.

Fig.24 (a) and (b): Sony's 'Hana-Akari lantern
Credit: © Robert Baum

In contrast to the obvious metallic grid on the front side of CS cells, with TF it is usually a full area transparent collector, TCO or Transparent Conductive Oxide. The back side colour depends on the colour of the back contact layer. When a transparent conductive layer is used, front and back of the TF sheet are similar in colour. Non-transparent layers are for instance silver in colour and semi-transparently patterned.

Even though speaking most of the time of a unicolour of the solar cells, it must be noted that the colour impression of any kind of PV can be quite changeable, depending on the intensity of the sunlight but also on the encapsulating material. About a BIPV installation at **Toyota's Dream House 'PAPI'** - Appendix B: 746, Higuchi and Kato wrote: *"On sunny days, the DSC panels have a magenta granitic or marbled appearance, whereas on cloudy days they take on a dark raspberry color and fade into the background, so that the outer glass shields clearly reflect the scenery of the surrounding garden".*[119]

2.5.3 Light-transmission

Similar to CS there are different ways to achieve light-transmission with TF too. As in the case of amorphous-silicon or CIGS, the structuring of the semiconducting layer into linear and parallel cells usually by laser scribing, and the use of TCO as transparent collector allows

[117] Guérin (2011); Yella et al. (2011)
[118] Sony Corporation (2009)
[119] Higuchi and Kato (2006)

light to pass through these tiny gaps between the cells. By simply altering the width of these gaps, the light-transmission rate can be adjusted. As the size of the cells is much smaller than with CS, usually in the range of 1~3 cm, resulting in a homogeneous small scale zebra effect, the light can pass much more uniformly through a TF sheet. Examples are the **SCHOTT Ibérica** in Sant Adrià de Besòs, Barcelona, Spain - Appendix C: tf12[120] - and the **BP-Solar Harmony Gas Station** in Paris, France - Appendix C: tf5.

Fig.25: SCHOTT Ibérica
Credit: © CISOL

Fig.26: BP-Solar Harmony Gas Station
Credit: © Warren Gretz - DOE/NREL

A different approach than widened scribing lines, that initially was called 'see-through' - see also 2.2.7 Translucency and transparency - 'light-through' and 'see-through' - achieved transmission of light by patterning the TF layer with microscopic holes in regular intervals, that yields an even more uniform transparency. With both methods virtually any percentage for light-transmission is possible. The finer the light-transmitting pattern and the higher the percentage, the more the thin-film PV will be similar to the appearance of tinted 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",*[121] which of course applies to crystalline silicon PV as well. However, similar to a tinted car window, appearance and visibility changes dramatically from inside to outside, or more generally from the dark side to the bright side, as can be seen at the two images of the Kulturhaus Milbertshofen - see Fig.27 and Appendix C: tf9.

[120] The yellow colour on the photograph is a feature of the glass, not the PV itself.
[121] 'Glossary of Words: Visible Light Transmission (VLT)' (undated)

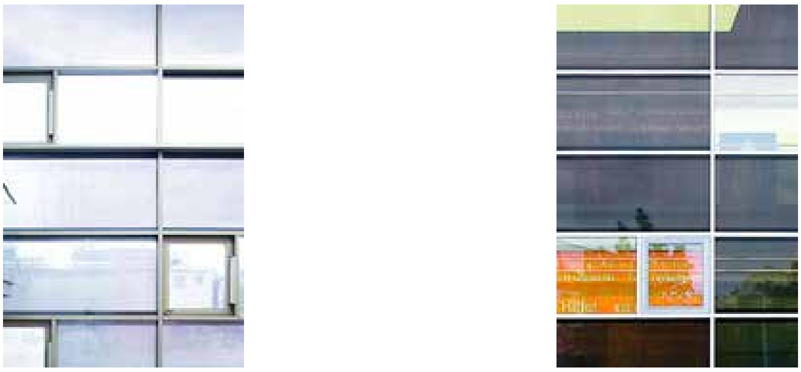


Fig.27: Kulturhaus Milbertshofen - (a) inside and (b) outside
Credit: © Arnold Glas, Remshalden

In contrast to the patterning approaches, in the case of DSC and OPV, the photoactive dye itself can be translucent as an inherent feature of the technology.[122] Here it is interesting to note, that in contrast to a-Si, CIGS and CdTe, where the TF sheets have a very homogeneous appearance due to the small-scale cellular structure, DSC and OPV products so far have a clearly recognisable cell structure and thus appear patterned rather than homogeneous.

Fig.28: Konarka Power Plastic®
Credit: © George Disario

2.6 Energy balance

2.6.1 Energy payback time – EPBT

A metric often used to evaluate the energy balance and sustainability of different technologies is the energy payback time (EPBT). It gives the time necessary to recover the energy that was used to produce the energy generator. According to Randolph and Masters[123] EPBT is calculated by:

[122] Takeda et al. (2009)
[123] Randolph and Masters (2008) p.175

$$EPBT = \frac{E_{iot}}{E_o} \quad (1)$$

with E_{iot} the indirect one-time energy input to produce and install the generating system, and E_o the annual energy output. E_{iot} can be calculated by:

$$E_{iot} = E_{Mod} + E_{Bos} + E_{Tran} + E_{Dis} \quad (2)$$

with E_{Mod} the embedded energy to produce the PV module, E_{Bos} the embedded energy of the electrical and mechanical BOS components - see 2.2.6 Solar cell, string or sheet, laminate, panel or module, array, system for explanation, E_{Tran} the energy required for transportation to site and installation and E_{Dis} the energy needed for end-of-life disposal. Some recent EPBT in the literature, all for standard, opaque modules, are summarised in Tab.4.

Tab.4: EPBT

Notes: PR – Performance Ratio
(accounting for losses due to shading, snow cover, heat loss and DC-AC conversion);
1) European production, 2) U.S. Production, 3) framed module, 4) frameless module, 5) pre-pilot stage, 6) mechanical BOS only, 7) lowest value for South at tilt 30° and highest for West at tilt 90° installation

authors	technology	included	PR	insolation [kWh/(m2 yr)]	EPBT
Alsema and de Wild-Scholten (2005)	ribbon Si 1)	E_{Mod} 3), E_{Bos}	0.75	1700	1.7 yr
Alsema and de Wild-Scholten (2005)	multi-Si 1)	E_{Mod} 3), E_{Bos}	0.75	1700	2.2 yr
Alsema and de Wild-Scholten (2005)	mono-Si 1)	E_{Mod} 3), E_{Bos}	0.75	1700	2.7 yr
Knapp and Jester (2001)	mono-Si 2)	E_{Mod} 3)	0.80	1700	4.1 yr
Knapp and Jester (2001)	CIS 2)	E_{Mod} 3)	0.80	1700	12.1 yr 5)
Knapp and Jester (2001)	CIS 2)	E_{Mod} 3)	0.80	1700	2.2 yr
Fthenakis and Alsema (2006)	multi-Si 1)	E_{Mod} 3), E_{Bos}	0.75	1700	2.2 yr
Fthenakis and Alsema (2006)	CdTe 1)	E_{Mod} 3), E_{Bos}	0.75	1700	1.0 yr
Fthenakis and Alsema (2006)	CdTe 2)	E_{Mod} 4), E_{Bos}	0.84	1700	1.1 yr
Battisti and Corrado (2005)	multi-Si 1)	E_{Mod} 3), E_{Bos} 6), E_{Tran}, E_{Dis}	0.80	1530	2.9-3.8 yr
Lu and Yang (2010)	mono-Si	E_{Mod} 3), E_{Bos}, E_{Tran}	n.a.	Hong Kong	7.1-20.0 yr 7)

Alsema and de Wild-Scholten (2005) investigated roof-top installations with different crystalline silicon technologies and found EPBTs of 1.7 to 2.7 years. Knapp and Jester (2001) did an empirical investigation into two manufacturing plants, one for monocrystalline silicon, the other for thin-film CIS and found EBPTs of 4.1 and 2.2 years (12.1 years at pre-pilot stage). Fthenakis and Alsema (2006) summarised their previous studies with EPBTs of 2.2 years for a multicrystalline silicon roof-top installation from European production, 1.0 years for a thin-film CdTe roof-top installation from European production and 1.1 years for a CdTe ground-mount installation of U.S. production. Battisti and Corrado (2005) analysed different roof installations and found EPBTs of 2.9 to 3.8 years for a tilted roof installation, the lower value for integration and the higher value for retrofit. Lu and Yang (2010) modelled BIPV installations in Hong Kong with different directions and tilt angles, and calculated EPBTs from 7.1 to 20.0 years. It is worthwhile to note, that most of the EPBT studies are considering building related PV installations, and that most studies reveal an EPBT about one magnitude below an expected lifespan of 25-30 years. Even the most unfavourable case in the study of Lu and Yang (2010), a West-facing vertical installation still has an EPBT below the expected lifetime.

The most and most detailed studies were conducted about crystalline silicon technologies, with the earliest being Hunt (1976). As he calculated an EPBT for the solar cell only of 11.6 years, it can be said that great improvements have been achieved since then, both in terms of significant energy reductions as well as by extending the system boundaries for the studies.

2.6.1.1 System boundary

However, the question remains, whether the system boundary is set wide enough to truly understand the whole picture, as many studies don't include energies required for transportation to site, installation and disposal. To get a handle on their amount, let's look at the study of Battisti and Corrado (2005). Here 90.9% of the embedded energy is required for multicrystalline silicon PV module production, 5.39% for mechanical BOS, 3.64% for transportation and installation, and 0.0781% for landfill disposal without any material or energy recovering process. This clearly illustrates that most of the energy is required to produce the module and BOS (as only mechanical BOS was included, this part should be slightly higher when electrical BOS is included as well), and little for transportation and disposal. In the case of thin-film PV, that requires less energy for module production, but has lower efficiencies thus requiring a larger area for the same capacity, the percentage shares for BOS, transportation, installation and disposal are higher. However, the gross energy requirement is nevertheless expected to be lower than with crystalline silicon technology.

2.6.1.2 Potential for reduction

That said, there are many areas where energy reductions for production of crystalline silicon PV modules can be achieved. The most energy intensive part is processing and purification of the silicon itself, which alone according to Battisti and Corrado (2005) requires up to three quarters of the energy for module production. Most of the silicon feedstock used in the PV industry is scrap from the electronic industry. The use of 'electronic-grade' silicon has been the easiest and most economical way for the supply of the PV industry with silicon. However, as the electronic industry requires very high purities, also the scrap has high values of embedded energy. Less energy intensive processes can be used in the production of 'solar-grade' silicon, but as data wasn't sufficiently available Battista and Corrado took a conservative approach and calculated with 'electronic-grade' silicon. Furthermore, Müller et al. (2006) compared the energy demand for the production of new wafers with wafers made of recycled modules and found, that recycled wafers require only 30% of the energy input for new wafers. Last but not least, technological progress is expected to further reduce wafer thickness from 270-380 microns[124] to far below 200 or even 100 microns and an increase in cell efficiency above 20%.[125] All approaches will contribute significantly in reducing the embodied energy in each individual cell and overall EPBT.

2.6.1.3 Future estimates

The International Energy Agency published an updated technology roadmap for solar photovoltaic energy in 2010, in which they state some estimates of general technology targets, estimating a 50% reduction of the EPBT until 2020 - Tab.5. Targets until 2030 are based on currently available first and second generation technologies, but for the 2050 target of 'typical' module efficiencies above the Shockley-Queisser-limit - see 2.3.3 Third generation, a progress in third generation technologies is anticipated.

Tab.5: General technology target
Source: IEA (2010a) p.23.

Targets (rounded figures)	2008	2020	2030	2050
Typical flat-plate module efficiencies	Up to 16%	Up to 23%	Up to 25%	Up to 40%
Typical maximum system energy pay-back time (in years) in 1500 kWh/kWp regime	2 years	1 year	0.75 year	0.5 year
Operational lifetime	25 years	30 years	35 years	40 years

2.6.2 Embedded energy savings potential with building-integrated PV

In the case of building integration, especially with material integration, i.e. substitution of other building materials, the embedded energy of the substituted façade or roofing materials should be positively included in the energy balance. Furthermore, some parts of PV installations like frame or mechanical BOS, that are included in most of the studies, can be significantly reduced. Frameless modules are often preferred for building integration because of more favourable aesthetics and better integration possibilities with other cladding materials.

124 This range is an assumption in the studies of Alsema and de Wild-Scholten (2005) and Knapp and Jester (2001).
125 Sanyo Electric Co., Ltd. (2009b)

For crystalline silicon modules, a standard aluminium frame contributes about 6% to the module's embedded energy,[126] in the case of thin-film CIS modules the frame contributes 20.4%,[127] a substantial savings potential. If the PV modules are installed using standard curtain walling and roofing systems, a separate supporting structure, the mechanical BOS, isn't required. The avoided embedded energy is ranging from 5.39%[128] to 16.16%.[129] To include such material savings even partially in the calculation can result in a significantly lower EPBT, especially when considering less ideal integration options as in the study by Lu and Yang. Even though the authors of the study were aware of this issue and pointing it out, they didn't make any provision for it. To include material offsets and calculate avoided energy can generally shed a more favourable light on building integration of PV. It must be noted, however, that material savings are more pronounced with glass-based PV and less with film or membrane based PV.

2.6.3 The case of light-transmissive PV

The discussion about energy balance and EPBT requires to look at light-transmissive PV separate from opaque PV.

There are two ways to achieve light-transmission that result in a different energy balance. In the first approach often called 'light-through', single opaque cells are spaced wider, which reduces the number of cells and the embedded energy per squaremetre and raises the percentage share of non-PV module parts like glass and frame. In the other approach often called 'see-through', opaque cells are processed by etching, scribing or drilling holes or groves, thus making the cells themselves semi-transparent. This increases the embedded energy and reduces the efficiency of each cell inversely proportional to the light-transmission ratio. The percentage share of non-PV module parts per square metre is thus reduced.

As the first approach is mainly used for crystalline silicon cells and the second approach mainly for thin-film cells, it can be said, that increasing the light-transmission ratio reduces the EPBT gap between both technologies.

Furthermore, light-transmissive PV panels of both technologies are often employed as shading elements, reducing undesired heat gain, glare and cooling demands of the building. This helps in reducing energy requirements and should be considered as offsets when speaking about EPBT and may once more shed a more favourable light on building integration of

126 Knapp and Jester (2001); Alsema and de Wild-Scholten (2005)
127 Knapp and Jester (2001)
128 Battisti and Corrado (2005)
129 Lu and Yang (2010)

PV, even when installed in less ideal positions like purely East- or West-facing vertical façades.

2.6.4 Comparison - EROI

EPBT has been a very helpful metric in understanding the sustainability of renewable energy generation. To conclude this section, the performance of energy generation from PV is compared to generation from fossil fuel with the help of another metric, the Energy Return on Energy Investment (EROI). According to Randolph and Masters, EROI is calculated by:

$$EROI = \frac{E_o}{E_i} \qquad (3)$$

with E_o the useful energy output, and E_i the indirect input of energy or *"the energy it takes to get energy"*.[130] For energy generation with photovoltaics E_i can be calculated by:

$$E_i = \frac{E_{iot}}{t_s} \qquad (4)$$

with E_{iot} the indirect one-time energy input to produce and install the generating system, and t_s the lifetime of the system, which is set to be 30 years.

For energy generation with photovoltaics EROI can be easily calculated by:

$$EROI_{PV} = \frac{E_o}{E_i} = \frac{t_s\, E_o}{E_{iot}} = \frac{t_s}{EPBT} \qquad (5)$$

With the numbers taken from Knapp and Jester's study (2001), for monocrystalline silicon: EROI = 30/4.1 = 7, and for thin-film CIS: EROI = 30/2.2 = 14.

An informative table with EROI for various energy source and systems can be found in Tab.6.[131] It is interesting to note, that the EROI for non-renewable fossil fuels is steadily declining due to dwindling resources, example U.S. oil and gas production from an EROI of 100 in 1930 down to 20 in 2000, whereas the EROI of renewable energy production is steadily increasing due to reduced energy requirements during manufacturing and extended lifetimes.

130 Randolph and Masters (2008) p.173

131 Please note: different, even contradicting values for similar sources/systems are due to values given in different literature sources, that were compiled in this table by Randolph and Masters.

Tab.6: EROI for Various Energy Sources/Systems
Source: Randolph and Masters (2008) p.175

Source / System	EROI
U.S. oil and gas production, 1930	100
U.S. oil and gas production, 2000	20
U.S. gasoline production	7
U.S. coal production, 1950	100
U.S. coal production, 2000	80
Electricity from hydro with reservoir	205
Electricity from wind	80
Electricity from sawmill wastes	27
Electricity from nuclear	16
Electricity from PV modules	9
Electricity from coal (with CO_2 scrubbers)	5
Electricity from natural gas CC (2000 km del)	5
Electricity from biomass plantation	5
Electricity from fuel cell, H_2 from NG reform	2
PV modules (thin-film CIS)	14
PV modules (crystalline silicon)	7
U.S. ethanol fuel from corn	0.78 ~ 1.67
U.S. ethanol fuel from switchgrass	0.79 ~ 10.3
U.S. biodiesel from soybeans	0.67 ~ 3.20

3 Architecture and PV

3.1 The first decade of solar batteries

3.1.1 Solar batteries for terrestrial test run

As described in a previous section - 2.3.1 Crystalline silicon PV, the development of photovoltaic products started in 1954 with the development of the modern solar cell at the Bell Laboratories. Bell Telephone System, the parent company of the Bell Laboratories, presented their invention of 1954 in advertisements as 'solar batteries', as the chemical battery was one of the very first counterparts for solar cells to challenge. They envisioned solar batteries as the ultimate, almost limitless power supply for any kind of terrestrial use, and tested them in 1955 to power telephone lines in rural areas. As these installations never went beyond the test phase, it was either the technical reliability or the financial viability or in fact both, that didn't speak for this kind of application at the time.[132]

3.1.2 Solar batteries for space application

Research and first viable applications following the 1954 invention coincided with the space race between the cold war superpowers, the Soviet Union and the United States of America. Concerns over national security, as well as symbolic prospects of achieving technological and ideological superiority meant good opportunities for ongoing funding of research into energy technologies vital for the success of space exploration.

On March 17, 1958, Vanguard 1 was launched, the fourth artificial earth-orbiting satellite. It had a radio transmitter powered by chemical batteries on board that stopped sending signals three months later in June 1958. The signals of a second transmitter that operated with a solar battery, however, were received for more than six years until May 1964.[133] On May 15, 1958, the Russian satellite Sputnik 3 was launched. It was equipped with chemical batteries powering instruments for space experiments, that lasted a month. A solar battery powered transmitter, however, sent signals until April 1960, when the satellite re-entered the earth atmosphere and disintegrated.[134]

This was a clear signal for the superior performance and longevity of solar batteries for space application, outperforming their chemical counterparts. Then finally in 1962, the first

[132] Both, visionary advertising posters of Bell Telephone system, as well as a short description of the test application can be found at 'Bell Labs - The Solar Battery (Photovoltaics)' (undated).
[133] 'Vanguard 1, NSSDC ID: 1958-002B' (undated)
[134] Christy (undated); Mitchell (2007)

telephone calls and television pictures were successfully relayed through space with the help of 3600 solar cells body-mounted on Telstar 1, the first communication satellite.[135] What didn't prove financially viable on earth at the time, soon become the standard for telecommunication through space.

3.1.3 First terrestrial applications - relay stations, beacons and buoys

In 1958, three years after commencing solar cell production in 1955, the Japanese company NEC installed a 70 W array of 2.7 m^2 and 4320 tiny round solar cells on Mt. Shinobu[136] in Fukushima prefecture, Japan - Fig.29, to power a wireless relay station operated by Tokyo Electric Power Corp.[137] In 1959 the Japan Coast Guard installed a smaller array of 648 NEC solar cells on the Suo Ikada Se light beacon[138] in Yamaguchi prefecture - Fig.30, and in 1963 a 23 W array of Sharp solar cells on the Tsurumi No.1 light buoy[139] in the bay of Yokohama, and on many more since then.[140]

Fig.29: Mt. Shinobu wireless relay station
Credit: © NEC

Fig.30: Suo Ikada Se light beacon
Credit: © NEC

3.1.4 Solar cells for consumer goods

But solar cells were not only used in remote locations. In fact, as the initial satellite and space market was a rather small one, solar cell manufacturers looked for other commercial outlets. The Japanese company Sharp developed some of the first consumer goods with solar cells: a transistor-radio with PV-cell and battery in 1961,[141] started production of commercially avail-

135 Smith (1991)
136 Japanese: 信夫山無線中継局 [Mt. Shinobu wireless relay station]
137 Kobayashi, Ishikawa and Hayashi (1959); Hilsum (1960)
138 Japanese: 周防筏瀬灯標 [Suo Ikada Se light beacon]
139 Japanese: 鶴見第 1 号灯浮標 [Tsurumi No.1 light buoy]
140 '観音埼に灯台が生まれて１４１年' [141 years since lighthouse was born in Kannonzaki] (2009)
141 'Milestones: Commercialization and Industrialization of Photovoltaic Cells, 1959' (undated)

able PV modules in 1963, and introduced the world's first solar-powered pocket calculator in 1976.[142] The same year the first thin-film cell made of amorphous silicon was reported by Carlson and Wronski from the American RCA Laboratories - see 2.3.2.1 Amorphous silicon (a-Si), but again it was a Japanese company, Sanyo, to be the first in scaling up production for commercially available small-scale amorphous silicon cells in 1980,[143] which paved the road to success for solar-powered calculators. In 1987 the first and inaugural Solar Challenge, a car race through the Australian Outback with solar-powered cars only, took place on a 3021 km transcontinental route from Darwin to Adelaide, and the experimental solar car GM Sunraycer won using high-efficiency GaAs cells.[144] However, the mass-produced consumer car powered by solar cells is still a dream and far away.

3.2 Solar electricity and buildings, part I - the pioneering years

This part is a historical case study of a few buildings and with them clients and designers who pioneered the incorporation of a virgin technological product into their buildings and work. Any kind of selection of buildings as historically 'typical' or even 'most typical' examples may appear subjective. However, the attention is directed at the underlying dualism of questions and possible answers given through coherent or novel design decisions, rather than aiming at discovering the exact primacy of it's occurrence.

3.2.1 Architecture in the mid-sixties to the mid-eighties

Even though the first viable applications were found in space and remote locations, it started roughly a decade after the initial invention and happened within two decades from the mid-sixties to the mid-eighties, that the space product 'solar battery' made its entry into the earthly realm of buildings, and thus into the task area of architects and architectural historians. Timewise it is interesting to see, what the accompanying streams in the discourse of architecture and architectural history were.

Noteworthy surely are the theoretical works: the publishing of *Complexity and Contradiction in Architecture* by Robert Venturi in 1966 and *The Architecture of the Well-tempered Environment* by Reyner Banham in 1969; as well as bold urban visions like two 1964 Archigram projects: *Plug-in-City* by Peter Cook and *The Walking City* by Ron Herron, inspired by the visions of the 1960s Metabolist movement in Japan.

142 The Sharp EL-8026 was powered by rechargeable batteries, that could be charged in bright sunlight with solar cells. However, they were mounted on the back side of the calculator. According to Woerner (2001), this disqualifies it as the first solar-powered calculator, an opinion which is not shared in this study.

143 Sanyo Electric Co., Ltd. <http://solar.sanyo.com/>

144 'Gallium Arsenide Solar Cells' (undated)

In 1972 the Nakagin Capsule Tower in Tokyo, Japan, by Kisho Kurokawa was built. In 1977 the Centre Pompidou in Paris, France, by Renzo Piano and Richard Rogers was opened. In 1984 the AT&T[145] Building (now the Sony Tower) in New York, USA, by Philip Johnson and John Burgee was completed. So these two decades roughly correspond with the continuing historical debate about and critical analysis of the values of Modernism, with the era of the Metabolist movement at its peak, the time of Postmodernism in architecture almost completely covered, and High-Tech architecture emerging. Even though any attempt of a clear distinction of styles is questionable, again it is the curious search for a certain kind of coherence in time-bound questions raised and possible answers given by design intentions shown. The development and applications of virgin PV technologies that happened at the same time will be briefly introduced in the following sections.

3.2.2 Fifteen years - from the mid-sixties to the end of the seventies

Building related installations emerged slowly. In 1966 Sharp installed a 225 W system on the **Ogami Island Lighthouse**[146] in Nagasaki Prefecture, Japan, at that time the world's largest PV array - Fig.31. The original Sharp S-224 modules with cut semi-circular 1 inch cells were replaced in 1978 by more efficient S-225 modules featuring 2 inch cells.[147] Until then lighthouses in off-grid situations, that didn't benefit from electricity supplied by the grid, had to be laboriously resupplied with oil, gas or batteries. To replace it with PV proved to be not only one of the first viable applications in buildings, but it is inevitably changing the typology of a lighthouse as a building. Lighthouses are critical to a safe passage of ships. Lighthouses, most famously the Pharos of Alexandria - Fig.32, have been workplace and home to lighthouse keepers since ancient times. By successfully equipping the last manned lighthouses with PV all over the world, the original meaning of 'house' in lighthouse may come to its end, or survive only as a metaphor by providing shelter for light rather than for humans.

[145] AT&T - American Telephone & Telegraph Company is the parent company of the Bell Laboratories, were the first modern solar cell was developed - see 2.3.1 Crystalline silicon PV.
[146] Japanese: 尾上島灯台 [Ogami Island Lighthouse]
[147] These achievements have been recognised as part of Sharp’s Commercialization and Industrialization of Solar Cells as an IEEE Milestone, as reported by Sharp Corporation (2010).

Fig.31: Ogami Island Lighthouse
Credit: © Japanese Coast Guard

Fig.32: Lighthouse of Alexandria
Credit: Drawing by archaeologist Hermann Thiersch (1909)

Then in 1973 '**Solar One',** one of the world's first photovoltaic powered residences and in fact a hybrid with photovoltaic and solar thermal collectors, was built at the University of Delaware's Institute of Energy Conversion (IEC) under the supervision of director Karl Wolfgang Böer and architecture firm Harry Weese and Associates.[148] To avoid an *"unsightly"* attachment on top of the roof and to design an *"attractive"* solar powered residence, the PV/T system was integrated into the gable roof *"saving unnecessary plywood and shingles".*[149] As such it is not only one of the first building related photovoltaic and solar thermal installations, but surely one of the very first examples of 'building-integration' of PV and PV/T, long before the term was coined - see 2.2.1 - BIPV.

Fig.33: 'Solar One' at University of Delaware
Credit: © Steven Hegedus

[148] Farber (1975) p.48;
'The Institute of Energy Conversion, The First Twenty-five Years: 1972-1997' (undated)
[149] Böer and Riehl (2010)

3.2.3 The first five years of the eighties

As soon as the eighties started, the number of houses with solar panels increased. Was it either the skyrocketing oil prices after the 1973 oil crises and even more after the 1979 energy crisis that caused a lot of rethinking of energy strategies, or was it the availability of products from the manufacturers? Supposedly it was a combination of both that stirred the interest among clients, architects and builders. But most importantly it was about financing. Without generous support through research grants or an expected promotional effect as built case study advertisement for manufacturers, most of the following examples simply wouldn't have been built. The seventies ended and the eighties started with a famous building, the **Spiller House** by Frank O. Gehry, built in Venice, CA, USA, with two thermal-type solar collectors[150] eye-catchingly mounted on top of the house, like satellite antennas that receive rays of sunlight.

Fig.34: Carlisle House
Credit: © Steven Strong / Solar Design Associates

At about the same time, in 1980, the **Carlisle House,** a U.S. Department of Energy case study house designed by Steven Strong of architecture firm Solar Design Associates, was built in Carlisle, MA, USA. It has two shed roofs staggered in height, a larger flatter one facing north, and a smaller steeper one facing south. On top of the south facing roof a 1000 sq.ft, appr. 92.90 m^2 photovoltaic installation (7.3 kWp, 126 Solarex modules, 72 cells per module, 9500 kWh/year) and 100 sq.ft, appr. 9.29 m^2 thermal-type solar collectors were mounted on the roof, completely covering the south facing half up to the roof edges.[151] The same year another model home with financial backing from the US DoE, the **John F. Long**

[150] To avoid any confusion, thermal-type solar collectors aren't photovoltaic panels, and thus the Spiller House doesn't count as a PV example. However, due to its fame and to set a time frame it is mentioned here.
[151] Stepler (1981)

Homes Model House was built in Phoenix, AZ, USA.[152] It was a modified version of the builder's gable roof 'Fiesta' model with added passive features designed by Jeffrey Cook,[153] professor of architecture at Arizona State University and consultant to John F. Long Homes.[154] On top of the passive measures it had an active, integrated photovoltaic installation (7.2 kWp, 120 modules, 60 cells per module, 4 inch[155] monocrystalline Arco Solar cells, 11,000~13,000 kWh/year expected, 5463 kWh measured during the first ten months of operation).[156] The shingled solar cells on a metal batten seam roofing system[157] were the special feature, novel in these early days of building integration and *"the first fully architecturally integrated non-glass-cover-plated photovoltaic roof system in the United States".*[158]

Fig.35: Universe of Energy Pavilion
Credit: © Ingo B. Hagemann

Then in 1982 the American solar cell and module manufacturer Solarex equipped its **'PV Breeder' manufacturing plant** in Frederick, MD, USA, with a PV array (200 kWp, 2500 m^2, 3120 Solarex modules).[159] To fit this array onto a generic, usually flat-roof plant, the south façade was tilted at appr. 45° on its full length to form a dominating shed roof, onto

152 An image of the roof with Arco Solar cells can be found in Simington (1981) p.66, and in a presentation by Steve Coonen <http://www.ornl.gov/sci/solarsummit/presentations/ORNL-Coonen.pdf>, p.12
153 John F. Long Homes, Inc. (1980) - *"the home's special energy-saving features are expected to yield a saving of well over 50 percent in the energy required to cool or heat the living space".*
154 Cook (1983) - The fact that Jeffrey Cook was consultant to John F. Long Homes to properly integrate the passive solar aspects into the house plan of the standard model was confirmed by Jake Long and R.K. (Casey) Kayes (program manager in charge of the solar home project) - personal communication with Valerie Riedler / John F. Long Properties LLLP, October 12, 2011.
155 There appears to be some discrepancy in the literature about the size of the cells used. Simington (1981) and Cook (1981), both published in popular magazines, report 3 inch cells. Arco Solar, Inc. (undated), however, based the power assumption on 4 inch cells, a size confirmed by the report of McNeill and Solman (1981). As Arco Solar was the cell and module manufacturer, I used their stated diametre.
156 Arco Solar, Inc. (undated); McNeill and Solman (1981); Simington (1981)
157 'Raise the (solar) roof and lower your utility bills' (1981)
158 Schoen (2002)
159 NREL (1997) p.8

which the solar array was mounted. The same year the **Universe of Energy Pavilion** at Walt Disney World's Epcot Park in Orlando, FL, USA, was opened. The pavilion has a square footprint with the corners at the cardinal directions. Whereas the northern part of the roof is flat, the southern half was sloped downwards to form a shed roof. Seven bracketing frames, like alice bands on top, provide a proper inclination for a solar array (77 kWp, 2200 modules, 36 cells per module, 3 inch cells).[160]

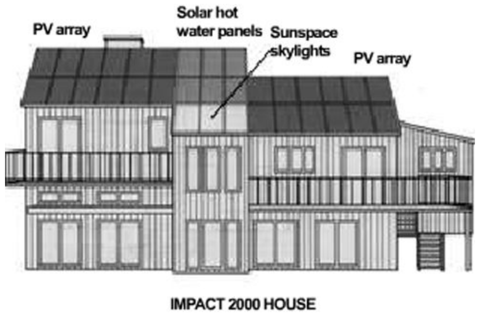


Fig.36 (a) and (b): Brookline or Impact 2000 House
Credit: © demosite.ch

In 1983 the **Brookline House** (also called 'Impact 2000' House or Solar Electric House), a further house design by architecture firm Solar Design Associates and a PV/T hybrid, was built in Brookline, MA, USA. The gable roof is asymmetrical, with the ridge shifted to increase the pitch on the southern face to an ideal inclination for the solar array (4 kWp, 53.50 m², 24 modules). The construction of the house was broadcast as the subject of the fifth season of the American TV series 'This Old House' with 26 half-hour episodes. It premiered on TV station PBS viewed by an audience of over 9 million and was, in the words of the house's architect Steven Strong, *"[f]or many . . . a first glimpse at the future of zero-energy, carbon-neutral home design".*[161]

[160] Spence (2010)
[161] O'Neil (undated); 'all-solar house gives a vision of the sustainable future' (undated)

Fig.37 (a) and (b): Intercultural Center
Credit: © Georgetown University

In 1984 the **Intercultural Center** of Georgetown University, designed by architecture firm Metcalf and Associates, was completed in Washington, D.C., USA. The building shape is optimised to accommodate a large 337 kWp solar array (3318 m^2, 4464 Solarex modules).[162] Both north and south wing have an appr. 45° tilted shed roof. The roof surface of the south wing extends visually down to the first floor by five increasingly projecting floors and balconies with inclined balustrades. Solar panels are mounted on the two roofs and the inclined balustrades. The solar array generated appr. 360,000 kWh of annual electricity at start of operation, which dropped significantly over the years due to soiling and degradation. After some serious cleaning in 1993 and major repairs after 2007 it generated appr. 200,000 kWh during FY2010.[163]

Fig.38: Kyocera Sakura Solar Energy Center
Credit: © Kyocera Corporation

The same year when the Intercultural Center was completed, the Japanese company Kyocera established the **Sakura Solar Energy Center** in Sakura City, Chiba Prefecture, Japan.

[162] NREL (1997) p.10
[163] 'Sustainability at Georgetown University' (undated)

The building has a flat roof and and almost square foot print with three corners facing west, north and east. The south corner is cut away on ground floor and the set back increases on each of the two upper floors. On this stepped south side an appr. 45° tilted frame was added with a solar array mounted on top (43 kWp, 434 m^2, 1016 Kyocera modules, 36 cells per module, 4 inch cells).[164] The innovation here was of technological nature, as the cells used were made of multicrystalline silicon. Kyocera was the first in the world in 1982 to launch mass-production of this alternative to monocrystalline silicon solar cells.[165] Also in 1984 the **Chronar PV Port Jervis Factory** by architecture firm Kiss + Cathcart, Architects was built in Port Jervis, NY, USA. This building as well boasted solar panels made of an innovative PV technology, in this case one of the earliest examples of amorphous silicon modules, boldly mounted on rails above the skylit entrance hall. Interesting are the manifold colours of the early a-Si PV panels, see Fig.39(b), matching the coloured leaves of the Indian Summer.

Fig.39 (a) and (b): Chronar PV Port Jervis Factory
Credit: © Kiss + Cathcart, Architects

3.2.4 Price of solar electricity

According to the *Popular Mechanics Magazine* of February 1981, there existed *"at least eight"* [166] so called solar electric or photovoltaic houses like the John F. Long Homes Model House in the United States. How about the cost of solar electricity in these pioneering days? The additional expense for the PV system of the John F. Long Homes Model House was \$70,000[167] ~ \$120,000.[168] Many of these early experimental houses in the United States were only buildable with substantial financial support.

164 Kyocera Corporation (2009b);
Koichiro Nakano / Kyocera Corporation, personal communication, October 13, 2011
165 'Kyocera's History in Solar Energy : 1982-1986' (undated)
166 'Raise the (solar) roof and lower your utility bills' (1981)
167 Ibid.
168 Simington (1981) p.68

In the case of the John F. Long Homes Model House, the development, installation and testing of the integrated roof was financed with a $260,000 US DoE contract.[169] This was, compared to the base price for a typical compact car of the time, $6032 for a Ford Fairmont, $6495 for a Mazda 626 and $7975 for a VW Jetta,[170] a highly prohibitive level for the consumer market. However, prices were expected to drop significantly *"through the economies of mass production . . . a practical solar power system costing $10,000 or less could be put on the market in about five years' time".*[171] Even though and according to McNeill and Solman,[172] with a measured electricity generation of 5463 kWh during the first ten months of operation, extrapolated to 7590 kWh for a one year period, the monetary value was equal to $453 with electricity costs at $.06/kWh and a 100% buy-back rate of surplus energy through the utility. In financial terms this expected lower cost still meant a ROI period of more than 22 years without considering maintenance or inflation or interest rates.

3.2.5 LTPV enters the stage

At this time, last but not least, the first noteworthy examples of architecturally integrated, multi-functional LTPV entered the stage. Two examples will be briefly introduced.

Fig.40 (a) and (b): Demonstration solar house in Mexico
Credit: © Ken-ichi Kimura

One is a **Demonstration Solar House** in Mexico, where solar cells were installed in the glazed roof of an attached green house. The Japanese architect and emeritus professor of Waseda University, Ken-ichi Kimura, who visited the house during the Mexico 1984 PLEA conference,[173] valued such installations as a useful companion to methods for passive and low energy architecture, to act as shading devices and prevent overheating, while supplying ne-

[169] John F. Long Homes, Inc. (1980); Simington (1981)
[170] 'Detroit besieged: PM's guide to the '81 import invasion' (1981)
[171] John F. Long Homes, Inc. (1980) p.3
[172] McNeill and Solman (1981)
[173] Ken-ichi Kimura, personal communication, August 13, 2010

cessary electricity for the operation of fans to improve air circulation within the house and thus for better overall thermal comfort.[174]

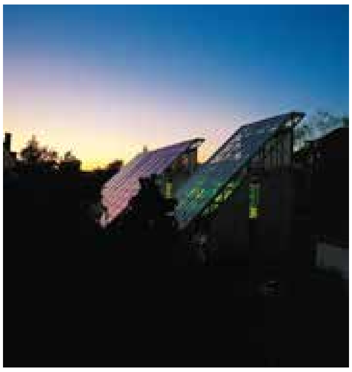


Fig.41 (a) and (b): 'Wohnanlage Richter'
Credit: (a) © Richard Schenkirz, (b) © Verena Herzog-Loibl

The other is the **'Wohnanlage Richter'** designed by Thomas Herzog and Bernhard Schilling, a residential complex built 1982 in Munich, Germany - see Appendix C: cs1. The architecture is a manifestation of a passive solar approach spiced with active photovoltaic. It has a building-high fully-glazed 45° inclined south-facing shed roof that dominates the appearance so strongly, that the whole building looks like a rotated triangular prism. The design received the Association of German Architects BDA Bavaria Chamber Prize 1983 for its interior spatial qualities based on convincing qualities of the floor plan combined with passive energy measures but the section was questioned.[175]

3.2.6 The first two decades of architectural integration of PV - concluded

So what can be said about the first two decades of architectural integration of photovoltaic when looking once more at the twelve[176] selected projects? It is interesting to note that most attempts were undertaken with residential houses. A reason, probably, was the astronomic price tag of photovoltaic that made large installations almost impossible, and small additions to large buildings look ridiculous. The playful addition of an expensive high-tech accessory fitted visually and programmatically much better to the scale of the Spiller House. Furthermore, the available roof area against the total floor area, and by that the possible supply of electricity of the PV array against the need of a family made photovoltaic on houses surely look attractive. A second reason, maybe, was that photovoltaic in buildings was seen reason-

[174] Kimura (1994) pp.416-417
[175] 'Wohnanlage Richter, München' [Residential complex Richter, Munich] (undated)
[176] The Spiller House with a solar thermal-type application is not included in this number.

able only after basic and much cheaper passive solar design strategies to save energy were fully exploited. As such these two measures, passive strategies and photovoltaic were seen intertwined, or as the two sides of the same coin, right from the start. Generally speaking, the vocabulary of solar design had been more commonly associated with residential buildings. A third reason, possibly, electricity prices for private households are often more expensive than for corporate customers and utility prices. So combining the latter two reasons, the huge potential to save energy with a large number of consumers possibly willing to buy photovoltaic, made supporting the development of products for small scale installation on residential houses with research and development grants surely look attractive.

The second typology are manufacturer owned facilities with larger scale PV installations. But what kind of typology are these? Are they factories or solar power plants? Programmatically they are some kind of 'decorated sheds', large-scale test beds and visually impressive advertisements at the same time, a unique combination of industrial R&D and marketing activity made manifest with and through an architectural form. This raises a question inherent in a quote that occurred in 1993, a little while after the selected projects were built: *"PVs may even serve to create entirely new building types".*[177]

Without giving an answer, but capitalising on this, another remark could be drawn from looking at the examples. It is the impact that the photovoltaic installation had on the design strategy of each building. The least impact can be seen at the lighthouse and the Chronar PV Port Jervis Factory. They appear like being designed without any consideration of 'integrating' the solar modules (which surely holds true for the lighthouse built long before the solar modules were added), but boldly mounting them in an ostentatious position. Here it is interesting to note, that the Spiller House's collage-style addition did not survive, the solar thermal modules were later removed without replacement. However, the advantage of addition can be seen at the remote lighthouse, with two subsequent replacements.[178] An added module can be replaced more easily or even removed, and as such the removal from the Spiller House didn't leave any scars or recognisable marks. Most of the other examples were driven by a requirement to provide optimally oriented and tilted areas, and reacted by modulating, altering and adapting the building envelope. The John F. Long Model House has undergone the least modification, keeping a symmetrical gable roof on a simple house volume. The Solar One, Carlisle House and Brookline House adjust and provide differently sized and tilted roofs for

[177] Kiss Cathcart Anders Architects, P.C. (1993) p.6

[178] The original Sharp S-224 modules lasted about 12 years and were replaced by Sharp's second generation S-225 modules after their introduction in 1978. However, in 2009 these modules were replaced too, as confirmed by Hideyuki Yoshimoto / Japan Coast Guard, personal communication, December 1, 2011.

their north and south side. The Universe of Energy Pavilion and the Sakura Solar Energy Center have similarly shaped footprints, the former translating the requirement with virtue into an integrated solution, and the latter carving and squeezing it into an attached something. The yet not mentioned examples, the 'PV Breeder', the Intercultural Center, the Mexican Demonstration Solar House and the 'Wohnanlage Richter' share a formal expressive reaction in the shape of an extruded right-angled triangular section with the hypotenuse facing south (as they are all located on the northern hemisphere), providing an angled roof that starts low and rises high. Such formal solutions appear driven by the desire to maximise the sun-facing area for a certain point during the day - noon. That this approach does not necessarily fall back on photovoltaics alone but on passive solar considerations as well, becomes obvious with the green house design at the Mexican Demonstration Solar House and the 'Wohnanlage Richter', especially the latter with a rather small area for photovoltaic.

If the consideration of solar energy as a passive and active source of energy, made usable with design and technology, is maybe an answer, than freely adapted from Cedric Price, we must not forget the question. The jury, awarding the BDA Bavaria Chamber Prize to the 'Wohnanlage Richter', asked this fundamental question: *"ob architektonische Gesamtlösungen unter Berücksichtigung nur eines Aspektes von Architektur - in diesem Fall Solartechnik - möglich und sinnvoll sind. Die Jury sieht insbesondere die Gefahr der Vernachlässigung städtebaulicher Belange in stärker durch Gegebenheiten geprägten Situationen".*[179] [whether holistic architectural solutions taking into account only one aspect of architecture - in this case solar technology - are possible and useful. The jury sees the particular danger of neglect of urban development issues in situations characterized by more severe conditions.]

3.3 Solar electricity and buildings, part II - PV becomes BIPV

3.3.1 The economical and political situation for PV in the nineties

Having past the pioneering efforts, some developments didn't happen as expected. Noticably the oil glut with prices continuously falling weakened the initially strong interest in alternative technologies. That this had a major impact on the PV industry is easily understood. The missing economies of mass production kept prices for solar modules high. As expected price reductions were not achieved in time, a strain was put on the business model of many companies. However, as the fundamental problem of the finite amount and instability of fossil fuel supply wasn't solved, it was a time for review, rather than

[179] 'Wohnanlage Richter, München' [Residential complex Richter, Munich] (undated)

backpedalling. The most important lesson learned, was that scale of production is the most crucial economic factor for the breakthrough of the technology.

The 1990's started with the establishment of numerous international and national research programmes to understand and remove barriers on the way to widespread dissemination. For PV it was notably the establishment of the IEA PVPS - International Energy Agency's Photovoltaic Power Systems programme in 1993, capitalizing on the efforts and outcomes of the IEA SHC - International Energy Agency's Solar Heating and Cooling programme established already in 1977 as an international joint R&D effort. The cooperative international effort was amplified by a number of national dissemination programmes, like the US DoE's PV:BONUS programme 1993-1997 and 1997-2000,[180] Germany's *1000 Roofs* programme 1990-1992 and the later following *100,000 Roofs* programme 1999-2003, Japan's *70,000 Roofs* programme that started 1994,[181] the European *1,000,000 Photovoltaic Systems* campaign proposed in 1997[182] or the US American *Milion Solar Roofs* Initiative endorsed the same year.[183] However, even though these targeted numbers of subsidised PV installations on buildings may sound impressive, they could affect only a very small fraction of the overall building market.[184] It was not until the inauguration of the German EEG - *Erneuerbare-Energien-Gesetz* [Renewable Energy Act] in 2000, that innovatively combined premium and guaranteed but falling feed-in tariffs with a mandatory purchase requirement for the utilities without any charge to the public purse, that ultimately boosted installations beyond expectations and laid the stepping stone for other countries to introduce similar tariffs.

However, what was anticipated with horror by many and mainly architects, was the unsightly later attachment of generic solar modules to otherwise and in general decently designed buildings, that prevented an immediate and happy acceptance among the profession. To address this obvious barrier was the objective for quite a few of the international and national dissemination research programmes, some Tasks were briefly introduced in section 2.2.2 PV in buildings and 2.2.4 PV in architecture, whith follow up programmes still emerging.[185] This situation coincided with the emergence of the acronym BIPV as explained in section 2.2.1 BIPV, which has been a major impact in raising awareness about PV among

180 Eiffert and Kiss (2000) p.66
181 Maycock (2005) pp.905-906
182 EC (1997) p.27
183 NREL (2003); Strahs and Tombari (2006)
184 In the case of the proposed European campaign, 500,000 installations were targeted for the domestic market, *"less than 2% of the 30 million houses and non-residential units which will probably be built between now and 2010. This is without taking into consideration the equally large potential for PV retrofitting in existing buildings."* (EC, 1997, p.28)
185 Currently the IEA SHC Task 41 Solar Energy and Architecture, scheduled from May 2009 to April 2012 - see Wall, Windeleff and Lien (2008) and 'Solar Energy and Architecture' (undated).

building professionals, as well as the quality and the status of PV as a building material since then. Noteworthy are also efforts that tried to propagate the variety of BIPV products as well as demonstrate possibilities for customised PV, as in the case of IEA PVPS Task 7's Exhibition Centre for Photovoltaic Integration called Demosite,[186] that was built in 1992 at the EPFL[187] in Lausanne, Switzerland. There the **Pyramids at Demosite** - see Appendix C: cs3 were showcasing early non-standard, non-rectangular, but customisable LTPV panels.

3.3.2 Light - once again the architectural feature of PV

The 1990's also coincided with the beginning success story of thin-film PV technology as a serious alternative for building-integration to the standard solar modules.

Fig.42 (a) and (b): APS Fairfield PV facility, PV 'cube' and PV skylight
Credit: © Kiss + Cathcart, Architects

In 1991/93[188] the **APS Fairfield PV facility** by architecture firm Kiss Cathcart Anders, Architects was built in Fairfield, CA, USA - see Appendix C: tf1. The company Advanced Photovoltaic Systems[189] installed their own amorphous silicon thin-film laminates as a showcase project on their manufacturing facility at three different locations: as façade spandrel panels on the exposed control centre cube, as awnings above the entrances and as a

186 *"The Demosite was dismantled in 2008 to make room for the EPFL Rolex Learning Center"*, designed by Japanese architects SANAA. However, *"The website stays active for virtual visits, factsheets and tutorials but will no longer be updated."* - see <http://www.demosite.ch/>

187 École polytechnique fédérale de Lausanne [Swiss Federal Institute of Technology]

188 The completion date of the building is not exactly clear, as two different years were found: 1991 - on the website of the architectue firm <http://www.kisscathcart.com/aps_fairfield.html>; and 1993 - Eiffert and Kiss (2000), one author of the book, Gregory Kiss, being one of the principals of the architecture firm too.

189 The Chronar PV Port Jervis Factory and APS Fairfield PV facility, both designed by Kiss + Cathcart, Architects, were built by the same investor. According to Braun and Skinner (2007): *"After Chronar filed bankruptcy in 1990, the principal investor formed Advanced Photovoltaic Systems, Inc. (APS)"* (p.51). After APS filed bankruptcy in 1995, assets including the Fairfield factory were purchased by BP Solar in 1996 (p.32), and in 1998 BP Solar acquired Solarex (p.53) and the 'PV Breeder' factory described earlier.

translucent PV skylight on the cube's roof. All laminates were standard products, with a light-transmission of 4~5% through the scribing lines. The technical property was used as an architectural feature mainly for the skylight, but as the illumination levels were feared to be too low, clear glass panels were installed side by side the solar electric glass. As for the façade, all spandrel panels are thermally insulated and covered on the inside. When taking the picture - Fig.42(b) - two covers were removed beside the clear vision glass windows, to show the effect in façade application.[190]

Fig.43 (a) and (b): EMR Centre 'Energie-Forum-Innovation'
Credit: © Archimedes Facility-Management GmbH

In 1995 the **EMR Communication and Technology Centre 'Energie-Forum-Innovation'** by Frank O. Gehry Architects was built in Bad Oeynhausen, Germany - see Appendix C: tf2.[191] Beside its unique formal volumes and spatial qualities, it employs a number of energy-saving and advanced energy harnessing technologies, like cooling-assisting ventilation shafts and solar collectors for hot water. Natural light enters the building through a number of differently sized windows and skylights, modulating the interior spatial perception. The auditorium has the largest skylight, with a darker central area made of insulated semi-transparent thin-film PV panels (4 kWp, 80 m², 12% light transmission)[192] and a brighter, surrounding area made of insulated clear glass panels.

The appearance of thin-film PV, 'disguised' with just a darker tint than the clear glass panels, didn't seem to be familiar to the untrained eye of book and magazine editors and architecture critics of the time, and as such, despite the fame of the building's designer the well-integrated LTPV didn't find any proper and correct appreciation in the literature. Levene

190 As was stated by Gregory Kiss, personal communication, November 29, 2011.
191 Two architects that worked on the project, Randall Stout as project architect for Frank O. Gehry, and Hartwig Rullkötter as executive architect for EMR - see Levene and Cecilia, 1995, p.250 - worked together again in 2000 on the **Steinhude pavilion** - see Appendix B: 095 - for the same client EMR.
192 Ragati and Kreikenbohm (1996) p.115

and Cecilia, in an El Croquis issue about Frank Gehry, mention PV cells integrated into the roof forms, but without any word of the light-transmitting ability.[193] Ragati and Kreikenbohm, in their book about the EMR Centre, describe certain technical features of the amorphous silicon thin-film PV technology in detail on two pages, but their explanation is illustrated with a graphic showing a crystalline silicon laminate.[194] Finally Ragheb, in an exhibition and book about Frank Gehry, even wrongly placed the solar panels on the roof,[195] which gives the impression of roof-mounted solar modules to the reader. It is a pity, that light as an important spatial and architectural quality, combined with PV in a novel way to that date, was treated so inattentively. The negligence could also illustrate that PV and LTPV were not regarded as 'materials' but as rather technical devices, with editors emphasising their power generating properties[196] rather than their material qualities or light and space altering abilities, and by classifying it this way, didn't require any closer attention when presenting the works of the *"master at transforming the material environment"*.[197]

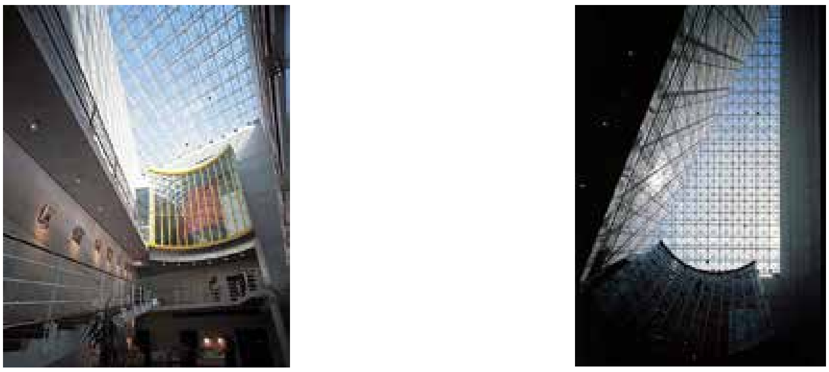


Fig.44 (a) and (b): Tamayu Health Spa
Credit: © Taiyo Kogyo Corporation

In 1996 the **Tamayu Health Spa**[198] in Matsue, Shimane prefecture, Japan, designed by architecture firm Shin Takamatsu Architect & Associates, was built - see Appendix C: tf3. It

[193] Levene and Cecilia (1995, p.134) *"Roof forms integrate photovoltaic cells for supplementary power production, and solar collectors for hot water use in the kitchen facility. A solar air heater is also planned to preheat air entering the mechanical system."* [underlines added]
[194] Ragati and Kreikenbohm (1996) p.115
[195] Ragheb (2001, p.143) *"In addition to the use of natural light, the building is structured to employ several other energy-saving elements, including solar panels placed on the roof to harness energy, and ventilation shafts employed during warmer months to assist in cooling the building."* [underlines added]
[196] Here it is interesting to note: during the design phase of the building the colour of the PV skylight on the outside was anticipated to be blue as with crystalline silicon solar cells, as can be seen in pictures of the model in Levene and Cecilia (1995) pp.137-139.
[197] Ragheb (2001) p.13
[198] 'Tamayu Health Spa' is the name of the project by Shin Takamatsu, the name derieved from the buildings location in the Tamayu neighbourhood. However, the facility names itself 'Tamatsukuri Spa YuuYu', also used by Sato (1998) - see spa homepage <http://www.tama-yuuyu.com/>

features a 'see-through' type skylight floating above the five storey high entrance hall, triangular in shape (5 kWp, 180 m², 30% light transmission).[199]

Even though one of the early few examples of semi-transparent PV installations, it wasn't precisely the world's first application of this newly developed kind of light-transmissive PV - see 2.2.7 Translucency and transparency - 'light-through' and 'see-through', as claimed by the Spa itself.[200] One of the forerunners[201] is an otherwise rather generic office building of the company **Tsukasa Electric Industry Corp.** in Hirakata, Osaka prefecture, Japan - see Appendix B: 744, equipped in 1993 with a PV façade, partly opaque and partly semi-transparent, that used the same kind of 'see-through' type amorphous silicon thin-film PV developed by the Japanese company Sanyo (5.1 kWp of which 1.4 kWp are 'see-through' PV in windows, overall: 158.6 m²).[202]

3.3.3 The Whitehall Ferry Terminal - urban integration of PV

An interesting case of photovoltaic technology and urban development in severe conditions is, in fact, a drama in four acts, that started in 1992 but went on for thirteen years and ended with the dedication of the **Whitehall Ferry Terminal** in New York, NY, USA - see Appendix C: cs47. The PV aspect of the project is often overlooked, so to shed some light will be of interest for a better understanding of historical developments of PV in buildings and urban contexts. The prelude is a fire in 1991, that damaged the original structure of 1907.

In 1992, an international competition was announced *"to create a major civic statement at the tip of Manhattan",*[203] and sponsored by the New York City Department of Transportation (DOT) and Economic Development Corporation (EDC). Six teams were chosen, among them well known architecture firms like Aldo Rossi Studio di Architettura, Hardy Holzman Pfeiffer Associates, James Stewart Polshek & Partners, Rafael Vinoly Architects, and Skidmore, Owings & Merrill. But it was the joint entry of Venturi, Scott Brown & Associates and Anderson/Schwartz Architects that unanimously won the competition,[204] *"a soaring, barrel-*

199 '玉造温泉ゆ～ゆ' [Tamayu Health Spa] (1998);
'太陽電池入りガラス / 玉造温泉「ゆ-ゆ」' [Solar cells-containing glass / Tamayu Health Spa] (1997)

200 The 'first application' actually refers to the 'TSS Solar' façade and roof system developed by the company Taiyo Kogyo using Sanyo's thin-film PV, that was used for the Tamayu Health Spa, see also Taiyo Kogyo website for more information <http://www.taiyokogyo.co.jp/tm/tss.html>

201 Sanyo test-installed 'see-through' a-Si thin-film PV in a door at the company's model home called SHAINS house at it's Gifu plant in 1987 - see Tanaka et al. (1988) p.61, as well as in windows at the company's former **Tokyo Yushima Office Building** in 1992, now the JFA House - Japan Football Association HQ - see Appendix B: 791.

202 'Series Advertisement Gallery : 1994 - 5' (undated); Hagemann (2002) pp.257, 350, 433; Hamakawa (2004) pp.223-224

203 'Postings: $100 Million Rebuilding; Ferry Terminal Contest' (1992)

204 Dunlap (1992); 'whitehall ferry terminal' (undated) > click on 1992

vaulted terminal crowned with a gigantic illuminated clock. . . . Of the six designs, this is the most conspicuous landmark, an architectural billboard impossible to ignore".[205] An election the following year and a change in the govenment of New York from the Dinkins to the Giuliani administration gave rise to the influence of Staten Island Borough President Guy V. Molinari,[206] who became a fervent opponent of the design, and the bold iconoclastic gesture of the giant 120 feet (36.5 m) tall clock the bone of contention.[207] At this first design stage there was no PV intended, neither in the winning scheme, nor in any of the other five entries.

Instead of advancing to the project phase, the new administration rejected the competition winning entry and drastically reduced the budget, calling for a necessary redesign. During this second design stage that went until 1995, a more economic building with an alternative civic façade without the giant clock was proposed by the design team. It had a lower, saddle-shaped section that echoed the reduced budget. A spatial flourish was the upward rising roof on the land side that opened the entry hall to the city to welcome and see off commuters. On the harbour side the building was book-ended with a flag-shaped and curvy civic façade, a full-scale programmable electronic message board for the by ferry arriving tourists and commuters. It was precisely during this stage, inspired by the city-facing upsweep of the roof and angled towards the sun, that PV panels were proposed, *"that would provide significant electrical power for the facility, and as well demonstrate this evolving green technology on a governmentally-funded facility".*[208] However, the billboard-like façade failed again to gain an official approval.

During the third design stage in 1996 a simple, glass-walled waterfront according to the wishes of the administration was incorporated into the design, which was in the opinion of Venturi, Scott Brown & Associates *"an inappropriate architectural expression for a civic building in a prominent location at the turn of the century",*[209] thus they resigned from the design team. Frederic Schwartz of Anderson/Schwartz Architects, the remaining half of the former joint design team, however, insisted: *"We were inspired by lighthouses, . . . luminous, glowing, warm",*[210] and continued the project into the last stage.

[205] Muschamp (1992) provided a review of all six competition entries shortly before the results were announced.

[206] The Whitehall Ferry Terminal is not located in Staten Island, but in Manhattan and thus outside the jurisdiction of the Staten Island Borough President, however, Guy V. Molinari was a Republican as well as Rudy Giuliani, whereas David N. Dinkins was a Democrat, which led Jacobs (1997) to the following conclusion: *"Architect attempts bold gesture. Politics kills it."*

[207] Dunlap (1992); Jacobs (1997) p.28

[208] 'whitehall ferry terminal' (undated) > click on 1995

[209] 'whitehall ferry terminal' (undated) > click on 1996

[210] Jacobs (1997) p.28

Under the direction of Schwartz Architects the idea of a billboard-like façade, which was the contentious part of the previous designs, was ultimately abandoned during the fourth and final design stage that went until 1999. According to Evitts, however, this created the opportunity to suggest a public, rooftop waterfront viewing deck as a major design feature. In terms of urban development this fit in well with some larger city-wide effort to re-integrate the waterfront with the city.[211] Here it is now interesting to note, that the integration of photovoltaic, even though it was scaled down in terms of size, achieved a push as a design feature. In 1996, a real shed, the **Rikers Island Compost Facility**, part of New York's borough of the Bronx, received a solar photovoltaic roof made of light-transmissive PV panels, allowing dappled sunlight to enter the building - see Appendix C: cs5. This facility was visited by Ron Evitts of the Whitehall Ferry Terminal's design team already in 1995/96.[212] Positively influenced, the opportunity to alter photovoltaic from opaque modules to light-transmitting panels inspired the design team to change the suggested PV installation away from simply being mounted on the roof and to propose a prominent position as a V-shaped crown elevated above the roof and publicly accessible viewing deck, functioning as a canopy to provide shade for people on this vantage point. A second line of PV panels got integrated into the top rim of the façade as spandrel panels.

Fig.45: Whitehall Ferry Terminal in 2008
Credit: Daniel Schwen / Wikimedia Commons

What started as a bold civic statement in 1992 mimicking the grand railway terminals of the early 20th century decorated with energy consuming late 20th century electronic media

[211] McKinley Jr (1992); 'whitehall ferry terminal' (undated) > click on 1999 - confirmed by personal communication with Ron Evitts, October 15, 2011

[212] As confirmed by Ron Evitts, personal communication, October 16, 2011.
The LTPV panels for the Rikers Island Compost Facility were manufactured by Atlantis Energy. Evitts remembered to have seen pictures at that time of two Swiss projects of the company using LTPV laminates in a canopy or skylight, the **Pyramides at Demosite** in Lausanne built 1992 - see Appendix C: cs3 - and the **Kantonsschule** in Solothurn built 1993 - see Appendix B: 354. Atlantis Energy was the company to manufacture the LTPV panels for the Whitehall Ferry Terminal too.

façades, became a functional transportation hub, more modern than postmodern, but equipped with 21st century discreet architectural and public urban integration. The major shift occurred in the use and meaning of civic symbols, away from the representational towards the phenomenal.

3.4 Summary

The justification for PV installations in the built environment - see 2.2.2 PV in buildings - has followed the paradigm of integration since the early days - see 3.2 Solar electricity and buildings, part I - the pioneering years. Integration was seen as a multi-functional - see 2.2.3 PV as multi-functional building element - but often primarily structural integration into the building envelope - see 2.2.1 BIPV. However, a piece of architecture has had to inherently fulfil the trinity of *firmitas, utilitas, venustas* since the ancient times of Vitruvius - see 2.2.4 PV in architecture. The focus primarily on the traditional building-related functional integration of PV was combined with the hope that aesthetic integration will be achieved automatically. But even 50 years after the invention of the first modern solar cell, Svensson and Wittchen remarked, that *"PV as we know it today was developed to produce energy to spacecrafts and – as a matter of course – without aesthetical considerations. And in spite of the fact that PV has been used in building for more than 30 years, only a limited development of its architectural form and appearance has taken place. It is obvious that a development of the architectural quality of cells and panels are necessary to make them attractive and widely used building components"*.[213]

In fact, PV wasn't seen as an architectural material for a long time. The focus on its energy generating property had drastically impoverished the attention towards the potential brought by this new material. To some extent this can be attributed to the demand for sun-exposure with strongly believed in geometrical orientation and the equally strong reaction of formally unified expressive shapes - see 3.2.6 The first two decades of architectural integration of PV - concluded - which was rather viewed as restricting than extending design opportunities. However, as the photovoltaic semiconductor requires light exposure, it is usually, at least partially encapsulated in highly transparent materials. As such the complex PV product inherits both attributes, which can be altered for a variety of translucent and semi-transparent applications - see 2.2.7 Translucency and transparency - 'light-through' and 'see-through'. This feature proved crucial in replacing tinted or patterned glazings for skylights, atria and greenhouse structures. In these areas sunshading is often crucial, and what had to be added to standard glass by prints or tints has been an inherent feature of PV panels since the beginning

213 Svensson and Wittchen (2004) p.57

- see 3.2.5 LTPV enters the stage. As such, PV as a widely acceptable building material entered the stage quasi through the back door into parts of the building envelope, where its material surface, visible and haptic qualities were least important. With the advent of thin-film technology in the 1990s PV started to smoothly blend with the architecture, indiscernible from other building materials - see 3.3.2 Light - once again the architectural feature of PV. As the degree of light-transmission is mostly inversely proportional to the areic electricity generation efficiency, LTPV is hardly advocated by the majority of PV manufacturers. In buildings, however, light-transmitting areas are seen as a necessity, rather than as a harm. The dualism of light and shadow combined with visibility between adjacent spaces and the ability to freely alter the relation between them, has been a driving force for building and architectural design surely even before Vitruvius. When using the terminology of efficiency, it can be easily argued, that the areic loss of electricity generation efficiency isn't in fact a loss at all, but a much more valuable gain in design flexibility for enhancing the spatial, visual, architectural and cultural qualities of the building. Beside stimulating electrons in a semiconductor to generate electricity, it is the 'other' properties of light like heat and colour and brightness that greatly matter for human shelters.

In conclusion it can be said, that the discussion of building integration focussed often more on tectonic qualities than on ephemeral qualities, which is about to change when light-transmission becomes an essential part of the discussion. As such, the next chapters will introduce built examples with light-transmissive PV installations - see 4 Corpus of LTPV examples, and analyse as well as illustrate how to influence the key design factors of LTPV - see 5 Six-Level-Matrix for analysis.

4 Corpus of LTPV examples

4.1 The whole corpus

The whole corpus of LTPV examples - see Appendix B - consists of 610 projects. Each project has got a three-digit project number for easy reference. The annual distribution of the projects according to the year of completion is presented in Fig.46, the global distribution by country in Fig.47.

Colours indicate the PV technology according to the generation groups as introduced by Martin Green,[214] with blue - [blue colour swatch] - for the first generation of crystalline silicon PV and magenta - [magenta colour swatch] - for the second generation of thin-film PV. An intermediate violet - [violet colour swatch] - is used for projects that use PV of both generations. The majority of projects within the corpus belong to the first generation. A third generation of low-cost and high-efficiency technologies doesn't exist yet. A darker shade of the colours was used, when the year of completion is known and confirmed, a brighter shade when the year of completion could not be confirmed during this study.

Fig.46: Whole corpus by year

[214] Martin Green (2001b)

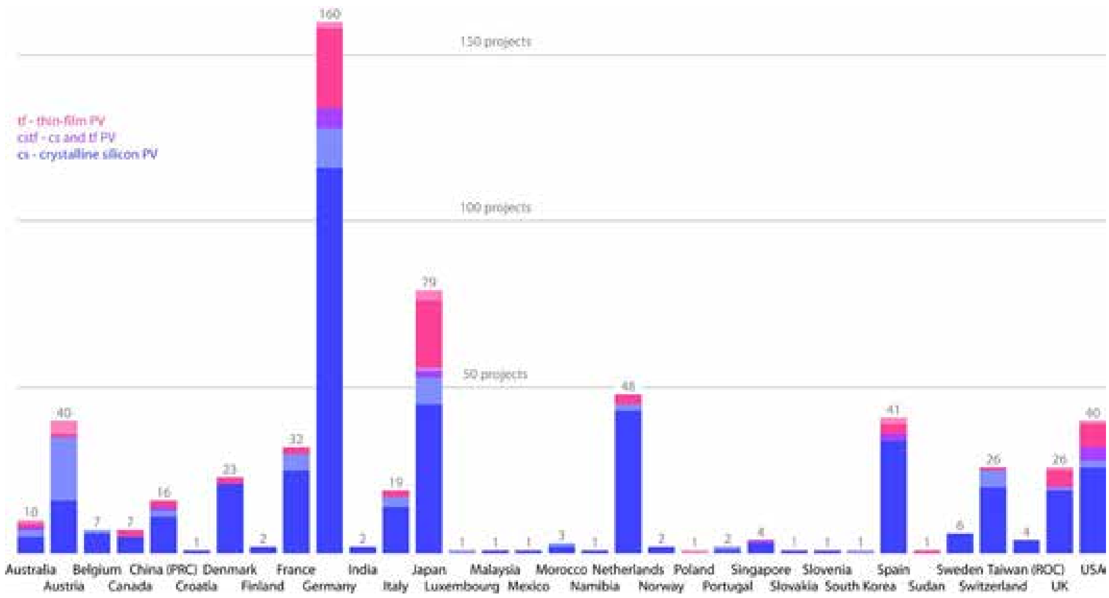


Fig.47: Whole corpus by location

4.2 Selected projects for analysis

From the whole corpus a variety of 116 projects from five continents were selected for the detailed analysis - Tab.7 and Appendix C. Criteria for this selection are:

- ➔ early examples,
- ➔ variety in geographic location,
- ➔ variety in building typology,
- ➔ variety in building integration as building element,
- ➔ variety in PV technology,
- ➔ variety in LTPV design parameters,
- ➔ unique approaches,
- ➔ but also well published examples.

Every selected project got a unique project ID made of letters and digits. The letters indicate the used PV technology: - **cs** - for crystalline silicon PV, - **tf** - for thin-film PV and - **cstf** - when both PV technologies were used in the same project.

Tab.7: Study cases

*(*1) cs – crystalline silicon PV, tf – thin-film PV, cstf – both PV 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, as with renovations, etc.; (*3) rated power of LTPV installation, (rated power in brackets indicates an additional opaque PV installation); n.a. - non available*

ID (*1)	Project name	Location	Year (*2)	Architect, designer, artist, engineer or designing PV company	Rated power [kWp] (*3)
cs1	'Wohnanlage Richter' residential complex	Munich, Germany	1982	Thomas Herzog and Bernhard Schilling	n.a.
cs2	STAWAG	Aachen, Germany	1991/ 1996	Georg Feinhals	4.2/ 4.5
cs3	Pyramids at Demosite	Lausanne, Switzerland	1992	n.a.	0.41
cs4	Brundtland Centre	Toftlund, Denmark	1995	KHR AS arkitekter	14.2
cs5	Rikers Island Compost Facility	New York, USA	1996	n.a.	40
cs6	Ecumenical Community Centre Kirchsteigfeld	Potsdam, Germany	1997	Burelli e Gennaro Architetti with Architekturbüro Oppert + Schnee	8.1
cs7	Café Ambiente	Bremen, Germany	1997	Ingenieurbüro Mencke & Tegtmeyer	9.5
cs8	Solar Office Doxford International	Sunderland, UK	1998	Studio E Architects	73.1
cs9	Tobias Grau lighting GmbH	Rellingen near Hamburg, Germany	1998/ 2001	BRT Bothe Richter Teherani	5.04/ 13.00
cs10	Solarsail Münsingen	Münsingen, Switzerland	1999	Halle 58 Architekten	8.2
cs11	SBL offices 'Wirtschaftshof Linz'	Linz, Austria	1999	Architekturbüro Schimek	20.08
cs12	Shell solar cell factory	Gelsenkirchen, Germany	1999	Uwe Hohaus + Partner	10.5 (26.4)
cs13	Solarcafé 'Sonnenzeit'	Kirchzarten, Germany	1999	Roland Rombach	1
cs14	Solar Catamaran RA 66 'Helio'	Lake Constance, Germany/Switzerland	1999	Christoph Behling with Tilla Goldberg	4.2
cs15	Waterworks Schwerin	Schwerin, Germany	1999	Architekt Roland Schulz	7.56
cs16	Jubilee Campus, Nottingham Univ.	Nottingham, UK	1999	Michael Hopkins and Partners	53
cs17	Academy Mont-Cenis	Herne, Germany	1999	Jourdà & Perraudin with HHS	1000
cs18	Fire Station Houten	Houten, Netherlands	2000	Samyn & Partners	23.9
cs19	Baptistery of the Epiphany Church	Hanover, Germany	2000	n.a.	2.34
cs20	Hestestalds-karréen, Gasværksvej 16	Copenhagen, Denmark	2000	Peter Holst Arkitektur & Landskab	6.1
cs21	The Entrance Canopy at the Earth Centre	Doncaster, UK	2001	Feilden Clegg Bradley Architects	107
cs22	Jakob-Kaiser-Haus, building 3 and 7	Berlin, Germany	2001	Busmann + Haberer	29 (17)
cs23	Kelvin Grove Urban Village	Brisbane, Australia	2001	Hassell Architects	2.3
cs24	Alès Tourist Office	Alès, France	2001	Jean-François Rougé	9.2
cs25	Bo01 Harmony house	Malmö, Sweden	2001	Harmoni Utvecklings AB / Midroc Project Development AB	8
cs26	Pichler Werke	Weiz, Austria	2001	Erwin Kaltenegger	5.5
cs27	Gemini House	Weiz, Austria	2001	Erwin Kaltenegger, Roland Mösl	4 (2.7)
cs28	Children's Museum of Rome	Rome, Italy	2001	F. Pagani & A. Pagani, Studio Italplan Consulting Engineers	15.2 (part opaque)
cs29	Gentofte Teknikhytte	Gentofte, Denmark	2002	Box 25 Arkitekter	0.3
cs30	Youth Centre Vestervang - Dannebrogsgade	Copenhagen, Denmark	2002	Entasis	n.a.
cs31	Floriade 2002	Hoofddorp, Netherlands	2002	Niek Roozen bv.	2286
cs32	Kollektivhuset - Collective house in Østerbro	Copenhagen, Denmark	2002	Claus Sondergaard / Domus Arkitekter	10.95
cs33	Ski Lifts Kriegerhornbahn	Lech am Arlberg, Austria	2002	Hans Riemelmoser	9.47
cs34	Lycée du Pic Saint-Loup 'Jean Jaurès'	Saint Clément de Rivière, France	2003	Agence Pierre Tourre	5.25
cs35	Fujipream Kohto Factory	Tatsuno, Japan	2003	n.a.	21.66
cs36	Ekoviikki, As Oy Helsingin Salvia building	Helsinki, Finland	2003	Arkkitehti Oy Reijo Jallinoja	24

ID (*1)	Project name	Location	Year (*2)	Architect, designer, artist, engineer or designing PV company	Rated power [kWp] (*3)
cs37	Daito Bunka University, Itabashi Campus, bldg. No. 3	Tokyo, Japan	2003	Ben Nakamura and Associates, Yamamoto Hori Architects	30
cs38	Christliches Kinderhaus Ulmenstrassee	Dresden, Germany	2003	Reiter & Rentzsch Architekten	1.1
cs39	WZH Waterhof	The Hague, Netherlands	2003	Ton Voets architecten BV BNA	21.9
cs40	HRDC - Habitat Research and Development Center	Windhoek, Namibia	2004	Nina Maritz	n.a.
cs41	McDonald's Cycle Center	Chicago, IL, USA	2004	Muller + Muller	7.48
cs42	PV Pergola in the Andalucia Technology Park	Malaga, Spain	2004	Pablo Coles, Ismael Eyras, Fernando Arribas	56
cs43	Caltrans District 7 Headquarters	Los Angeles, CA, USA	2004	Morphosis Architects	92
cs44	CCM 'The Brain'	Graz, Austria	2005	ILA	1.1
cs45	Footbridge at Nishinomiya Kitaguchi Station	Nishinomiya, Japan	2005	Yoshida Muto Architects	~13
cs46	The Core at the Eden Project	Bodelua, UK	2005	Nicholas Grimshaw & Partners	1.75 (28.72)
cs47	Whitehall Ferry Terminal	New York, NY, USA	2005	Frederic Schwartz Architects	40 (part opaque)
cs48	Community Centre Ludesch	Ludesch, Austria	2006	Architekten Hermann Kaufmann	~19
cs49	Fern Room at the Marjorie McNeely Conservatory	St. Paul, MN, USA	2006	HGA Architects and Engineers	11.5
cs50	SIMS Administration Building	Lonavla, India	2007	Christopher Charles Benninger Architects	30 (part opaque)
cs51	[Pod #001]	Copenhagen, Denmark	2007	Cecilia Wendt and Rikke Luther / Learning Site	0.26
cs52	Solar Tree Protoype	Vienna, Austria	2007	Ross Lovegrove	0.38
cs53	Q-Cells OF1 Thalheim	Bitterfeld-Wolfen, Germany	2007	bhss Architects	48
cs54	Berufsschulzentrum Riesstrasse	Munich, Germany	2007	Bauer Kurz Stockburger+Partner	n.a.
cs55	'La Vaguada' shopping mall	Madrid, Spain	2007	Chapman Taylor Espana	5.21 (95.18)
cs56	Vidursolar car park	Manresa, Spain	2007	Vidursolar	3.91
cs57	AquaCity Blue Sapphire	Poprad, Slovakia	2007	Pavel Kučera + Filip Rubáš / Archstudio	24.5
cs58	Kankakee Community College, Arts & Sciences Building	Kankakee, IL, USA	2007	Legat Architects	42
cs59	London City Hall	London, UK	2007 (2002)	Foster + Partners	~19 (~48)
cs60	Sun Monument 'Greeting to the Sun'	Zadar, Croatia	2008	Nikola Bašić	15
cs61	AEON LakeTown	Koshigaya, Japan	2008	Obayashi Corporation	13.3 (481)
cs62	SMA Solar Technology HQ	Niestetal, Germany	2008	HHS Planer+Architekten AG	n.a.
cs63	Oslo Operahuset	Oslo, Norway	2008	Snøhetta	35
cs64	True North / Lux Nova - Wind Tower	Vancouver, BC, Canada	2008	Sarah Hall (artist), Clive Grout, Walter Francl (architects)	0.4
cs65	Power Valley Jinjiang International Hotel	Baoding, China (PRC)	2008	n.a.	300
cs66	Marrakech Ménara Airport	Marrakech, Morocco	2008	E2A Architecture, AGA architecture, CR architecture, S. de Pretto	55.44
cs67	Le Losserand building 'Hotel Industrial'	Paris, France	2008	Emmanuel Saadi Architecte with Jean-Louis Rey, François da Silva	123.43
cs68	GreenPix - Zero Energy Media Wall	Beijing, China (PRC)	2008	Simone Giostra & Partners	79
cs69	The Main Stadium for the World Games 2009	Kaohsiung, Taiwan (ROC)	2008	Toyo Ito & Associates	1027.74
cs70	California Academy of Sciences	San Francisco, CA, USA	2008	Renzo Piano Building Workshop	172
cs71	Fifteen SunFlowers, An Electric Garden	Austin, TX, USA	2009	Harries/Héder Collaborative	13.69
cs72	Public lighting at Columbia Heights Civic Plaza	Washington, D.C., USA	2009	Zimmer Gunsul Frasca Architects	3.12
cs73	Novartis 'Gehry' building	Basel, Switzerland	2009	Gehry Partners, LLP	92.47
cs74	Dutch Nature Trust 'Nieuwkoopse Plassen'	Nieuwkoop, Netherlands	2009	MIII architecten	n.a.

ID (*1)	Project name	Location	Year (*2)	Architect, designer, artist, engineer or designing PV company	Rated power [kWp] (*3)
cs75	Natura Towers - MSF Group HQ	Lisbon, Portugal	2009	GJP Arquitectos	53.6
cs76	Partille Municipal Office	Partille, Sweden	2009	Figura Arkitekter AB	2
cs77	PV Frisbee	Taipei, Taiwan (ROC)	2009	Kao Ying-Chao, Bio Architecture Formosana	6.8
cs78	OLV Hospital	Aalst, Belgium	2009	VK STUDIO	46
cs79	Sequana Tower - Bouygues Telecom HQ	Issy-les-Moulineaux, France	2010	Bernardo Fort-Brescia / Arquitectonica	almost 30
cs80	Breeze Shelters at Marina Bay Sands	Singapore	2010	Cox Architecture with Architects 61	4
cs81	Centro de Arte Alcobendas	Alcobendas, Spain	2010	Fernando Parrilla and Maria Isabel Muñoz Parrilla	19
cs82	Cité du Design	Saint-Étienne, France	2010	LIN Fin Geipel + Giulia Andi	n.a.
cs83	Ombrière SUDI prototype	Saint-Étienne, France	2010	Le groupe Hervé and RCP design Global	n.a.
cs84	National Museum of Taiwan History	Tainan, Taiwan (ROC)	2011	Chien Hsueh-yi	195
cs85	Heron Tower	London, UK	2011	Kohn Pederson Fox	over 200
cs86	Welios - OÖ Science Center Wels	Wels, Austria	2011	archinauten	8.8
cs87	L'hôtel du Lac [SAPHIR]	Nagahama, Japan	n.a.	Akihiro Minamihira	n.a.
cstf1	Pompeu Fabra Library	Mataró, Spain	1996	Miquel Brullet i Tenas	22.49 (30.3)
cstf2	Simon Glas Factory	Bückeburg, Germany	2000	Simon Glas GmbH & Co. KG	0.9
cstf3	Tsukuba OSL	Tsukuba, Japan	2001	Nihon Sekkei	11.4
cstf4	Solar Centre MV	Wietow, Germany	2003	Gerd Vogt	1.44 (22.4)
cstf5	Lillis Business Complex	Eugene, OR, USA	2003	SRG Partnership	8.6 (36.1)
cstf6	CSIRO Energy Centre	Newcastle, Australia	2003	Cox Richardson	102 (part opaque)
cstf7	C.C.C. Kei Wai Primary School (Ma Wan)	Hong Kong, China (PRC)	2004	n.a.	4 (36)
cstf8	PTM Zero Energy Office (ZEO) building	Bandar Baru Bangi, Malaysia	2007	Ruslan Khalid Associates	11.64 (80.36)
cstf9	Experimental building of the TU Darmstadt, Solar Decathlon entry	Washington, D.C., USA	2007	TU Darmstadt, FG ee, Prof. Manfred Hegger	4 (9)
cstf10	Nursery school 'El Blauet'	Sant Celoni, Spain	2008	Petritxol 6 Architects	11.5
cstf11	Zero Energy Building @ BCA Academy	Singapore	2009	DP Architects	~2 (~190)
tf1	APS Fairfield PV facility	Fairfield, CA, USA	1991	Kiss Cathcart Anders Architects	0.4 (8)
tf2	EMR Center 'Energie-Forum-Innovation'	Bad Oeynhausen, Germany	1994	Frank O.Gehry & Associates Inc.	4
tf3	Tamayu Health Spa	Matsue, Japan	1996	Shin Takamatsu Architect & Associates	5
tf4	'Under the Sun' exhibition	New York, USA	1998	FTL	
tf5	BP-Solar Harmony Gas Station	Paris, France	2001	n.a.	10.4
tf6	Würth Holding Administration Building	Chur, Switzerland	2002	Jüngling + Hagmann	3.7
tf7	Primary School Trudering - Riem	Munich, Germany	2003	Krug & Partner Architekten	~2.2
tf8	House of the Future - Timber House	Sydney, Australia	2004	Innovarchi	n.a.
tf9	Kulturhaus Milbertshofen	Munich, Germany	2005	RPM-Architekten	4.7
tf10	Stillwell Avenue Terminal	New York, USA	2005	Kiss + Cathcart, Architects	199
tf11	Kanazawa Bus Terminal	Kanazawa, Japan	2005	TODEC Inc.	112
tf12	SCHOTT Ibérica	Sant Adrià de Besòs	2005 (2001)	Torsten Masseck / CISOL	1.35
tf13	Tiger Woods Learning Center	Anaheim, CA, USA	2006	Langdon Wilson	6.7
tf14	Herwig Blankertz School	Wolfhagen, Germany	2009	HHS Planer+Architekten AG	193.32
tf15	SFMTA Bus Shelters	San Fransisco, CA, USA	2009~	Lundberg Design	~0.01
tf16	GENyO	Granada, Spain	2010	Planho Consultores	19.3
tf17	NTC Tower	Khartoum, Sudan	2010	AINA International, CENTECS	51.39 (53.28)
tf18	Carport Roof at the 'Abfallwirtschaftsamt'	Munich, Germany	2011	Ackermann und Partner	145.73

4.3 Location, year of completion, rated power output

116 projects from five continents - see Fig.48:

- ➔ 75 from Europe - Germany: 23, Austria: 8, Spain: 8, France: 7, Denmark: 6, the UK: 6, the Netherlands: 4, Switzerland: 4, Sweden: 2, Belgium: 1, Croatia: 1, Finland: 1, Italy: 1, Norway: 1, Portugal: 1, Slovakia: 1,
- ➔ 18 from America - the USA: 17, Canada: 1,
- ➔ 17 from Asia - Japan: 7, China (PRC): 3, Taiwan (ROC): 3, Singapore: 2, India: 1, Malaysia: 1,
- ➔ 3 from Africa - Morocco: 1, Namibia: 1, Sudan: 1, and
- ➔ 3 from Australia.

Fig.48: Global distribution of selected projects

All selected projects were realised within the last 30 years, one in the 1980s, 21 in the 1990s and 94 since 2000, with the oldest crystalline silicon application dating from 1982, in the case of thin-film from 1991. The rated power output ranges from less than 1 kWp to 2.28 MWp, with most of the projects having between 1 kWp and 100 kWp installed. In some cases, LTPV are a supplement to a much larger opaque PV installation.

4.4 'Light-through' vs. 'see-through'

87 projects use crystalline silicon technology, 18 use thin-film technology and 11 use both technologies. This corresponds roughly with the general market share of both technologies. Even though a certain coherence of PV technology and type of LTPV can be observed, with crystalline silicon usually the 'light-through' type and thin-film the 'see-through' type, a few examples show that the other way round is possible too. Projects that use 'see-through' crystalline silicon cells are the **Solarcafé 'Sonnenzeit'** - cs13, **Ski Lifts Kriegerhornbahn** - cs33, **Community Centre Ludesch** - cs48 - and **Novartis 'Gehry' building** - cs73, whereas the **Carport Roof at the 'Abfallwirtschaftsamt'** - tf18 - utilises opaque thin-film in a 'light-through' way. **Simon Glas Factory** - cstf2 and **Experimental building of the TU Darmstadt** - cstf9 - employ both possibilities in the same building, 'see-through' CS cells and opaque thin-film in a 'light-through' way.

4.5 Building typology

LTPV have become integrated into many different kinds of buildings, and building structures, as well as non-building structures - Tab.8. It is quite surprising to see the variety of typologies, and it will be hard to find a niche where they were not applied. So it can be said, that the general application of LTPV is independent of the purpose of the building.

"[PV] should also be compatible with many other existing types of buildings not commonly associated with solar design (in particular, larger-scale, non-residential applications); PVs may even serve to create entirely new building types." [215]

[215] Kiss Cathcart Anders Architects, P.C. (1993) p.6

Tab.8: Built examples ordered based on typology

arts, sports and leisure	
museum	cs28, cs70, cs84, cstf1
entertainment centre, multi-purpose	cs68
design centre, multi-purpose	cs82
art and culture centre	cs81
recreation centre	cs30
stadium	cs69
swimming pool, spa	cs57, tf3
ski lift	cs33
opera	cs63
greenhouse, conservatory	cs49, cs51

community and healthcare	
community centre	cs48, tf9
religious building	cs6, cs19
hospital	cs78

science and education	
research facility	cstf3, cs40, cstf6
university	cs16, cs37, cstf5, tf16
vocational	cs50, cs54
school	cs34, cstf7, cs77, tf7, tf14
kindergarten, nursery school	cs38, cstf10
other facilities	cs17, cs46, cs58, cs86, cstf4, tf13

residential	
single family house	cs27
multi-family	cs1, cs20, cs25, cs36
elderly people	cs39
disabled people	cs32

public administration / public works	
central / federal government	cs22
regional	cs43
municipal	cs59, cs76, tf18
tourist office, visitor centre	cs24, cs74
fire station	cs18
waterworks	cs15
recycling facility	cs5
technique cabin	cs29

corporate and industrial	
office building	cs2, cs4, cs8, cs9, cs11, cs26, cs62, cs53, cs67, cs75, cstf2, cstf8, tf6, tf12, tf17, cstf11
high-rise, office building	cs79
multi-purpose	cs73, tf2
production facility	cs9, cs12, cs35, tf1

commerce, retail and mixed-use	
caféteria	cs7, cs13
shopping centre	cs55, cs61
exhibition hall	cs31
hotel	cs65, cs87
high-rise, mixed use	cs85
bicycle parking and repair	cs41

transportation	
airport terminal	cs66
train station	tf10
ferry terminal	cs47
bus station	tf11
car park	tf18

of which are	
retrofit	cs7, cs20, cs24, cs26, cs28, cs32, cs55, cs67, cs74, cs76, cstf4, tf10, tf12
heritage listed building	cs24, cstf4

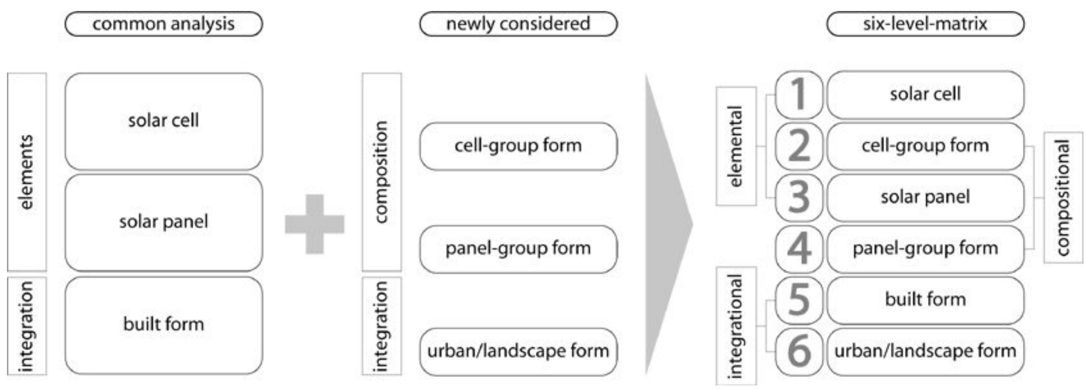
PV experimental building or structure	
	cs3, cs27, cs51, cstf9, tf8

non-building structures (NBS)	
plaza canopies	cs21, cs48
sculpture	cs10, cs44, cs71
urban furniture, lighting	cs52, cs72, cs80
urban media installation	cs60
pergola	cs40, cs42
playground	cs77
park shelter, bus shelter	cs3, cs23, tf15
gas station	tf5
footbridge	cs45
carport	cs56, cs83
ventilation tower	cs64
catamaran	cs14

5 Six-Level-Matrix for analysis

5.1 Limitation of common analysis

As a matter of fact, the PV market has been dominated by opaque products since the beginning. Generally speaking, there is nothing wrong with opaque products. However, as the photovoltaic semiconductor requires light exposure, it is usually, at least partially encapsulated in transparent materials. As such the complex PV product inherits both attributes, which can be altered for a variety of translucent and semi-transparent PV products. As the degree of light-transmission is mostly inversely proportional to the areic electricity generation efficiency, it is not advocated by the majority of PV manufacturers. In buildings, however, light-transmitting areas are seen as a necessity, rather than as a harm. The dualism of light and shadow combined with visibility between spaces, inside / outside in a building, and the ability to freely alter the relation between them, has been a driving force for building and architectural design surely even before Vitruvius. When using the terminology of efficiency, it can be easily argued, that the areic loss of electricity generation efficiency isn't in fact a loss at all, but a much more valuable gain in design flexibility for enhancing the spatial, visual, architectural and cultural qualities of the building.



(a) (b) (c)

Fig.49: Evolution of a matrix for analysis

Even though many built examples of LTPV are included in the reference literature - see 1.1 Research background and Appendix A, the analysis commonly focused on opaque PV due to the overwhelming market share and further reasons like areic efficiency explained. This kind of 'common analysis' focused on the integration of PV products as elements into the building envelope or built form - Fig.49(a). My thesis is, that the ability to alter and adapt these elements into a compositional whole is not well covered by the common approach. Certain issues that consider the compositional qualities - Fig.49(b) - are only recently noticeable or noticeable only when looking from the point of LTPV. Therefore an extended matrix for analysis - Fig.49(c) - is suggested.

5.2 Rationale for extended analysis

The development of opaque PV modules has been driven by maximising packing density of solar cells for assembly into rectangular solar panels. An example of this trajectory can be studied by looking at monocrystalline silicon cells, and the displacement of round cells in favour of pseudo-square cells. Even though the trimming of a round ingot results in material loss, it is outweighed by higher space efficiency to fit more cells into a standard rectangular panel with less redundant areas. What has been the driving force for opaque standard PV modules is having a strong impact on the development of the niche product LTPV as well. However, the introduction of 'light-through' LTPV - see 2.2.7 Translucency and transparency - 'light-through' and 'see-through' - has rendered the basic necessity of a high packing density less important in exchange for light transmission. When the initial assumption is neutralised, the result is less pre-determined and left open for alteration. Here I suggest to freshly look at the issue of the cell arrangement possibilities, which I call **cell-group form.**

Furthermore, the standard rectangular PV module may have its advantage in terms of manufacturing efficiency, but should be challenged as a 'standard' in terms of architectural integration for two reasons. The first reason is, that external, design influencing factors like site or legal conditions result often enough in non-rectangular design decisions. To denounce such conditions as 'non-standard' is irritating to say the least. The second reason is the tendency in contemporary building envelope designs to favour non-rectangular, *"polygonal tessellations"* and question, even *"oppose the Cartesian grid"*.[216] The effect of both reasons is noticeable for LTPV, but applies to opaque PV as well. Here I suggest to look at the panel shapes and arrangement possibilities, which I call **panel-group form.**

Last, but not least, the focus of discussion and research into BIPV has been on building-integration. It is often set as the preferred alternative to simply building-mounted PV - see 2.2.1 BIPV. A shortcoming of both terms is the fixation on buildings, which refers to building structures, thus excluding all non-building structures. The focus on buildings leaves out many well integrated examples of PV in bus shelters, works of art, etc. - see 2.2.5 NBS - non-building structures. Furthermore, integrated was set as an opposite to simply added, integration into the building fabric and building energy network as opposed to the addition 'on top' of a PV-independent building, neither depending on PV as building material, nor on the energy supplied by the PV array. However, both PV systems, building-integrated as well as

[216] Zaera-Polo (2009) p.22

building-mounted, are located in close proximity to the building's envelope. When looking at it from the distance, the discussion on integrated vs. mounted appears superficial. Integration in architectural terms extends beyond the building envelope. The analysis of integration into the human environment should be considered on a wider level, including building envelopes and the whole range of urban surfaces, even extending into already developing new forms of landscape patterns.[217] Again, this issue is not limited to LTPV, but relevant for opaque PV and other forms of renewable energy generation as well. Here I suggest to look at the macro scale, which I call **urban / landscape form.**

The issues addressed by the common analysis and the suggested three newly considered issues are combined to form a **Six-Level-Matrix** with two elemental, two compositional and two integrational levels. The characteristic features of each level are illustrated in - Fig.50.

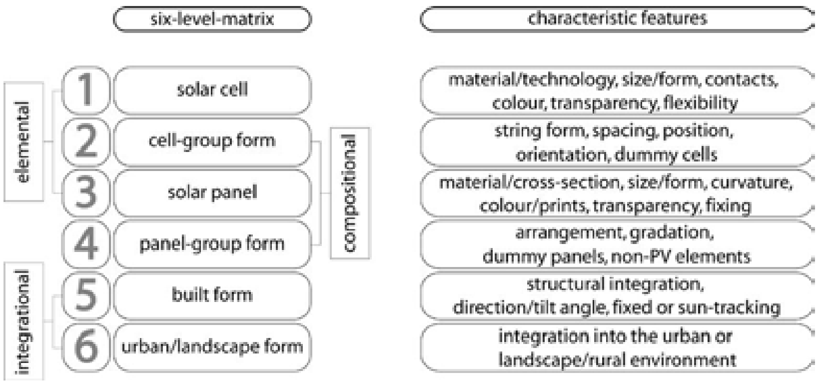


Fig.50: Six-Level-Matrix and characteristic features

5.3 Overview of levels and projects

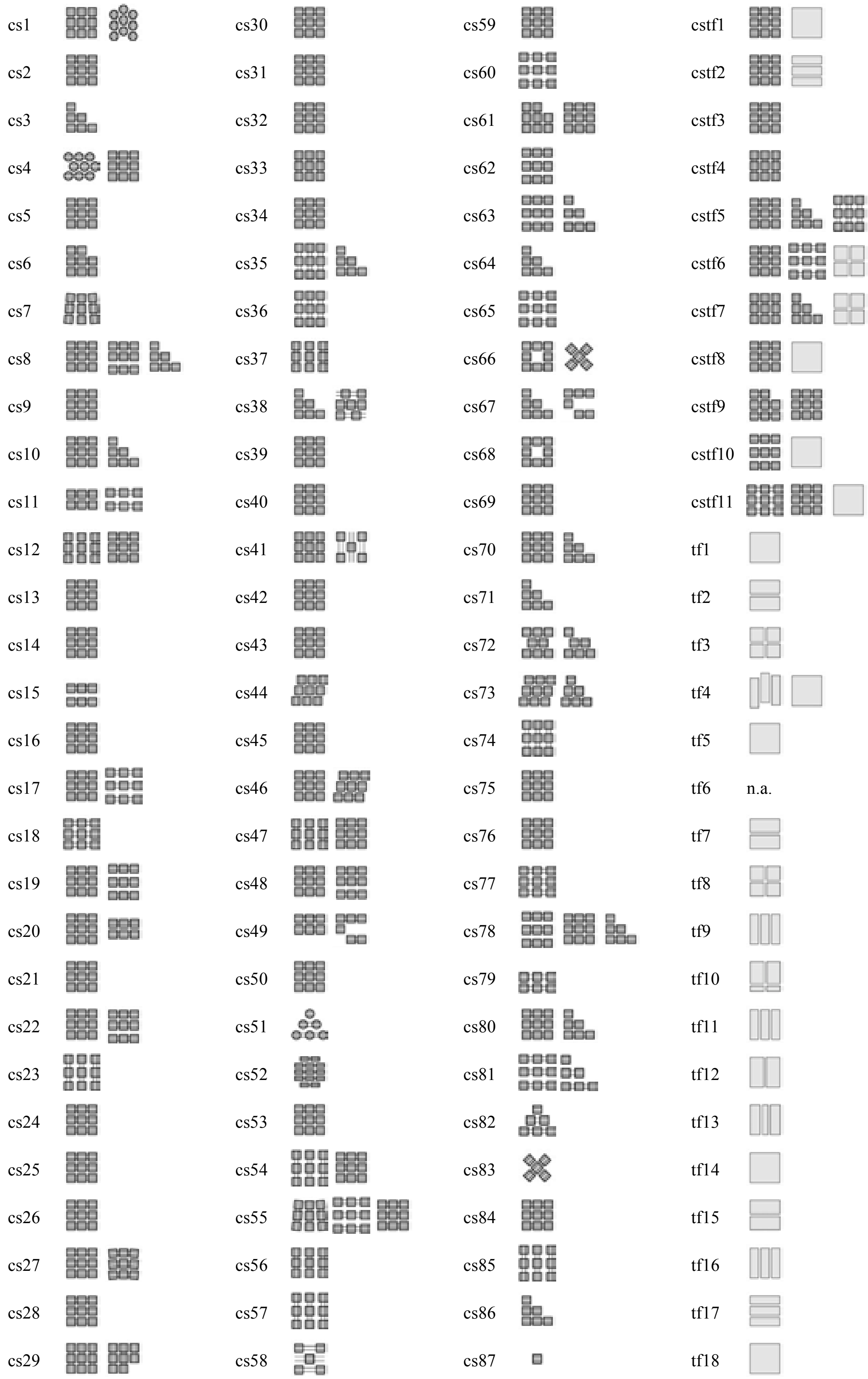
This part of the study is intended to be a rather comparative analysis. Tab.9 to Tab.14 - present a level based overview of the selected projects - see 4.2 Selected projects for analysis. For quick reference a graphical representation based on small icons was chosen. In contrast to the manifold features at each level - see Fig.50, the icons as such can only represent a selection of certain aspects in a reduced graphical language. A more detailed individual introduction to each project with images, technical and descriptive information plus the same graphical icons can be found in Appendix C, where a data sheet for each project is included. The sections that follow after the tables will analyse each feature step by step and provide an overview of the design criteria based on the built examples and available technologies.

[217] Swaffield (2009)

Tab.9: Level 1 - solar cell

cs1	c-Si c-Si	cs30	mc-Si	cs59	c-Si	cstf1	100 100 a-Si
cs2	100	cs31	125	cs60	125	cstf2	mc-Si TF
cs3	100	cs32	c-Si	cs61	mc-Si	cstf3	150 125 a-Si
cs4	c-Si c-Si	cs33	100	cs62	c-Si	cstf4	c-Si mc-Si a-Si
cs5	125	cs34		cs63	100	cstf5	mc-Si a-Si
cs6	125	cs35	mc-Si	cs64	125	cstf6	c-Si mc-Si DSC
cs7	100	cs36	100	cs65		cstf7	150 a-Si CIS
cs8	100	cs37	156	cs66	156	cstf8	mc-Si a-Si c-Si
cs9	100	cs38	mc-Si	cs67	150	cstf9	a-Si 125 125
cs10	125	cs39		cs68	125	cstf10	156 a-Si
cs11	125	cs40	100	cs69	mc-Si	cstf11	125 mc-Si a-Si CIGS
cs12	mc-Si	cs41	c-Si	cs70	125	tf1	a-Si
cs13	100	cs42	c-Si	cs71	156	tf2	a-Si
cs14	100	cs43	c-Si	cs72	156	tf3	a-Si
cs15	100	cs44	mc-Si	cs73	100	tf4	a-Si
cs16	125	cs45	125	cs74		tf5	a-Si
cs17	100 100 125	cs46	125 mc-Si	cs75	156	tf6	CIS
cs18	mc-Si	cs47	mc-Si	cs76	125	tf7	a-Si
cs19	mc-Si	cs48	125	cs77	156	tf8	DSC
cs20	mc-Si	cs49	c-Si mc-Si	cs78	c-Si	tf9	a-Si
cs21	125	cs50	mc-Si	cs79	c-Si	tf10	a-Si
cs22	c-Si	cs51	100	cs80	125	tf11	a-Si
cs23	100	cs52	mc-Si	cs81	mc-Si	tf12	a-Si
cs24	mc-Si	cs53	156	cs82	c-Si	tf13	a-Si
cs25	mc-Si	cs54	c-Si	cs83	125	tf14	a-Si
cs26	100	cs55	156	cs84		tf15	OPV
cs27	125 100	cs56	156	cs85	156	tf16	a-Si
cs28	125	cs57	125	cs86		tf17	a-Si
cs29	mc-Si	cs58	156	cs87	c-Si	tf18	a-Si

Tab.10: Level 2 - cell-group form

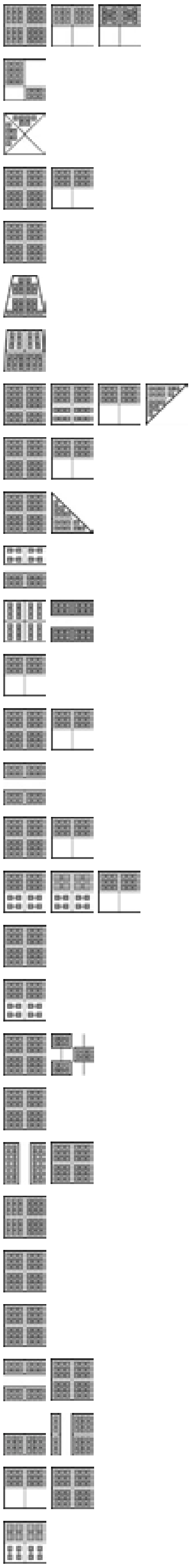


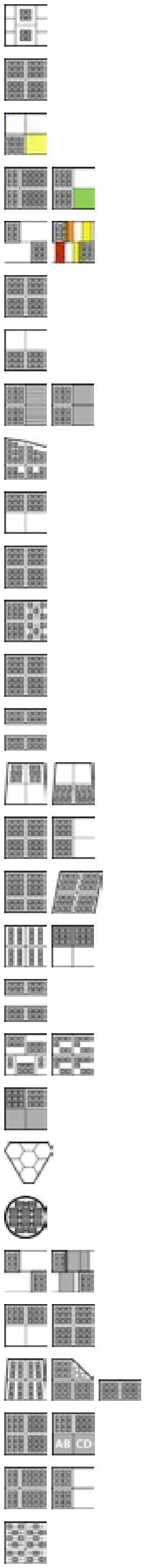
Tab.11: Level 3 - solar panel

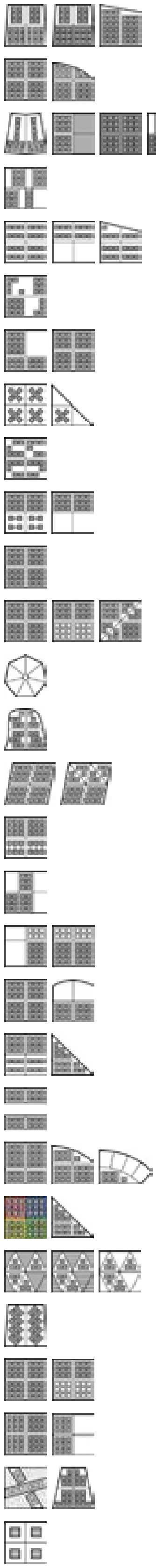
cs1	cs30	cs59	cstf1
cs2	cs31	cs60	cstf2
cs3	cs32	cs61	cstf3
cs4	cs33	cs62	cstf4
cs5	cs34	cs63	cstf5
cs6	cs35	cs64	cstf6
cs7	cs36	cs65	cstf7
cs8	cs37	cs66	cstf8
cs9	cs38	cs67	cstf9
cs10	cs39	cs68	cstf10
cs11	cs40	cs69	cstf11
cs12	cs41	cs70	tf1
cs13	cs42	cs71	tf2
cs14	cs43	cs72	tf3
cs15	cs44	cs73	tf4
cs16	cs45	cs74	tf5
cs17	cs46	cs75	tf6
cs18	cs47	cs76	tf7
cs19	cs48	cs77	tf8
cs20	cs49	cs78	tf9
cs21	cs50	cs79	tf10
cs22	cs51	cs80	tf11
cs23	cs52	cs81	tf12
cs24	cs53	cs82	tf13
cs25	cs54	cs83	tf14
cs26	cs55	cs84	tf15
cs27	cs56	cs85	tf16
cs28	cs57	cs86	tf17
cs29	cs58	cs87	tf18

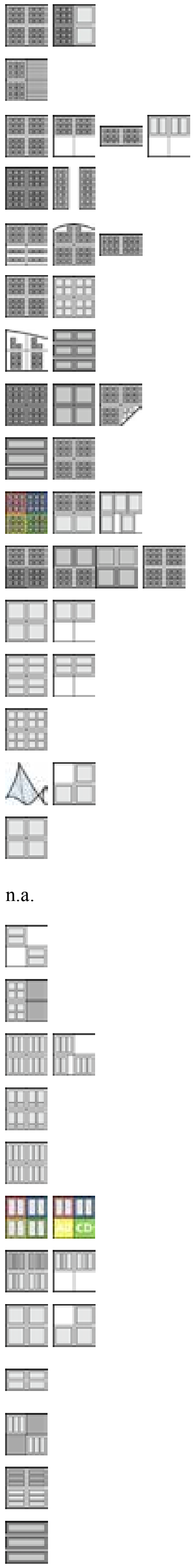
Tab.12: Level 4 - panel-group form

cs1		cs30		cs59		cstf1	
cs2		cs31		cs60		cstf2	
cs3		cs32		cs61		cstf3	
cs4		cs33		cs62		cstf4	
cs5		cs34		cs63		cstf5	
cs6		cs35		cs64		cstf6	
cs7		cs36		cs65		cstf7	
cs8		cs37		cs66		cstf8	
cs9		cs38		cs67		cstf9	
cs10		cs39		cs68		cstf10	
cs11		cs40		cs69		cstf11	
cs12		cs41		cs70		tf1	
cs13		cs42		cs71		tf2	
cs14		cs43		cs72		tf3	
cs15		cs44		cs73		tf4	
cs16		cs45		cs74		tf5	
cs17		cs46		cs75		tf6	n.a.
cs18		cs47		cs76		tf7	
cs19		cs48		cs77		tf8	
cs20		cs49		cs78		tf9	
cs21		cs50		cs79		tf10	
cs22		cs51		cs80		tf11	
cs23		cs52		cs81		tf12	
cs24		cs53		cs82		tf13	
cs25		cs54		cs83		tf14	
cs26		cs55		cs84		tf15	
cs27		cs56		cs85		tf16	
cs28		cs57		cs86		tf17	
cs29		cs58		cs87		tf18	

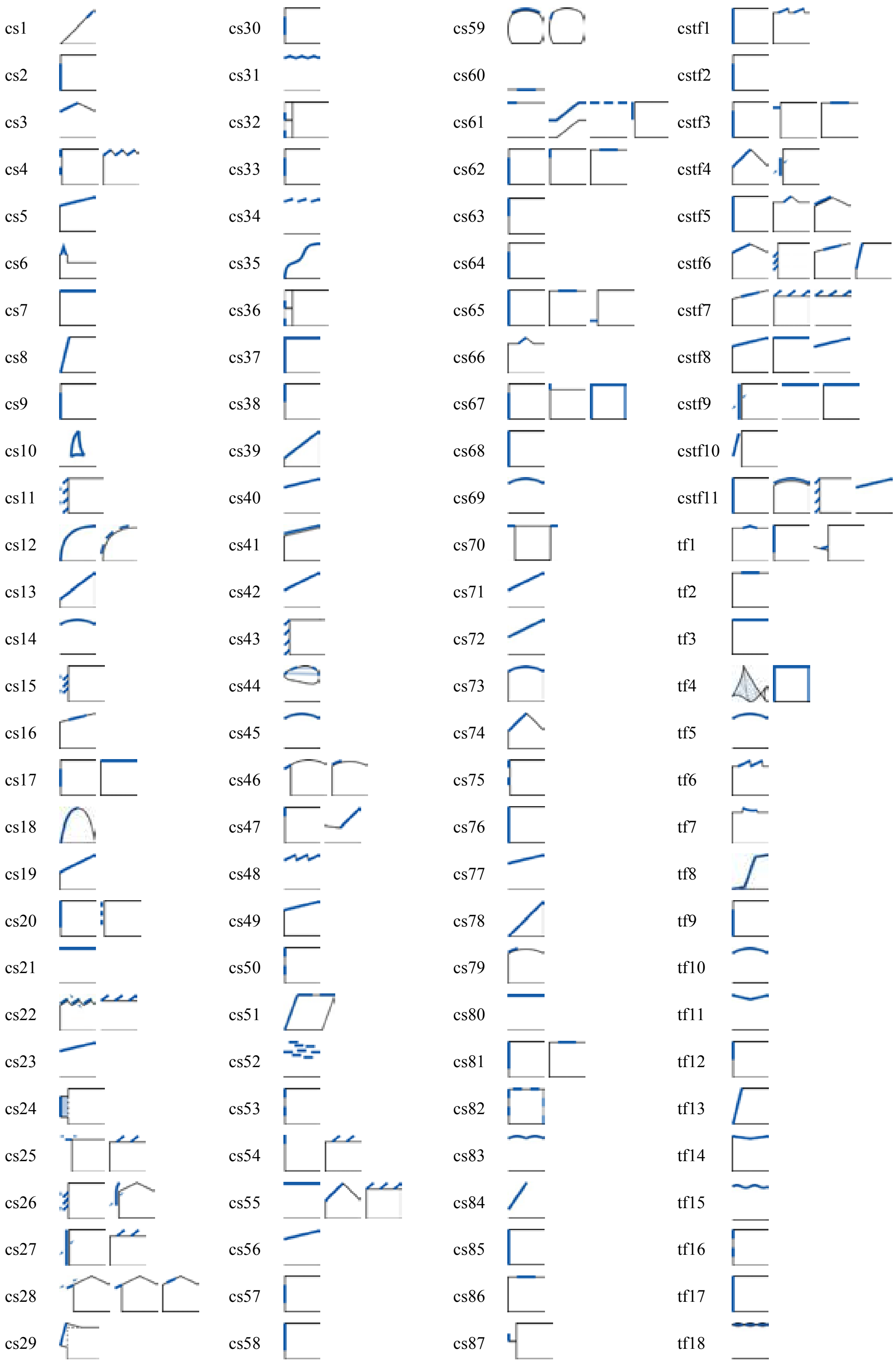




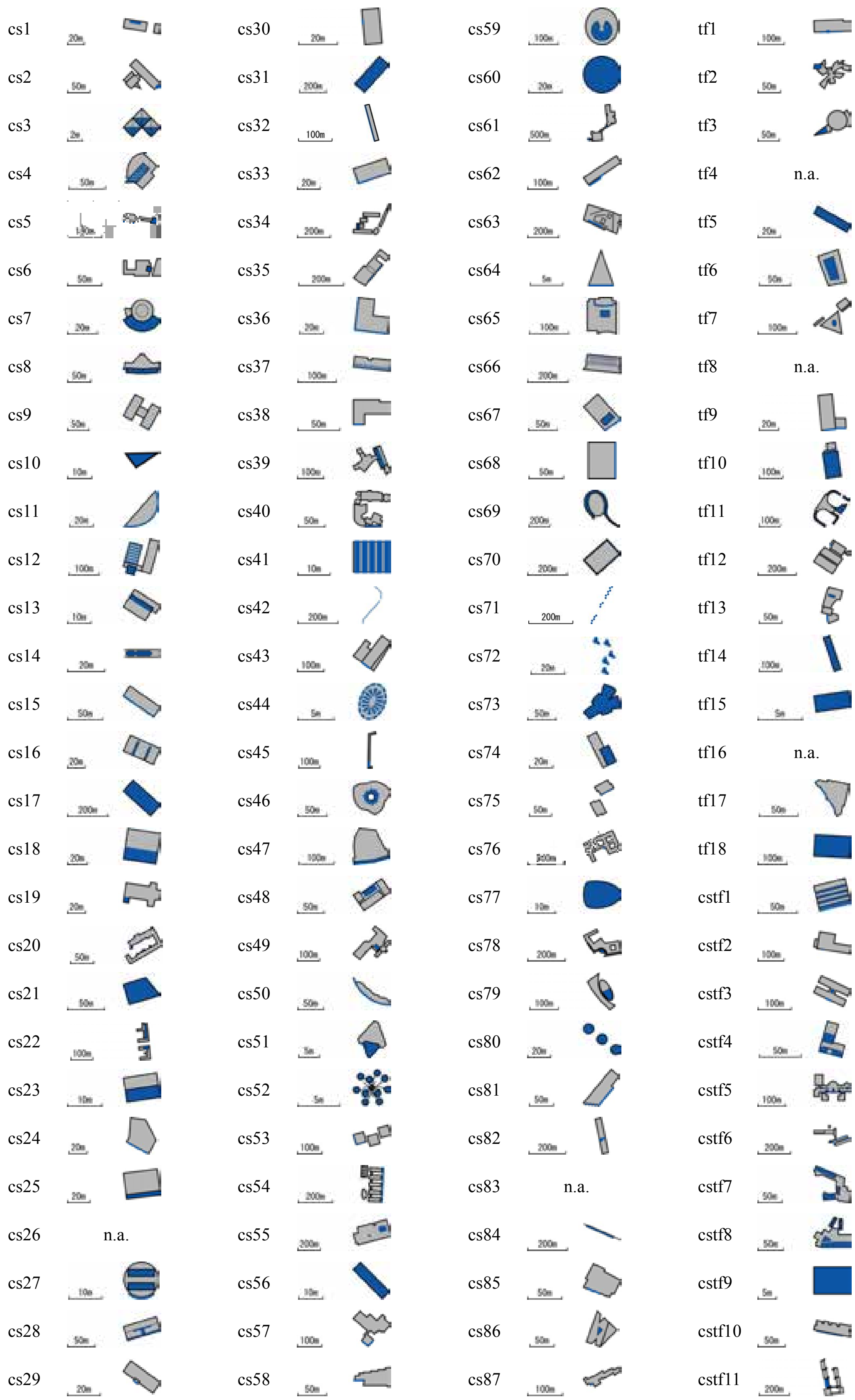




Tab.13: Level 5 - built form



Tab.14: Level 6 - urban / landscape form



5.4 Level 1 - solar cell

Due to strongly technology dependent characteristics, mainly separated in the two major groups of crystalline silicon cells and thin-film cells, it is best to analyse the selected built examples on this level within these two distinctive groups.

5.4.1 Crystalline silicon cells

5.4.1.1 Material and technology

Both variants of crystalline silicon, mono- and multicrystalline cells were used in the built examples. Even though multicrystalline is the younger technology of the two, almost all examples, except the early **'Wohnanlage Richter' residential complex** in Munich, Germany - cs1, were built after the widespread introduction of the technology thus giving both technologies the same chance to be used. In fact, it isn't possible to see any preference within the examples for either of the two technologies. In some rare cases, both technologies are used in separate panels side by side, for example at the **Academy Mont-Cenis** in Herne, Germany - cs17. Most of the multicrystalline silicon cells were produced using the standard casting process, but at the **Waterworks Schwerin** in Schwerin, Germany - cs15 - cells produced by the alternative EFG-process are used.

5.4.1.2 Shape

Almost all projects use full-size cells. Most of the projects use either square or pseudo-square (monocrystalline silicon) cells. Round (monocrystalline silicon) cells were used in only a few projects, the **Brundtland Centre** in Toftlund, Denmark, built 1995 - cs4, the **Tsukuba OSL** in Tsukuba, Japan, built 2001 - cstf3, the **[Pod #001]** in Copenhagen, Denmark, built in 2007 - cs51, as well as in the opaque PV panels of the **'Wohnanlage Richter'** built 1982 - cs1. It was assumed that round cells were more often used in earlier projects, which is probably true in relative numbers, but difficult to verify in absolute numbers, as only very few examples exist. However, what had been a necessity in 1982 when most standard modules used round cells, becomes a deliberate, almost vintage or retro design intent in 2007. Cut cells are hardly ever used, but half-size cells were chosen for the window shutters at the **Solar Centre MV** in Wietow, Germany - cs15. This might be attributed to the small size of the panels with smaller cells resulting in more gaps, but also the horizontal arrangement of the cells being more similar to the traditional appearance of louvred wooden shutters. Third-size cells are used in some standard, opaque modules at **The Core at the Eden Project** in Cornwall, UK - cs46. A different kind of cut cells, randomly cut but electrically not connected dummy cells to adjust the cell pattern with the panel shape, are described later - see 5.5.3 Dummy cells.

5.4.1.3 Size

All projects use cells in one of the three 'standard' sizes of 100 mm, 125 mm or 150~156 mm. No less common cell dimensions were found in LTPV applications within the corpus of selected examples. Most projects stick to the use of one size of cells throughout the project, only a few use different sizes but in different areas that can't be seen together. Exceptions are the **Academy Mont-Cenis** - cs17 - and the **Gentofte Teknikhytte** in Gentofte, Denmark - cs29 - were different sizes were used in adjacent panels to achieve a gradation of light and visibility.

5.4.1.4 Contacts and front pattern

The most often used cell is the H-pattern standard cell with 2 bus bars. H-pattern cells with 3 bus bars were used at the **AquaCity Blue Sapphire** in Poprad, Slovakia - cs57, as well as in opaque standard panels at **'La Vaguada' shopping mall** in Madrid, Spain - cs55 - and at **The Core at the Eden Project** - cs46. Back-contact cells were used at the **California Academy of Sciences** in San Francisco, USA - cs70. However, all of these cells are 'standard' depending on the manufacturer.

5.4.1.5 Colour

The colour of the solar cells is mostly technology specific, a darker blue or black for monocrystalline cells, and a slightly brighter blue for multicrystalline cells. Cells in these 'standard' colour are used most often. Grey or silver cells were used for the window shutters at the **Solar Centre MV** - cs15 - with grey a neutral tone that matches the gamut of warm colours used for the building, and at the **Novartis 'Gehry' building** in Basel, Switzerland - cs73 - where the grey colour integrates the solar technology into the steel-glass high-tech material aesthetic of the building. At the **Alès Tourist Office** in Alès, France - cs24 - brown/black cells were used to match the tone of the building's original stone façade.

5.4.1.6 Transparency and light-transmission

Even though semi-transparent cells are usually not associated with CS technology, it is interesting to see the significant number of projects that use semi-transparent cells, even though only one company manufactures them. As such, 'see-through' CS cells can be regarded as a well-established technology. Built examples are the **Solarcafe 'Sonnenzeit'** in Kirchzarten, Germany - cs13, the **Ski Lifts Kriegerhornbahn** in Lech am Arlberg, Austria - cs33, the **Community Centre Ludesch** in Ludesch, Austria - cs48, the **Novartis 'Gehry' building** - cs73, the **Simon Glas Factory** in Bückeburg, Germany - cstf2, and the **Experimental building of the TU Darmstadt** for the Solar Decathlon 2007 in Washington, D.C., USA - cstf9.

The most common light-transmission rate is 10%. Semi-transparent cells were mostly used end-to-end.

5.4.1.7 Flexibility and bent cells

Similar to transparent cells, flexible or bent cells are usually not associated with CS technology due to the generally brittle material property. Nevertheless, that this isn't impossible is illustrated by a few applications: a showcase installation at the **Fujipream Kohto Factory** in Ibo, Hyogo prefecture, Japan - cs36, a test development at the **Gemini House** in Weiz, Austria - cs27, and most beautifully at the **Solar Catamaran RA 66 'Helio'** that runs on the Lake Constance between Switzerland and Germany - cs14, with further application in later catamaran models by the same manufacturer Kopf Solarschiff GmbH.[218]

5.4.1.8 Bifacial cells

Such cells have the great advantage of being photoactive on the front and back side, which makes them ideal for applications exposed to the morning and evening sun, like in North-South oriented balustrades, barriers or free-standing walls. An example is the noise barrier at the **Trade School Centre** in Munich, Germany - cs54.

5.4.2 Thin-film cells and sheets

5.4.2.1 Material and technology

In contrast to crystalline silicon, thin-film technology is much more varied in terms of the PV technology with more and new photoactive materials still emerging. The longest established technology for building integration is based on amorphous silicon, and as such the large majority of built LTPV examples of thin-film PV use this material. Few LTPV examples exist that use CIGS, and none were found that use CdTe. Nonetheless, both latter technologies are well established too, especially CdTe with a significant market share in opaque PV modules. Noteworthy, however, are the first applications of the still young DSC and OPV technology, both mostly still in the research phase with few available products on the market. DSC was used at the temporary **Houses of the Future - Timber House** built 2004 in Sydney, Australia - tf8 - and a test installation at the **CSIRO Energy Centre** built 2003 in Newcastle, Australia - cstf6. OPV was used at the **SFMTA Bus Shelters** in San Francisco, USA - tf15.

[218] Kopf Solarschiff GmbH <http://www.kopf-solarschiff.de/>

5.4.2.2 Shape and size

The shape in all applications are rectangular cells and sheets, with sizes dependent on the manufacturer. Most projects use full-size sheets. Sometimes smaller sheets are added beside larger sheets to fill the required panel area, an example for this is the **Stillwell Avenue Terminal** in New York, USA - tf10. Two projects use thin stripes of TF sheets mounted on louvres, the **Experimental building of the TU Darmstadt** - cstf9 - and the **Simon Glas Factory** - cstf2.

5.4.2.3 Colour

Similar to crystalline silicon cells, the 'standard' colour of the TF cells is mostly technology specific. In the case of a-Si TF it is usually a dark reddish or black shade, in the case of CIGS it is a dark shade close to black. DSC, however, are primarily colourful with the two built examples mentioned earlier using a deep red-orange dye. Other, non-standard colours were not found within the corpus of built examples.

5.4.2.4 Transparency and light-transmission

In contrast to crystalline silicon, semi-transparency is one of the main features clearly associated with thin-film PV cells/sheets, which can be specified and ordered. The built examples have a transparency that starts at the technology specific minimum of about 4~5% at the **APS Fairfield Factory** in Fairfield, CA, USA - tf1 - or the **Stillwell Avenue Terminal** - tf10, and goes up to 50% with CIGS thin-film PV at the **Würth Holding Administration Building** - tf6. At the **Tiger Woods Learning Centre** in Anaheim, CA, USA - tf13 - different transparencies were chosen for different panels to provide a gradation from shaded area to vision area, 5% at the top, 25% in the middle and vision glass at the bottom.

Even though a flexible adjustment of the light-transmission of the monolithic TF structure is theoretically possible, only a few manufacturer dependent fixed values dominate the product range. A value of 10% especially with a-Si LTPV appears to be a manufacturer introduced and somewhat established compromise in balancing maximum electricity generation with semi-transparency towards a bright sky or exterior. As such, the shading aspect is given a very important role too.

5.4.2.5 Flexibility

The other main feature clearly associated with thin-film PV is the flexibility of TF cells/sheets to easily adjust to curved surfaces. Interestingly here, that two examples of application at curved surfaces use opaque TF laminates embedded or added to transparent membranes, at the **Car Park of the Municipal Waste Management Office** in Munich, Germany

- tf18 - and the tensile structure at the **'Under the Sun' exhibition** in New York, USA - tf4. As such the combination of opaque TF with a light-transmissive supporting membrane is a 'light-through' type of LTPV installation. An example for the use of flexible 'see-through' type of LTPV are the **SFMTA Bus Shelters** - tf15.

5.4.3 Level 1 - summary

The strongest differentiation between projects at this level runs along the technological line of first generation crystalline silicon PV and second generation thin-film PV, and as such both technology groups were analysed separately. In terms of PV technological research, the most effort is surely directed at this level, at the scale of the solar cell, to improve light-converting and energy-generating efficiencies of the photoactive materials. The variety of PV technologies - see 2.3 PV technologies, as well as material characteristics - see 2.4 Characteristics of crystalline silicon PV and 2.5 Characteristics of thin-film PV, is proof of this. However, from a PV application point of view, the variety of technologies has not equally resulted in a large variety of customer choice except for the choice of technology. The execution of choice at this level could be best described with 'sticking to the standard' and often 'efficiency rules' with only few exceptions. The best example are the 'colour' solar cells. Even though crystalline silicon cells in 'other' colours than the dark blue or black 'standard' have been available for quite some time, they are hardly ever used. This can have many reasons. The most likely reason is the reduced efficiency of colour cells - see 2.5.2 Colour. The other reason might be the limited range of available cells in alternative colours, with just one or two dozen at most. But maybe it is also the nature of LTPV installations, often in skylight and roofs, where the sun-exposed side and its colour isn't as important as for instance in façade applications at street level. As such, the use of colour at this level is still technology specific rather than customised and surely not as varied as with other artificial building materials that are available in a range of colours. However, a limited range of colour has never been a problem with natural materials, like timber or stone, quite the opposite. With natural materials it is seen as a 'given' limitation that might not require customisation. In fact, even though solar cells are an industrial product and artificial material, their surface texture can be as varied as with natural materials, as is beautifully illustrated with Fig.51, the **Solarsail** in Münsingen, Switzerland - cs10.

Fig.51: Different shades of blue monocrystalline silicon cells
Credit: © Halle 58 Architekten

Nevertheless, examples that use alternative solar cell colours as a distinct and characteristic feature of its architecture exist, as the next two projects, not included in the corpus of selected examples, illustrate. The **WKÖ Tirol** in Austria - see Appendix B: 301 - has a balustrade with embedded yellow-greenish[219] multicrystalline silicon cells that fit to the gamut of natural colours of the building and the mountainous environment. At the **'home+' experimental building** - see Appendix B: 493, a contribution of the HFT Stuttgart to the prestigious Solar Decathlon Europe competition in Madrid 2010, coloured multicrystalline silicon cells in gold and bronze - see Fig.14(b) and Fig.14(d) - were used at the façade beside black monocrystalline silicon cells on the roof.[220]

Fig.52: WKÖ Tirol
Credit: © ertex Solar

Fig.53: 'home+' Experimental building
Credit: © Sunways

219 Even though the cells look greenish, their colour name is 'Metallic Gold' - see Fig.14(l) in section 2.4.3 Front and back side colour and pattern and 'High Efficiency Color PV Expert' (2010) p.21.
220 Sunways AG (2010)

5.5 Level 2 - cell-group form

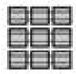
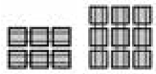
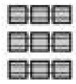
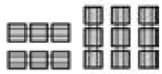
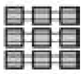
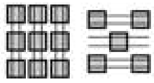
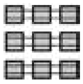
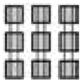
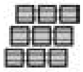
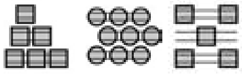
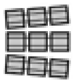
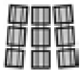
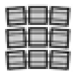
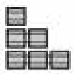
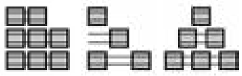
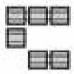
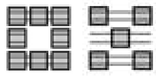
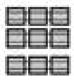
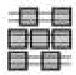
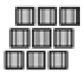
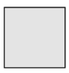
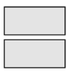
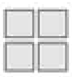
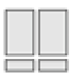
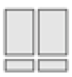
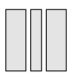
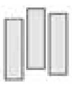
The cell-group form (level 2) is the number of arranging possibilities of individual cells (level 1), but also sheets in the case of thin-film PV. Whereas the previous level could be considered as 'conservative' in terms of execution of choice, it completely changes at this level. May it be the absence of an LTPV standard per se, as most 'standards' in PV derive from opaque modules, or the possibility of altering an aboriginally architectural feature in terms of light-transmitting or shading pattern, an interesting variety of custom or 'bespoke' solutions was found.

As this is surely and strongly dependent on the PV technology, crystalline silicon and thin-film are analysed separately. The established key design parameters are summarised in Tab.15, parameters (a) to (m) for CS cells, and (A) to (E) for TF sheets. This table is not exhaustive in terms of technological or conceivable design possibilities, but solely derived from the built examples.

5.5.1 Crystalline silicon cell-group form

Even though the most common design patterns - Tab.15 - are based on parameters (b), (c) and (d), with (c+d) or (b') as the wide spacing variation of (b), within a rectangular solar panel, the existence of others shows, that far more variations are possible. Alternative designs are necessary, when the solar panel, due to its integration into the building design, isn't rectangular. Parameter (e) follows parallelogram shaped panels, (e) and (f) follow trapezoidal shaped panels, (g) follows curved panels, and (h) or any combination with (h) can be used for any shape. This approach can be called **'top-down',** as it derives a design for the subordinate level, in this case the arrangement of cell groups (level 2), from the superordinate level, here the shape of the solar panel (level 3). However, parameters (i), (j), (k), (l) and (m), but also (h) as used in the built examples show a different tendency. This alternative approach can be called **'bottom-up',** as they are applied more freely to rectangular as well as differently shaped solar panels.

Tab.15: Cell-group form for crystalline silicon cells and thin-film sheets

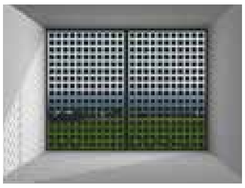
Main image	Variations / Combinations	Pattern description	Built examples
		Crystalline silicon cells	
		(a) single cell or string	cs87 (dummies)
		(b) parallel strings, equal distances	majority, also partially including (e) and (h)
		(c) equally increased and wider string distance	cs12, cs15, cs19, cs37, cs47, cs56, cs62, cs63, cs78, cstf10
		(d) equally increased and wider cell distance	cs18, cs35, cs36, cs41, cs58, cs74, cs77, cs79, cstf5, cstf11
		(c+d) or (b') as variation of (b) with equally 'wide' cell and string distance	cs11, cs17, cs23, cs51, cs54, cs55, cs57, cs60, cs65, cs81, cs85, cstf6
		(e) offset strings	cs1, cs4, cs41, cs46, cs51, cs58, cs72, cs73, cs82
		(f) radiating strings	cs7, cs55
		(g) curved strings	cs27
		(h) shortened string length	cs3, cs6, cs8, cs10, cs29, cs35, cs38, cs51, cs52, cs61, cs63, cs64, cs66 ~ cs68, cs70 ~ cs73, cs78, cs80 ~ cs83, cs86, cstf5, cstf7, cstf9
		(j) gaps	cs41, cs49, cs58, cs66, cs67, cs68
		(j) varied string distance	cs8, cs22, cs48
		(k) varied cell distance	cs38
		(l) rotation in relation to laminate edges	cs66
		(m) broken strings	cs44
		Thin-film sheets	
		(A) single sheet	cstf8, cstf10, cstf11, tf1, tf4, tf5, tf14
		(B) adjacent sheets one-directional	cstf2, tf2, tf7, tf9, tf11, tf12, tf13, tf15, tf16, tf17
		(C) adjacent sheets two-directional	cstf6, cstf7, tf3, tf8, tf10
		(D) different sheet sizes	tf10, tf13
		(E) offset sheets	tf4

5.5.1.1 Standard patterns for crystalline silicon PV

The most common arrangement of the cells is in a rectangular grid with equal or near equal spacing between the cells in both directions. A comparison of the different cell sizes with an equal distribution of 50% cells and 50% gaps for translucency is shown in Tab.16.

Tab.16: Square and round crystalline silicon cells
50% cells and 50% gaps for translucency

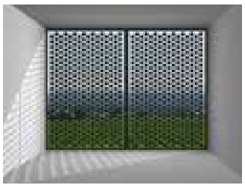
(a)
546 square cells 100x100 mm,
hor/ver 40/35 mm spacing



(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

This clearly illustrates that with larger cells much less are required, which reduces the amount of electrical connections, but reinforces view obstructions. This isn't a standard per se, but as it is widely offered by many manufacturers, it slowly develops into a kind of quasi-standard for LTPV. Round cells are arranged either in a rectangular grid, a built example can be seen at the **Tsukuba OSL** - cstf3 and Tab.16(d), or in an oblique hexagonal grid as at the **Brundtland Centre** - cs4 and Tab.16(e).

5.5.1.2 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 of end-to-end interconnected cells, the strings than clearly forming homogeneous stripes - Tab.17.

Tab.17: Variation of wider cell spacing in one direction

(a)

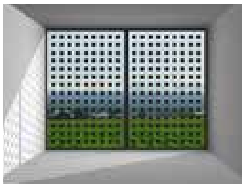
(b)

At façades or inclined roofs the orientation can be distinguished in horizontally, an example is the **Oslo Operahuset** in Oslo, Norway - cs63 - or vertically oriented stripes as **Daito Bunka University, Itabashi Campus, bldg. No. 3** in Tokyo, Japan - cs37. Strings can have variable spacing within a laminate as was suggested by Pellegrino et al.[221] and a built example is the **Solar Office Doxford International** in Sunderland, UK - cs8, but for a large façade or skylight it might be sufficient to combine laminates with different string spacing as was done at **OLV Hospital** in Aalst, Belgium - cs78 - and at **Lillis Business Complex** in Eugene, OR, USA - cstf5.

An aberration of this common variation is a wider cell spacing within the strings but with edge-to-edge side-by-side strings, that also result in a striped appearance, but the 'cell stripes' are orthogonal to the strings. An example is the **Dutch Nature Trust 'Nieuwkoopse Plassen'** in Nieuwkoop, the Netherlands - cs74.

Tab.18: Variation of equal cell spacing in two directions

(a)



(b)

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 - Tab.18. A very dense spacing, the 'standard' arrangement of crystalline silicon cells in opaque modules as well as many LTPV projects, is used for shading and to limit unwanted heat gains as is done in many projections that use PV as external sunshades or brise-soleil. A wide spacing on the contrary permits more light, views to the outside and desired heat gains to enter the building. At **Academy Mont-Cenis** - cs17 - dense as well as wide types of cell-group forms were used to create a cloud-like roof-scape with interesting and varied shadow and light plays.

[221] Pellegrino et al. (2002)

Tab.19: Centre/frame variation

(a)

(b)

Both functional requirements, shading as well as allowing for views or light to pass, can be combined in the same PV panel - Tab.19. A centred distribution leaves the edges free of cells, a built example is the **Youth Centre Vestervang - Dannebrogsgade** in Copenhagen, Denmark - cs30. A frame like arrangement, that looks familiar to windows in a wall, orientates the cells at the edges but keeps the centre free of cells as in the **GreenPix - Zero Energy Media Wall** in Beijing, China (PRC) - cs68.

Tab.20: Chequerboard

(a)

(b)

The arrangement of cells side by side is not an imperative, Tab.20 shows alternating cell position. The dense pattern is known as chequerboard, as in the **McDonald's Cycle Center** in Chicago, IL, USA - cs41, but with a wide spacing the appearance changes to dotted spots of cells as can be seen at **Kankakee Community College** in Kankakee, IL, USA - cs58.

Tab.21: String variation for non-rectangular panel shapes

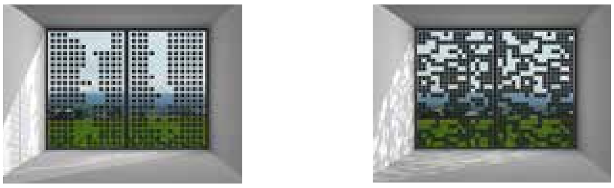
(a) radiating strings

(b) offset strings

(c) differing string lengths

So far all patterns were ideal for rectangular laminates, but sometimes the architecture requires the use of non-rectangular laminates. Radiating strings - Tab.21 - follow the widening of trapezoidal shapes, a built example is **Café Ambiente** in Bremen, Germany - cs7, offset strings follow the oblique angles of parallelogram or parallelogram-like trapezoidal shapes, as at **CCM 'The Brain'** in Graz, Austria - cs44, and differing string lengths can be used for basically any shape, best suited for laminates with curved or inclined edges, like the **Solar-sail Münsingen** - cs10. Non-rectangular shaped laminates are often used in canopies, like at **'La Vaguada' shopping mall** in Madrid, Spain - cs55, sunshades, like **The Core at the Eden Project** - cs46, at building corners, as were used at **California Academy of Sciences** - cs70, or in urban installations and works of art, like **Fifteen SunFlowers** in Austin, TX, USA - cs71 - or **Public lighting at Columbia Heights Civic Plaza** in Washington, D.C., USA - cs72.

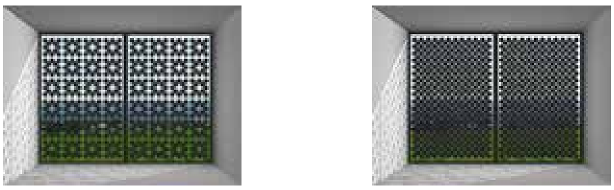
Tab.22: Non-uniform gaps



(a) (b)

Partial non-uniform gaps - Tab.22 - break with the strict linear graphic quality of the 'standard' arrangement and overlay the purely technical photovoltaic imagery with references from other fields. At **True North / Lux Nova** in Vancouver, BC, Canada - cs64 - the artist Sarah Hall thought of a flowing river, and at **Hotel Industrial** in Paris, France - cs67 - the architects used a pixelated imitation of a stone texture, a process and graphic result that is reminiscent of early low-resolution monochrome computer graphics.

Tab.23: Rotation of whole pattern



(a) (b)

So far all patterns were aligned with the laminate edges, but a rotation, hardly ever done, is easily possible too - Tab.23, as can be found at **Marrakech Ménara Airport** in Marrakech, Morocco - cs66. The inspiration for the rotation came from strongly geometric, traditional Arabic patterns, with the skylights reminiscent to mashrabiya. The translation of traditional patterns into patterns for PV can be a fruitful method, as analysed by Baum and Liotta.[222] A less culturally inspired example is the **Ombrière SUDI prototype** - cs83.

[222] Baum and Liotta (2011)

Tab.24: Varied cell distance within strings

Even the grid-like arrangement of the cells within a string with equal cell spacing, an assumption followed by all patterns discussed so far, is questionable and can be manipulated - Tab.24. A built example and the only one found within the corpus of LTPV examples is the **Christliches Kinderhaus Ulmenstrasse** in Dresden, Germany - cs38.

Finally, the strong linear arrangement of the cells in strings seems to be fixed due to the interconnection of the current 'standard' H-pattern solar cell with bus bars front to rear of the next cell. Scognamiglio et al. suggested to make this more flexible for alternative PV patterns.[223] The only example found is **CCM 'The Brain'** in Graz, Austria - cs44. Surprisingly here, this strategy, that requires more effort for cell interconnection, did not lead to any new cell pattern design in this built example, but could have been achieved easily with offset strings too.

However, the development of back contact cells - see 2.4.3 Front and back side colour and pattern - may provide an opportunity for an elegant new interconnection technology, as was also pointed out by Sinke.[224]

5.5.2 Thin-film cell and sheet form

Tab.25: Differently sized thin-film sheets

(a) one sheet per laminate (b) four sheets per laminate (c) nine sheets per laminate

In the case of TF technology, the variety of different sheet arrangements as found in the built examples has not been as varied and refined as with CS solar cells. All projects use either one sheet per laminate, or a number of sheets are closely aligned in laminates of larger size - Tab.25. As such, 'see-through' TF PV is perceived as a darker tinted glass rather than as a

[223] Scognamiglio et al. (2006)
[224] Sinke (2008)

technological PV product, and blurs smoothly with other architectural elements. An interesting example in the selected corpus surely is the tensile structure at the **'Under the Sun: An Outdoor Exhibition of Light'** - tf4, where opaque TF sheets got bonded onto a semi-transparent fabric. To follow the curvature of the fabric, differently sized sheets were arranged in shifted positions for a less rigid and rather streamlined impression.

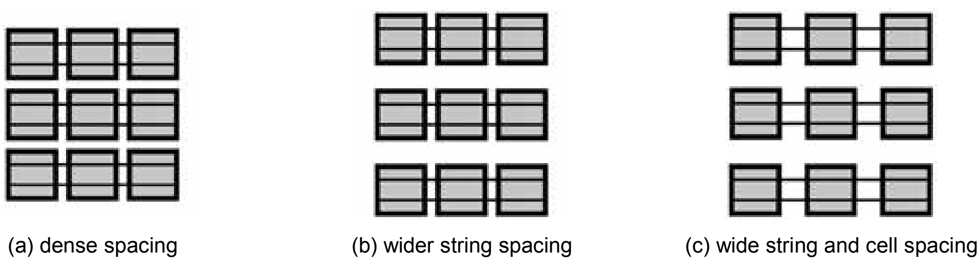
5.5.3 Dummy cells

Dummy cells are either electrically unconnected solar cells or solar cell imitations that are added for aesthetic reasons. If cells in a string are prone to mismatch, it might be better to not connect them. Reasons might be more often than usual shaded areas, an example is the **Brundtland Centre** - cs4, cut cells that would limit the current, see the **Sun Monument 'Greeting to the Sun'** in Zadar, Croatia - cs60, or single cells that are placed away from the rest and that don't justify a more complex interconnection, see the **Kei Wai Primary School (Ma Wan)** in Hong Kong, China (PRC) - cstf7. In areas where the cells are clearly visible, the use of real solar cells as dummies might be necessary to avoid a different appearance, in less visible areas, the use of imitations or screen prints might suffice.

5.5.4 Level 2 - summary

A wide variety of different approaches to alter the appearance of the PV cell-group form has emerged. The variety of choice, however, is not at all free of limitation, quite the opposite. The electrical interconnection of H-pattern cells by stringing and tabbing - see 2.2.6 Solar cell, string or sheet, panel or laminate, module, array, system - results in straight strings, with only one notable exception of a test installation with cells in curved strings at the **Gemini House** - cs27.

Tab.26: From the 'standard' of opaque to a 'quasi-standard' of light-transmissive



Most patterns of CS solar cells were developed starting from the end-to-end and grid-like arrangement of cells as is common with opaque modules - Tab.26(a). All alterations were derived from here. It is interesting to note, that the alteration most often chosen is not the closest in energy-efficiency to the standard pattern and simplest to manufacture in terms of standard processes of end-to-end interconnection, by simply spacing cell-strings that result in a striped appearance - Tab.26(b), but it is the most pattern-alike alteration, by equally spacing cell-strings as well as cells within a string - Tab.26(c). What looks like stretching the cell grid and revealing the cellular structure of crystalline silicon PV has the advantage of providing a more equal light-transmission without striped shadows.

What appears so trivial is actually a quite fundamental shift in balancing different architectural functions and away from the dictum of most efficient photovoltaic conversion and PV manufacturability. Such a shift for primarily aesthetic reasons is surely less arguable or defendable, as can be seen in the less often executed choice of alternative cell colours, as was described before - see 5.4.3 Level 1 - summary. Here, arguably also a preferred aesthetic choice, it is supported by a more rational consideration of providing even illumination levels.

However, this argument might not hold true when it comes under scrutiny, because it should then lead to the preference of 'see-through' cells over 'light-through' spacing of cells, which isn't always the case. More likely is, that the equal or near-equal spacing of cells and strings is slowly but surely developing into a quasi-standard for crystalline silicon based LTPV, as can be seen by the many manufacturers that offer such products.

Thin-film sheets on the other hand, are mostly embedded edge-to-edge without any additional spacing between adjacent sheets than the technological minimum (and similar to opaque CS modules).

5.6 Level 3 - solar panel

At level 3 the grouped cells or sheets get encapsulated to form a solar panel. Sometimes they are called laminate, when lamination is the encapsulation process. Common is also the term solar module, which refers to the laminate plus the added junction box or cables for electrical connection. For a more refined description of the different terminologies - see 2.2.6 Solar cell, string or sheet, laminate, panel or module, array, system.

In contrast to the two previous levels, at this level the separate, PV technology specific analysis doesn't seem to be appropriate anymore. Rather the characteristics of the encapsulating materials and PV technology independent common variations define this level. As such, built LTPV examples of both PV technologies are viewed in parallel and only when a distinctive difference occurs, will it be pointed out.

5.6.1 Materials

Solar panels are composite materials, with the photoactive material encapsulated by two protective layers, one at the front light-exposed side and one at the back side. For LTPV all encapsulating materials must be at least translucent. With thin-film PV one of the protective layers is often already part of the TF sheet, either as sub- or superstrate onto which the TF material is deposited, thus requiring only one additional protective layer. The laminant is usually a full-size EVA or PVB[225] foil between solar cells and outer protective layers.

Glass is one of the most often used encapsulating materials, as it is an extremely good barrier against water and chemical substances. For building-integrated LTPV as a substitute to curtain-wall or skylight glazing, glass is also an obvious choice, and to confirm this, glass/glass panels are used by the majority of built examples within the LTPV corpus. Glass used for solar panels is different from the usual float glass, which has a green tinge, most obvious at the glass edges. The ideal glass for solar panels, however, is low in iron-oxide content for a better, colour-neutral light transmission to the solar cells. It is called white glass, extra or ultra clear glass, or simply low iron glass. Common trademarks are AGC Krystal Klear or SUNMAX, SGG Diamant, Pilkington Optiwhite, PPG Starphire and Guardian UltraWhite. Glass for solar modules is offered in different surface qualities - Fig.54.

Fig.54: glass surfaces - (a) extra-clear, (b) smooth, (c) diamond pattern
Credit: © AGC Solar

A big disadvantage of glass is its fragility that requires a certain thickness and makes it a heavy choice. An alternative to glass are foils or membranes that are thin, lightweight and flexible. Widely used in opaque modules as backsheet layer is PVF,[226] better known as Tedlar. Glass/foil panels (glass/membrane panels) are the standard for opaque PV. Light-transmissive glass/foil panels are used for example at the **Floriade 2002** in Hoofddorp, Netherlands - cs31 - and at the **Kollektivhuset** in Copenhagen, Denmark - cs32.

When front and backsheet are made of foil or membranes, than the whole PV composite becomes flexible, as it is sometimes done with TF, but rarely with CS due to the brittle nature of CS. As such, the possibility for flexible panels is a major advantage of TF over CS. Foil/foil panels (membrane/membrane panels) are the choice for membrane roofs, like at the

[225] EVA - ethylene vinyl acetate; PVB - polyvinyl butyral
[226] PVF - polyvinyl fluoride

Carpark of the Municipal Waste Management Office - tf18 - or the **'Under the Sun: An Outdoor Exhibition of Light'** - tf4.

Another alternative are plastics like acrylic or polycarbonate, giving a stability to the panel similar to glass, but with the advantage of drastically reduced weight, higher resistance against breakage and the opportunity to easily manufacture axially and spherically curved panels - see 5.6.3 Curvature below.

A novelty within the corpus of LTPV examples is the **L'hôtel du Lac [SAPHIR]** in Nagahama, Shiga prefecture, Japan - cs87, that uses crystalline silicon cells embedded in glass blocks.

5.6.2 Size and shape

Standard opaque modules are available in manufacturer dependent sizes but always rectangular, and that has shaped the image of a solar module in general. It became obvious very early that a variety of sizes and customisable shapes are essential for building integration of PV. Even though the most widely used shape for LTPV panels is nevertheless the rectangular - see Tab.11, panels in other shapes are used too, triangular, trapezoidal, parallelogram shaped, with inclined or curved edges. The use of non-rectangular panels can be a major design feature as in many of the non-building structures, or a requirement for a smooth transition of the building envelope. At the **California Academy of Sciences** - cs70 - rectangular LTPV panels were integrated into the canopy on all four sides of the building. To achieve a smooth transition at the building corners, however, trapezoidal panels were used instead. Non-rectangular panels might be better suited for integration into undulating surfaces. At the **Novartis 'Gehry' building** - cs73 - trapezoidal shaped panels were used to achieve a smooth transition of the curved building envelope, sometimes substituted with two triangular panels to avoid a strong angular deviation between the surface normals of adjacent panels.

5.6.3 Curvature

In general, solar panels are flat, if not for any other reason but exposing all solar cells equally to the light to avoid power mismatch. Within the corpus are, however, a few examples using stiff curved panels with either encapsulated CS or TF solar cells. An early, non-building example is the **Solar Catamaran RA 66 'Helio'** - cs14. The crystalline silicon cells in this kind of PV panels are sandwiched between two sheets of Plexiglas - a PMMA acrylic,[227] or Makrolon - a lightweight polycarbonate.[228] The **Gemini House** - cs27 - is a case study house for

[227] 'Solar Katamaran' (undated)
[228] 'Plastics TechCenter: Flexible solar modules in Makrolon® ' (undated)

many energy saving features. One type of crystalline silicon PV are axially curved panels installed at the top of the PV sunscreen, that rotates around the vertical axis of the house, thus following the sun. A second building-integrated example is the **Fujipream Kohto Factory** - cs35, a showcase project of the module manufacturer Fujipream, where CS solar cells were embedded in the undulating panels. The **SFMTA Bus Shelters** - tf15 - on the other hand use flexible Power Plastic, OPV panels, laminated between undulating layers of polycarbonate.[229] Solar cells can even be integrated into spherically curved panels. Such panels made from acrylic or polycarbonate have been used in many examples of solar car roofs since the 1990s (Mazda Sentia/929, Mazda Eunos 800/Xedos 9; recently: Audi A8, Toyota Prius, Fisker Karma, Smart Car2Go),[230] but buildings or built structures using such panels were not found within the corpus of LTPV examples. An exception once more using a flexible fabric is the tensile structure at the **'Under the Sun: An Outdoor Exhibition of Light'** - tf4.

Examples integrating flexible panels on membrane or tensile structures are explained in 5.8.2.3 Membrane structures and 5.8.2.4 Tensile and textile structures.

5.6.4 Insulation

Laminated solar panels are often integrated into insulated double or triple glazing units with air or noble gas filled intermediate space, often necessary when the solar panel is integrated not only into the draining layer but also as part of the thermally insulating building envelope. This makes the solar panel a fully integrated building and multi-functional BIPV element even in the strictest sense of Weller et al. - see 2.2.1 BIPV. An extreme example surely is the **Novartis 'Gehry' building** - cs73 - featuring *"High performance triple glazing with krypton filling and Ug-value 0.7 W/(m^2 K), external laminated glass - HS 10/6 mm with intermediate photovoltaic cells on a screen printing adjusted to the shape of cells, internal laminated glass - 2 x HS 6 mm, centre pane toughened glass 6 mm".*[231]

5.6.5 Colour

Colour, as already mentioned in 5.4.3 Level 1 - summary, is an important feature of architectural design. At this level, there is again the chance and opportunity to alter the colour this

229 Spiering (2009); Konarka Technologies, Inc. <http://www.konarka.com/>

230 Here it is interesting to note, that the early PV car-roofs used thin-film PV - see 2.2.7 Translucency and transparency - 'light-through' and 'see-through', but with recent models the preferred technology seems to be crystalline silicon cells. The PV roof for the Karma Fisker, e.g. uses monocrystalline CS modules made by asola Solarpower GmbH - see ' "Automotive" solar modules' (undated), and the panels for the Toyota Prius uses multicrystalline CS modules made by Kyocera - see Kyocera Corporation (2009a).

231 'Novartis Pharma AG Basel (Switzerland)' (undated)

time of the encapsulating or embedded materials. Ideally this is done behind the solar cells, as any alteration in front will reduce light-transmission. With glass/foil panels the easiest choice is to change the colour of the backsheet, which, in fact, was done with most glass/foil LTPV panels. The standard backsheet colour of an opaque module is white, that is often substituted with a transparent one for an LTPV panel. Similarly in glass/glass panels, the colour of the back side glass can be altered, as was done at **Nursery school 'El Blauet'** in Sant Celoni, Spain - cstf10. At **Fifteen SunFlowers** - cs71 - a blue gel, like the kind used in theatrical lighting, was sandwiched into the panels.[232] At **Kollektivhuset** - cs32 - a movable colour panel was installed behind the solar panel. The colour of the back panel is clearly visible inside and as a softer pastel shade from the outside.

Panels with more intense colours similar to medieval stained glass works, were done in a number of projects by artists together with the company Glasmalerei Peters, for example **Christliches Kinderhaus Ulmenstrasse** - cs38 - or **True North / Lux Nova** - cs64. For the latter, the colouring process involved a number of subsequent steps, resulting in a multilayer of colour and texture: a base float glass, kiln fired with glass frit for a sparkling and textured surface, sandblasted white areas, several layers of airbrushed colour re-fired to fix the colours, plus a number of dichroic glass crosses.[233] The stained glass is in fact a separate layer behind the PV laminate, but only together they constitute this art work. Other built examples of artistic stained glass installations manufactured by Glasmalerei Peters, but not included in the corpus of selected LTPV projects, are **Districtshuis Deurne** in Antwerp, Netherlands, together with artist Joost Caen - see Appendix B: 55, **Grass Valley Elementary School** in Portland, OR, USA, together with artist Sarah Hall - see Appendix B: 266, **'SolarGlasKunst' at the parking garage Pilgrimstein** in Marburg, Germany, together with artist Jochem Poensgen - see Appendix B: 478, **Pearl Avenue Branch Library** in San José, CA, USA, together with artist Lynn Goodpasture - see Appendix B: 494,[234] and **'Lux Gloria' at the Holy Family Catholic Cathedral** in Saskatoon, SK, Canada, together with artist Sarah Hall - see Appendix B: 452.[235]

232 Lajos Heder / Harries/Héder Collaborative, personal communication, November 4, 2011
233 'True North / Lux Nova : Work-in-Progress for North America's First Photovoltaic Art Glass' (undated)
234 all examples see 'Mit der Sonne selbst zu malen: Photovoltaik & Glasgestaltung' [Painting with the sun itself: photovoltaics & glass design] (undated)
235 'LUX GLORIA: Solar Stained Glass' (undated)

5.6.6 Prints

As glass is a very common encapsulation material, all methods to alter glass are basically open to glass embedded LTPV as well. In the case of insulated double/triple glazed LTPV it is even easier to alter the appearance of the composite by changing the separate glass pane. A very common treatment to glass is screen printing to add texture, patterns or images on the glass surface. Even though this is rarely done with LTPV panels, some examples exist. At **AquaCity Blue Sapphire** - cs57 - thin stripes were printed on the inner glass pane. At the **California Academy of Sciences** - cs70 - squares were printed on the backside, slightly larger and covering the rear side of the solar cells. The square pattern continues on adjacent non-PV clear glass panels.

5.6.7 Holographic films

Holographic films, or holographic optical elements (HOE) can be used to divert sunlight. It may sound a little bit contradictory to the initial approach of spacing opaque cells to let light pass, but holographic films offer the chance to concentrate sunlight onto the remaining solar cells when used with LTPV. Although holographic foils have no intrinsic colour, their ability of light dispersion lets them shimmer in the spectral colours of the rainbow.[236] Such foils were used at the **Academy Mont-Cenis** - cs17. Other projects not included in the corpus of selected projects are the **Demonstration Houses for IGA-Expo** built 1993 in Stuttgart, Germany - see Appendix B: 352, the **PIZ Photovoltaik-Informationszentrum**[237] built 2000 in Gelsenkirchen, Germany - Appendix B: 400 - and the **SHK training centre** built 2001 in Cologne, Germany - Appendix B: 483. The latter three have PV with HOE integrated on one axis sun-tracking louvres. An interesting LTPV product using HOE in combination with bifacial solar cells are Prism Solar's HPC modules.[238]

5.6.8 Level 3 - summary

Level 3 is a quite controversial to summarise. On the one hand, there are a number of manufacturers that offer customised LTPV products, and many projects exist, where such panels were used. Especially with glass as encapsulating material the shape and size of a solar panel is fully customisable. In contrast to the limited range of coloured solar cells at level 1, a solar

[236] Schmitz (2002)
[237] The PIZ Photovoltaik-Informationszentrum was the customer information centre and part of the Shell Solar manufacturing site in Gelsenkirchen, to which one of the selected projects belonged, the **Shell solar cell factory** - cs12.
[238] Prism Solar Technologies, Inc. <http://www.prismsolar.com/>

panel can be altered in the full available colour range of the encapsulating materials glass, plastics and foils, membranes or fabrics. Furthermore, screen printed glass, embedded intermediate layers or separate layers behind the laminate extend the range of possible alterations. Even though a small number of projects exists, that exploit the offered potential, the majority by far doesn't. As such, after the firework of chosen opportunities 'beyond' the commonly offered choices by the manufacturers, that best described level 2, the execution of choice by architects at level 3 is again a rather conservative one with generally speaking more choices available than used.

As explained earlier, to avoid reduced light-transmission onto the solar cell, it is suggested to make any kind of alteration or addition behind the cells. However, the German-Italian research and demonstration project PVACCEPT (2001-2004),[239] that was concerned about the colour and front-side surface of PV *"in sensitive areas such as monument preservation and landscape conservation",*[240] suggested an interesting solution. By adding an irregular pattern to the front-side of a TF panel and deliberately accepting the loss in generation efficiency caused by this intentional shading, it is possible to disguise the common appearance of PV completely. For such an approach thin-film PV technologies are better suited due to their superior performance under partial shading. The realised two demonstration boards are opaque panels, but combined with LTPV it could be an interesting feature.

5.7 Level 4 - panel-group form

The panel-group form (level 4) can be best described as the combination of all subordinate levels (level 1 to 3) on the transition into the built form (level 5). When looking at Tab.12 it becomes clear, that the variety of different panel-group forms is immense. Even though some features are probably technology specific (more distinct with either crystalline silicon or thin-film solar cells), a strict separation of the analysis into these technologies is not considered to be appropriate. Both technologies are therefore viewed in parallel.

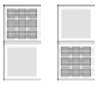
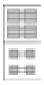
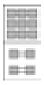
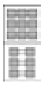
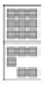
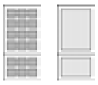
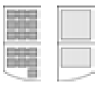
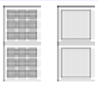
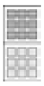
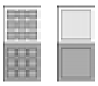
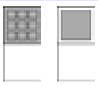
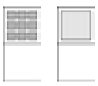
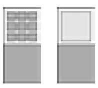
5.7.1 Combination patterns

An attempt is made to bring some order into the ocean of possibilities. The panel-group analysis of the built examples lists the different features that are combined according to the level they originate - Tab.27.

239 for further information see <http://www.pvaccept.de/eng/index.htm>
240 Bruns et al. (2011) p.204

Tab.27: Panel-group form

The column 'Image' is split into a left and right part, the left part for CS PV, the right for TF PV. If the relevant part is shown, built examples are included, otherwise built examples are not included.

Image	Combination pattern	Built examples
	Level 1 features	
	(1a) different technologies	cstf1, cstf2, cstf10, cstf11
	(1b) different transparencies	tf13
	(1c) different cell sizes	cs17, cs29
	Level 2 features	
	(2a) different string + cell distance	cs11, cs17, cs19, cs68
	(2b) different string distance	cs8, cs78, cstf5
	(2c) different cell distance	cs41, cs74
	(2d) different cell densities	cs17, cs19, cs38, cs41, cs64, cs65, cs67, cs68, cs74, cs78, cs84, cstf7
	Level 3 features	
	(3a) different panel size	cs2, cs6 ~ cs8, cs27, cs33, cs38, cs46, cs49, cs55, cs57 ~ cs59, cs62, cs63, cs65, cs80, cs81, cs86, cstf7, tf9, tf15
	(3b) different panel shape	cs8, cs10, cs27, cs38, cs44, cs59, cs60, cs63, cs70, cs72, cs73, cs78, cs80, cs81, cstf5, cstf7, tf11
	Level 4 features	
	(4a) equal panels	majority
	(4b) dummy panels	cs55, cs70, cs76, cs80, cs84, cs86
	(4c) LTPV + opaque PV	cs12, cs27, cs46, cs50, cs59, cs69, cstf1, cstf11, tf17
	Level 5 features	
	(5a) opaque PV + semi-transparent / transparent non-PV	cs1, cs47, cstf2, cstf9, tf18
	(5b) LTPV + semi-transparent / transparent non-PV	cs1 ~ cs4, cs8, cs9, cs13, cs14, cs16, cs17, cs28, cs30, cs32, cs33, cs36 ~ cs40, cs44, cs45, cs51, cs54, cs56, cs57, cs62 ~ cs66, cs68, cs70, cs75 ~ cs77, cs80, cs82, cs85, cstf3, tf1, tf2, tf4, tf7, tf9, tf12 ~ tf14
	(5c) opaque non-PV	cs34, cs37, cs50, cs53, cs82, tf8, tf16

The most common pattern is (4a), followed by (5b). Apart from pattern (4a) that favours homogeneity, the other patterns introduce variety into the PV area. Heterogeneity can be caused by factors that prohibit homogeneity, or a deliberate design intent. Apart from patterns (3a), (3b) and (4a), the other patterns allow for a variation in light transmittance. The level change can be smooth, or in stark contrast. A most basic pattern is (5a), the 'light-through' pattern on the module level. It is the same basic pattern as the 'light-through' pattern on the cell level - see 2.2.7 Translucency and transparency - 'light-through' and 'see-through', a combination of an opaque area with an adjacent area of light-transmissive transparency though in a different scale and level. Generally speaking, this pattern is independent of technology, even materials, and the most basic approach to control the level of light transmission with opaque materials. It is a link to simple and elaborate approaches throughout the history of architecture and buildings.

5.7.2 Arrangement

As can be seen from the examples, a homogeneous arrangement with equal panels is the most common pattern. The reason is easy to understand, because standardisation and a large number of equal elements results in a straight forward simplification of planning, manufacturing and installation and an associated cost reduction. More surprising is, that homogeneously looking built examples can require a larger number of different panels, whereas some very heterogeneously arranged examples are made of only one or two different panels. An example for 'homogeneously looking but...' is the **Kankakee Community College** - cs58 - were four different panels are required, or the **Breeze Shelters at Marina Bay Sands** - cs80 - with seven different sizes for just 32 modules in total. In general, a patchwork with non-PV panels or elements is a very simple way to achieve heterogeneity.

5.7.3 Gradation

The two major groups for gradational changes are either by size / shape mainly to fit the panels along curved or inclined building edges, examples are the **Solarsail Münsingen** - cs10 - and the **London City Hall** - cs59, or by cell densities to achieve a change in light-transmission ratio. Examples are the **GreenPix – Zero Energy Media Wall** - cs68, the **Dutch Nature Trust 'Nieuwkoopse Plassen'** - cs74 - and the **OLV Hospital** - cs78. It is interesting to note, that a similar strategy of differently spaced cell-strings was done on the cell-group level at the **Solar Office Doxford International** - cs8, but on the panel-group level at the **Lillis Business Complex** - cstf5.

5.7.4 Dummy panels

About dummy panels can be said basically the same as was about dummy cells - see 5.5.3 Dummy cells. At the **National Museum of Taiwan History** - cs84 - dummy panels were used for the lettering of the museum's name. At the **California Academy of Sciences** - cs70 - the backside of all PV panels has a screen-print with a pattern of squares slighter larger than the solar cells. Adjacent non-PV panels with the same screen-printed pattern mediate between opaque cell areas and a print-free glass margin. A rather unconventional example for the use of dummy panels is the **Welios - OÖ Science Center Wels** - cs86. The building has an atrium with an LTPV skylight. But more obvious when approaching the building is a crisscross pattern on the façade of the building. What appears to be single-string solar panels at first sight are actually dummies that look like PV but are a multicolour lighting installation without PV function,[241] an ironic mimicry.

5.7.5 Non-PV elements

The most common non-PV element to be combined with LTPV are, not surprisingly, clear vision glass panels. As glass encapsulated solar panels are often installed in glass façades or skylights, the combination is an obvious choice. Even though glass encapsulated solar panels and clear vision glass panels are made by a similar material, the appearance is most often heterogeneous and this is more distinct with crystalline silicon than thin-film PV. However, this isn't detrimental but an often exploited feature to introduce patchwork-like patterns. But not only glass, other opaque, translucent or semi-transparent materials are used too.

Generally speaking, non-PV elements are sometimes used in areas where a regular PV panel doesn't fit, to avoid irregular PV panels, like at the **EMR Centre 'Energie-Forum-Innovation'** - tf2 - or the **PV Frisbee** - cs77. But more often they have similar sizes to the solar panels and can thus be used interchangeably. At the **Cité du Design** - cs82 - the PV is just one kind of ten different triangular building skin elements. At the **Q-Cells OF1 Thalheim** - cs53 - permanently installed solar panels are complemented by movable sliding screens. At the **Lycée du Pic Saint-Loup 'Jean Jaurès'** - cs34 - multicoloured louvres give depth and add light and colour gradation to the shading canopy.

[241] As confirmed by Michael Schopf / Welios Betriebs-GmbH, personal communication, November 25, 2011.

5.7.6 Crystalline silicon vs. thin-film

When looking at Tab.27 again, it becomes obvious that the level 2 features that influence the panel-group form, and with it the light-transmission ratio, are basically key design parameters appropriate for crystalline silicon panels. Nevertheless, it isn't exclusive to CS. The preferred use with CS can be attributed to the different size of the basic element of a single CS solar cell versus a monolithic TF sheet. Whereas the smaller size of a CS cell has been used for a large variation of level 2 features, the same can not yet been said about TF sheets, as was also pointed out in 5.5 Level 2 - cell-group form. All other level features are equally rich in variation for both technologies.

5.7.7 Level 4 - summary

The panel-group form has been the most varied so far, with many solutions unique to each project. Generally speaking, options for customisation are plenty. The combination of PV with non-PV elements enriches the possibilities. The more PV is seen and used as an equal element among others, the more numerous the combination patterns tend towards heterogeneity. Despite of a solar panel being basically flat, the combination of PV with non-PV elements in a layered fashion introduces depth and the possibility to merge the PV layer with the construction layer.

5.8 Level 5 - built form

The built form is the level, that is addressed most often in the reference literature, and many building related PV studies distinguish their case projects based on the area of integration, see for instance Hagemann.[242] In relation to a building, the level 5 - built form is basically a sub-building level, as it often focuses on a structurally and functionally distinct part of the building envelope.

5.8.1 Built examples ordered based on structural integration

In accordance with most of the reference studies, the selected projects were distinguished in roof, skylight, canopy, façade, fixed or movable sunshade and non-shelter integration - Tab.28. The last category is unique to this study. It allows the equal consideration of art projects or other types of environmental integration at this sub-building level, bridging already into the later following level 6 - urban / landscape form.

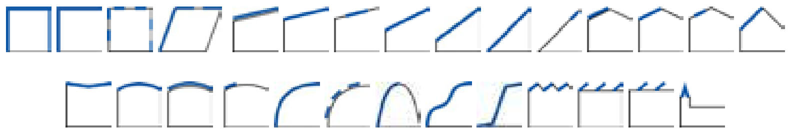
242 Hagemann (2002);
The second most common organisation principle in the BIPV reference literature is building typology, see for instance Nelli (2006) and Nelli (2007).

Tab.28: Built examples ordered based on structural integration

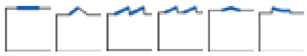
roof		
	flat, integrated	cs7, cs37, cs51, cs67, cs82, cstf9, tf3, tf4
	flat, added on top (opaque)	cs22, cs25, cs27, cs54, cs55, cstf7, cstf8
	flat with gabled roof sections	cs31
	flat with shed sections	cs17
	inclined, pitched, integrated	cs1, cs5, cs13, cs16, cs19, cs39, cs49, cs74, cstf6, tf8, tf14
	inclined, pitched, added	cs46, cstf4, cstf5
	gabled	cs28
	shed	cs4
	hipped, pyramidal	cs55
	spire	cs6
	curved	cs12, cstf11
	parabolic	cs18
	double-curved sections	tf18
	domed	cs59
	undulating	cs35, cs69, cs73
skylight		
	flat	cs62, cs81, cs86, cstf3, cstf6, cstf7, tf2
	gabled, shed sections	cstf1, cstf5, tf1, tf6
	pyramidal	cs66
	inverted dome, hammock	tf7
canopy		
	flat	cs21, cs55, cs61, cs70, cs80, cstf8, tf11
	inclined, pitched, v-shaped	cs23, cs40, cs42, cs47, cs56, cs61, cs77, cstf11
	shed sections	cs48
	hipped, pyramidal	cs3
	curved	cs14, cs45, cs83, tf5, tf10
	undulating	tf15
	tensile structure	tf4
façade		
	vertical and plane	cs2, cs9, cs20, cs30, cs33, cs35, cs37, cs38, cs47, cs57, cs58, cs61 ~ cs65, cs67, cs68, cs75, cs76, cs81, cs82, cs85, cstf1 ~ cstf3, cstf5, cstf11, tf4, tf9, tf12, tf16, tf17
	vertical, curved along vertical axis	cs50
	inclined	cs8, cs29, cs51, cs78, cstf6
	inclined and curved	tf13
	balcony, balustrade	cs32, cs36, cs67, cs87
	oriel	cs24
	vertical noise barrier wall	cs54
	tilted wall	cs84
fixed sunshade		
	vertical shading element at façade	cs4, cs53
	inclined shading element at façade	cs59, cstf10
	awning	cs28, cs46, cstf3
	horizontal louvres at façade	cs26, cs43, cs79, cstf6, cstf11
	overhead at roof or canopy	cs34, cs41, cstf7
movable sunshade		
	awning	cs28
	horizontal louvres, one-axis sun-tracking	cs12, cs15
	door-like foldable elements	cstf9
	window shutters	cstf4
	curved façade, hor/ver louvres, one-axis sun-tracking	cs27
	curved vertical sun sail, movable around the corner of the building	cs26
	flat horizontal sun sail, movable	cs25
	inclined louvres, above roof, one-axis sun-tracking	cs22
non-shelter integration		
	lighting, art	cs52, cs71, cs72
	sail-like tensile structure	cs10
	sculpture	cs44
	pavement	cs60

Tab.29: Icons used to illustrate building integration

roof

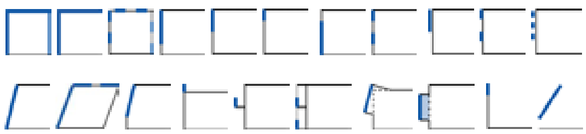


skylight



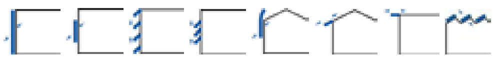
canopy

façade



fixed sunshade

movable sunshade



non-shelter integration

The icons that are used in the selected project overview - Tab.13, as well as in - Appendix C - are ordered for quick reference into the same categories in - Tab.29.

Typological studies for the design and building integration of solar technical systems into the building envelope were previously done by Krippner and Herzog. In terms of constructional integration in relation to the draining layer, they distinguished five positions: *"on top"* as with rear-ventilated rainscreen cladding, *"on"* without rear-ventilation, *"within"* as part of the draining layer, *"between"* draining layer and inner surface of the wall, and *"interior"* as part of the interior design without direct connection to the building envelope.[243] Most of the

[243] Krippner and Herzog (2001) p.243

roof, canopy and façade installation of the selected projects belong to the *"within"* group, only a few have added installations that together with all sunshades belong to the *"on top"* group. The examples that belong to the *"on"* group are without exception opaque panels bonded onto roofing materials or fabric. No LTPV example belonging to the *"interior"* group was found, and only one that belongs to the *"between"* group. At the **Carport Roof at the 'Abfallwirtschaftsamt'** - tf18 - flexible thin-film sheets were bonded onto the middle layer of a three layer cushion. Here it is noteworthy again, that the non-shelter integration projects can not be organised according to the five positions by Krippner and Herzog, as they don't require a draining layer.[244]

5.8.2 Three-dimensional integration possibilities

It is true that most of the integration examples of the last three decades are planar surfaces using planar PV laminates. To illustrate the state of the art of integration into non-planar surfaces, this part of the study includes both examples from the selected corpus - Appendix C, the full corpus - Appendix B, further projects using primarily opaque PV panels as well as unbuilt study and design proposals. The latter may be economically unfeasible in terms of available technology, but as such they may expand the boundary set by available technology. This inclusive approach is expected to reveal further opportunities for future applications.

5.8.2.1 Non-planar surfaces using planar laminates

While using standard, available technologies, the focus of the following projects has been on the integration of common, planar laminates into curved, undulating or free-form surfaces of the architectural envelope. Four case studies that solve the issue in different ways. At the **Fire Station** in Houten, Netherlands - cs18 - a combined roof/façade envelope, parabolic shaped in section, wraps over the interior spaces. The parking area for the fire engines is a building-high atrium and the atrium part of the parabolic shaped envelope is made with semi-transparent PV panels. The integration of the rectangular panels is unproblematic, without disturbing the smooth curvature of the envelope. Similarly at the **World Games Stadium** in Kaohsiung, Taiwan (ROC) - cs69 - the PV panels are integrated into the undulating roof covering the seating areas and shopping facilities, however, the PV panels are standard products. **The Core at the Eden Project** - cs46 - was designed based on natural, exponential growth

[244] The suggested five positions by Krippner and Herzog (2001) take their inspiration from the functional requirements and layered section of a building's wall structure. The LTPV panels that are part of glazed building skins with the LTPV panel functioning as outer surface, draining layer and inner surface simultaneously, belong to the *"within"* group. The strength of Krippner and Herzog's approach is the anticipation of *"interior"* installations, the drawback the reference on a draining layer.

algorithms, mathematically expressed by ‘Fibonacci’ numbers and visually a double spiral. As an assuming intentional expression of the architectural tour de force to integrate rectangular PV panels that don't match the shapes resulting from the double spiral, standard opaque PV panels were mounted on the roof. In contrast, bespoke parallelogram shaped, light-transmissive PV panels were integrated into the eaves. At the **Novartis 'Gehry' building** - cs73 - semi-transparent silicon cells were used to provide evenly distributed natural light. Most laminates have a parallelogram shape following the smooth curvature of the roofs, but are split into two triangular panels where the curvature increases. In contrast to the standard rectangular panels, triangular panels provide a higher flexibility for integration into non-cartesian building envelopes, see also 5.10.1 Triangulated surfaces.

Fig.55: Fire Station Houten
Credit: © Christian Richters

Fig.56: World Games Stadium
Credit: © Robert Baum

Fig.57: The Core at the Eden Project
Credit: © www.solarcentury.co.uk

Fig.58: Novartis 'Gehry' building
Credit: © Alex Learmont

In the latter three projects, PV panels were integrated into a highly expressive, architecturally predefined form. Considerations regarding insolation, orientation to the sun or maximising energy yield were of secondary importance. However, as the integration happened into the roof shapes, the energy yield at the projects locations is supposedly higher as in similarly non-ideal vertical façade installations.

5.8.2.2 Non-planar surfaces using non-planar laminates

In the case of larger surfaces the approaches described in the previous section may be sufficient, but easily reach their practical limitation with smaller surfaces or stronger curvatures. For such situations, bent or undulating laminates can be used. As built examples within the corpus were already briefly introduced - see 5.6.3 Curvature - only some images are added here for **Solar Catamaran RA 66 'Helio'** - cs14, **Gemini House** - cs27, **Fujipream Kohto Factory** - cs35, and **SFMTA Bus Shelters** - tf15.

Fig.59: RA 66 Solar Catamaran
Credit: © Tilla Goldberg

Fig.60: Gemini House
Credit: © City of Weiz

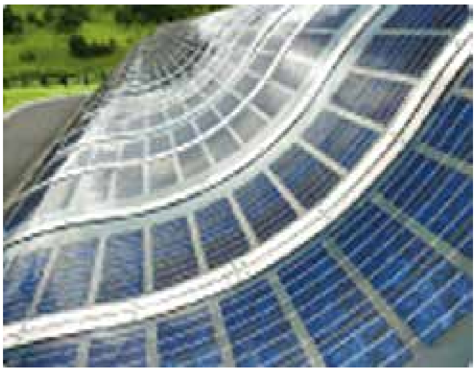


Fig.61: Fujipream Kohto Factory
Credit: © Fujipream

Fig.62: SFMTA Bus Shelters
Credit: © Ryan Hughes

5.8.2.3 Membrane structures

Solar cells can be integrated into membranes as well. Probably the first built example are opaque shading membranes at the **MWB Messwandler Bau** in Bamberg, Germany.[245] A recent building with PV on a Texlon membrane roof by Vector Foiltec, the same material as

[245] See patent by Dorison et al. (1995), some images are included in Hagemann (2002) p.356. The patent describes PV cells bonded to membrane structures but also standard opaque crystalline modules mounted on a cable net. The supporting structure for the latter had to be quite substantial due to the weight of the standard modules. All variations described in the patent were installed and tested at the MWB company facility in Bamberg, Germany in the early 1990s.

was used for the National Aquatics Centre 'Watercube' at the Beijing Olympic Games 1998, is the **Classroom of the Future** in London, UK - Appendix B: 765.[246] The **Car Park of the Municipal Waste Management Office -** tf18 - is located opposite the famous Munich Olympic Stadium from 1972, with the tensile membrane structure designed by Behnisch & Partner and Frei Otto. The car park was completed in 1999 and featured a tensile membrane roof structure that collapsed after heavy snowfall in 2006. The new canopy is made of ETFE-cushions with bonded thin-film PV. The design of a **Soft House for IBA Hamburg** by architecture firm Kennedy & Violich Architecture - Appendix B: 710 - uses thin-film PV bonded onto membranes and by using such a lightweight, flexible, towards the position of the sun dynamically adjustable material, questions the inflexibility of our traditional building materials.

Fig.63: Classroom of the Future
Credit: © Studio E Architects

Fig.64: Carport Roof at the 'Abfallwirtschaftsamt'
Credit: © Taiyo Europe GmbH

Fig.65: Soft House for IBA Hamburg
Credit: © Kennedy & Violich Architecture

[246] A permanent PV installation was retrofitted after the completion of the Classroom of the Future, as confirmed by David Lloyd Jones / Studio E Architects, personal communication, November 25, 2011. As the photographs were taken soon after the completion, the PV does not show, however, it can be clearly seen on photographs by the manufacturer of the roof membrane, Vector Foiltec - see <http://www.vector-foiltec.com/en/projects/pages/gb-london-classroom-of-the-future.html>

5.8.2.4 Tensile and textile structures

The support of PV cells or modules with tensile structures is another way to design PV-integrated non-planar surfaces.

Fig.66: BMW exhibition area at IAA 1990
Credit: © BMW / Friedrich Busam, Frankfurt

Fig.67: Suntiles - Energy curtain
Credit: © Astrid Krogh

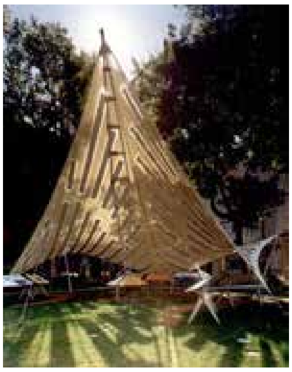


Fig.68: 'Under the Sun' exhibition
Credit: © FTL

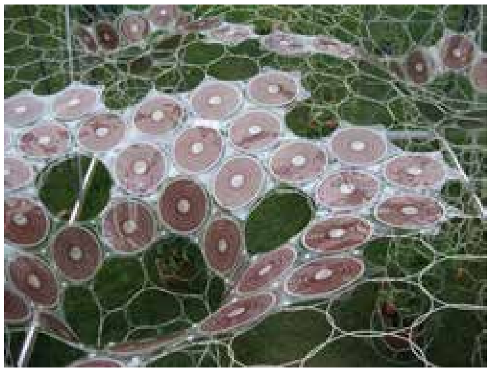


Fig.69: Metabolic Media
Credit: © Studio Loop.pH

Fig.70: Energy harvesting textiles (prototype)
Credit: © Kennedy & Violich Architecture

Fig.71: SmartWrap
Credit: © KieranTimberlake

The colourful laminates that were installed at the **BMW exhibition area at IAA 1990** in Frankfurt, Germany - Appendix B: 078 - appear to float in midair. They are lightweight and made of acrylic plastic. The **Suntiles - Energy Curtain**, design: Astrid Krogh and Smith

Hammer Lassen - Appendix B: 726 - are intended for interior use and are hanging from the ceiling. FTL designed a tensile structure with PV bonded onto a translucent fabric for the **'Under the Sun: An Outdoor Exhibition of Light'** - tf4. The **Metabolic Media installation** at the London Design Festival, design: Studio Loop.pH - Appendix B: 760 - featured a self supporting structure of interwoven circles, to which circular organic PV cells with integrated batteries and lights were clipped on. Kennedy & Violich Architecture went a step further and prototyped an energy harvesting textile for their **Soft House** project. Architecture firm KieranTimberlake proposes **SmartWrap** *“to replace the conventional "bulky" wall with a composite of millimeter scale that integrates climate control, power, lighting, and information display on a single substrate”*.[247]

5.8.3 Level 5 - summary

About half of the projects from the selected corpus are roof integrated, the other half façade integrated with some overlaps, buildings that integrate PV in the roof as well as the façade. Generally it can be said that LTPV is applicable within both areas. The most common integration are in flat and pitched roofs or canopies, skylights and vertical façades. External sunshades are installed fixed or movable, either manually user operated or automatically sun-tracking. Basically, LTPV has been integrated into almost every part of the building skin.

Most if not all projects use PV in areas that are sun-exposed at least at times during the day. In dark parts, if required, the preferred choice are dummy panels imitating PV. With falling prices, however, it can be anticipated, that this dogma will fall sooner or later, allowing larger areas to be equipped with PV. Furthermore, an increasing consideration of indirect light sources may give rise to the use of light-reflecting surfaces to direct more light to the PV. An early and singular example are the white wall and light-reflecting awnings at the **APS Fairfield PV facility** - tf1.[248] The **PV façade at the Ski Lifts Kriegerhornbahn** - cs33 - make use of the natural reflectance of snow at the height of 2170 m.

One of the major advantages of thin-film PV over crystalline silicon PV often mentioned, is the possibility to manufacture flexible BIPV products, that can easily adjust to any curved surface. This is surely true to curves with very small radii, but does not hold equally true to curved surfaces with a larger radius. In the case of stiff panels quite a number of projects using CS PV were found, see 5.8.2 Three-dimensional integration possibilities. However, the continuous flexibility of TF PV allows its use and easy integration with membranes, tensile and textile structures, where the brittleness of CS solar cells limits its widespread use.

247 'SmartWrap™: Building Envelope of the Future' (undated)
248 Hagemann (2002) p.63

5.9 Level 6 - urban / landscape form

The level 6 is the suggested last level on a way that started with the solar cell. In contrast to the preceding levels it is open-ended, as no further level is suggested in this study. Whereas the previous levels and especially level 5 were clearly dominated by buildings or building structures, the intention here is to open the discussion about the forms of energy generation in the wider environment that starts beyond the building skin. As such, it is already clear, that a precise analysis of this level based on the corpus will be impossible. The reason for this early statement is obvious, as the content of the corpus is dominated by singular buildings and built structures, and any conclusion about the world 'beyond' is therefore incomplete.

Nevertheless, some keywords can be given.

5.9.1 Visibility and context sensitivity

As mentioned before, the controversy about 'integrated' versus 'added' arose not least about aesthetics and the appearance of the PV solution - see 2.2.1 BIPV. Such a controversy is of course not limited to PV solutions. Generally speaking, a building never ends at the building skin, but is always committed to contribute to the appearance of the wider environment. This issue is especially delicate in historical or heritage listed environments. The following studies addressed the visibility issue of a PV system.

Task 7 of the IEA PVPS programme suggested six 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"* [249]

Not a study in the real sense, but a description of formal compositions in architecture, Lüling formulates five tendencies:

- ➔ *"CollageStyle . . .*
- ➔ *Integrative . . .*
- ➔ *Blatantly-Integrative . . .*
- ➔ *IntegrativeUnpretentious . . .*
- ➔ *ChameleonMimicry . . . "* [250]

[249] Kaan and Reijenga (2004) p.408
[250] Lüling (2009) pp.29-49

Munari Probst and Roecker developed a framework and suggested acceptability levels by specific local factors, weighted with high, medium or low:

- ➔ *"Urban context sensitivity (the quality of the architectural environment);*
- ➔ *System visibility (close and remote visibility of the proposed system);*
- ➔ *Socio-political context (political and energetic priorities specific to place and time)."* [251]

5.9.2 Art and media installations - urban fabric

Art and media installations require usually a high visibility. But as pieces of art, they generally fall into an own category, and it can be assumed, that even in highly sensitive historical urban areas, where a PV façade or roof might not be allowed by the local building regulations, an art installation could still be possible.

A more ephemeral kind of integration are media installations. Illuminated with artificial light, the PV array changes into a performance area, either vertical like a huge video-screen, see the **GreenPix - Zero Energy Media Wall** - cs68, or horizontal and integrated into the paving like the **Sun Monument 'Greeting to the Sun'** - cs60. In both examples the solar panels are translucent and light-transmission does not apply to natural light, but to artificial light illuminating the translucent screen.

5.9.3 Perception - from machine to organism, from technology to nature

PV can be perceived quite differently. Even though it is a purely technical product, it allows for a number of natural and biological references. In fact, photoelectrochemical cells like dye-sensitised solar cells or purely organic PV already mimic the photosynthesis in plants. But not limited to DSC or OPV, the way PV is seen by architects ranges from the technical metaphors of machine and power plant, e.g. Lundgren and Torstensson: *"The architect resembles the building to a power plant, inspired by early functionalistic ideas of the building as machine".*[252] about **Ekoviikki, As Oy Helsingin Salvia building** - cs36 - or Wigginton: *"The skin of glass . . . changes from location to location, from daylight-welcoming transparency to a hard-working power station",*[253] to animal or plant organisms and biomimicry, Wigginton again in the same article: *"Biomorphic analogies in buildings can be glib, but it is tempting to speculate that if a tree can collect energy effectively by the process of photosynthesis taking place in its leaves, then buildings might more effectively gather their own en-*

[251] Munari Probst and Roecker (2011)
[252] Lundgren and Torstensson (2004) p.6
[253] Wigginton (1996) p.233

ergy".[254] The analogy of foliage is mentioned by a number of architects, e.g. according to Lowenstein about **The Entrance Canopy at the Earth Centre** - cs21: *"Feilden Clegg abbreviated it to an 'abstracted tree' canopy".*[255] The reason for this should be attributed less to the energy generating property, but to the dappled patterns of light and shade that fall through the gaps between opaque cells. Quoted here are Kara Hill about the **Fern Room at the Marjorie McNeely Conservatory** - cs49: *"the additional dappled shade ferns receive in a natural forest environment",*[256] architecture firm Kiss + Cathcart, Architects about the **Stillwell Avenue Terminal** - tf10: *"we designed the glazing to cast a dappled pattern of varying intensities of daylight, which we believe is more stimulating and interesting than diffuse light",*[257] or Nina Maritz about the **HRDC - Habitat Research and Development Center** - cs40: *"a kind of dappled intermediate shade that acts as interface between the solid shade of the foyer and the bright sunlight of the courtyard gardens".*[258] Nina Maritz also acknowledges the influence of weather on aesthetics in general: *"Weather shapes how communities get together, and weather influences aesthetics".*[259] This leads to a further analogy often drawn, weather phenomena like clouds. Dagmar Eble describes the PV patterned skylight at the **Primary School Trudering-Riem** - tf7 - as a cloud-like floating skylight, through which the 'true' clouds are visible,[260] an analogy that also inspired the design for the PV roof at the **Academy Mont-Cenis** - cs17.

5.9.4 Beyond building and building skin

Here again two design proposals that are not included in the corpus are introduced, that allow for some insights into the issue of urban / landscape form. At **Forest Hotel** by Enric Ruiz-Geli of architecture firm Cloud 9 a large number of tiny, self-sufficient leafs, each equipped with a photovoltaic cell, battery and LED, are fixed to a stainless steel mesh offset from concrete walls and glass façade.[261] As the name of the project already indicates, the proposal takes primarily inspiration in the plant analogy (even though the lighting feature could be in-

254 Wigginton (1996) p.233
255 Lowenstein (2002) p.28
256 Hill (2006)
257 see Kiss + Cathcart, Architects <http://www.kisscathcart.com/stillwell/energy.html> - when clicking on the 8th of 9 images.
258 Nina Maritz, personal communication, November 9, 2011
259 Cockram (2007)
260 Dagmar Eble / Krug Grossmann Architekten, personal communication, November 4, 2011
261 More information about this proposal can be found on the websites of the architect Enric Ruiz-Geli <http://www.ruiz-geli.com/04_html/04_forestinprogress.html>, as well as the lighting consult James Clar <http://www.jamesclar.com/index.php?page=cloud-9-habitat-hotel>. According to the latter, *"This model was created for the exhibition "New Spanish Architects" at the MoMA in New York, Feb 2006. This piece is now part of the MoMA's permanent collection."*

terpreted as fireflies). Architecture firm R&Sie.D/B:L on the contrary imagine the reactive building that deforms and responds on contact with renewable energies, with the help of long hairy thermal sensors and swelling photovoltaic cells. Self-sufficiencycy is the aim, and when the state is achieved, the generic building can emblematically **(Un)Plug** from the energy network and even from the urban ground, not a machine anymore but an animated something, neither object nor being, freed of its inherent and imposed numbness and dependency.[262]

Fig.72: Forest Hotel
Credit: © James Clar

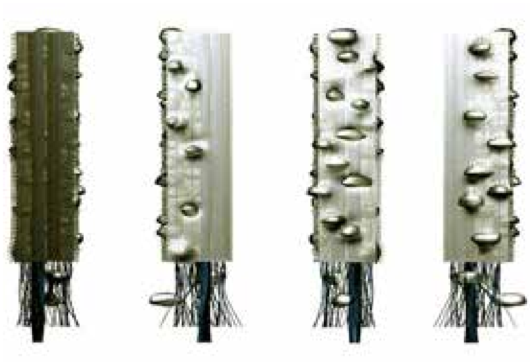


Fig.73: (Un)Plug
Credit: © R&Sie(n)

Both design proposals project their sunlight collectors far beyond the traditional building envelope and as such anticipate the necessity for such protrusions. Both projects also draw the attention to the scale and consideration of possible shapes and formal expressions of energy generation.

5.9.5 Level 6 - open end

An insight at this level that was gained despite or probably thanks to the corpus dominated by building in urban areas, is that the scale and size required not only for energy generation, but to balance these areas with already existing demands on any site will require a fresh look at our image of the productive city and landscape, as was also pointed out by Scognamiglio et al.[263]

Different possible 'visions' are present by various stakeholders. A common vision by the major manufacturers of PV modules is often advertised at PV product fairs and illustrated with Fig.74, a diorama of the world as we know it today with PV modules staggered on top. An aversion to this has caused the majority of the architectural profession to favour an 'invisible' integration approach. Such a nostalgic view, however, is often harshly put into question

262 More information about this project can be found on the website of the architects R&Sie(n) <http://www.new-territories.com/unplug.htm>

263 Scognamiglio et al. (2011)

by an opposite reality that wishes to maximise efficiency and yield and illustrated with Fig.75 showing a gas station with a roughly five-storey tall solar power plant placed on top. Another common vision by many stakeholders are the ground-mounted, mega-solar power plants in the countryside - see Fig.76, where cheap land is available and urban problems caused by density hardly exist.

Fig.74: Diorama with PV
Credit: © Robert Baum

Fig.75: Gas station with solar tower in Tokyo
Credit: © Robert Baum

Fig.76: Lonza Solarpark, Waldshut-Tiengen, Germany
Credit: © SUNWAYS

As can be seen, the options to integrate PV are manifold, however, whether the result is pleasing or acceptable is often a totally different issue.

5.10 Comparative case study using the Six-Level Matrix

The comparative case study presented here illustrates the narrative and explanatory potential of the Six-Level-Matrix for comparative analysis of built LTPV examples. It investigates, how LTPV has been integrated into triangular surfaces of four examples. Analysing existing examples in contemporary architecture can help in promoting the application in future projects.

5.10.1 Triangulated surfaces

Triangles are not only the most basic shape, but also the strongest shape, widely used in buildings and structures. With the advent of complex architectural, computer generated free-form surfaces, a subdivision process called triangulation, that segments any complex free-form surface into planar triangular panels, is often used.

Fig.77: Queen Elizabeth II Great Court
Credit: Eric Pouhier / Wikimedia Commons

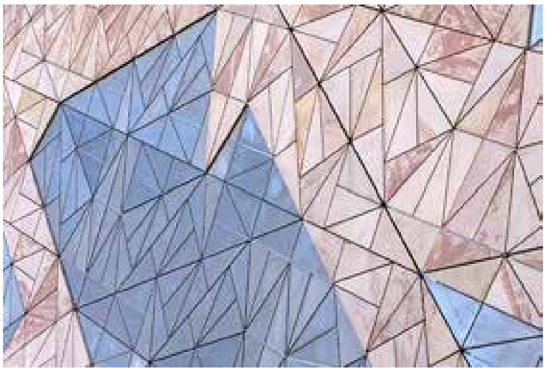


Fig.78: Federation Square
Credit: Seo75 / Wikimedia Commons

Fig.79: BMW Welt
Credit: Maximilian Dörrbecker / Wikimedia Commons

Fig.80: Guangzhou Opera House
Credit: 圍棋一級 */ Wikimedia Commons*

These reasons have given rise to the growing number of contemporary buildings with triangulated envelopes. Just to name some examples: the transparent roof of the **Queen Elizabeth II Great Court** in London, UK by architecture firm Foster and Partners, 2000; the façade at the **Federation Square** in Melbourne, Australia by architecture firm Lab Architecture Studio, 2002; the tornado-like, hourglass-shaped event hall at the **BMW Welt** in Munich, Germany by architecture firm Coop Himmelb(l)au, 2007; or the **Guangzhou Opera House** in Guangzhou, China (PRC) by architecture firm Zaha Hadid architects, 2010.

5.10.2 LTPV study cases

The four case study projects, as an early example the **Pyramids at Demosite** in Lausanne, Switzerland from 1992 - cs3, and three more recent projects: the **Marrakech Ménara Airport** in Marrakech, Morocco, 2008 - cs66, the **Cité du Design** in Saint-Etienne, France, 2010 - cs82 - and the **House of Music** in Aalborg, Denmark, ~2012 - Appendix B: 320.

Fig.81: Pyramids at Demosite
Credit: © demosite.ch

Fig.82: Marrakech Ménara Airport
Credit: © John Bridges

Fig.83: Cité du design
Credit: © Jan-Oliver Kunze

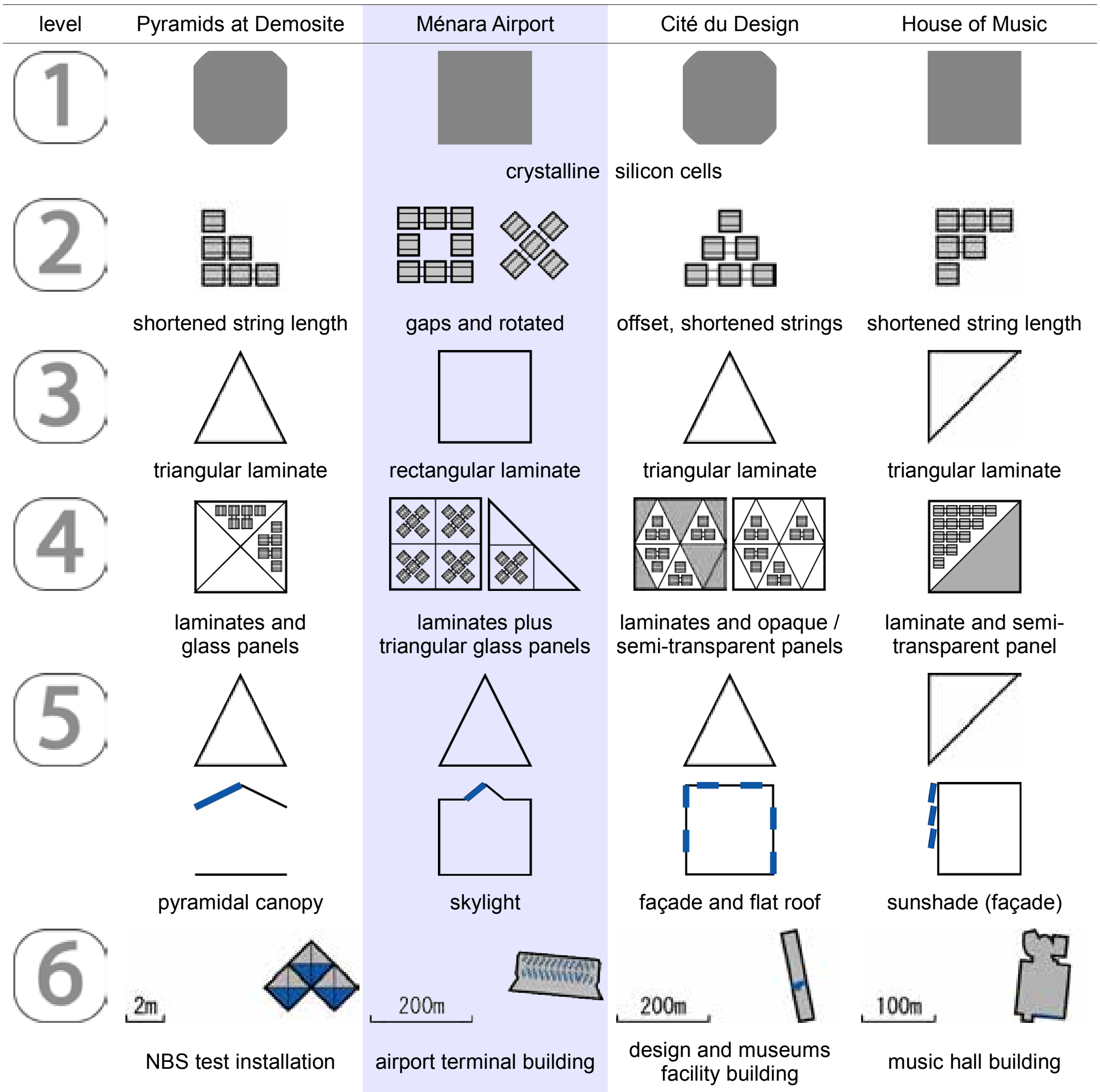
Fig.84: House of Music
Credit: © SFL Stallhofen

Even though each project is unique in its own right, the Six-Level-Matrix allows for an easy comparison of the PV design - see Tab.30. All four projects use crystalline silicon cells (level 1) and work with triangles on different areas of the architectural envelope (level 5). However, it can be said, that the Ménara Airport is very distinct from the other three projects on the three intermediate levels. Whereas the other three projects maximise the number of cells in a laminate (level 2), at the Ménara Airport gaps are deliberately introduced and cells rotated in relation to the laminate edges, a well-considered design intent that takes inspiration in traditional mashrabiya.[264] Where the other three projects introduce the triangle already as

[264] Baum and Liotta (2011) p.288

laminate shape (level 3), the designers of the Ménara Airport stick with the standard rectangular shape. Where in the other three projects, a single laminate is similar in size to the required size for integration into the architectural envelope, at the Ménara Airport a number of similar laminates are combined with simple triangularly glazed parts (level 4) to compose one triangular side of a pyramidal skylight. It must be noted, that in the Cité du Design the LTPV modules are only one of ten different kinds of triangular façade and roofing modules. As such the composition of PV and non-PV modules can be seen as belonging rather to the built form (level 5) than to a distinct and separate PV panel-group form (level 4).

Tab.30: Comparison



level	Pyramids at Demosite	Ménara Airport	Cité du Design	House of Music
1		crystalline	silicon cells	
2	shortened string length	gaps and rotated	offset, shortened strings	shortened string length
3	triangular laminate	rectangular laminate	triangular laminate	triangular laminate
4	laminates and glass panels	laminates plus triangular glass panels	laminates and opaque / semi-transparent panels	laminate and semi-transparent panel
5	pyramidal canopy	skylight	façade and flat roof	sunshade (façade)
6	2m NBS test installation	200m airport terminal building	200m design and museums facility building	100m music hall building

5.11 Design strategies with LTPV in architecture

Finally, after the detailed level 1 to 6 based analysis of the built projects, it is time to have a wider look at the architectural design strategies. Not looking at the details with a magnifying glass anymore, but it's time to get a feeling for the wider picture and intentions that resulted in the PV designs.

It goes without saying that PV and LTPV are chosen in any project because of their power generating ability in the first place. This most basic reason is common sense and doesn't need any elaboration. More interesting here is to shed some light on *"other architectural functions"* [265] - see 2.2.1 BIPV - that LTPV is intended to perform in the examples.

As mentioned before, a major advantage of LTPV over opaque PV is variable light-transmission, the ability to change the degree of light-transmittance. As such, it is the dualism of light and shade that counts, and balancing both requirements provides the architect with two basic directions for a design strategy integrating LTPV.

5.11.1 Providing homogeneous illumination levels

Where daylight is scarce, in projects with larger interior spaces, entrance halls or atria, a strong focus is on providing homogeneous illumination levels. This is often done by integrating LTPV into skylights, roofs or canopies. Many examples are included in the selected corpus (**Brundtland Centre** - cs4, **Rikers Island Compost Facility** - cs5, **Ecumenical Community Centre Kirchsteigfeld** - cs6, **Café Ambiente** - cs7, **Shell solar cell factory** - cs12, **Fire Station Houten** - cs18, **Floriade 2002** - cs31, **Fujipream Kohto Factory** - cs35, **Power Valley Jinjiang International Hotel** - cs65, **Welios - OÖ Science Center Wels** - cs86, **Tsukuba OSL** - cstf3, **CSIRO Energy Centre** - cstf6, **C.C.C. Kei Wai Primary School (Ma Wan)** - cstf7, **PTM Zero Energy Office (ZEO) building** - cstf8, **EMR Center 'Energie-Forum-Innovation'** - tf2, **Tamayu Health Spa** - tf3, **Würth Holding Administration Building** - tf6). Due to a strong shading ability to avoid glare and overheating at the same time, such LTPV integrated glazed roofs and skylights can be easily larger and without the requirement for additional shading devices than their glazed non-PV counterparts, resulting in favourable economics - see also 5.12.2 LTPV performance as source of light.

5.11.2 Provision of shade or vision barrier

In projects where daylight isn't scarce, the provision of shade gains in importance. All projects with LTPV as sunshading devices - see 5.8.1 Built examples ordered based on structural

[265] Kiss and Kinkead (1995) p.4

integration - belong to this group. Shading devices like louvres are often elements added to the basic building volumes. They can fulfil their shading function and at the same time maximise energy yield from the PV power generator. As added elements their orientation is often rather flexible and by orienting them towards the sun, fixed or equipped with sun-tracking devices, both functional requirements are ideally met (**SBL offices 'Wirtschaftshof Linz'** - cs11, **Waterworks Schwerin** - cs15, **Jakob-Kaiser-Haus, building 3 and 7** - cs22, **Pichler Werke** - cs26, **Gemini House** - cs27, **Caltrans District 7 Headquarters** - cs43, **Berufsschulzentrum Riesstrasse** - cs54, **Sequana Tower** - cs79).

Another large group of shade providing structures are many non-building structures, that are often free-standing so illumination isn't any issue (**Pyramids at Demosite** - cs3, **Solar Catamaran RA 66 'Helio'** - cs14, **The Entrance Canopy at the Earth Centre** - cs21, **Kelvin Grove Urban Village** - cs23, **Footbridge at Nishinomiya Kitaguchi Station** - cs45, **Vidursolar car park** - cs56, **PV Frisbee** - cs77, **Breeze Shelters** - cs80, **Ombrière SUDI prototype** - cs83, **BP-Solar Harmony Gas Station** - tf5, **Kanazawa Bus Terminal** - tf11, **SFMTA Bus Shelters** - tf15). But also in buildings such kind of shading structures can be found, often as canopies or eaves (**HRDC** - cs40, **The Core at the Eden Project** - cs46, **Whitehall Ferry Terminal** - cs47, **Community Centre Ludesch** - cs48, **'La Vaguada' shopping mall** - cs55, **London City Hall** - cs59, **Experimental building of the TU Darmstadt** - cstf9).

A further group are examples, where partial patches of LTPV form an integrated part of either a glazed façade (**Tobias Grau lighting GmbH** - cs9, **Ski Lifts Kriegerhornbahn** - cs33, **AquaCity Blue Sapphire** - cs57, **Oslo Operahuset** - cs63, **Partille Municipal Office** - cs76, **Heron Tower** - cs85, **Pompeu Fabra Library** - cstf1, **NTC Tower** - tf17) or glazed roof (**'Wohnanlage Richter' residential complex** - cs1, **Solarcafé 'Sonnenzeit'** - cs13, **Jubilee Campus** - cs16, **Novartis 'Gehry' building** - cs73).

The provision of shade can fulfil a social function as a semi-transparent vision barrier as well, like in **Kollektivhuset** - cs32 - and **Ekoviikki** - cs36 - where LTPV panels got integrated as balcony balustrade, or the stair tower of **Hestestalds-karréen** - cs20.

5.11.3 Limitations for homogeneous levels of light and shade

So far the mentioned projects provided very homogeneous levels of light and shade by often a very homogeneous distribution of crystalline solar cells - see also 5.5.4 Level 2 - summary - or constant transparency ratios of thin-film sheets. In some cases the extent of the LTPV area is limited by the available PV technology. With two installations at **Tobias Grau lighting GmbH** - cs9, a smaller array installed 1998 and a larger more complete array installed three years later in 2001, it can be assumed that the lower cost at the time of the later installation made a larger array feasible. Here the cost of available PV technology was a limiting or enabling factor. At **Stillwell Avenue Terminal** - tf10 - and similarly at **SCHOTT Ibérica** - tf12, both are retrofit projects, the architects designed LTPV panels with centred TF sheets and a wider clear glass margin. The reason for such unconventional designs can be the limited range of available TF sheet sizes and manufacturer dependent transparency ratios. Fully covered TF panels in customisable sizes and preferred transparency ratios are on the wish list of architects especially for integration in retrofit situations to avoid size mismatches. One way of overcoming this dilemma is to adjust the design strategy, as for instance Kiss + Cathcart, Architects did at Stillwell Avenue Terminal when saying that a dappled pattern is more stimulating and interesting than diffuse light - see 5.9.3 Perception - from machine to organism, from technology to nature.

Other limiting factors can be non-rectangular shapes in the architectural form, as can be seen at **PV Frisbee** - cs77 and **EMR Centre 'Energie-Forum-Innovation'** - tf2, where rectangular LTPV panels are integrated in the centre area and supplemented with a margin of clear glass panels to complete the architectural amoebae shape of PV Frisbee's canopy or align the skylight with the curved walls of the conference room at EMR Centre. By sticking to one standard size of LTPV panel in both examples, power-generating functional honesty prevented the use of look alike dummy panels. The opposite approach is, of course, the use of dummies - see 5.5.3 Dummy cells and 5.7.4 Dummy panels - to achieve not only a formally complete architectural image, but also functionally in terms of continuously providing homogeneous illumination levels (**Brundtland Centre** - cs4, **Community Centre Ludesch** - cs48, **Breeze Shelters** - cs80). In some other cases, dummy cells or panels were intentionally made recognizably different from the real cells or panels, most often by much brighter imitations than their real counterparts (**'La Vaguada' shopping mall** - cs55, **California Academy of Sciences** - cs70, **Partille Municipal Office** - cs76). Which approach yields more pleasing results might be questionable, and surely depends on the overall architectural intention, however, the example at California Academy of Sciences leads to the next design strategy to integrate LTPV.

5.11.4 Provision of smoothly graded illumination levels

An alternative to homogeneous levels can be the provision of graded illumination levels. This can be done by either altering the light-transmission ratio or with additional, secondary elements. At the California Academy of Sciences brighter dummy panels mediate between the darker LTPV panels and clear glass margins or the sky respectively. For a smooth gradation an every now and then occurring method is to alter the crystalline silicon cell or string spacing (**Solar Office Doxford International** - cs8, **SBL offices 'Wirtschaftshof Linz'** - cs11, **Dutch Nature Trust 'Nieuwkoopse Plassen'** - cs74, **OLV Hospital** - cs78, **Lillis Business Complex** - cstf5). This method often yields visually smooth results, as the density can be varied at cell-group level.

5.11.5 Patchwork patterns

Variations at the higher panel-group level appear less smooth or rather coarse, like a patterned patchwork. Patchwork patterns are a design opportunity, that attempts to loosen visual rigidity and dullness by introducing variety. Many of the panel-group forms described in - 5.7 Level 4 - panel-group form - can be used for patchwork patterns. An easy method is to combine LTPV and clear glass panels in either an orderly fashion (**STAWAG** - cs2, **WZH Waterhof** - cs39, **APS Fairfield PV facility** - tf1) or with a random casualness (**SMA Solar Technology HQ** - cs62, **Natura Towers** - cs75, **Primary School Trudering-Riem** - tf7, **Kulturhaus Milbertshofen** - tf9, **Herwig Blankertz School** - tf14). LTPV panels can be combined with opaque PV or non-PV panels (**SIMS Administration Building** - cs50, **GENyO** - tf16). An extreme case is **Cité du Design** - cs82, where LTPV panels are one of nine equally sized semi-transparent and opaque multifunctional panel types for cladding the roof and façade of the building. Less often yet applied methods for adjacent panels are the use of differently sized CS cells (**Academy Mont-Cenis** - cs17, **Gentofte Teknikhytte** - cs29), different TF transparencies (**Tiger Woods Learning Center** - tf13) or different cell patterns (**McDonald's Cycle Center** - cs41). At **Fern Room** - cs49 - LTPV panels with off-centre distribution of cells were simply rotated by 180 degree to achieve a patchwork pattern.

At **Zero Energy Building @ BCA Academy** - cstf11 - a patchwork like façade is the testbed for different PV technologies in LTPV and opaque PV. Crystalline silicon and thin-film LTPV where also combined at **Nursery school 'El Blauet'** - cstf10, enhanced by different colours of the panels' encapsulating glass. A patchwork façade made with differently coloured LTPV panels can also be seen at **Centro de Arte Alcobendas** - cs81 - and **SCHOTT Ibérica** - tf12, where the interior is illuminated with colourfully filtered light. At **Kollektivhuset** - cs32 - such patches of coloured sliding panels are an additional element behind the LTPV panels. At **Q-Cells OF1 Thalheim** - cs53 - sliding panels in grey contrast with the fixed LTPV panels and their blue solar cells. By the user movable overhead sunshades made of LTPV panels are integrated in **Bo01 Harmony house** - cs25 - and **Children's Museum of Rome** - cs28. At the **Experimental building of TU Darmstadt** - cstf9 - narrow opaque louvres were integrated into almost building high foldable frames like doors to be opened or closed by the user. This project is furthermore an example for using opaque TF in a 'light-through' way, other examples are the tent structures at **'Under the Sun: An Outdoor Exhibition of Light'** - tf4 - and ETFE cushions of the **Carport Roof at the 'Abfallwirtschaftsamt'** - tf18. In both projects single opaque TF sheets were bonded in a distributed and spaced arrangement on light-transmissive membranes. Other examples are **Hestestalds-karréen** - cs20, **Lycée du Pic Saint-Loup 'Jean Jaurès'** - cs34 - and **AEON LakeTown** - cs61.

5.11.6 Artistic and playful PV

With the last examples of the previous section, distributed panels were mentioned as a method for patchwork patterns. Wide spaced cells at **Kankakee Community College** - cs58, some patches of cell-groups at **Youth Centre Vestervang** - cs30 - and wide spaced panels at **Kollektivhuset** - cs32 - give a less rigid impression. LTPV in these examples appears more like a playful addition to the building. At **Welios - OÖ Science Center Wels** - cs86 - the crisscross lines, even though made of dummy modules, may well belong to this category.

Pure art projects in general are often small-scale in relation to their immediate environment and highly visible (**Solarsail Münsingen** - cs10, **CCM 'The Brain'** - cs44). In some cases LTPV art projects themselves are distributed in the wider urban environment (**Fifteen SunFlowers** - cs71, **Public lighting at Columbia Heights Civic Plaza** - cs72, but also **Solar Tree Prototype** - cs52, **SFMTA Bus Shelters** - tf15). The use of colour in art projects, see **Christliches Kinderhaus Ulmenstrasse** - cs38 and **True North / Lux Nova - Wind Tower** - cs64, is often more refined and much smaller in scale than in the patchwork architecture projects in the previous section, due to the smaller scale of the projects. The latter is a multi-media project combining a colourfully stained glass art work with a light and music installation. With urban media projects, medium-size or even larger scales are easily imaginable (**Sun Monument 'Greeting to the Sun'** - cs60 - and **GreenPix - Zero Energy Media Wall** - cs68) - see also 5.9.2 Art and media installations - urban fabric.

5.11.7 Natural metaphors and ephemeral phenomena

From a power plant metaphor (**Ekoviikki** - cs36) reminiscent to the machine metaphor of the early modernism, to the provision of dappled shades, a biomorphologic analogy to foliage (**Fern Room at the Marjorie McNeely Conservatory** - cs49, **Stillwell Avenue Terminal** - tf10, **HRDC** - cs40), some examples for the range of metaphorical design associations were mentioned in 5.9.3 Perception - from machine to organism, from technology to nature. Imitation of sky and clouds (**Primary School Trudering - Riem** - tf7, **Academy Mont-Cenis** - cs17, **National Museum of Taiwan History** - cs84), or undulating water and sea surfaces

(**GreenPix - Zero Energy Media Wall** - cs68) are examples for natural phenomena as fruitful metaphors. A tree / dinosaur like structure at **The Entrance Canopy at the Earth Centre** - cs21 - or a snake / dragon / river like structure of **The Main Stadium for the World Games 2009** - cs69 - illustrate the power of the living and animated world to initiate imaginative design approaches.

5.11.8 Clothing and masks

Since Gottfried Semper's *Bekleidungstheorie* the metaphor of clothing has been a continuous inspiration for architectural design. Like a striped cloak or cloth draped over the interior spatial functions, the façade at **Daito Bunka University** - cs37 - is partially covered with LTPV and semi-transparent non-PV panels, and partially left open. At **Cité du Design** - cs82 - the building's cloak is complete. Curved building surfaces enhance the appearance of clothing (**Fire Station Houten** - cs18, **Fujipream Kohto Factory** - cs35). The rotating solar screen at **Gemini House** - cs27 - is attached like a mask to the front of the building's face - the façade. At **Hestestalds-karréen** - cs20 panels are added with spacing to the plastered façade leaving larger openings at windows and interestingly even additional openings at imaginary windows, masking frames for a 'complete' window pattern. Furthermore, as the LTPV panels are added to the opaque parts of the façade, their light-transmissive feature isn't required for neither illumination nor shading, but renders the appearance of LTPV more like bobbin lace, a filigree layer for partial, incomplete screening and to contrast with the massive walls.

5.11.9 Retrofit and adaptation to existing building

Beside complete new developments, renovations and with it a retrofit including LTPV panels that fit to a predefined formal language of the existing buildings, especially in historic settings, will surely be an increasing task in architecture - see also 5.9.1 Visibility and context sensitivity. It is this field where the demand for PV and LTPV in a variety of colours for a visible integration is required most urgently.[266] At **Alès Tourist Office** - cs24 - brownish CS cells were used, and grey cells were used at the **Solar Centre MV** - cstf4. Many other examples of retrofitted buildings are included in the corpus (**Café Ambiente** - cs7, **Hestestalds-karréen** - cs20, **Pichler Werke** - cs26, **Children's Museum of Rome** - cs28, **Kollektivhuset** - cs32, **'La Vaguada' shopping mall** - cs55, **Le Losserand building 'Hotel Industrial'** - cs67, **Dutch Nature Trust 'Nieuwkoopse Plassen'** - cs74, **Partille Municipal Office** - cs76, **Stillwell Avenue Terminal** - tf10 - and **SCHOTT Ibérica** - tf12).

[266] See also Rexroth (2005)

5.11.10 Cultural references, geometric patterns, pixelisation

As was pointed out by Baum and Liotta, cultural referencing can be a fruitful method for achieving public acceptance.[267] At **Baptistery of the Epiphany Church** - cs19 - LTPV panels with different cell densities were arranged to form a symbolic cross. At **Marrakech Ménara Airport** - cs66 - LTPV panels were designed reminiscent to Arabic traditional *mashrabiya*. Mashrabiya often at oriel windows are functional screens made of geometric latticework. A simpler, less traditional geometric pattern was used for the design of the LTPV panels at **[Pod #001]** - cs51.

Baum and Liotta further analysed so called low-res(olution) strategies like pixelisation in art, design and architecture for their potential being applied to the design of LTPV patterns.[268] Examples are **Marrakech Ménara Airport** - cs66 - with their low-res, abstracted version of mashrabiya, **Le Losserand building 'Hotel Industrial'** - cs67 - with a pixelised image of the existing building's stone façade as a starting point for the design of the LTPV pattern,[269] but also the previously mentioned projects that took inspiration in natural phenomena, **Primary School Trudering - Riem** - tf7 - and **Academy Mont-Cenis** - cs17 - with their abstracted images of low-res clouds floating above, or **National Museum of Taiwan History** - cs84 - the wall as a cloud with inscribed name of the museum. Furthermore, the urban media projects, (**Sun Monument 'Greeting to the Sun'** - cs60, **GreenPix - Zero Energy Media Wall** - cs68) use pixelised low-res strategies for light projections.

5.11.11 Providing opportunities for activated, performative envelopes

Last but not least it is the opportunities that come with the power generating ability of LTPV panels, that are yet explored very sporadic. It is again the media installations **Sun Monument** - cs60 - and **GreenPix** - cs68 - that here too need to be mentioned. Lüling sees activated *"Surfaces in Electron Flux"* [270] as key in uncovering the true and ultimate potential of the not so new material PV for architecture.

[267] Baum and Liotta (2011) p.294
[268] *"Low-res, or low resolution, usually describes the insufficient amount of a pixellated screen or image, where instead of a smooth gradation of colours or levels of brightness, the individual pixels can be distinguished, thus revealing a "digital" origin. In the world of computers, screens and digital images or films, low-res has been seen equal or near to bad quality. In the field of product design (e.g. Ron Arad's pixel sofa Do Lo Res), the computer derived pixel art and architecture, however, it is seen as an inspirational approach for design and pattern generation."* Ibid. p.291 A short analysis and presentation of a few contemporary buildings is included in the paper.
[269] *Le Pavillon de l'Arsenal: Collection Paris Architectures: #11 Emmanuel SAADI, Hotel Industriel, Paris 14e* (2007)
[270] Lüling (2009) p.45

5.12 LTPV performance

5.12.1 LTPV performance as power generator

Generally speaking, performance characteristics of LTPV as a power generator are similar to standard and opaque PV, foremost dependent on the technological conversion efficiency. Except for the special characteristics of DSC and OPV as 'truly' semi-transparent solar energy conversion devices, it is only the actual semiconductor and thus the opaque part of any crystalline silicon cell and a-Si or CIS / CIGS thin-film sheet, that generates power. With LTPV the semiconductors and these opaque parts are simply less densely distributed. An increase in transparency by 10%, or from the point of power generation a decrease of semiconductor area by 10%, almost equally relates to a decrease of 10% energy yield from the same module area. In the case of semi-transparent DSC and OPV this 'reduction' in areic conversion efficiency is already included in the technological cell conversion efficiency. When only comparing the active power generating semiconductor area of opaque PV with LTPV than there shouldn't be a significant difference in efficiency. It must be noted, that a slightly lower yield may occur in LTPV due to longer electrical connections and thus an increase of resistance, thus resistance losses, however, and without being overly critical or emphatic on this issue, to consider cable length has never been of high importance to architects when designing a building, and it will seem odd if suddenly PV is the only area to consider such thoughts. On the other hand, spacing cells may reduce the cell's and encapsulation material's local heat increase, especially in comparison to quite popular 'all black' opaque modules with a black backsheet, thus counterbalancing any resistance losses with less temperature dependent performance losses. Heat losses again count negatively on insulated modules performance yield.

The other most influential factor on power generating performance is the orientation towards and insolation from the major energy source, the sun. Again, there shouldn't be a significant difference between opaque PV and LTPV.

As important as efficiency is in achieving a high yield, it is not the only parameter to consider. Due to the changing position of the sun a strong emphasis is always put on avoiding any shading, as this mostly results in a disproportionately high reduction in yield. The countermeasure for any ground or flat roof installation is a sufficient spacing between adjacent rows of tilted modules. Unfortunately this results in an inefficient use of the site or roof area, as the low altitude of the winter sun is the determining factor. A similar situation with building integrated PV and LTPV is a saw-tooth roof. At **Brundtland Centre** - cs4, for instance, the cells in the lower shaded part of each skillion roof part are non-active dummy cells, altogether 40% of all cells. At **Community Centre Ludesch** - cs48 - each module was split into three parts, a lower usually shaded part (27%), a middle seasonally shaded part (27%) and an upper non-shaded part (46%). The lower part are non-active dummy cells, but the middle and upper part are connected to separate inverters to optimise energy yield. Both examples show, that an optimal orientation of the shed sections and active cells towards the sun resulted in quite substantial proportions of inactive and reduced effective areas. At **L3/L7 Restaurant at Shell Head Office** in Rijswijk, Netherlands - see Appendix B: 149 - a different approach was taken. After initial considerations to built a saw-tooth roof, finally a horizontal roof was built. Even though the orientation of the modules is not optimal, resulting in a 15% loss of energy yield per module according to Lundgren and Torstensson, this approach allowed 63% more modules to be installed and a 38% higher yield of kWh/m^2 of horizontally projected roof area.[271] After visiting and studying several horizontal PV installations, ter Horst and Smulders found neither dirt nor filth contamination to be any serious problem and concluded that the advantages and potential applications outweigh any disadvantage.[272]

It is interesting to see, how buildings with similarly integrated LTPV systems at different locations perform. **Natura Towers - MSF Group HQ** - cs75 - in Lisbon, Portugal (location: 38°46′N, 9°10′W; orientation: East of South; horizontal insolation: 1773 kWh/(m^2 year); annual yield: 409 kWh/kW$_p$) and **Heron Tower** - cs85 - in London, UK (location: 51°31′N, 0°05′W; orientation: West of South; horizontal insolation: 996 kWh/(m^2 year); annual yield: over 460 kWh/kW$_p$). Both buildings have LTPV panels integrated into a vertical façade. Even though the horizontal insolation in Lisbon is 80% higher when compared to London, it doesn't relate to an equally higher yield. Reasons are surely the lower altitude of the sun in London, that better suits a façade integration, but also the virtual absence of any shading onto the high-rise façade of the Heron Tower, whereas the South tower of the two Natura Towers shades the LTPV panels on the North tower partially during the day.

5.12.2 LTPV performance as source of light

With regard to a flexible adjustment of the light-transmission ratio: in the case of thin-film LTPV, even though a smooth gradation and adjustment of the monolithic TF structure is theoretically possible, only a few manufacturer dependent fixed values, mostly at 5% or 10% intervals dominate the commercially available product range. A value of 10% especially with a-Si LTPV appears to be a manufacturer introduced and somewhat established compromise in balancing maximum electricity generation with semi-transparency towards a bright sky or exterior. As such, the shading aspect is given a very important role too. LTPV made from CIGS

[271] Lundgren and Torstensson (2004) pp.18-20
[272] ter Horst and Smulders (undated)

is offered up to a light-transmission ratio of 50%. As DSC and OPV are still an infant technology, it is difficult to predict the later commercially available range of transparencies.

In the case of crystalline silicon, the single cell structure allows for an individual spacing of the cells, and as such virtually any percentage of light-transmission is easily achievable. However, as the standard back to front bus bar connection requires a minimum spacing plus an often slightly wider non-active edge margin, values below 10% are rather uncommon.

Whereas with thin-film LTPV lower light-transmission ratios and most often 10% appear common, with crystalline silicon LTPV it is generally higher percentages around 20~50%. This tendency can be clearly seen at some built examples, that use LTPV of both technologies in the same building, like **Tsukuba OSL** - cstf3 - (CS: ~56%, TF: 10%) or **Nursery school 'El Blauet'** - cstf10 - (CS: 27%, TF: 10%). Here it must be noted again, that these percentages refer to the absolute VLT (visible light-transmission) based on the percentage of transparent areas in relation to opaque areas. But more important for the human eye is the perceived VLT: *"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",*[273] illustrating the subjectively perceived effectiveness of already very low absolute VLT ratios. However, similar to a tinted car window, appearance and visibility changes dramatically from inside to outside, or more generally from the dark side to the bright side - see also 2.5.3 Light-transmission.

With regard to sun protection: according to Riedel one of the advantages of LTPV over conventional sun protection is *"a particular quality of light; sunlight filtered through structured solar modules retains its natural color".*[274] This of course applies only to colourless LTPV. Furthermore, integrated LTPV that functions as sunshading too has according to Bahaj et al. very attractive economics. They analysed the benefits and drawbacks of architectural integration of PV in buildings and arrived at the conclusion, that due to *"a significant reduction in capital cost [and] also in the maintenance burden associated with a normal shading solution . . . [i]t is this multi-functionality of PV in atria that creates a scenario where the 'most expensive' BIPV system per kWp has the shortest financial payback time of the case study examples".*[275]

With regard to the distribution of light: the major advantage of 'see-through' PV is an even distribution of light without any stark contrasts, which makes it better suited for office environments and work spaces. The major characteristic of 'light-through' PV is a strong patterning of opaque areas and light-transmissive regions, casting a dappled shade. The impression

273 'Glossary of Words: Visible Light Transmission (VLT)' (undated)
274 Riedel (2010)
275 Bahaj, James and Jentsch (2007) p.67

might be similar to a natural leaf canopy, mediating between areas of bright sunshine and dark shade, an effect often exploited for atria or corridors.

5.12.3 LTPV performance - summary

Concluding it can be said, that the unique characteristics inherent in any LTPV technology make their range of application quite distinct. It is less a question of which technology performs better, but to understand the unique features of each technology and then choose the appropriate area of application. A high efficiency is only one measure to evaluate LTPV power generation performance, but a high yield can be achieved by different approaches. It is the combination of power generation and an inherent flexibility to adjust between light-transmission levels and sun protection that is the unique advantage of all LTPV.

6 Alternative patterns for PV and LTPV

6.1 The quest for designed, parametric patterns

Even though few built examples exist, an interest in heterogeneous patterns can be taken for granted. Pellegrino et al. suggested PV panels with increasing string distance using the red scale of the Modulor.[276] Scognamiglio et al. suggested patterns with random solar cell positions taking inspiration from Piet Mondrian's painting Broadway Boogie-Woogie.[277] The random omission of solar cells in a grid-like arrangement leads to patterns, reminiscent to early, low-resolution, pixellated computer graphics.[278]

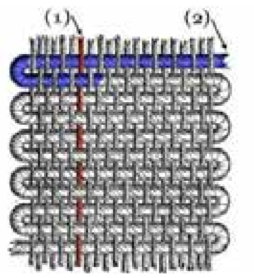
More generally speaking, in the advent of designed, parametric pattern generation, Patrick Schumacher, partner at Zaha Hadid Architects, values patterns as *"a potent device for architectural articulation",*[279] and Alejandro Zaera-Polo as *"critical expressive devices".*[280] Furthermore, Zaera-Polo identifies an opposition to the Cartesian grid-division in contemporary building envelopes. However, if an orthogonal grid is used as the organising structure for the construction, *"it is usually disguised by introducing an overlapped pattern or a 3-D manipulation of the surface".*[281] Scognamiglio et al. describe this tendency as *"substituting orthogonal matrixes with innovative geometries developed by means of complex generative processes, based on casualness".*[282] This raises the question, whether standardised orthogonal PV patterns that reinforce the orthogonal grid are able to satisfy such needs.

But how can a general approach of 'disguised by introducing an overlapped pattern' be achieved? The German-Italian research and demonstration project PVACCEPT study suggested an added irregular screen-print on the front cover glass of thin-film PV - see 5.6.8 Level 3 - summary. An almost complete disguise of the common appearance of PV was achieved, but only by deliberately accepting the loss in generation efficiency caused by this intentional shading. As mentioned before, for such an approach thin-film PV technologies are better suited due to their superior performance under partial shading. With crystalline silicon such an approach would result in a presumably much higher and therefore unacceptable loss of efficiency. The following two design proposals suggest a different approach for CS.

276 Pellegrino et al. (2002)
277 Scognamiglio et al. (2006)
278 Baum and Liotta (2011)
279 Schumacher (2009) p.31
280 Zaera-Polo (2009) p.22
281 Ibid. p.26
282 Scognamiglio et al. (2006)

6.2 Design proposal 1 - 'W(e)AVE' - tilted and wave-like cell patterns

Here I'd like to draw an analogy to the craft of weaving, where a pattern is created by interlacing two distinct yarns. The intersection of warp and weft form a crisscross pattern - Fig.85.



(1) warp yarn

(2) weft yarn

Fig.85: Weaving
Credit: User:Ryj, Derwok / Wikimedia Commons

Textile weaving forms, strictly speaking, an orthogonal grid, for the purpose of stability of the fabric. However, in the case of PV stability is given by encapsulation. The analogy of weaving, that I call **'W(e)AVE'**, can be applied to PV as basically a two-directional pattern generating approach. The process of overlapping liberates the generation of patterns from the linearity of the cell-strings by superimposing the electrical interconnection in cell-strings with a deliberate crossing pattern - Fig.86.

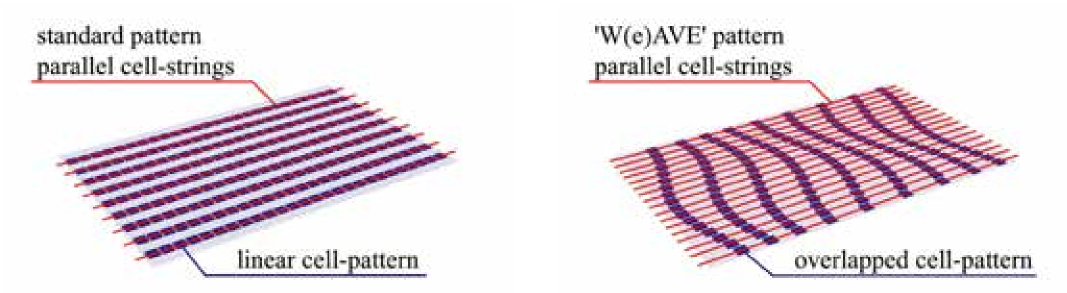


Fig.86: Comparison of standard pattern and 'W(e)AVE' pattern
Credit: © Robert Baum

To make this approach operational, 'W(e)AVE' is based on two parameters:

- ➔ First, the spacing of the solar cells in cell-strings can have more than one distance. However, linearity is kept in cell-strings.
- ➔ Second, interconnection between neighbouring cell-strings doesn't require the cells to lie exactly side by side, an offset between cells is possible. However, parallel position of cell-strings is kept.

In combining the two parameters, tilted and wave-like arrangements of solar cells become possible. Furthermore, in keeping linearity and parallel position of cell-strings, an easy integration into manufacturing processes can be achieved. Clear parameters also allow for parametric design, to run through a whole series of design options and to quickly understand the impacts of changing the pattern on levels of transparency, light transmission, number of photovoltaic solar cells and energy generation.

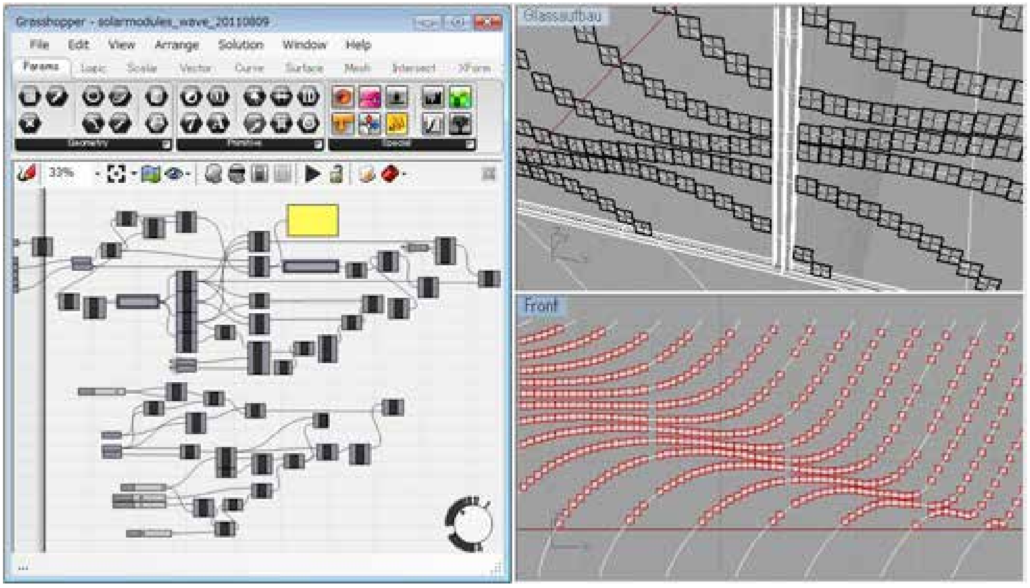


Fig.87: 'W(e)AVE' generating algorithm using Rhino / Grasshopper software
Credit: © Robert Baum

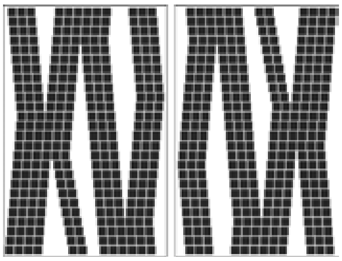


Fig.88: 'W(e)AVE' case study I: tilted pattern, two-panel BIPV
Credit: © Robert Baum

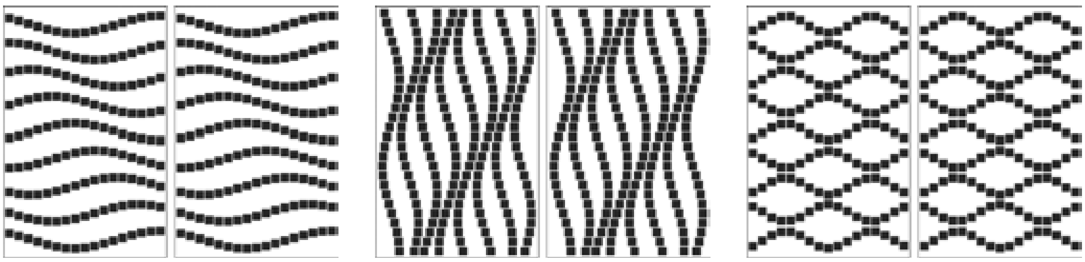


Fig.89 (a), (b) and (c): 'W(e)AVE' case study II: sinusoidal patterns
Credit: © Robert Baum

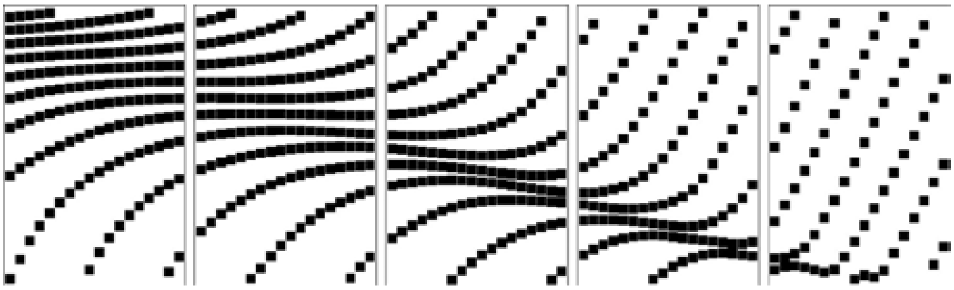


Fig.90: 'W(e)AVE' case study III: free-form pattern, five-panel BIPV
Credit: © Robert Baum

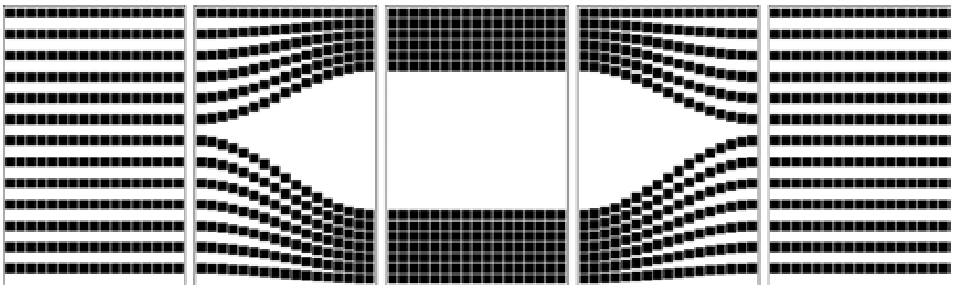


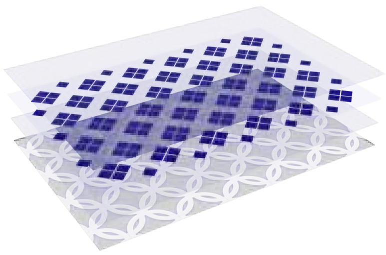
Fig.91: 'W(e)AVE' case study IV: transition between linear standard patterns
Credit: © Robert Baum

To proof the versatility of 'W(e)AVE', a number of alternative patterns were generated and visualised using the parametric design software Rhino / Grasshopper - Fig.87. As can be seen from the case studies in Fig.88 to Fig.90, 'W(e)AVE' enhances the options for individual designs and architectural integration of PV under the premise of 'disguising' greatly. It also allows for smooth pattern transition between more generic patterns - Fig.91.

6.3 Design proposal 2 - layered, culturally inspired patterns

The following design proposal is an investigative approach into applying the inventory of local cultural heritage as an inspiration for technological innovation. Light-transmissive photovoltaic laminates provided the technological test bed and Japanese traditional family crests were the cultural ingredient for this case study. Even though PV is in general highly appreciated to contribute positively to a building's energy requirement in a sustainable manner, their actual use and integration into the building skin is lacking far behind their full potential. From a cultural point of view this is a matter of acceptance of a product appreciated for its technology, but not its appearance. One of the main reasons given, is that the standard products offered by the PV industry are regarded as insufficient to pleasantly merge the technological product with the demands of contemporary architectural design,[283] thus rendering the appearance as 'added' instead of 'integrated'.

For this study, *kamon* or traditional Japanese family crests were chosen as source of inspiration. *Kamon* depict plants, animals, natural or man-made objects. Some are very figurative, others are more abstract, but most inhere certain geometric qualities, and despite being monochrome exhibit a layered depth. *Kamon* that are composed of square, rectangular or linear elements were selected as they can be easily translated into single or groups of photovoltaic solar cells. Strong linear arrangement of PV cells is one of the requirements for an automated manufacturing process. Thus the selected *kamon* were applied to generate alternative light-transmitting PV patterns.



– outer transparent layer of glass or foil
– solar cell layer between adhesive, binding films (EVA*)
– inner transparent layer of glass or foil
– semi-transparent print on either side of the inner layer

* EVA – EthylVinylAcetate

Fig.92: Layered structure of an LTPV laminate with additional screen print
Credit: © Robert Baum

Fig.92 shows the layered structure of a light-transmissive PV laminate with a semi-transparent print on either side of the inner layer. This feature is a common option for glazings, but hardly explored in the application of light-transmissive PV.

Three exemplary case studies are illustrated in Tab.31, showing the source of inspiration, the translation into two layers, one solar cell layer plus an additional screen printing layer, and a rendered image of a possible façade application seen from inside the building.

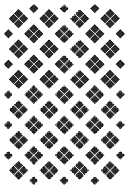
[283] Scognamiglio et al. (2006); Mercaldo et al. (2009)

Tab.31: Study cases
source of kamon: <http://www.kamon18.com/index.html>

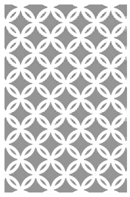
Case study A: 丸に四つ割り石 [Maru ni yottsu-wari-ishi - Four stones in a circle]

Family crest

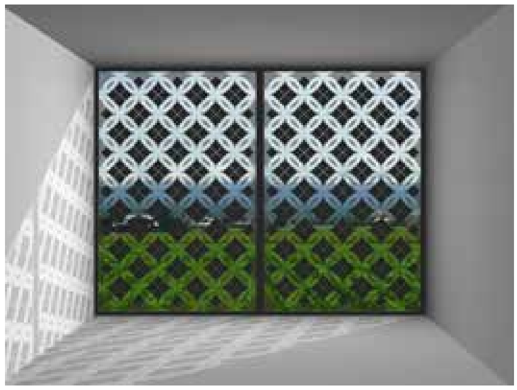
Solar cells



Print

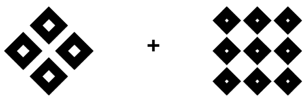


Interior rendering

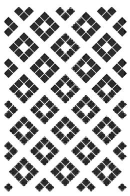


Case study B: 七つ割り隅立て四つ目+繋ぎ九つ目
[Nanatsu-wari sumi-tate yottsu-me + Tsunagi kokonotsu-me]

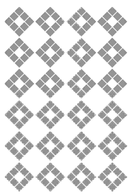
Family crest



Solar cells



Print

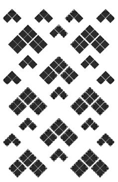


Interior rendering

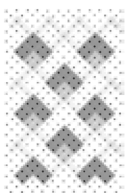
Case study C: 三つ目 [Mittsu-me]

Family crest

Solar cells



Print



Interior rendering

6.4 Design proposal 3 - Solarize

The following design proposal was submitted to the 1st ENEOS Solar Energy Public Art Contest 2010 in a Japanese version under the title 'Solarize it.' - Fig.98 - as well as presented at UIA2011 TOKYO, The 24th World Congress of Architecture as an English poster under the title 'Solarize Tokyo'[284] - Fig.99. The following text is equal to the latter poster.

solar energy X urban density – from symbiosis to heliotropism

In 1960 the architect Kisho Kurokawa started to use the word symbiosis to call for a new perception of architecture and the interaction between cultures and nature.

In 1977 the engineer Kosuke Kurokawa innovated distributed energy generation by suggesting a dispersed photovoltaic network that cooperates through the grid, a symbiosis of distribution.

Today, in 2011, let's bring the ideas of the two Kurokawas here in Tokyo, the metropolis of density and guerilla flower pots together. It is often argued that cities should reduce their environmental footprint.

Fig.93: Guerilla flower pots lead an urban symbiotic lifestyle.
Credit: © Robert Baum

Today this is a matter of cost, BUT in 2050 it will be primarily a matter of SPACE.

As we can see today, the dense urban fabric of Tokyo seems to make it difficult if not impossible to properly use the sun for solar energy generation. Here the idea of symbiosis gains ground, as it promotes the idea of looking into the possibility for a mutual benefit of seemingly mutually exclusive issues. An example from Tokyo are the manifold flower pots, used as a guerilla tactic to introduce green and nature to paved and concreted urban areas.

284 Baum (2011)

Photovoltaics and with it solar architecture require solar insolation, for the same reason that plants require it. The heliotropic symbiosis for solar architecture in the dense urban environment of Tokyo will deploy the tactical approach of guerilla, which is a creative process. To "create", from the Latin word crescere is related to "become visible, to arise" and "to grow, to thrive; to multiply", a flux process for solar architecture.

– a tactical campaign towards 2050 and beyond

The proposed tactics are:

(1) SCOUTING

... to identify blank spots in the urban fabric, spaces that are empty, unused, or underused. It reveals that density is not distributed evenly and suitable spaces are there in abundance.

Fig.94: Scouting
Map based on Google Maps

(2) TEMPORARY SEIZURE

... to occupy the available empty space, a temporary symbiosis of empty space and solar architecture. Especially the vertical space is used very uneven and it looks promising to explore it more closely. Above urban infrastructure, like streets, canals, parks, parking spaces and roads is a huge potential for solar architecture.

If a different use for the space is required, it can easily be cleared.

Fig.95: Odaiba - Yume no Ohashi
Credit: © Robert Baum

(3) BRANDING

... to make the transformation distinct and identifiable.

Solar flower seedling, a possible design example, a symbiosis of Buckminster Fuller's lightweight constructivism with energy generation, is implanted to initiate the conversion process.

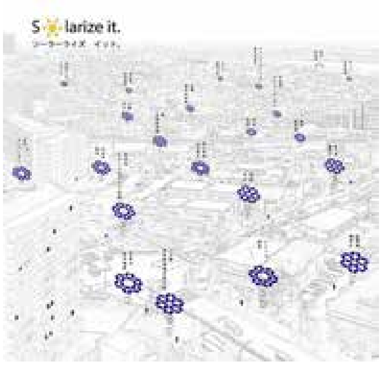


Fig.96: Advertising poster explain and make the transformation recognisable.
Credit: © Robert Baum

(4) COEXISTENCE

... to minimise undesired effects but maximise the symbiotic value. The gain is added value in addition to sustainable green energy.

Solar architecture starts to grow like a seedling, it follows the urban fabric and grows exuberantly. The symbiosis turns towards heliotropism.

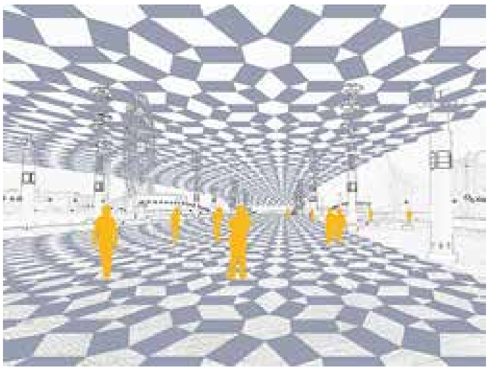


Fig.97: Coexistence
Credit: © Robert Baum

With this campaign Tokyo will embark on the path to shift its energy supply for the year 2050 and beyond towards renewable sources.

If the campaign is successful in Tokyo, it can be successful in all developed and developing metropolises.

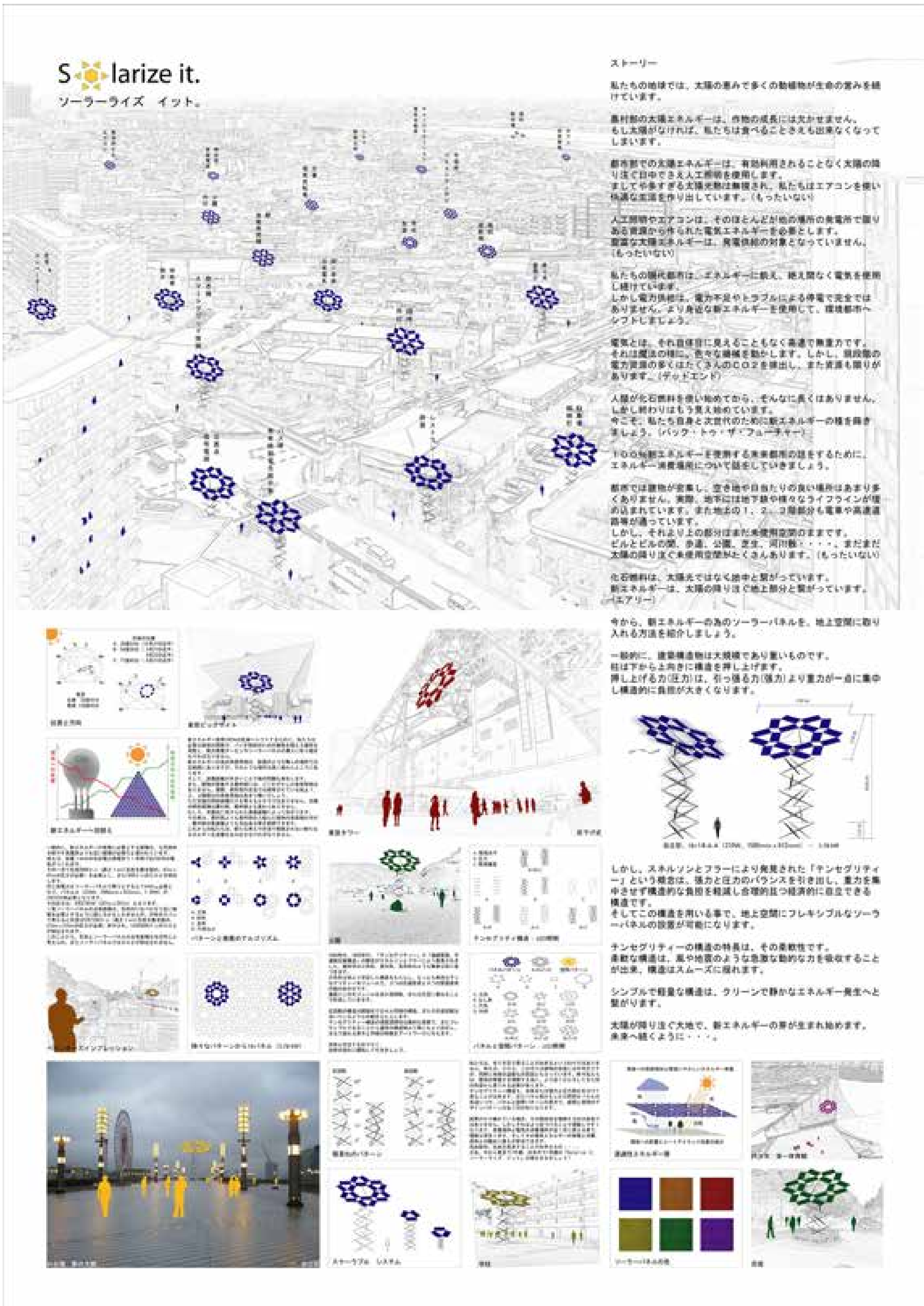


Fig.98: Solarize it.
a competition entry to the 1st ENEOS Solar Energy Public Art Contest 2010
Credit: © Robert Baum

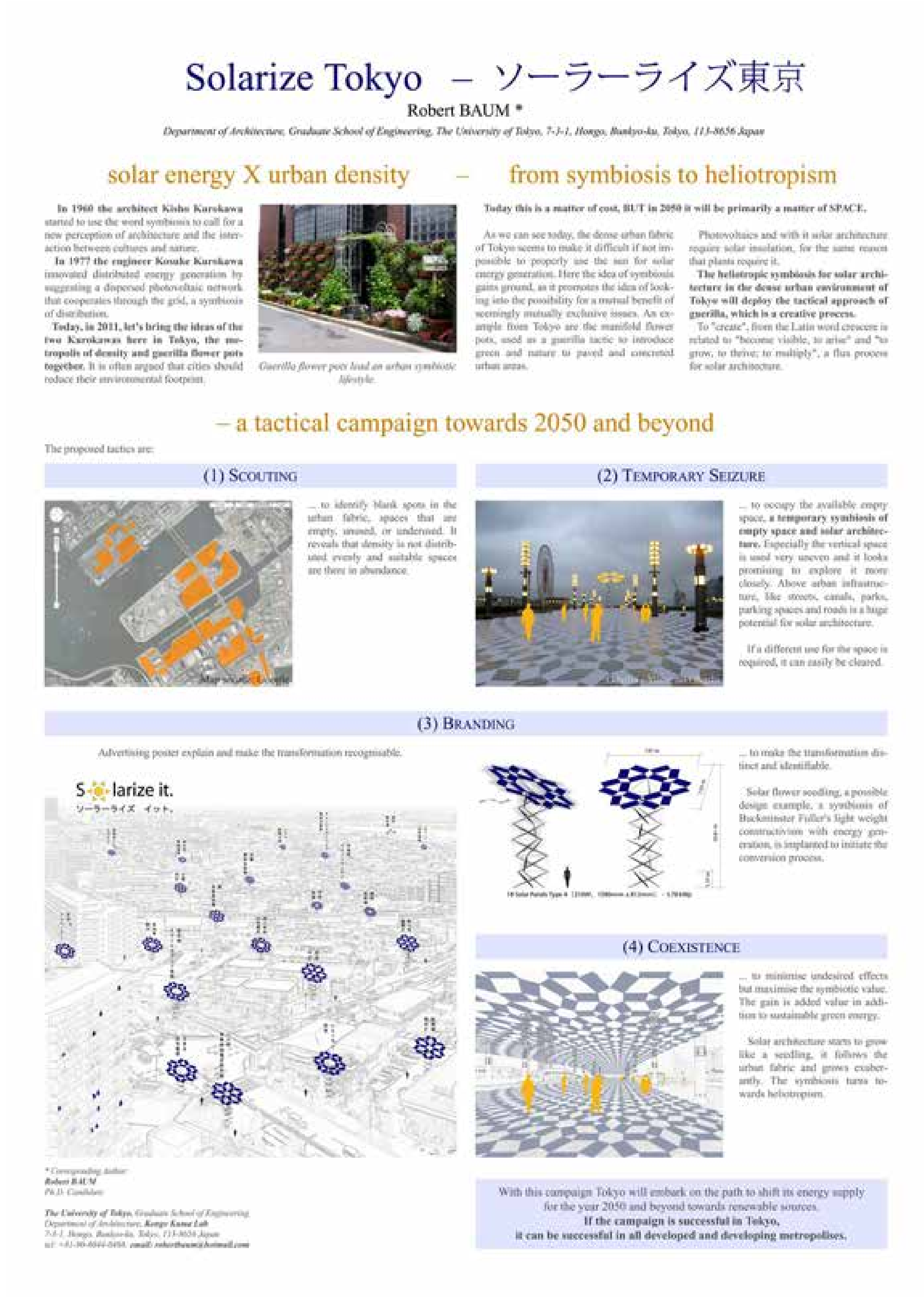


Fig.99: Solarize Tokyo - ソーラーライズ東京
a poster presented at UIA2011 TOKYO, The 24th World Congress of Architecture
Credit: © Robert Baum

6.5 Summary

In this chapter, three design proposals were presented.

The first two are for alternative, mainly crystalline silicon solar cell patterns. The focus on crystalline silicon cells happened for two reasons: (a) the manufacturer independent standardisation of the solar cell, which allows for widespread utilisation of the design proposals; and (b) the affinity of the additive tiling of solar cells to contemporary low-res strategies. Low-res strategies are often employed as an organisational and pattern generating principle inherently suited for crystalline silicon cells. Here the smallest 'pixel' or 'particle' is equivalent with a single square, semi-square or round solar cell. Low-res strategies can be employed to de-materialise an otherwise ready-made industrial PV product.

The first proposal and parametric approach 'W(e)AVE' overlays and disguises the linear cell interconnection with a second pattern, that allows for tilted and wave-like designs. Technically this is achieved by a variable spacing of the solar cells within a cell string.

The second proposal takes inspiration in traditional patterns, to achieve a wider public acceptance of PV with the help of cultural referencing. It highlights the importance of implementing into contemporary design not only present technologies, but also cultural uniqueness. Here it must be noted, that this is not an attempt of bringing traditional icons without thought into the context of modern design, but to highlight the importance of cultural adaptation of technology. Careful consideration must be taken to not cheapen the value of traditions. Technically the second proposal can be achieved by combining a solar cell pattern with an additional pattern on the encapsulating material. Of course, the second approach is not at all limited to traditional patterns.

Both solar cell design proposals illustrate, that using the analytic insights gained with the help of the Six-Level-Matrix and by simply adjusting only one or two of the key-design parameters, a wide range of solar cell pattern variations akin to contemporary architectural design become possible, of which some are illustrated with renderings. Furthermore, a flexible change in the level of transparency beyond the light-transmission ratio enables the architect to set the visible connection between the interior space and outside of a building into a complex relation.

The third design proposal points to the growing importance of space as a prerequisite to supplying a noteworthy share of human energy needs with solar power, and the challenge to provide space in densely populated urban areas. It sees an opportunity in the typical urban multi-layered space use, and suggests four tactics. Instead of seeing the city as a functional machine it re-reads it as a productive landscape. A machine and the current city require the continues input of energy usually supplied from external sources, and the lack thereof results in an immediate halt, as is best understood by frequently occurring wide-area blackouts. A productive landscape, however, optimises the use of any locally available energy supply. Such a comparison takes inspiration in more traditional, rural and vernacular forms of human habitat, like the Japanese Satoyama and Satoumi. It doesn't take a nature romantic view, but instead trusts in a mutually beneficial relationship between mankind and the ecosystem. With regard to the Six-Level-Matrix it points to the importance of the Level 6 to reconsider the urban / landscape form of not only PV or LTPV but any human activity.

7 Conclusion

7.1 Six-Level-Matrix

The integration of photovoltaic technology into light-transmissive panels as light-transmissive photovoltaic systems (LTPV) has created a modern building, architectural and design element.

As pointed out in the introduction, the common analysis of PV in buildings has been based on opaque PV due to the overwhelming market share. My thesis was, that certain issues, only recently noticeable or noticeable only when looking from the point of LTPV are showing the limitation of this approach. This study addressed the lack of research into LTPV.

The corpus on which the study is based, consists of 116 selected case study projects from a full corpus of 610 LTPV built examples. This is four to five times the number as in the comparable reference literature.

A Six-Level-Matrix is suggested as a framework for the analysis of built examples. Architectural integration has to be considered on all six levels. Analyses so far have focused mainly on the two elemental levels 'solar cell' (level 1) and 'solar panel' (level 3), and the first integrational level 'built form' (level 5). However, as solar cells are not available in any shape, the problem of how to manage the distribution of solar cells in an arbitrarily shaped solar panel arises. This controversy gave rise to the consideration of the 'cell-group form' (level 2) and similarly of the 'panel-group form' (level 4) as mediating compositional and intermediate levels. An analysis of the two newly considered compositional levels, and a subsequent categorisation of built examples was done here for the first time. An extension of the analysis beyond the building envelope into the macro-scale environment is suggested and included in the Six-Level-Matrix as the final level 'urban / landscape form' (level 6), to include non-building projects, integrated urban surfaces and new forms of energy generating, performative landscape patterns.

Advancing from level 1 to level 6 can be seen as a vertical axis, that relates to the scale under consideration and increasing combinatorial possibilities. The analysis and subsequent case study of built examples using the Six-Level-Matrix revealed, that the newly considered compositional levels 'cell-group form' (level 2) and 'panel-group form' (level 4), and the other levels too, follow two opposing tendencies for uniformity, homogeneity and heterogeneity. When added as a horizontal axis, the Six-Level-Matrix forms a coordinated system - Fig.100 - ideal for the analysis and categorisation of light-transmissive and opaque PV in built projects, as well as for the product variety offered by PV manufacturers, a reference for further design, application and development.

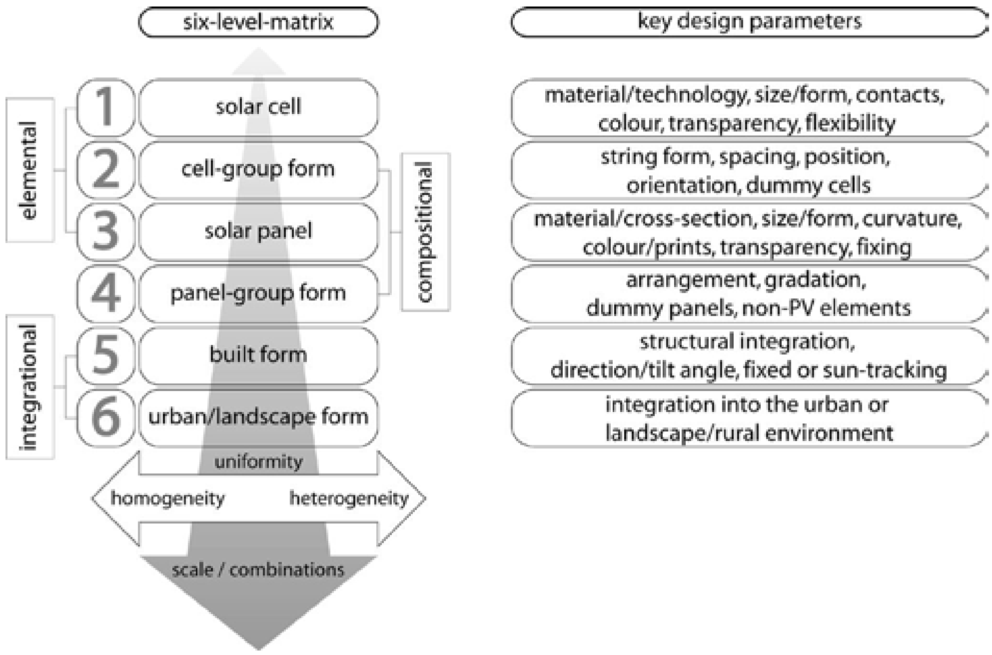


Fig.100: Six-Level-Matrix and key design parameters
with the two axial tendencies for scale / combination and uniformity (homogeneity / heterogeneity)

7.2 LTPV as architectural and design element

Regardless the technology a large variety of different designs are achievable. It became clear, that the available 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 flexibility in influencing the key design parameters. The suggested Six-Level-Matrix has not only helped in understanding the integration process of PV into buildings, but has also opened the door for a more analytic approach in generating alternative patterns for LTPV, as was exemplified with two design proposals.

It appears reasonable to state, that the full range of available PV materials has not been equally applied to LTPV. It is not only the active PV technology itself, that an architectural LTPV element is made of. Already the required encapsulation provides opportunities for variations. Especially here, the combination of at least two uniquely different materials, photovoltaic semiconductor and encapsulant, with their inherently different material characteristics and visual appearance could offer an extended range of combinatorial and customisable choice still waiting to be fully exploited. Furthermore, the combination with other non-PV elements 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.

It can be said, that architectural integration treats PV not as a product that comes in standard sizes, but as a fully customisable element similar to other architectural elements, contributing with it's inherent and unique material, functional and aesthetic characteristics to the overall performance. Architectural integration focuses on integration into the design process, not solely as a substituting element or green feature, but rather treat it as an indispensable element of the architectural process, which is as customizable as other design parameters to the individual project's characteristics. Architectural integration of PV can be seen as a 'craft'. A reference in time may be drawn to early modern experiments with concrete, or the experiments by Alvar Aalto with brick at his Muuratsalo Experimental House, and his oeuvre in general. It is time to closely study the material and compositional qualities of LTPV, and PV in general, as a superior architectural element, whose parameters can be influenced on all levels.

7.3 Future outlook

➔ A continuing strong political will to financially support the dissemination of PV as alternative energy source was observed during the time of this study. Furthermore, the 2010 Deepwater Horizon oil spill and the 2011 Fukushima nuclear disaster brought the often underestimated risks of the oil and nuclear industries in terms of insufficient preventive risk management and negative environmental and financial impact following the disaster once again to a global attention. Due to the wide area negative impact of these disasters, it can be assumed that they will have a measurable impact on the attitude of the affected citizens and thus at least regional public opinion to favour alternative energy resources.

➔ Further steep increases in globally installed PV capacity and resulting declining prices for PV systems, private end-customer grid-parity is in sight in the near future.

➔ Whereas large-scale ground installed PV power plants are often investment and provider driven, small- to medium-scale and most building-integrated PV systems can be both, provider as well as consumer driven. As soon as grid-parity is achievable, and incentives like FiTs - Feed-in Tariffs with law-enforced purchase requirement for the utilities most likely abolished soon afterwards, building integration of PV will gain a further, major advantage over ground-installations. Whereas a PV power plant owner will have to sell the generated electricity to the utilities at utility prices, a building owner may have the option to sell it to the tenants at near end-customer prices.

➔ If the peak power demand can be satisfied by the building-integrated PV, it will relieve the strain on the utilities, but on a larger scale also take away a premium, thus sensible part of the utilities' market share. This will have a major impact on utilities' pricing models.

➔ Energy requires space. As most energy for buildings and human activity in them is required in dense urban areas, a general lack of ideally oriented sun-facing areas can be assumed. With dwindling prices and a reasonable ROI - return on investment period for PV, the areas of application in a building will diversify, away from the dogma of sun-exposure towards all surfaces of the building envelope. The continuing challenge to design triple-zero energy-neutral buildings is a second driving force supporting this assumption.

➔ As such, increasing cell efficiency will continue to be the guiding principle for any technology roadmap. Application in buildings, however, will be driven by increasing yield, by either capitalising on higher cell efficiencies, or by increasing installed capacity even in areas with less ideal conditions.

➔ The use of dummy modules in less ideal situations has been common, and due to expensive PV products was done "for aesthetic reasons". This luxury may prove unnecessary with PV prices coming down. However, PV installed under many different conditions will require more effort in the electrical design of the PV system to maximise power output and avoid mismatch. The same holds true for undulating surfaces with varying orientation of each panel, a tendency in modern architectural design that may grow stronger.

➔ The search for the "best" technology will be less focused on the technologies themselves, but rather proceed as a flexible search for the "optimum", the ideal application for each technology. Tailored products are key for success in a fiercely competitive market. The competition between the technologies is driving them equally to find and strongly highlight their outstanding areas of application. Crystalline silicon LTPV will continue to be dominantly used in areas with ideal sun exposure, whereas thin-film LTPV has an advantage in shaded areas, and a more stable performance at increasing temperatures.

➔ Even though 'see-through' capability and flexibility are commonly associated with thin-film LTPV, it isn't a unique feature of TF. Further product development in these areas with crystalline silicon LTPV will continue to challenge this association. On the other hand, neither 'light-through' nor a single cellular structure are unique to crystalline silicon LTPV. Further development and imaginative applications in these areas with thin-film LTPV will continue to yield CS-like results. Both tendencies will further blur the distinctive appearance of both PV generations.

➔ Technology and product uniqueness can be equally an advantage that makes it standing out from the market, but also a disadvantage when the range of application is too narrow. During the time of this study, it was especially the success of First Solar's CdTe products, now the only thin-film manufacturer in the Top Ten of the largest PV companies. The success is remarkable because BP Solar as another big and long time committed manufacturer closed its CdTe activities after 25 years of R&D in 2002, the same year that First Solar started commercial production, however, they don't manufacture light-transmissive PV. Examples for uniqueness that led to failure are Evergreen Solar with a proprietary string-ribbon manufacturing process for multicrystalline silicon cells, bankruptcy in August 2011, and Solyndra that manufactured proprietary tubular solar modules, bankruptcy in September 2011. Even though a number of promising alternative technologies and innovative products are developed, it is difficult to predict their success and thus their availability in the future.

➔ The emerging thin-film technologies DSC and OPV may find their unique niche in products for extreme low light situations like building interiors. Beside having a cost/performance-advantage under such conditions, long-term durability, one of the current disadvantages of the technology, isn't the major concern. Interior materials are more often anyway and more easily replaced than materials for the exterior building envelope. Furthermore, the material cost benefits of OPV and DSC are best exploited by avoiding expensive encapsulation materials.

➔ There are generally two sorts of companies offering LTPV products, either traditional PV manufacturers or companies specialised in glass or other encapsulation or building materials. Whereas LTPV products for the first group are at most a side business who generally look for sales of large quantities of a standard product, it is mainly the second group that provide unique bespoke and tailored solutions to the individual wishes of architects and clients. As the number of glazing companies in this area is quite substantial, it is an opportunity to combine the competences of the two industries, PV and glass, by a stronger focus on the latter to offer a much wider range of bespoke module designs. Versatility in module design is the key for success. It has been the missing imagination that set the limit.

➔ With "cheap" PV ubiquitously integrated, the areas of application for PV will see an increase in diversification and new acronyms developing, e.g. AIPV - Automotive Integrated PV - with PV as car roofs, etc. or EIPV - Electronics Integrated PV - for mobile phones, etc. The same kind of diversification will happen with tailored BIPV products, as Paula Mints put it *"BIPV is not just shingles or roof tiles".*[285] As such LTPV offers a strategy and chance for diversification.

➔ Power generation as an inherent feature of a building material is still novel to the building designers and hardly explored as self-powered element. Photovoltaic will be another stepping stone, like electric lighting has been as explained by Banham (1969), that will extend the meaning of an architectural building material towards ephemeral phenomena.

7.4 A partially ironic wish list and vision for photovoltaics of the future

While learning and understanding the complexity and variety of today's PV/LTPV design parameters, a continuous temptation to long for 'simple' PV/LTPV prevails.

This temptation, a deep and overwhelming sensation, is caused by the demands of an already complex design and building process. It may be technology inherent restrictions that cause this feeling of 'added' complexity, because something that doesn't fit easily to existing processes has to be made fit by an additional enormously felt effort. It surfaces in a longing for PV as just a 'simple' feature of other materials, likely expressed in a quote from Frank O. Gehry: *". . . creating the technology to make it more appealing to put on buildings. So material that looks like what we already use to create buildings, but that is actually more energy efficient - smart bricks, smart concrete, smart metal. Then it would be a lot easier to incorporate it into buildings without having to redesign the entire structure".*[286] This temptation is fuelled by outlooks for a solar paint that hopefully could easily be applied to any surface without restrictions of form or shape. It should come, of course, without the need of the building designer's attention for solar cell structures or electrical interconnection requirements, while delivering appropriate if not to say high power yields, available in any colour and first and foremost in WHITE, the most architectural of all colours.[287]

A different future vision bets on the ephemeral properties of future building materials made possible with PV. So far the generated electricity from BIPV has been used exclusively to power existing devices. Here, the ingenious architect and innovative product designer is required to envision, even prototype, parametrise, process and script, to devise the rules and embed the logic for not only architectural design but more importantly the future building materials. It is highly unlikely that such materials will come out of today's PV manufacturing lines. Performative, ephemeral capacities have to reach out from design software platforms not only into the building process but ultimately to the building materials, to properly deal with relationships, boundaries and energies - form follows (energy) flux. To quote Baum and

[285] Mints (2011)
[286] Leonard (2010)
[287] see also Wigley (2001)

Liotta: *"In this regard, parametric photovoltaic patterns have the poetic and pertinent potential to precisely promote performance, or in short: patterns promote performance",*[288] and Wigginton: *"This is not a dream, because technology plus poetry equals architecture . . . All architects . . . have to do is make it happen".*[289]

A third, more pragmatic vision for LTPV takes inspiration in simple and elaborate approaches to control the level of light transmission throughout the history of buildings and architecture. Such devices may have been intended initially not for illumination or shading, but for a culturally rooted longing for disguise. The obsession with (literal) transparency, made possible by the invention of flat glass, has been a recent trait in architectural history since early modernism. As such, it is just a bit older than the invention of the modern solar cell, but changed the course of architecture fundamentally. However, the inflationary repetition of buildings with transparent façades is becoming boring, and the time may come to have a fresh look at disguising strategies.[290] Traditional Arabic *mashrabiya* were mentioned frequently in this study. Apart from their formal expression as lattice work, their use as a cultural and architectural disguising strategy exists presumably as a ubiquitous craftsmanship in all building cultures of the world: Indian *jaalis,* Afghan *panjare,* Japanese *kōshimado,*[291] any kind of lattice screens, grilles, louvres, blinds or curtains, Japanese *shōji,*[292] medieval stained glass windows, wrought-iron fences, pergolas and trellis in garden and landscape architecture, up to brise-soleil made of concrete in modern architecture. Not shade but dappled shade, not harsh light but filtered light and twilight. (Seen this way a metaphoric afterglow dimension is added to the red filtered light of DSC/OPV panels.) To conclude this part once more a quote from Baum and Liotta: *"It must be understood that light is more than the presence of it, and shadow more than its absence. . . . From whatever side the issue of light and shadow is approached, important are not the ends, but the superimpositions that occur on the path towards each other, where the dichotomy essentially merges".*[293]

[288] Baum and Liotta (2011) p.291
[289] Wigginton (1996) p.238
[290] see also 6.1 The quest for designed, parametric patterns
[291] Japanese: 格子窓 - kōshimado - a kind of lattice screen
[292] Japanese: 障子 - shōji - sliding doors made of tranlucent paper on a wooden lattice frame
[293] Baum and Liotta (2011) p.289

7.5 Final remark

Summarising and as final conclusion, whereas the 19th century saw the growing influence of the structural engineer on architecture and architectural form, and the 20th century the growing influence of the mechanical engineer, the 21st century may witness the growing influence of the electrical engineer, and thus a further shift in the diversification and contribution of building professionals. I hope, and here I speak as being an architect myself, that this study will raise the awareness of the architectural profession of the possibilities in shaping, crafting and creatively influencing this process.

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