ARCHITECTURAL INTEGRATION OF LIGHT-TRANSMISSIVE PHOTOVOLTAIC (LTPV)

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ABSTRACT: This paper is a study of light-transmissive photovoltaic (LTPV) and the state of the art of their integration into buildings and non-building structures. LTPV are truly multifunctional and highly architectural elements, surpassing the individual materials' characteristics. From a corpus of ~500 built examples that have been realised since 1982 throughout the world, 111 projects, rich in variety, were selected. Based on an analysis of the selected projects, the key design parameters for LTPV and their architectural integration were established.

A **Six-Level-Matrix** as a basis for comparison and categorisation, as well as a reference for further application and PV development, is suggested. A case study illustrates the narrative and explanatory potential for comparative analysis. Findings indicate a number of innovative solutions that extend the possibilities for integration in an architectural and aesthetically pleasing way.

Keywords: Building Integrated PV (BIPV), Light Transmissive PV (LTPV), Solar Architecture

1 INTRODUCTION

Within the last years many books about building-integrated photovoltaics (BIPV) – by Weller et al. [1], Lüling [2], Roberts & Guariento [3], Scognamiglio et al. [4], Nelli [5], Nelli [6], Prasad & Snow [7], Hagemann [8], Thomas [9], Eiffert & Kiss [10], Sick & Erge [11], Humm & Toggweiler [12] – or Zero Energy architecture including BIPV examples – by Guzowski [13] – were published. On average they include 15-20 case studies, exceptions are Nelli [6] and Hagemann [8] with more than 100 projects each (Table I).

Table I: Reference BIPV literature

	Weller, et al., 2010 [1]	Guzowski, 2010 [13]	Lüling, 2009 [2]	Roberts & Guariento, 2009 [3]	Scognamiglio et al., 2009 [4]	Nelli, 2007 [5]	Nelli, 2006 [6]	Prasad & Snow, 2005 [7]	Hagemann, 2002 [8]	Thomas, 2001 [9]	Eiffert & Kiss, 2000 [10]	Sick & Erge, 1996 [11]	Humm & Toggweiler, 1993 [12]
337 case studies	8	10	34	14	11	44	157	22	129	8	16	20	43
130 with LTPV	4	5	13	8	2	39	69	12	58	3	6	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 almost forty percent 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.

This study is meant to fill the gap, the lack of research into LTPV as an architectural element.

This study is intended to:

- provide a comparative overview of architectural integration of LTPV,
- establish key design parameters based on built examples,
- illustrate development potential for PV manufacturing and architectural integration.

2 APPROACH

To fulfil the first objective of the study, a corpus of ~500 realised LTPV projects from the last two decades has been compiled. This means about four times more built examples than the case studies published in the books about BIPV (Table I).

To fulfil the second objective, 111 projects were selected for the detailed analysis (Table II). 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,
- but also well published examples, to understand their stance in terms of architectural integration.

Based on this analysis, the third objective is realised.

3 LTPV – light-transmissive photovoltaic

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 [14], the field of potential application in overhead glazings and curtain walls is extremely wide [15], and their impact on saving energy is higher [16]. 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 [17], sun protection and reducing heat gains [18].

4 TRANSLUCENCY AND TRANSPARENCY

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.

However, when the focus is less on technology, but more on the quality of light transmission, a different classification seems to be required. To achieve light transmission there are two common ways.

4.1 'Light-through'

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

4.2 'See-through'

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

Recent research & development has opened the door to a new type of thin-film cells, namely dye-sensitised or organic cells, that are truly transparent though coloured yet. The primary applications in buildings are included in this study.

4.3 'Unique' approaches

Some manufacturers have developed unique, proprietary approaches to achieve transparency, like 'Sphelar Glass' by Kyosemi Corporation [19][20], the 'Photovoltaic Glass Unit' by Pythagoras Solar [21], or the 'Sliver cell' by ANU-CSES [22]. However, as building related projects were not found, these approaches are not discussed further in this paper.

5 ANALYSIS OF BUILT EXAMPLES

5.1 Location, year of completion, rated power output

From the corpus of ~500 built projects with LTPV, a variety of 111 projects from 5 continents were selected (Table II), 73 from Europe (DEU: 23, ESP: 8, GBR: 7, AUT: 7, FRA: 6, DNK: 6, NLD: 4, CHE: 3, SWE: 2, FIN: 1, BEL: 1, ITA: 1, SVK: 1, HRV: 1, PRT: 1, NOR: 1), 17 from Asia (JPN: 7, CHN: 4, TWN: 3, IND: 1, MYS: 1, SIN: 1), 15 from America (USA: 14, CAN: 1), 3 from Africa (MAR: 1, NAM: 1, SDN: 1) and 3 from Australia (AUS: 3). All selected projects were realised within the last 30 years, 1 in the 1980s, 20 in the 1990s and 89 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 – 100 kWp installed. In some cases, LTPV are a supplement to a much larger opaque PV installation.

5.2 'Light-through' vs. 'see-through'

87 projects use crystalline silicon technology, 15 use thin-film technology (including the emerging dye-sensitised technology) and 9 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 cs13, cs32, cs47, cs73, cs86, cstf2 and cstf7, whereas cstf2, cstf7, tf8 and tf14 utilise opaque thin-film in a 'light-through' way.

5.3 Building typology

LTPV have become integrated into many different kinds of buildings, and building structures, as well as non-building structures (Table III). 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.

5.4 Building integration

About half of the projects from Table II are roof integrated, the other half façade integrated with some overlaps, buildings that integrate PV in the roof as well as the façade (Table IV). 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 curtain-wall façades. External sunshades, whether movable or fixed, are more often used at façades than roofs. Basically, LTPV has been integrated into almost every part of the sun-facing building skin.

Table II. Selected examples of LTPV

id (*1)	name	location	Year (*2)	architect, designer, artist, engineer or pv company	rated power [kWp] (*3)	building type	building element (*4)	cells/laminate; feature (*1, *4)
cs87	L'hôtel du Lac [SAPHIR]	Nagahama, Shiga, Japan	n.a.	Akihiro Minamihira	n.a.	hotel	balcony, balustrade	single cells in glass blocks
cs86	House of Music	Aalborg, Denmark	~2012	Coop Himmelb(l)au	n.a.	concert hall	façade, fixed sunshade	triangular laminates, semi-transparent cells
cs85	Heron Tower	London, UK	2011	Kohn Pederson Fox	>200	high-rise, mixed use	curtain-wall	blue screenprint on inner side
cs84	Pearl River Tower	Guangzhou, China	2011	Skidmore, Owings & Merrill	24	high-rise, mixed use	free form curtain-wall	parallelogram laminates
cs83	National Museum of Taiwan History	Tainan, Taiwan	2011	Chien Hsueh-yi	195	museum	inclined wall	text pattern
cs82	Cite du Design	Saint-Etienne, France	2010	LIN Fin Geipel and Giulia Andi	n.a.	design centre, multi-purpose	façade + flat roof	triangular laminates
cs81	Centro de Arte Alcobendas	Madrid, Spain	2010	Fernando Parrilla	19	cultural centre	façade	multicoloured backsheets
cs80	Breeze Shelters	Singapore	2010	The Cox Group, Architects 61	n.a.	NBS, urban furniture	circular canopy	
cs79	Sequana Tower	Paris, France	2010	Arquitectonica	30	high-rise, office building	hor louvres at roof	
cs78	OLV Hospital	Aalst, Belgium	2009	VK STUDIO	46	hospital	inclined façade	varied string distance
cs77	PV Frisbee at TES Swire European Primary Campus	Taipei, Taiwan	2009	Kao Ying-Chao, Bio Architecture Formosana	6.8	education, primary + playground	canopy	organic shaped canopy
cs76	Partille Municipal Office	Partille, Sweden	2009	Figura Arkitekter AB	2	municipal government, renovation	curtain-wall	printed, dummy laminates
cs75	Natura Towers	Lisbon, Portugal	2009	GJP arquitectos	53.6	office building	curtain-wall	long laminates, pattern
cs74	Visitors Centre, Dutch Nature Trust	Nieuwkoop, Netherlands	2009	MIII Architecten	n.a.	visitor centre, renovation	pitched roof	striped laminates, gradation
cs73	Novartis Campus	Basel, Switzerland	2009	Gehry Partners LLP	92.47	corporate, multi-purpose	free form roof	offset strings, semi-transparent cells
cs72	Public lighting “Columbia Heights”	Washington DC, USA	2009	Zimmer Gunsul Frasca Architects	3.12	NBS, lighting	tilted	special shaped laminates
cs71	SunFlowers	Austin, TX, USA	2009	Harries/Héder Collaborative	14.26	NBS, sculpture	tilted	blue gel in laminates
cs70	California Academy of Sciences building	San Francisco, CA, USA	2008	Renzo Piano Building Workshop	172	museum	canopy on four sides	rectangular, trapezoidal at the corners, prints
cs69	World Games Stadium	Kaohsiung, Taiwan	2008	Toyo Ito	1027	stadium	free form roof	
cs68	GreenPix – Zero Energy Media Wall	Beijing, China	2008	Simone Giostra & Partners	79	entertainment centre	façade, media wall	varied regular cell densities
cs67	Hotel Industrial	Paris, France	2008	Emmanuel Saadi, Jean-Louis Rey, François da Silva	123.43	office building, renovation	façade + balustrade + roof	varied irregular cell densities, stone imitation
cs66	Marrakech Ménara Airport	Marrakech, Morocco	2008	E2A Architecture	55.44	airport terminal	skylight	cell pattern, rotated cells
cs65	Power Valley Jinjiang International Hotel	Baoding, China	2008	n.a.	300	hotel	ver curtain-wall + flat roof	non-PV windows
cs64	True North/Lux Nova	Vancouver, BC, Canada	2008	Sarah Hall (artist), Clive Grout, Walter Francl (architects)	0.4	NBS, ventilation tower for underground library	façade	artistic pattern, dichroic glass
cs63	Q-Cells OF1 Thalheim	Thalheim, Germany	2008	bhss Architects	48	corporate, office building	façade, fixed ver sunshade	combined with movable metal mesh screens
cs62	SMA Solar Technology Headquarter	Niestetal, Germany	2008	HHS Planer+Architekten AG	n.a.	corporate, office building	curtain-wall + skylight	irregular façade pattern
cs61	AEON Koshigaya Lake Shopping Center	Koshigaya, Japan	2008	Obayashi	13.3 (481)	shopping centre	eaves	trapezoidal laminates
cs60	Sun Monument ”Greeting to the Sun”	Zadar, Croatia	2008	Nikola Bašić	15	NBS, urban media installation	pavement	laminates with curved edges, cut cells
cs59	London City Hall	London, UK	2007 (2002)	Norman Foster and Partners	~19 (~48)	municipal government	domed roof + fixed ver sunshade	trapezoidal laminates; PV added later
cs58	Kankakee Community College	Kankakee, IL, USA	2007	Legat Architects	42	education, other	curtain-wall	dotted cell pattern
cs57	AquaCity Blue Sapphire	Poprad, Slovakia	2007	Archstudio Kučera & Rubáš	24.5	swimming pool	curtain-wall	print on inner glass pane
cs56	Vidurglass car parking	Manresa, Spain	2007	VidurSolar	3.91	car park	pitched canopy	
cs55	Madrid-2 La Vaguada	Madrid, Spain	2007	ErtexSolar	5.2	commercial and leisure centre	canopy	trapezoidal laminates, radiating strings
cs54	Trade School Center	Munich, Germany	2007	Bauer Kurz Stockburger Partner	n.a.	education, vocational	noise barrier	bifacial cells
cs53	Opera House	Oslo, Norway	2007	Snøhetta	35	opera house	façade	strings as hor stripes
cs52	Solar Tree Protoype	Vienna, Austria	2007	Ross Lovegrove	n.a.	NBS, urban furniture	lighting	round laminates
cs51	[Pod #001]	Copenhagen, Denmark	2007	collective N55	0.26	experimental building, greenhouse	inclined wall + roof	hexagonal pv panel with round cells
cs50	SIMS - Samundra Institute of Maritime Studies	Lonavla, India	2007	Christopher Charles Benninger Architects	90	education, vocational	façade, curtain-wall	
cs49	Fern Room at the Marjorie McNeely Conservatory	St. Paul, MN, USA	2006	HGA Architects and Engineers	11.5	conservatory	pitched roof	stripes + gaps, laminate pattern
cs48	Whitehall Ferry Terminal	New York, NY, USA	2006	Frederic Schwartz Architects	40	ferry terminal	pitched canopy	stripes
cs47	Community Centre Ludesch	Ludesch, Austria	2006 (2005)	Hermann Kaufmann	~19.00	community centre	courtyard canopy with sawtooth sheds	semi-transparent cells
cs46	The Core at the Eden Project	Cornwall, UK	2005	Nicholas Grimshaw & Partners	1.75 (28.72)	education centre	eaves	parallelogram laminates
cs45	Nishinomiya Kitaguchi Station	Nishinomiya, Japan	2005	n.a.	~13	NBS, footbridge	curved canopy	
cs44	Climate Control Machine 'The Brain'	Graz, Austria	2005	ILA	1.1	NBS, sculpture		trapezoidal laminates
cs43	Caltrans District 7 Headquarters	Los Angeles, CA, USA	2004	Morphosis	92	regional government	façade, fixed hor louvres	
cs42	PV Pergola in the Andalusia Technology Park	Malaga, Spain	2004	Pablo Coles, Ismael Eyras, Fernando Arribas	56	NBS, pergola	tilted canopy	landscape integration
cs41	Kei Wai Primary School (Ma Wan)	Hong Kong, China	2004	n.a.	4 (36)	education, school	atrium roof	curved laminates, unconnected cells
cs40	McDonald's Cycle Center	Chicago, IL, USA	2004	Muller & Muller	7.48	bicycle parking, repair	flat roof	chequered pattern
cs39	HRDC - Habitat Research and Development Center	Windhoek, Namibia	2004	Nina Maritz	n.a.	NBS, pergola	canopy	
cs38	WZH Waterhof	The Hague, Netherlands	2003	Ton Voets Architecten	21.9	residential, elderly peoples home	pitched roof	laminate pattern
cs37	Christian Kindergarten Ulmenstrasse	Dresden, Germany	2003	Reiter & Rentzsch	1.1	education, kindergarten	windows	unequal cell spacing, artistic additions
cs36	Daito Bunka University, Itabashi Campus, building 3	Tokyo, Japan	2003	Ben Nakamura and Yamamoto Hori Architects	30	education, university	curtain-wall + flat roof	striped laminates, striped façade and roof
cs35	Ekoviikki	Helsinki, Finland	2003	Reijo Jailinoja	24	residential, multi-family	balcony balustrade	
cs34	Fujipream Kohto Factory	Ibo Gun, Japan	2003	Fujipream	21.66	factory	curved façade	bent laminate
cs33	School ‘Lycée du Pic Saint-Loup’	Saint Clément de Rivière, France	2003	Pierre Tourre	5	education, school	hor louvres at roof	multicoloured metal and pv louvres combined
cs32	Ski Lifts Kriegerhornbahn	Lech am Arlberg, Austria	2002	Hans Riemelmoser	9.47	sports facility, ski lift	curtain-wall	semi-transparent cells
cs31	Kollektivhuset	Copenhagen, Denmark	2002	Domus Arkitekter, Claus Sondergaard	10.95	residential, disabled people	balcony balustrade	movable, coloured back sheets

id (*1)	name	location	Year (*2)	architect, designer, artist, engineer or pv company	rated power [kWp] (*3)	building type	building element (*4)	cells/laminate; feature (*1, *4)
cs30	Floriade PV Plant	Hoofddorp, Netherlands	2002	n.a.	2280	exhibition hall	gabled roof sections	glass/membrane laminates
cs29	Recreation center Vestervang	Copenhagen, Denmark	2002	Entasis	n.a.	recreation centre	curtain-wall	laminates with cells at the centre and empty border
cs28	Technique Cabin, Gentofte station	Gentofte, Denmark	2002	Box 25 architects	0.3	technique cabin	inclined façade	different cell sizes
cs27	Children's Museum of Rome	Rome, Italy	2001	Pagani & Pagani, Studio Italplan	15.2	museum, renovation	pitched roof + eaves	laminate pattern
cs26	Gemini House	Weiz, Austria	2001	Erwin Kaltenegger	3.6 (3.1)	prototype, residential, single family	curved façade + hor + ver louvres	curve-edged laminates, movable, one-axis tracking
cs25	Pichler Werke	Weiz, Austria	2001	Erwin Kaltenegger	5.5	corporate, office building	façade, curved ver sun sail + louvres	movable around the corner of the building
cs24	Bo01 Harmony house	Malmö, Sweden	2001	n.a.	8	residential, multi-family	flat hor sunsail at roof	movable canopy
cs23	Ales Tourist Office	Ales, France	2001	Jean-François Rougé	9.2	tourist office, heritage listed building	façade, oriel	
cs22	Kelvin Grove Urban Village	Brisbane, Australia	2001	Hassell Architects	2.3	NBS, bus shelter	canopy	
cs21	Jakob-Kaiser-House, building 3	Berlin, Germany	2001	Busmann + Haberer	29	federal government	sunshade above sheds of a sawtooth roof	inclined one-axis sun-tracking
cs20	Baptistery of the Epiphany Church	Hannover, Germany	2000	n.a.	2.34	religious, baptistery	pitched roof	cross pattern
cs19	Fire Station Houten	Houten, Netherlands	2000	Samyn & Partners	23.9	fire station	parabolic roof	
cs18	The Earth Centre canopy	Doncaster, UK	1999	FCB Architects	107	plaza canopy	canopy	
cs17	Academy Mont-Cenis	Herne, Germany	1999	Jourdà et Perraudin + HHS	1000	education, other	flat roof + curtain-wall	roof pattern
cs16	Jubilee Campus, Nottingham Univ.	Nottingham, UK	1999	Michael Hopkins and Partners	53	education, university	pitched atrium roof	
cs15	Waterworks Mühlenscharrn	Schwerin, Germany	1999	Roland Schulz	7.56	waterworks	façade, hor louvres	one-axis sun-tracking
cs14	Solar Catamaran RA 66 “Helio”	Lake Constance Germany	1999	Christoph Behling + Tilla Goldberg	4.2	NBS, catamaran	barrel canopy	bent laminates
cs13	Solarcafé "Sonnenzeit"	Kirchzarten, Germany	1999	Roland Rombach	1	café	pitched roof	semi-transparent cells
cs12	Shell solar cell factory	Gelsenkirchen, Germany	1999	Uwe Hohaus & Partner	36.9	production facility	curved façade	ver stripes
cs11	Wirtschaftshof Linz	Linz, Austria	1999	Architekturbüro Schimek	20.1	office building	hor louvres, one-axis sun-tracking	varied cell-spacing in adjacent panels
cs10	Solarsail	Münsingen, Switzerland	1999	Halle 58 Architekten	8.2	NBS, sculpture	sail like structure	non-rectangular laminates
cs9	Tobias Grau Lighting GmbH	Rellingen near Hamburg, Germany	1998/ 2001	BRT Bothe Richter Teherani	5.04/ 13.005	corporate, head office and manufacturing	curtain-wall	
cs8	Solar Office Doxford International	Sunderland, UK	1998	Studio E Architects	73.1	office building	inclined curtain-wall	non-rectangular + irregularly striped laminates
cs7	Café Ambiente	Bremen, Germany	1997	Mencke + Tegtmeyer	9.5	café, renovation	pitched roof	trapezoidal laminates, radiating strings
cs6	Church Kirchsteigfeld	Potsdam, Germany	1997	Augusto Romano Burelli & Paola Gennaro, Venezia-Udine	n.a.	religious, church	spire	trapezoidal laminates
cs5	Rikers Island Compost Facility	New York, USA	1996	n.a.	40	compost facility	pitched roof	
cs4	Brundtland Centre	Toftlund, Denmark	1995	KHR AS arkitekter	14.25	office building	sawtooth atrium roof + sawtooth canopy	round cells
cs3	Pyramids at Demosite	Lausanne, Switzerland	1992	Colt / Solution	n.a.	NBS, experimental structure	pyramidal canopy	triangular laminates
cs2	STAWAG (Aachen Municipal Utilities)	Aachen, Germany	1991	Georg Feinhals	4.2	office building	curtain-wall	chessboard laminate pattern
cs1	Housing	Munich, Germany	1982	Thomas Herzog	n.a.	residential	pitched roof	
cstf8	Nursery School “El Blauet”	Sant Celoni, Spain	2008	Petritxol 6 Architects	11.5	kindergarten	inclined curtain-wall	cs + tf, coloured glass
cstf7	Experimental building of the TU Darmstadt, “Solar Decathlon” entry	Washington DC, USA	2007	TU Darmstadt, Prof. Hegger	4 (9)	experimental building	flat roof + sunshade hor louvres (façade)	semi-transparent cs + “light though” opaque tf
cstf6	PTM Zero Energy Office (ZEO)	Selangor, Malaysia	2007	Ruslan Khalid Associates	92	office building	skylight	cs + tf
cstf5	Lillis Business Complex at the University of Oregon	Eugene, OR, USA	2003	SRG Partnership	8.6 (29.9)	education, university	curtain-wall + skylight	stripes with varied spacing
cstf4	Solar Centre MV	Wietow, Germany	2003	Gerd Vogt	1.44 (22.4)	information centre, heritage listed mansion	integrated into trad. window shutters	green back glass
cstf3	Tsukuba OSL	Tsukuba, Japan	2001	Nihon Sekkei	11.4	research facility	curtain-wall + eaves + skylight	round cells in curtain wall
cstf2	Simon Glas Factory	Bückeburg, Germany	2000	Simon Glas GmbH & Co. KG	0.9	office building	window	cs + tf
cstf1	Pompeu Fabra Library	Mataro, Spain	1996	Miquel Brullet i Tenas	22.49 (30.3)	museum	curtain-wall + shed skylight	cs + tf
tf14	Car Park of the Municipal Waste Management Office	Munich, Germany	2011	Ackermann und Partner Architekten BDA	n.a.	car park	curved canopy	ETFE-cushions, air-filled, 'light-through' approach
tf13	NTC Tower	Khartoum, Sudan	2010	n.a.	51.38 (53.28)	office building	curtain-wall	
tf12	Herwig Blankertz School	Wolfhagen, Germany	2009	HHS Planer+Architekten AG	220	education, school	pitched roof	transparent / semi-transparent pattern
tf11	GENyO, Pfizer-University of Granada-Junta de Andalucía	Granada, Spain	2009	Enrique Vallecillos · Emiliano Rodríguez	19.3	education, university	curtain-wall	laminate pattern
tf10	Schott Iberica	Barcelona, Spain	2006 (2001)	Torsten Masseck	1.35	office building, renovation	curtain-wall	coloured glass + screen printing
tf9	Tiger Woods Learning Center	Anaheim, CA, USA	2006	Langdon Wilson, Solar Design Associates	n.a.	education, other	inclined + curved curtain-wall	gradation, 5%, 25% and clear glass
tf8	Classroom of the Future	London, UK	2006	Studio E Architects	n.a.	education, school	membrane roof	spaced opaque tf laminates
tf7	Kanazawa Bus Terminal	Kanazawa, Japan	2005	TODEC, Taiyo Kogyo Corp.	110	bus station	free form canopy	
tf6	Stilwell Avenue Terminal	New York, USA	2005	Kiss+Cathcart Architects	199	train station	barrel roof	renovation project
tf5	Kulturhaus Milbertshofen	Munich, Germany	2005	RPM-Architekten	4.7	community centre	curtain-wall	non-PV windows
tf4	Primary School Trudering – Riem	Munich, Germany	2003	Krug & Partner	2.1	education, school	skylight	laminate pattern
tf3	BP-Solar Harmony Gas Station	Paris, France	2001	BP-Solar	10.4	NBS, gas station	curved canopy	
tf2	Energy-Forum-Innovation	Bad Oeynhausen, Germany	1995	Frank O.Gehry & Associates Inc.	1.92	corporate, multi-purpose	skylight	
tf1	APS Factory	Fairfield, CA, USA	1991	Kiss Cathcart Anders Architects	0.4 (8)	factory	skylight	early example
csds1	CSIRO Energy Centre	Newcastle, NSW, Australia	2003	Cox Richardson	n.a.	research facility	inclined curtain-wall + flat roof	cs + ds
ds1	Houses of the Future	Sydney, Australia	2004	Innovarchi	n.a.	experimental building	window	

(*1) cs – crystalline silicon, tf – thin-film, ds – dye sensitised; cstf, csds – two technologies used in the same building
(*2) if two years are given, completion of PV installation and completion of the building or renovation (year in brackets) didn't happen the same year
(*3) rated power of light-transmitting PV installation, (rated power in brackets indicates an additional opaque PV installation)
(*4) ver – vertical, hor – horizontal

▨	case study examples in section 7

Table III: Built examples ordered based on typology

arts, sports and leisure	
museum	cstf1, cs27, cs70, cs83
entertainment centre, multi-purpose	cs68
design centre, multi-purpose	cs82
culture centre	cs81
recreation centre	cs29
stadium	cs69
swimming pool	cs57
ski lift	cs32
opera	cs53
concert hall	cs86
greenhouse, conservatory	cs49, cs51
community and healthcare	
community centre	cs47, tf5
religious building	cs6, cs20
hospital	cs78
science and education	
research facility	cstf3, cs39, csds1
university	cs16, cs36, cstf5, tf11
vocational	cs50, cs54
school	cs33, cs41, cs77, tf4, tf8, tf12
kindergarten, nursery school	cs37, cstf8
playground	cs77
other facilities	cs17, cstf4, cs46, cs58, tf9
residential	
single family house	cs26
multi-family	cs1, cs24,cs35
elderly people	cs38
disabled people	cs31
public administration / public works	
central / federal government	cs21
regional	cs43
municipal	cs59, cs76, tf14
tourist office, visitor centre	cs23, cs74
fire station	cs19
waterworks	cs15
recycling facility	cs5
technique cabin	cs28
corporate and industrial	
office building	cs2, cs4, cs8, cs9, cs11, cs25, cs62, cs63, cs67, cs75, cstf2, cstf6, tf10, tf13
high-rise, office building	cs79
multi-purpose	cs73, tf2
production facility	cs9, cs12, cs34, tf1
commerce, retail and mixed-use	
café	cs7, cs13
shopping centre	cs55, cs61
exhibition hall	cs30
hotel	cs65, cs87
high-rise, mixed use	cs84, cs85
bicycle parking and repair	cs40
transportation	
airport terminal	cs66
train station	tf6
ferry terminal	cs48
bus station	cs22, tf7
car park	tf14
of which are	
renovation project	cs7, cs27, cs67, cs74, cs76, tf6, tf10
heritage listed building	cs23, cstf4
PV experimental building or structure	cs3, cs26, cs51, cstf7, ds1
non-building structures (NBS)	
plaza canopies	cs18, cs47
sculpture	cs10, cs44, cs71
urban furniture, lighting	cs52, cs72, cs80
urban media installation	cs60
pergola	cs39, cs42
shelter	cs3, cs22
gas station	tf3
footbridge	cs45
carport	cs56
ventilation tower	cs64
catamaran	cs14

Table IV: Built examples ordered based on building integration

roof integration, main building roof	
flat roof	cs17, cs36, cs40, cs41, cs51, cs67, cs82, cstf7, tf12, csds1
pitched roof	cs1, cs5, cs7, cs16, cs20, cs27, cs38, cs49, cs74
sawtooth roof with shed sections	cs4, cs21
flat roof with gabled roof sections	cs30
free form roof	cs59
parabolic roof	tf8, tf14
barrel roof	tf6
curved roof	cs19
domed roof	cs69, cs73
skylight	cs62, cs66, cstf1, cstf3, cstf5, cstf6, tf1, tf2, tf4
roof integration, other	
eaves	cs27, cs46, cs61, cstf3
flat canopy	cs18, cs22, cs39, cs55, cs70, cs77, cs80
inclined canopy	cs42, cs48, cs56
sawtooth canopy with shed sections	cs4, cs47
curved canopy	cs45, tf3
barrel canopy	cs14
pyramidal canopy	cs3
spire	cs6
free from canopy	tf7
roof, fixed sunshade	
horizontal louvres	cs33, cs79
roof, movable sunshade	
inclined louvres, one-axis sun-tracking	cs21
façade integration, structural or curtain-wall	
vertical	cs2, cs9, cs17, cs29, cs31, cs32, cs36, cs57, cs58, cs62, cs65, cs64, cs67, cs75, cs76, cs81, cs82, cs85, cstf1, cstf3, cstf5, tf5, tf10, tf11, tf13
inclined	cs8, cs13, cs28, cs50, cs51, cs78, cstf8, csds1
curved, along horizontal axis	cs12, cs34
inclined and curved, along vertical axis	tf9
free form	cs84
façade integration, other	
oriel	cs23
windows	cs37, cstf2, ds1
inclined wall	cs83
balcony, balustrade	cs35, cs67, cs87
media wall	cs68
noise barrier	cs54
façade, fixed sunshade	
horizontal louvres	cs11, cs 25, cs43
shading element	cs59, cs63, cs86
façade, movable sunshade	
horizontal louvres, movable	cstf7
horizontal louvres, one-axis sun-tracking	cs15
curved façade, hor/ver louvres, one-axis sun-tracking	cs26
flat horizontal sun sail, movable canopy	cs24
curved vertical sun sail, movable around the corner of the building	cs25
other	
pavement	cs60
sculptural elements	cs10, cs44, cs52, cs72

6 MATRIX FOR ANALYSIS

6.1 Common analysis

The analysis of BIPV (Figure 1, left) has commonly been based on opaque PV due to the overwhelming market share, as outlined in section 1. 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.

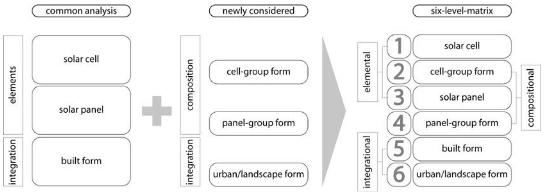


Figure 1: Evolution of a matrix for analysis

6.2 Newly considered

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 mono-Si 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, as explained in section 4.1, 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** (Figure 1, centre).

Furthermore, the standard rectangular PV module may have its advantage in 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” [23]. 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** (Figure 1, centre).

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 BAPV, or building-added PV. A shortcoming of both terms is the fixation on buildings, which refers to building structures (BST), thus excluding all non-building structures (NBS) [24]. The focus on buildings leaves out many good examples of integration into 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 elements, BIPV as well as BAPV, are located in close proximity to the building's envelope. When looking at it from the distance, the discussion on added vs. integrated appears to be 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 [25]. 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** (Figure 1, centre).

6.3 Six-Level-Matrix

The issues addressed by the common analysis and the suggested three newly considered issues are combined to form a **Six-Level-Matrix** (Figure 1, right), with two elemental, two compositional, and two integrational levels. The characteristic features of each level are illustrated in Figure 2.

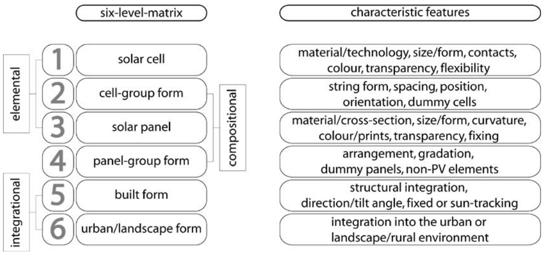


Figure 2: Six-Level-Matrix and characteristic features

To support my thesis, I'm going to focus on the newly considered two compositional levels, 'cell-group form' (level 2) and 'panel-group form' (level 4).

6.3.1 Cell-group form

The cell-group form (level 2) is the number of arranging possibilities of individual cells (level 1). 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 Table V, parameters (a) to (k) for crystalline silicon cells, and (l) to (m) for thin-film cells. This table is not exhaustive in terms of technological or conceivable design possibilities, but solely derived from the built examples.

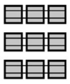
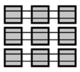
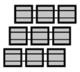
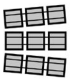
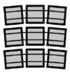
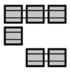
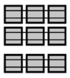
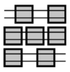
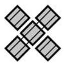
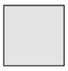
6.3.1.1 Crystalline silicon cell-group form

Even though the most common design patterns are based on parameter (b), (c) and (c+d) 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, (f) follows trapezoidal shaped panels, (g) follows curved panels, and (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) and (l), 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.

6.3.1.2 Thin-film sheet form

In the case of thin-film technology, the variety of different sheet arrangements as found in the built examples has not been as varied and refined as with crystalline silicon cells. All projects use either one sheet per laminate, or a number of sheets are closely aligned in laminates of larger size. As such, 'see-through' thin-film technology is perceived as a dark tinted glass rather than as a technological PV element, and blurs smoothly with other architectural elements.

Table V: Cell-group form for crystalline silicon cells and thin-film sheets

Image	Pattern	Built examples
	Crystalline silicon cells	
	(a) single cell	cs87
	(b) parallel strings, equal distances	majority
	(c) equally increased string distance	cs12, cs15, cs36, cs48, cs53, cs58, cs78, cs74, cstf5
	(d) equally increased cell distance	cs11, cs19, cs40
	(e) offset strings	cs4, cs40, cs44, cs46, cs51, cs58, cs72, cs73, cs82
	(f) radiating strings	cs7, cs55
	(g) curved strings	cs26
	(h) shortened string length	cs3, cs6, cs8, cs10, cs47, cs51, cs52, cs53, cs59, cs71, cs72, cs78, cs60, cs61, cs66, cs68, cs70, cs80, cs82, cs86
	(j) gaps	cs41, cs49, cs64, cs66, cs67, cs68
	(j) varied string distance	cs8, cs74
	(k) varied cell distance	cs37
	(l) rotation	cs66
	Thin-film sheets	
	(m) single sheet	cstf2, cstf7, cstf8, tf4, tf10
	(n) adjacent sheets	cstf1, cstf3, tf5, tf9

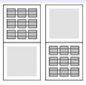
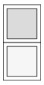
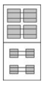
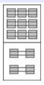
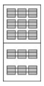
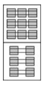
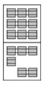
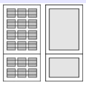
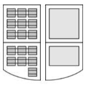
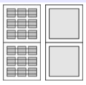
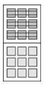
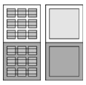
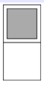
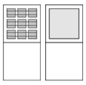
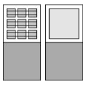
6.3.2 Panel-group form

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). Thus, the panel-group analysis of the built examples lists the different features that are combined according to the level they originate (Table VI). Even though some features are probably technology-specific (more distinct with either crystalline silicon or thin-film cells), a strict separation into these technologies is not considered to be appropriate. Both technologies are better viewed in parallel.

Table VI: Panel-group form

The pictures are split into a left and right part, the left part for crystalline silicon, the right for thin-film.

If the relevant part is shown, than built examples are included, otherwise built examples are not included.

Image	Pattern	Built examples
	Level 1 features	
	(1a) different technologies	cstf1, cstf2, cstf8
	(1b) different transparencies	tf9
	(1c) different cell sizes	cs17, cs28
	Level 2 features	
	(2a) different string + cell distance	cs17, cs20
	(2b) different string distance	cs8, cs49, cs78, cs74, cstf5
	(2c) different cell distance	cs11
	(2d) different cell densities	cs37, cs40, cs41, cs 65, cs67, cs68, cs83
	Level 3 features	
	(3a) different panel size	cs2, cs6, cs7, cs8, cs37, cs49, cs53, cs55, cs59, cs62, cs84, tf7
	(3b) different panel shape	cs8, cs10, cs26, cs37, cs41, cs44, cs53, cs78, cs60, cs70, cs73, cs80, cs81, cstf5, tf7
	Level 4 features	
	(4a) equal panels	cs (majority), tf2, tf3, tf6, tf12, tf13, csds1, ds1
	(4b) dummy panels	cs70, cs76
	(4c) LTPV + opaque PV	cs12, cs26, cs46, cs59, cstf1
	Level 5 features	
	(5a) opaque PV + semi-transparent / transparent non-PV	cstf2, cstf7, tf8, tf14
	(5b) LTPV + semi-transparent / transparent non-PV	cs1, cs2, cs8, cs14, cs16, cs17, cs27, cs29, cs31, cs32, cs36, cs38, cs40, cs44, cs45, cs49, cs50, cs51, cs54, cs62, cs63, cs65, cs66, cs70, cs75, cs77, cs82, cs83, cs85, cstf3, tf1, tf2, tf4, tf5, tf9, tf10, tf11, tf12
	(5c) opaque non-PV	cs33, cs36, cs82, tf11

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. An interesting, yet most basic pattern is (5a), the 'light-through' pattern of the thin-film examples. It is the same basic pattern as the 'light-through' pattern of crystalline silicon cells (section 4.1), though in a different scale and level, a combination of opaque PV with an adjacent area of light-transmissive transparency. Generally speaking, this pattern is independent of technology, even materials, and the most basic approach to control the level of light transmission. It is a link to simple and elaborate approaches throughout the history of architecture and buildings.

7 CASE STUDY

The 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 the built examples.

7.1 Non-PV references

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. These reasons have given rise to the growing number of contemporary buildings with triangulated envelopes. Just to name some examples: the Queen Elizabeth II Great Court in London, UK, architect: Foster and Partners, 2000; the Federation Square in Melbourne, Australia, architect: Lab Architecture Studio, 2002; the BMW Welt in Munich, Germany, architect: Coop Himmelb(l)au, 2007; or the Guangzhou Opera House in Guangzhou, China, architect: Zaha Hadid architects, 2010.

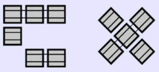
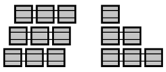
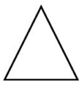
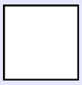
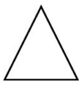
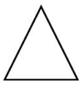
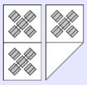
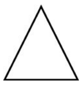
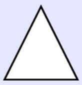
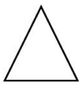
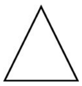
7.2 LTPV study cases

In this case study, four LTPV examples are analysed using the **Six-Level-Matrix** (Table VII). Analysing existing examples of triangular LTPV in contemporary architecture can help in promoting the application in future projects.

Even though all four projects use crystalline silicon cells (level 1) and work with triangles as a part of the architectural envelope, admittedly on different areas (level 5), 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 [26].

Where the other three projects introduce the triangle already as 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 triangular façade and roofing modules, so the composition of PV and non-PV modules is seen as belonging rather to the built form (level 5) than to a separate panel-group form (level 4). The final level 6 -urban / landscape form- was not considered in this case study.

Table VII: Study cases

	Pyramids at Demosite, Lausanne, Switzerland manufacturer: Colt / Solution, 1992	Ménara Airport, Marrakech, Morocco architects: E2A Architecture, 2008	Cité du design, Saint-Etienne, France architects: LIN - Finn Geipel+Giulia Andi, 2010	House of Music, Aalborg, Denmark architects: Coop Himmelb(l)au, ~2012
1	crystalline silicon cells		crystalline silicon cells	
2	 shortened string length	 gaps and rotated	 offset and shortened strings	 shortened string length
3	 triangular laminate	 rectangular laminate	 triangular laminate	 triangular laminate
4		 similar laminates plus glass		
5	 pyramidal canopy	 skylight	 façade and flat roof	 sunshade (façade)

8 CONCLUSION

On the building level it is quite surprising to see the variety of typologies, that LTPV has penetrated into, and it can be said, that the general application is independent of the purpose of the building. This is maybe an answer to the question, why LTPV are very often used as study cases in the BIPV literature (section 1). On the architectural level it must be said, that it is time to understand LTPV not only in terms of its energy generating and technological properties, but to start analysing its unique qualities. The development of LTPV has given shape to two subgroups called 'light-through' and 'see-through', which allow for categorisation based on the qualities of light transmission rather than the underlying technology.

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). An analysis of the two intermediate and mediating compositional levels 'cell-group form' (level 2) and 'panel-group form' (level 4), and a subsequent categorisation of built examples has been 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 compositional levels 'cell-group form' (level 2) and 'panel-group form' (level 4), and assuming 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 (Figure 3), 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.

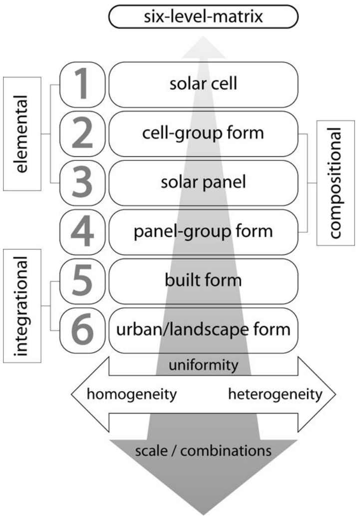


Figure 3: Six-Level-Matrix with the two axial tendencies for scale / combination and uniformity (homogeneity / heterogeneity)

Summarising this paper it can be said, that architectural integration treats PV not as a feature 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 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.

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