






Review

Photovoltaics on Landmark Buildings with Distinctive Geometries

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Received: 29 June 2020; Accepted: 17 September 2020; Published: 25 September 2020



Featured Application: This work illustrates that world-class architecture can be coupled with building integrated (BIPV) or building applied (BAPV) photovoltaic (PV) technologies, which can significantly contribute to improve both the architectural quality and the energy efficiency, further promoting their diffusion in the built environment and as virtuous examples for a broader impact to society and investors.

Abstract: This review study, framed in the Work group 4 “Photovoltaic in built environment” within the COST Action PEARL PV, CA16235, aims to examine applications of integrated and applied photovoltaic technologies on ten landmark buildings characterised by distinctive geometries, highlighting the aesthetics of their architecture and quality of PV integration based on a proposed set of seven criteria. The selected building samples cover a large design diversity related to the quality of PV systems integration into building envelope that could serve as a basis for general guidelines of best architectural and technological practice. After introducing the problem and defining the research methodology, an analysis of ten landmark buildings is presented, as representative models of aesthetics of their architecture, photovoltaic integration and implementation and energy performance. The study concludes with the main characteristics of photovoltaic integration on landmark buildings. The paper is intended to support both engineers and architects in comprehending the convergent development of contemporary architecture and photovoltaic technology, as well as the need for a closer collaboration, sometimes resulting in architectural masterworks that promote the diffusion of photovoltaics to the public.

Keywords: architecture; landmark buildings; photovoltaic; BIPV; BAPV

1. Introduction

The use of photovoltaics (PV) has registered a significant increase in the last decades, because of their higher efficiency and a rapid drop in their prices [1]. As most countries try to tackle their energy security problems and reduce greenhouse gas emissions [2], new policies are implemented to increase the distributed generation of energy in the built environment [3]. Towards that end, the use of PV

systems in landmark buildings, either private or public, represent virtuous examples for a broader impact to society and investors. “Buildings occupied by public authorities and buildings frequently visited by the public should set an example by showing that environmental and energy considerations are being taken into account” [3]. Furthermore, the use of PVs in these buildings can inspire architects and PV practitioners to move past the aesthetically neutral, towards a visually attractive element in an architectural context [4]. Landmark buildings are recognized easily in their built environment, by their size, shape, social importance, funds invested, etc. [5]. They range from constructions with high heritage and historical value (e.g., cathedrals, museums and government buildings) to contemporary architectures, such as stadiums, concert halls, exhibition centres, educational centers, public buildings, headoffices, etc. [6]. To that end, the exploitation of renewable energy sources in historical and heritage buildings has been extensively studied [7]. Some researchers proposed methodologies for retrofitting measures to improve the energy performance of historical buildings [8] and studied the integration of solar façades in buildings in the eastern Mediterranean [9]. Other researchers focused on the analysis of the energy saving potential in historical buildings in Europe as a source of national energy savings and building reuse improvement [10], assessing the energy performance and the costs of energy retrofitting and technological renovation of historical buildings without affecting their historic and architectural qualities [11], or towards achieving net zero energy classification [12]. Besides technical performance that has been extensively examined [2,13,14], the architectural aesthetic values, visibility and integration of PV are important aspects for the promotion and application of solar energy conversion systems in buildings integrated elements [15]. Firstly, practitioners need to consider the architectural value of integrated PV systems in buildings; secondly, architects should exploit the adoption of PVs on exceptional architectural examples; thirdly, contemporary investors of remarkable architectural buildings in terms of financial background of PV application, should consider the environmental impact and on the society [16]. This aspect was only recently considered by researchers on the dynamics of the transition of urban areas from traditional to sustainable and smart neighbourhoods [17] by investigating the context of cities with well-known traditions of sustainable urban development. This drive towards PV integration in landmark buildings is not limited to specific geographical boundaries, but is shared worldwide, as attested in the literature [16,18,19]. In this paper, ten landmark buildings are considered, based on a number of parameters like PV integration, geometry and visibility, size and shape and architectural value. The motivation of the study is to bridge the architectural design with the PV engineering, aiming at highlighting the architectural performance of PV integration systems in landmark buildings, which have significant dimensions and importance in the society.

2. Methodology and Sampling Process

This study examines ten landmark buildings based on their distinctive geometry and architectural feature. All buildings are in operation and have PV systems applied on (BAPV) or integrated into (BIPV) their building envelopes. Each case study has been analysed in terms of PV application impact on the building architectural value, by considering the following criteria:

1. PV system as an architectural and environmental value;
2. PV contribution in defining the fifth façade (i.e., the roof);
3. PV emphasizing the geometry of architectural building;
4. PV contribution to specific geometry of the architectural building;
5. PV as architectural accent;
6. PV integration in architectural visibility, sensitivity and quality;
7. PV as a peculiar element.

The aim of such a process is to examine diverse examples that could yield general conclusions to a wide range of landmark buildings with BAPV or BIPV systems. The sampling process started from the buildings designed by the architects awarded the Pritzker prize [20]. The sampling was

extended to five other landmark buildings representative of the countries taking part in the work group 4 “Photovoltaic in built environment” within the COST Action PEARL PV, CA16235 that frames this study. These aspects highlighted five buildings, two headquarters, one concert hall, one courthouse and one stadium. They are, namely, the Apple Headquarters, designed by UK architect Sir Norman Foster, the Novartis Campus Basel, designed by American architect Frank O’Gehry, the concert hall La Seine Musicale, by Japanese architect Shigeru Ban and French architect Jean de Gastine, the Paris Courthouse in Paris, designed by Italian architect Renzo Piano, and the Solar Powered Stadium in Taiwan, designed by Japanese architect Toyo Ito. Sport stadiums and arenas are architectural objects with high potential to PV installation systems and many experts consider them as the power plants of tomorrow because of their extensive building surface [21]. Numerous are the examples of BAPV on existing stadiums. One of them is the Maracanã stadium in Rio de Janeiro, Brazil, the iconic football arena, where a PV system was implemented as a part of the roof reconstruction for the FIFA World Cup 2014 [22]. Among the exhibition centres, which are characterized by large extended roofs surface suitable for PV installations, the Theme Pavilion, built for the international Shanghai Expo in 2010, represents one of the largest exhibition spaces in the world equipped with a PV system. Powerhouse Brattørkaia in Trondheim, Norway, is an office building designed by the renowned Snøhetta architectural and design firm. It is considered the northernmost BIPV building in the world. Educational buildings (e.g., schools, libraries), are often equipped with PVs and are buildings landmark due to their considerable volume and geometry and their pedagogic role in the society. In that regard, The Copenhagen International School has the largest BIPV façades in the world [23]. The selected landmark buildings are the following (Figure 1):

1. Maracanã Stadium, Rio de Janeiro, Brasil (BR)
2. Apple Headquarters, Cupertino, CA, United States (USA)
3. Shanghai Expo 2010 Theme pavilion, China (CN)
4. Powerhouse Brattørkaia, Trondheim, Norway (NO)
5. Paris Courthouse, Paris, France (FR)
6. La Seine Musicale, Paris, France (FR)
7. Umwelt Arena, Switzerland (CH)
8. Kaohsiung National Stadium, Taiwan (TW)
9. Novartis Campus, Basel, Switzerland (CH)
10. International School Copenhagen, Denmark (DK)

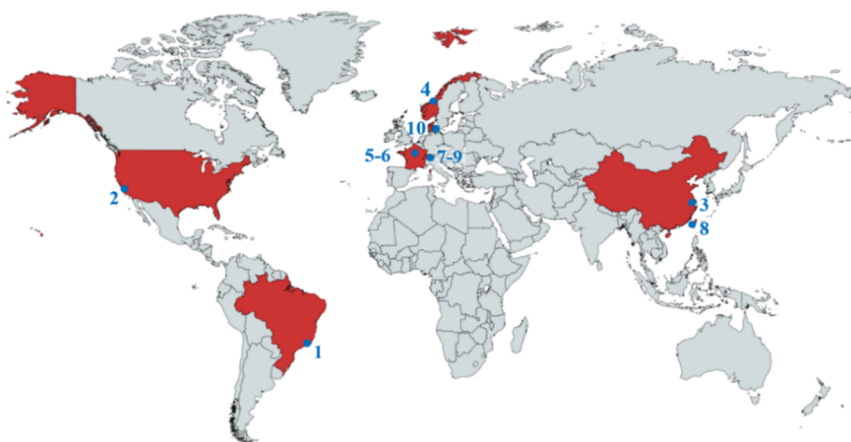


Figure 1. Geographical distribution of the examined case studies.

The assessment of architectural visibility, sensitivity and quality has been conducted through LESO-QSV (Laboratoire d’Energie Solaire–Qualité–Sensibilité–Visibilité) method [15] developed by

the EPFL-LES (École polytechnique fédérale de Lausanne (EPFL), Le Laboratoire d’Energie Solaire). The LESO-QSV method evaluates:

- Architectural integration quality allows assessing the quality of solar systems integration. The system is defined as fully integrated (i.e., designed as an integral part of the building architecture where all the formal characteristics of the solar system such as field size/position, visible materials, surface textures, colours, module shape/size and joints) when it is coherent with the global design logic of the building. The coherency of system geometry, system materiality and system modular pattern is evaluated using a three-level scale (fully; partly; not coherent). A circle made of three separated coloured sectors (green, yellow or red) according to the level of coherency of each aspect (Figure 2) expresses the quality of the system.
- Urban context criticality to assess the quality requirements for architectural integration depends to the local context, specifically to the sensitivity of the urban area and the visibility of the building surface (Figure 3).
- The context *sensitivity* takes into account the socio-cultural value of the urban zone where the analysed buildings are or will be located, and the architectural values of the context (e.g., historical centre is a high-sensitive context, an industrial area is low-sensitive, and a post-war residential development in most cases as medium sensitive).
- The system visibility evaluates the perception of solar systems from public spaces: close visibility from an urban perspective, remote visibility from a far observation point (Figure 4).

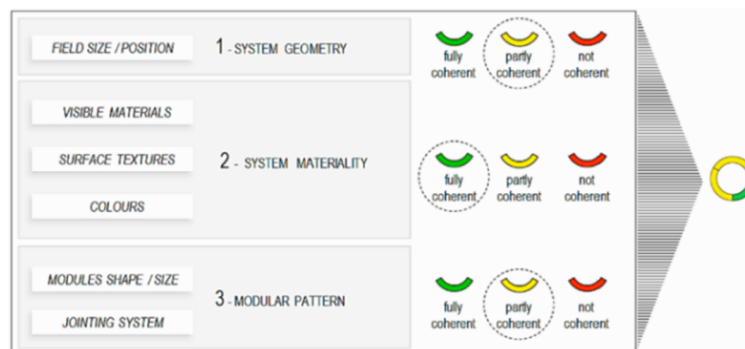


Figure 2. Levels of integration quality of the solar system. Reproduced with permission from Maria Cristina Munari Probst, Christian Roecker, Solar Energy; published by Elsevier, 2019 [15,24].



Figure 3. Criticity of city surfaces in relation with surface visibility and context sensitivity (on the left); Different levels of urban context sensitivity (on the right) Reproduced with permission from Maria Cristina Munari Probst, Christian Roecker, Solar Energy; published by Elsevier, 2019 [15,24].

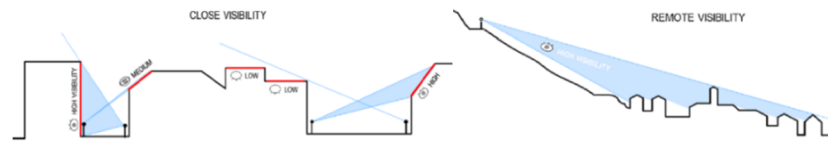


Figure 4. Levels of close (on the left) and remote (on the right) visibility of PV surfaces from public domain. Reproduced with permission from Maria Cristina Munari Probst, Christian Roecker, Solar Energy; published by Elsevier, 2019 [15,24].

3. Presentation of the Samples

The review of the selected samples consists of the ten selected buildings and contains a brief description of the building function and the architects/architectural office that designed the building, information about the BAPV/BIPV system and its main implication on architectural performance. The location and solar radiation data for each site is provided in Table 1. The data are compiled with Meteororm using the Perez model and available data for the 1991–2010 period [25].

Table 1. Location and solar radiation data for the examined cases.

Landmark Object	Location			Solar Irradiation		
	Latitude (°)	Longitude (°)	Altitude (m)	Global Horizontal (kWh/m ²)	Diffuse Horizontal (kWh/m ²)	Direct Radiation (kWh/m ²)
Maracanã Stadium (BR)	−22.91	−43.23	105	1692	818	1358
Apple Headquarters (USA)	37.33	−122.01	48	1735	644	1841
Theme pavilion (CN)	31.18	121.48	11	1274	826	714
Powerhouse Brattørkaia (NO)	63.43	10.40	0	885	441	1084
Paris Courthouse (FR)	48.89	2.31	32	1068	597	881
La Seine Musicale (FR)	48.82	2.23	35	1089	619	885
Umwelt Arena (CH)	47.42	8.37	400	1121	590	998
Kaohsiung Stadium (TW)	22.70	120.29	120	1525	866	1018
Novartis Campus (CH)	47.57	7.58	259	1131	598	1007
International School (DK)	55.71	12.60	0	1019	528	1015

3.1. Maracanã Stadium

The Maracanã stadium (Figure 5) is one of the biggest in the world and the most popular among the Brazilian stadiums refurbished for the FIFA World Cup 2014 [26]. The idea behind the integration of PV systems on the roof of the stadium was to make the World Cup event environmentally responsible. The Maracanã stadium was originally built in 1950, while its \$500 million modernization started in 2009 and was completed in 2013 [27].

The Maracanã stadium PV system consists of two rings (Figure 5, left) and has been integrated in the new roof's structure (Figure 5, right). The stadium was the venue for the final of the FIFA World Cup 2014, and for the opening and closing ceremonies of the 2016 Olympic Games [22]. The reconstruction of the roof, including the photovoltaic design, was done by the Schlaich Bergermann Partner architect office. The double metal ring encircling the top of the stadium consists of 1556 PV panels, with an installed capacity of 390 kWp producing about 500 MWh per year [28]. It prevents emission of 350 tons of carbon dioxide (CO₂) into the atmosphere annually. Not visible from the ground, the PV system is an architectural integrated element that emphasizes the elliptical shape of the stadium and contributes to the geometry of the stadium's fifth façade. Socially, the system influences the public awareness on green energy on a global level because of the importance of the building and the hosted events (e.g., 2016 Olympic Games opening and closing ceremonies, FIFA World Cup 2014 final). Dubbed as Maracanã Solar, the project was approved by Brazilian Instituto do Patrimônio Histórico e Artístico Nacional for its historical and artistic heritage value [29]. Conceptualization and organization of world scale events, like sport events, sometimes include the idea of sustainability and green energy in the background. Introduction of PV green energy was a strong environmental message for both the soccer fans and local/international society. Choosing one of the most iconic stadiums worldwide for integration of PV systems, particularly Maracanã Stadium, has shown how buildings geometry can be coupled efficiently

with PV integration. It also shows how the PV installation can contribute to emphasize the building architecture and its shape. This aspect was applied to other existing stadiums and arenas, which are equipped with PVs, among others, the Amsterdam Arena (Amsterdam, The Netherlands), St. Jakob Park (Basel, Switzerland), Bentegodi Stadium (Verona, Italy) and Lincoln Financial Field (Philadelphia, PA, USA).

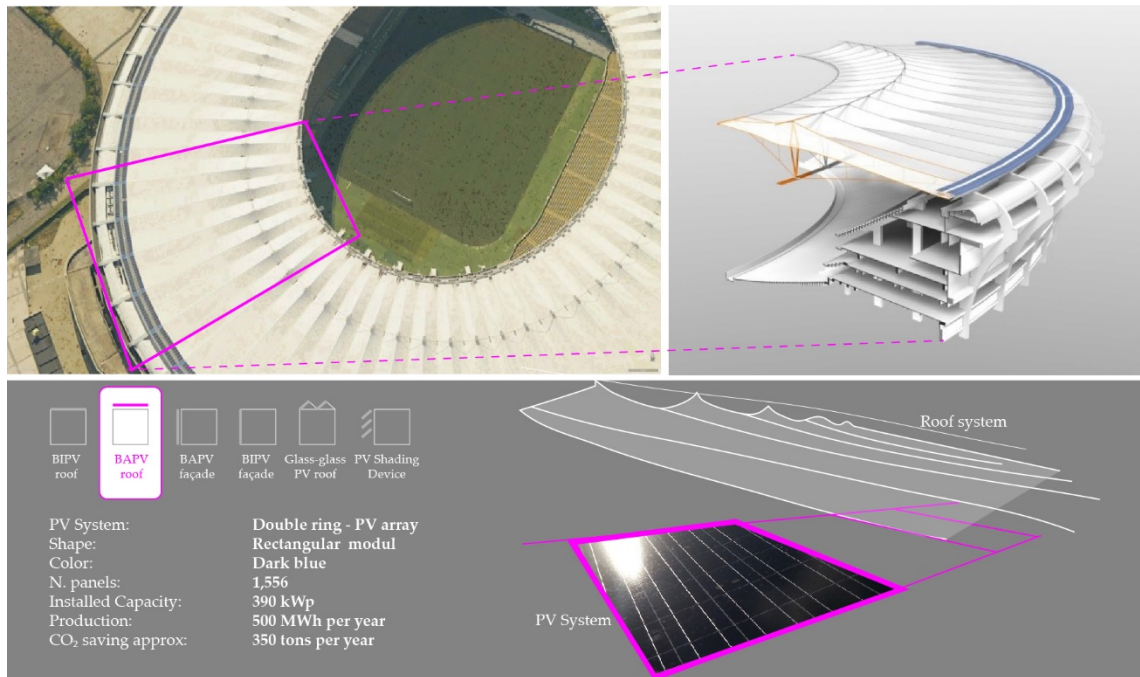


Figure 5. Maracanã Stadium (bird eye view from Google Earth, Google 2020) (on the top left); rendering detail (copyright Schlaich Bergermann Partner) (on the top right); Integration and characteristics of PV systems (on the bottom).

3.2. Apple Headquarters—Apple Park

The Apple Headquarters is a large circular building within the Apple Park in Cupertino (CA, USA) and a representative example of a landmark object in its neighbourhood (Figure 6).

Because of its peculiar geometry, the building is called “The Ring”, its opening being announced by architecture periodicals in 2017 as a “spaceship landing”. Designed by the Pritzker prize awarded UK architect Sir Norman Foster, it is the largest LEED (Leadership in Energy and Environmental Design) platinum certified building in the United States [30]. It is also considered one of the biggest on-site rooftop solar arrays (17 MWp) in the world [31]. The building hosts 12,000 employees and in the peak working time the solar system produces 75% of the power demand, while the remaining 25% comes from other renewable sources (4 MWp of biogas fuel cells) [32,33]. The building of the new headquarters is one of numerous Apple buildings powered with green energy and is part of the corporations’ worldwide initiative to obtain 100% green energy for its entire business [33]. The fifth façade of the building (the aerial view, Figure 6) is the dominant one and the PV system is its integral part, although mounted on the building roof. The PV modules, arrayed along the circular roof, makes a fine texture rather than a collection of elements.

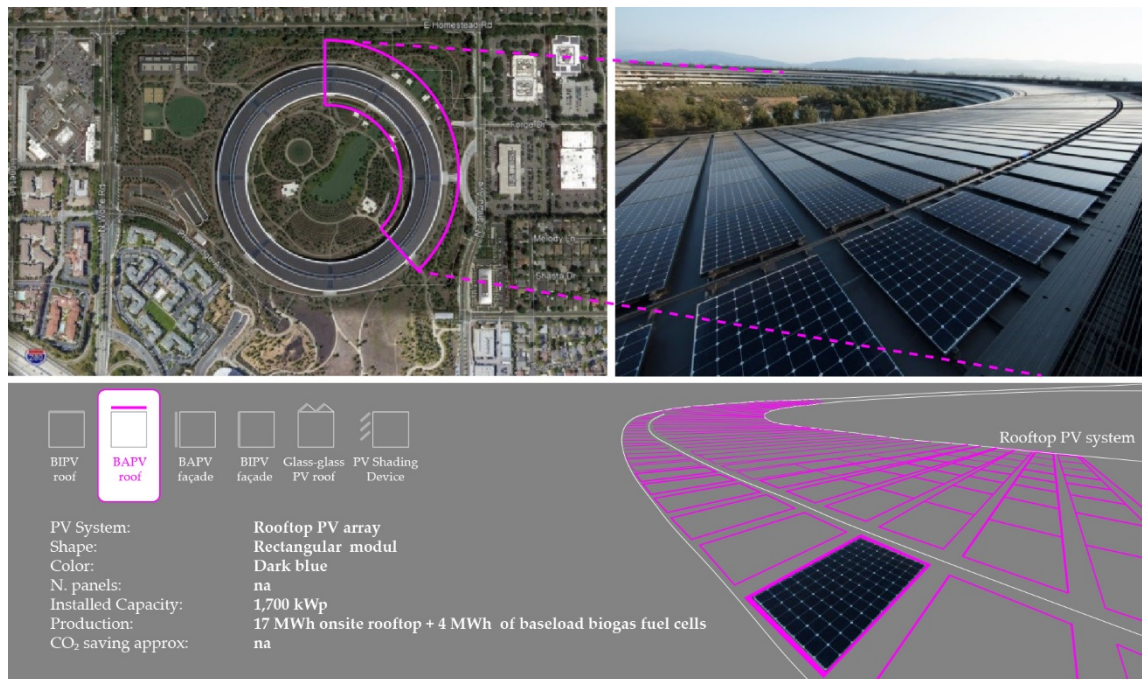


Figure 6. Apple Headquarters, aerial view of Apple Park (source: Google Earth, Google 2020) (on the top left) and BAPV detail (with permission from Apple) (on the top right); Integration and characteristics of PV systems (on the bottom).

3.3. Shanghai Expo 2010 Theme Pavilion

Expo 2010 in Shanghai, China (CN), under the title “Better City-Better Life”, was one in a series of universal exhibitions, with 192 participating countries, and over 73 million visitors. The use of solar energy was an important aspect of the Expo [34]. The Theme Pavilion (Figure 7) is one of the four permanent buildings of Shanghai Expo 2010, and one of the three equipped with photovoltaic systems [35]. When it was built, this building integrated the biggest BIPV installation (2.8 MWp) in Asia. The designers decided to apply the integrated technology, despite the fact that the lifetime of photovoltaics is smaller than the expected lifetime of buildings in China (at least 50 years) [36]. The PV modules cover half of the Theme Pavilion’s total roof area, more precisely 30,000 m² [37]. The geometry of solar panning consists of 18 rhomboids and 12 triangles, for a total of 16,250 polycrystalline silicon modules, visible from the aerial view and forming the building’s fifth façade. The BIPV contributes to the expressiveness of the building within the numerous unique national pavilions. It is recognizable from the top view, not only by its huge size and proximity to the Expo main axis, but also by its roof pattern, integrating the PV modules into the building’s roof surface.

3.4. Powerhouse Brattørkaia

Second in a series of the so-called powerhouse buildings, Powerhouse Brattørkaia (Figure 8) was designed by the internationally renowned Snøhetta architecture firm [38]. It is an office building, completed in 2019, in Trondheim, Norway (NO) and it is considered the northernmost energy positive building in the world [39]. It is one of the pilot buildings of the Research Centre on Zero Emission Buildings (ZEB) in Trondheim [40]. The gross area of the building is 17,800 m² and the area covered with PV modules is around 2860 m² installed on the roof and the upper parts of the façades, producing 458 MWh per year. The Powerhouse Brattørkaia reaches the ambitious level of ZEB-COM: the building’s renewable energy production compensates for greenhouse gas emissions from construction, operation and production of building materials. “The building has been designed based on environmental requirements. When environmental considerations come first, a new type of architecture emerges. For Powerhouse Brattørkaia, form follows environment, while optimal use of

solar energy has determined the building’s exciting and iconic architecture” [41]. It is estimated that in its lifetime, the building will produce twice the energy than was needed for its construction, operation and demolition [41]. Its geometry is based on an extruded irregular four-sided polygon cut with a sloped surface facing the south side of the building and representing the building roof. The so sloped mass was voided with an elliptical cylinder volume, forming the building atrium.

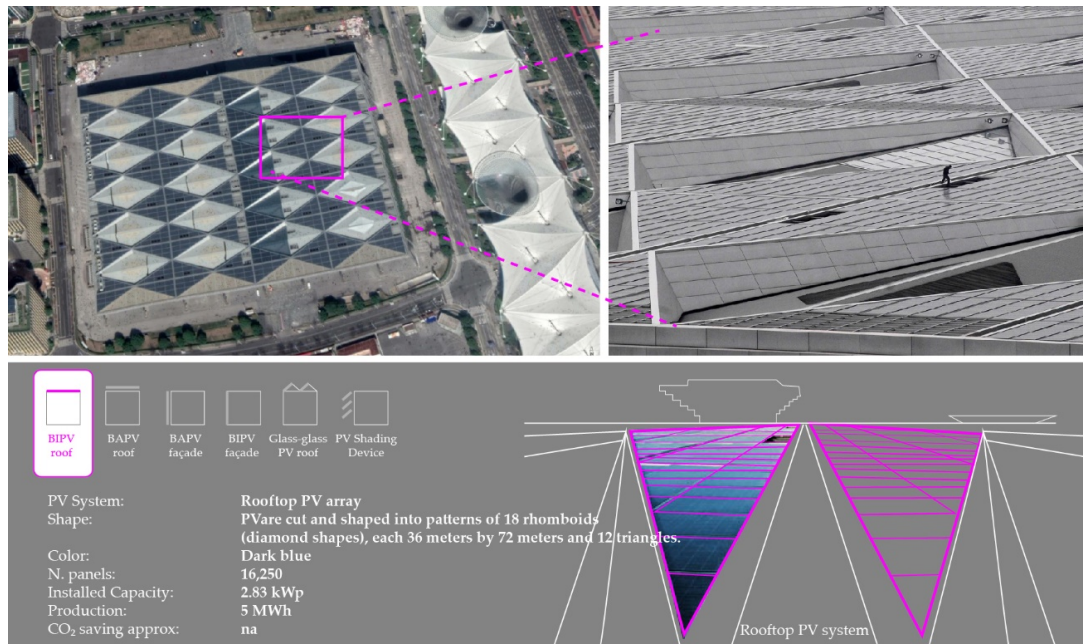


Figure 7. BIPV on the roof of Shanghai Expo 2010 Theme Pavilion, aerial view (source of illustrations: Google Earth, Maxar Technologies, 2020 (on the top left); REUTERS_China Daily (on the top right)); Integration and characteristics of PV systems (on the bottom).



Figure 8. Powerhouse Brattørkaia (photo on top by Ivar Kvaal, with permission from Powerhouse <http://powerhouse.no>) (on the top); Integration and characteristics of PV systems (on the bottom).

3.5. Paris Courthouse

Signed by Renzo Piano Building Workshop (Pritzker awarded architect in 1998), Paris Courthouse is a 160 m tall building, consisting of four different cuboids. It is built beside the Port de Clichy, and adjacent to the Martin Luther King Park on the east side (Figure 9) of Paris, France (FR). The idea of the architect was to reunite all the courthouse functions into one building. The project started in 2010 and the building was completed in 2017. Through its size and status, the building is regarded as a starting point for the rehabilitation of its neighbourhood [42]. Apart from its size, robustness and orthogonal geometry, the building is distinguished by its glazed, dematerializing façades and the horizontal and vertical arrays of photovoltaic sunshades. According to ISSOL, the company in charge for the photovoltaic aspect of the building, the installation consists of more than 1590 sun shades (1930 m²) on façade and 152 PV modules (360 m²) on the roof, with an installed capacity of 325 kWp. The expected annual power production is 312 MWh [43]. By exposing the PV modules on the east and west façades, the architect wanted to underline the environmental responsibility of the public building. Furthermore, apart from their main roles of producing energy and protecting from the sun, the PV modules are expressive architectural element, emphasizing the horizontal lines of the cuboids, and the vertical spines connecting the floating building parts.



Figure 9. Paris Courthouse east façade (photography with permission of author Sergio Grazia) (on the top); Integration and characteristic of PV systems (on the bottom).

3.6. La Seine Musicale

Another building in Paris, signed by another Pritzker winner (2014), the Japanese architect Shigeru Ban, in collaboration with local architect Jean de Gastines, is the concert hall named “La Seine musicale” (Figure 10) built from 2015 to 2016, after an international competition in 2013.

The building has an ellipsoidal shape on the Île Seguin (Sequin Island) and comprises of a 6000-seat music hall and a smaller auditorium of 1150 people [44]. One of the main characteristics of the building is its egg shaped corpus and a moving PV wall, which is mounted on rails that follow the path of the sun, every 15 min, from east to west, in order to harvest as much sunlight as possible throughout the day, shading the building and creating a changing display of shadows. According to the PV installer, 454 PV modules with a total area of 1000 m² and an installed capacity of 115 kWp were used. It is expected to yield more than 125 MWh of electricity annually [43]. Dynamizing the sail-like PV wall, the architects expose the idea of exploiting the solar energy by emphasizing the buildings’ sustainability.

The PV curved wall is a strong architectural accent and represents a specific case of BIPV, where the modules are integrated parts of the giant buildings' sunshade.

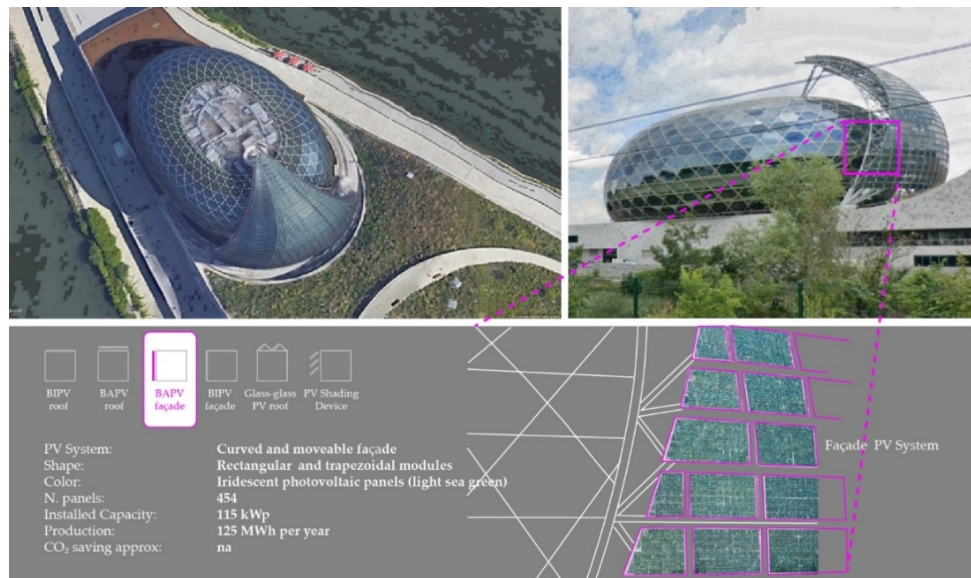


Figure 10. La Seine musicale (on top Source of illustrations Google Earth, Google 2020) (on the top); Integration and characteristics of PV systems (on the bottom).

3.7. Umwelt Arena

Umwelt Arena, “Environment Arena” or “Arena for Sustainability” is an exhibition centre and the first Swiss competence centre in ecology, commissioned in August 2012 in the town of Spreitenbach, near Zurich (Switzerland, CH). It is designed by the René Schmid Architekten office [45]. The building is erected on a 100 × 60 m oval plan with a size of a stadium. It aims to help visitors in experiencing and understanding sustainability (Figure 11).

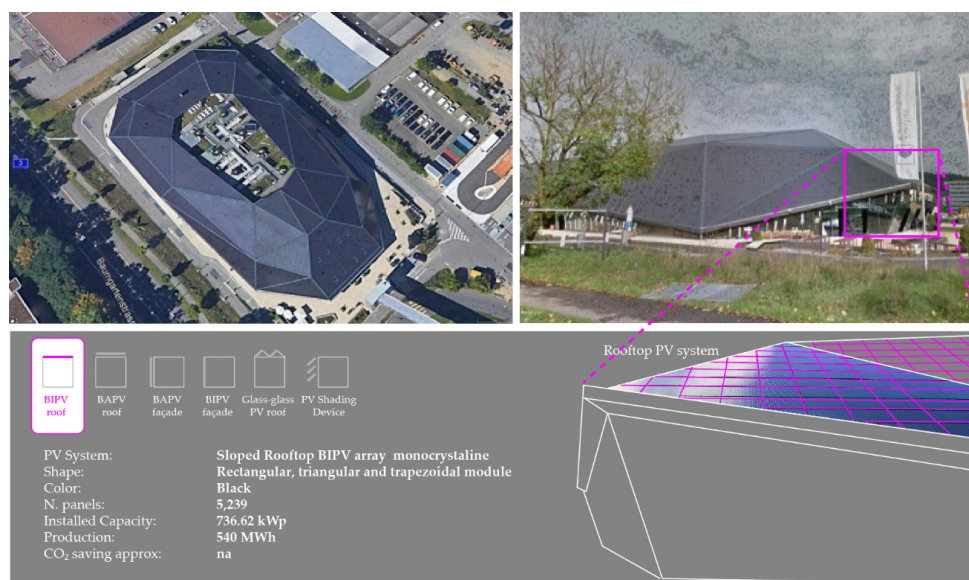


Figure 11. Umwelt Arena (a top and elevation views. Source: Google Earth, Google 2020, GeoBasis-DE/BKG 2020) (on the top); Integration and characteristics of PV systems (on the bottom).

The main geometric element of the Umwelt Arena is its giant roof consisting of 33 differently oriented flat trapezoidal surfaces, with a slope ranging from 6° to 62°, giving appearance of a crystal.

The entire 5333 m² roof is made of 5239 monocrystalline PV modules, with a total installed power of 736.62 kWp. The building produces 540 MWh per year, twice of its energy demand. It is the largest BIPV and one of the most famous energy plus buildings in Switzerland [46]. The Umwelt Arena received the “2012 Norman Foster Solar Award” [47]. Architecturally, the dominant external element is the BIPV roof visible to the visitors from all sides. The architects treat the fifth façade as equally important as all other façades. Choosing the BIPV principle for the roof materialization, they emphasize the institutional orientation towards environment protection and sustainability. This unique landmark building is a good example for other local, smaller and less exposed public and private buildings.

3.8. Kaohsiung National Stadium

The National Stadium (Figure 12) built from 2006 to 2009 in Kaohsiung, Taiwan (TW) was the largest commission of another Japanese Pritzker prize winner (2013), architect Toyo Ito [48].

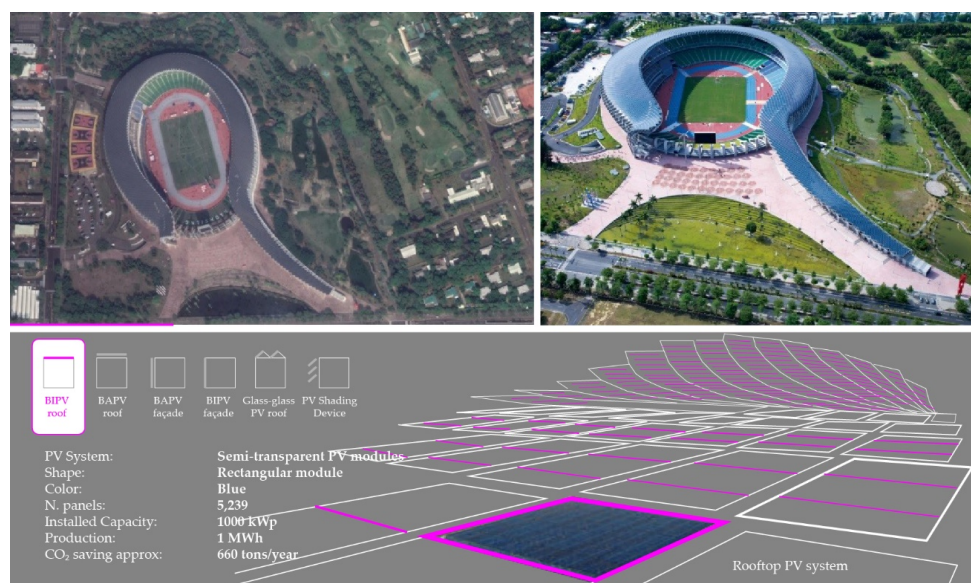


Figure 12. Kaohsiung National Stadium with the dragon shaped roof all covered by PV modules (top view of the stadium: Source illustration Google Earth, Google 2020, Maxar Technologies 2020 (on the top left)); view of the stadium: photo credits: CECI Engineering Consultant Inc., Taiwan) (on the top right); Integration and characteristic of PV systems (on the bottom).

The capacity of the stadium is 55,000 spectators and it is the largest sports facility in the country, as well as the largest solar powered stadium in the world, available to produce most of the electricity demand for its operation. The stadium was built for the 2009 World Games. It is a semi-open stadium creating a passage for the summer wind. This “dragon” shaped building is called a solar stadium [49] because of its 14,155 m² roof covered by 9720 semi-transparent PV modules [50]. The solar system power output is 1 MWp and it is a characteristic example of BIPV, allowing 30% of sunlight to pass into the stadium. The average generation of electricity is 3 MWh per day and 1.14 GWh annually. This unique solar plant is connected to the local grid and produces energy for its neighbourhood. It saves almost 660 tons of CO₂ emissions annually [51]. In the Kaohsiung National Stadium, the PV installation acts as a roof, a pleasant semi-transparent sunshade, and a fine texture of the giant roof, covering the “dragon” shaped geometry of the building.

3.9. Novartis Campus

Completed in 2008, the Novartis Campus building in Basel (Switzerland, CH) designed by the American architect Frank O’Gehry, and a Pritzker laureate (1989), is an unusual administrative building, consisting of five irregular bodies characteristic to O’Gehry’s architecture (Figure 13). The architecture

critics call the object “the O’Gehry building” because of its futuristic appearance, one of a couple of similar buildings designed by O’Gehry around the world. Apart from its distinctive geometry, this project is an outstanding example of PV integration on landmark buildings. The building is equipped with 92.7 kWp of PVs coming from semi-transparent roof glazing with integrated PV cells [52]. The energy produced by the PV installation is used for the building’s artificial lighting [53]. Distinctive by its size, position within the campus and proximity of the green open space on the south side, the building has excellent prerequisites for integration of solar systems. The materialization of the building, as well as the BIPV installation on the roof, demonstrates the orientation of the Novartis Campus towards the environmental issues. It demonstrates the architect’s capability to acquire new technologies and integrate them in its authentic architectural language.

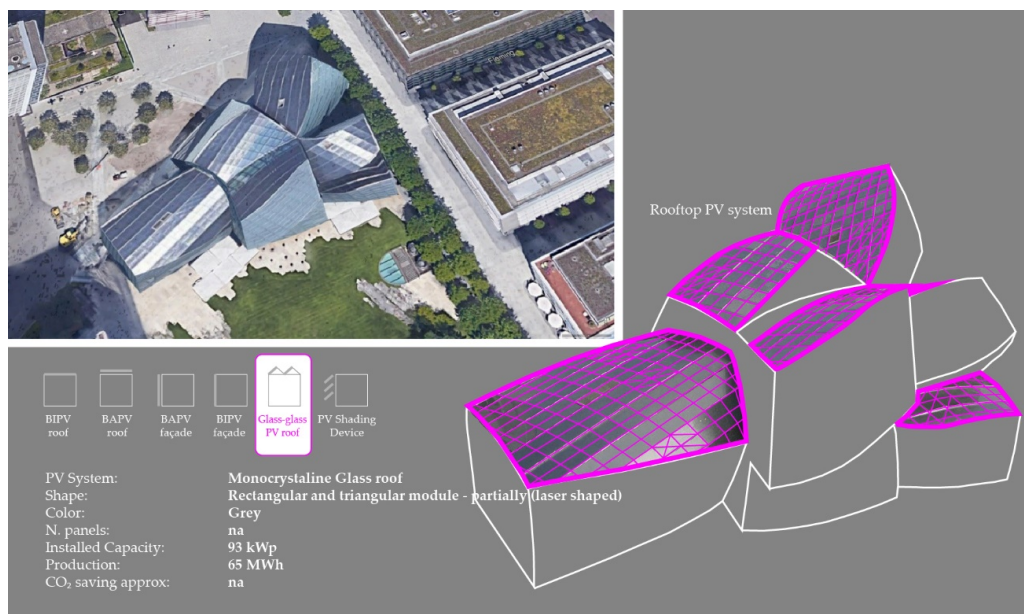


Figure 13. Novartis Campus (top view of the building. Source of illustration Google Earth, Google 2020) (on the top left). Integration and characteristic of PV systems (on the bottom).

3.10. Copenhagen International School

The Copenhagen International School, opened in 2017, is designed by the Danish office of C.F. Møller Architects and is located in Copenhagen outer harbour (Figure 14), Denmark (DK).

Some architectural critics regard this awarded building (2017 Iconic Award) as unprecedented architecture of willingness and foresight [54]. It is famous by its tiled sea green solar façade, distinguishing this large structure from its neighbour buildings and connecting it with the surrounding ocean. The façade exposes the building as a leader in sustainable design. In general, the building is a result of the synergic activity of a motivated client, well technically equipped architectural office and an international community of researchers and manufacturers. Geometrically the building of the Copenhagen International School is cubical, with a BIPV façade consisting of approximately 12,000 PV tiles of 700 × 700 mm each, completely covering the object. With its more than 6000 m² solar tiles, and an installed capacity of 720 kWp [55], it is considered one of the largest BIPV plants in Denmark. It is expected to produce 300 MWh of electricity per year, more than half of the School’s energy demand. The technology of the glass panels, developed at Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland [23], allows it to take one single colour with no need to apply pigments, thus decreasing panel efficiency. Having a possibility to choose between brick red, royal blue, golden yellow and sea green, the architects chose the sea green solution for the Copenhagen International School. The façade appearance is characterised by a stunning sequent-like effect, thanks to the 5° tilt angle of PV modules on four different orientations. This makes an effect of various colour hues, while in fact, all the PV

modules are of the exact same colour. With introducing the described solar façade, the aim of the architects was not only to contribute to the production of green energy, but also to offer a facility in which students could learn about the environment as well as global research and production activity. Equipped with LCD screens showing the energy production to the students, the building has a strong pedagogical impact. Details regarding the total number and type of PV modules, their installed capacity and annual electricity production, where available, related to the aforementioned presented landmark buildings, are summarized in Table 2.



Figure 14. Copenhagen International School (a top view and elevation: Source of illustration Google Earth, Google 2020) (on top). Integration and characteristic of PV systems (on the bottom).

Table 2. Total number and type of PV modules, installed capacity and annual electricity production for the ten landmark buildings.

Landmark Buildings with PV	Number and Type of PV Modules	Surface Area (m ²)	Rated System Power (kWp)	Annual Electricity Production (MWh)	Year
Maracanã Stadium (BR)	1552 Polycrystalline	2400	390	500	2012
Apple Headquarter (USA)	na	na	1700	17	2017
Shanghai Expo 2010 Theme Pavilion (CN)	16,250 Polycrystalline	30,000	2800	na	2010
Powerhouse Brattørkaia (NO)	1157 Crystalline	2867	415	458	2019
Paris Courthouse (FR)	1596 sunshades 152 solar panels na	1931	325	312	2016
La Seine Musicale (FR)	470 na	800	115	125	2016
Umwelt Arena (CH)	5239 Monocrystalline	5333	737	540	2012
Kaohsiung National Stadium (TW)	9720 Transparent	14,155	1000	1140	2009
Novartis Campus Building (CH)	na Monocrystalline	1300	93	65	2008
Copenhagen International School (DK)	12,000 Semi-transparent	6000	720	300	2017

4. Results and Discussions

Nowadays, the integration of photovoltaics into new and retrofitted buildings is a challenge for architects. Even the most renowned, awarded architectural names and offices are not an exception.

There are numerous examples of BIPV, in which the architects directed building designs, geometries at the first instance, to the technical and aesthetical needs of PV integration.

The fact that a designed architectural object, apart from its main function, could generate electricity by application of PV systems is a relatively new experience for many architects. A common belief that the PV technology might negatively influence the architectural appearance of buildings is still present. However, the fact that some surfaces of architectural objects could be activated in energy production influences contemporary architecture.

Examining the selected sample of landmark architectural buildings and considering the architectural performance parameters stated in Section 2, the architectural performances of the analysed object are presented in Table 3.

Table 3. Architectural performance of the examined sample buildings.

Landmark Buildings with PV	PV System as Architectural and Environmental Value	PV Contributing in Defining the Fifth Façade	PV Emphasizing the Geometry of the Arch. Building	PV Contributing to Specific Geometry of Architectural Building	PV as Architectural Accent	PV Integration in Architectural Visibility, Sensitivity and Quality	PV as Peculiar Element
Maracanã Stadium [BR]	✓	✓	✓			✓	
Apple Headquarters [USA]	✓	✓	✓			✓	✓
Shanghai Expo—Theme Pavilion [CN]	✓	✓		✓		✓	
Powerhouse Brattørkaia [NO]	✓	✓		✓		✓	✓
Paris Courthouse [FR]	✓			✓	✓	✓	
La Seine Musicale [FR]	✓		✓	✓	✓	✓	
Umwelt Arena [CH]	✓	✓		✓		✓	✓
Kaohsiung National Stadium [TW]	✓	✓		✓		✓	✓
Novartis Campus [CH]	✓	✓				✓	
Copenhagen International School [DK]	✓			✓		✓	✓

4.1. PV System as Architectural and Environmental Value

The clients are very often keen to use architectural elements that have an impact on society. This could demonstrate power, richness, social status, professional orientation, aesthetical understanding, etc. By applying PV systems, the impact on the society is manifold, but always oriented towards environmental responsibility and sustainability. For example, the PV systems on the roof of Maracanã Stadium, the Theme Pavilion and the Kaohsiung National Stadium reflect the green energy orientation of the events for which the buildings were reconstructed or built. The Copenhagen International School and the Umwelt Arena bring a pedagogic message related to environmental responsibility. The PV installations of the Apple Headquarters, the Powerhouse Brattørkaia and the Novartis Campus demonstrate the technical leadership of the companies in terms of sustainability. The PV visibility at the Paris Courthouse and La Seine Musicale guide the green regeneration of their neighbourhoods. It has to be noted that, although photovoltaic systems can currently be considered as “clean” and have a relative low environmental impact, depending on their installation location and local electricity mix, this might not always be the case, as many researchers have pointed out [2,14,56] and the same applies for their economic viability.

4.2. PV Contribution in Defining the Fifth Façade (i.e., the Roof)

PV systems, applied or integrated on the buildings, are sometimes visible only from the top view. If the geometry of such systems is well articulated, the roof becomes “the fifth façade” and is treated architecturally the same as the usual façades. In the examined sample the articulation of the fifth façade are the Maracanã Stadium, the Apple Headquarter, the Theme Pavilion, the Powerhouse Brattørkaia, Umwelt Arena, and the Kaohsiung National Stadium. A special case is represented by the Novartis

Headquarter, in which the PV system has been entirely integrated into already specifically articulated fifth façade.

4.3. PV Emphasizing Geometry of Architectural Building

Geometry of an existing architectural object sometimes allows efficient and smooth application of PV systems. Examples of such objects are existing stadiums such as the Maracanã Stadium in Rio de Janeiro, where the double elliptical PV ring perfectly fits in the shape of the object. Although visible only from the top view, the PV system affirmatively complements architectural performance of the stadium. Similar is the case of the Apple headquarter where the PV roof installation follows the circular shape of the huge building. In the case of La Seine Musicale a giant moving veil follows an ellipsoidal geometry of the building corpus. In this case, the moving PV installation adds to emphasizing the specific geometry of the concert hall building.

4.4. PV Contributing to Specific Geometry of Architectural Buildings

In the presented samples, many of the PV systems contribute to the geometry of the buildings. Such examples are the Theme Pavilion on Shanghai Expo, Powerhouse Brattørkaia, Paris Courthouse, Umwelt Arena, Kaohsiung National Stadium and the Copenhagen International School. In the case of the Theme Pavilion, the trapezoid PV system enriched the geometry of the building roof. Visible only from the top view, it is a valuable part of the building's fifth façade. In the case of Powerhouse Brattørkaia, a sloped, south oriented surface cuts the volume of the building, acting as a roof and a façade at the same time. The Paris Courthouse is a building of relatively simple geometry, consisting of several cuboids. The PV sunshades emphasize the vertical and horizontal lines of the building façade. Opposite to the Courthouse, the Umwelt Arena and the Kaohsiung National Stadium are buildings of a complex geometry with a dominant huge PV roof. Finally, the Copenhagen International School is a building with a BIPV façade and geometry which characterizes the entire building.

4.5. Architectural Accent of PV

The architectural accentuations are present in two cases of the examined sample: the Paris Courthouse and La Seine Musicale.

In the case of the Paris Courthouse the accent is discrete, and the PV system of sunshades is used to emphasize selected verticals and horizontals on the east and west façades. In the case of La Seine Musicale, the architectural accent is strong and dominant. The moving PV veil is one of the main elements of the building composition, and it complements the building ellipsoidal shape.

When applied as an accent, the PV installation is not aimed at producing significant amounts of energy, and is certainly not sufficient for the building demand, but rather to complement other sources of green energy and sending a clear message of sustainability.

4.6. PV Integration Using Architectural Visibility, Sensitivity and Quality

In Tables 4 and 5, the assessments of the architectural quality of the PV integration, the context sensitivity and the system visibility of the selected landmark buildings are reported.

Table 4. Architectural integration quality, context sensitivity and system visibility of the landmark buildings (first part).



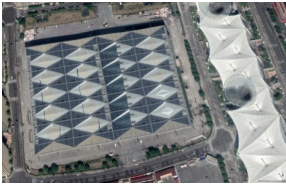























































































					
	<i>Maracanã Stadium (BR)</i>	<i>Apple Headquarter (USA)</i>	<i>Shanghai Expo 2010 Theme Pavilion (CN)</i>	<i>Powerhouse Brattørkaia (NO)</i>	<i>Paris Courthouse (FR)</i>
System geometry					
System materiality					
Modular pattern	 	 	 	 	
Context Sensitivity					
Urban area socio-cultural value	✓	✓	✓	✓	✓
System Visibility					
Close visibility	✓	✓	✓	✓	✓
Remote visibility		✓	✓	✓	✓

Table 5. Architectural integration quality, context sensitivity and system visibility of the landmark buildings (second part).

					
	<i>La Seine Musicale (FR)</i>	<i>Umwelt Arena (CH)</i>	<i>Kaohsiung National Stadium (TW)</i>	<i>Novartis Campus Building (CH)</i>	<i>Copenhagen International School (DK)</i>
System geometry	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent
System materiality	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent
Modular pattern	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent	 fully coherent /  partly coherent /  not coherent
					
Context Sensitivity	 low /  medium /  high	 low /  medium /  high	 low /  medium /  high	 low /  medium /  high	 low /  medium /  high
Urban area socio-cultural value		✓	✓	✓	✓
System Visibility	 low /  medium /  high	 low /  medium /  high	 low /  medium /  high	 low /  medium /  high	 low /  medium /  high
Close visibility		✓	✓	✓	✓
Remote visibility		✓	✓	✓	✓

In some cases of the presented sample, the PV installation is entirely integrated into the building skin. The most representative examples of BIPV are the Shanghai Expo 2010 Theme Pavilion, the Umwelt Arena, the Kaohsiung National Stadium, the Novartis Campus, the Powerhouse Brattørkaia and the Copenhagen International School. In the analysis conducted through the LESO-QSV method, the architectural quality of the PV systems' integration on the building envelope is fully coherent in all aspects, systems geometry, system materiality and modular pattern. In the case of the Umwelt Arena the entire roof is a PV system, similar to the Kaohsiung National Stadium, while in the case of the Copenhagen International School the entire façade is a PV system, and similarly in the Powerhouse Brattørkaia, the entire roof and the upper parts of the façades. However, in this last case, the modular pattern results to be partly coherent. For the Novartis headquarters, the architect decided also to totally integrate the PV system into the complex curved geometry of the building, so it becomes almost inseparable from the other building elements. In the rest of the analysed buildings, the architectural integration quality of the PV systems was found partly coherent in the Maracanã Stadium, where the PV elements have been installed following a refurbish intervention. In the Paris Courthouse and in the La Seine Musicale, even if the PV systems are not integrated on the building envelope but they have a peculiar function, such as shading control system and sun-tracking energy generation elements, the quality of the architectural integration was found fully coherent for all the analysed aspects (i.e., system geometry, system materiality and modular pattern).

Regarding the context sensitivity, it is important to underline that half of the analysed buildings are in urban areas characterized by low socio-cultural value. This has a twofold consequence: on one hand, it helps to increase their value as landmark buildings and, on the other hand, the buildings have an important role as "design driving force" to improve the overall quality of the remote areas where they are located. The rest of the buildings have medium context sensitivity. In that sense, for example, the Powerhouse Brattørkaia, the Paris Courthouse and the Copenhagen International School are located close to transport and commercial infrastructures, such as a railway station, a highway and a harbour, respectively. Those buildings are part of wider redevelopment strategies where new residential blocks, financial and commercial services are planned to be built. Their presence contributes to increase the architectural interest and financial attractiveness of the areas where they are located. Differently, the La Seine Musicale is the only building with high context sensitivity given its location within the cultural area on the Île Seguin, an island on the Seine river between Boulogne-Billancourt and Sèvres in the western suburbs of Paris.

Finally, regarding the PV systems visibility, the Powerhouse Brattørkaia, the Umwelt Arena, the Copenhagen International School and the La Seine Musicale, have high levels for both, close and remote visibility. All the buildings characterised by PV systems installed on the roof, such as the Maracanã Stadium, the Apple Headquarters, the Shanghai Expo 2010 Theme Pavilion, the Kaohsiung National Stadium and the Novartis Campus, have low close visibility and medium remote visibility. This aspect is emphasized by the fact that those buildings have the roof as the largest surfaces exposed on the sunlight and most of them are in remote areas characterised by very low urban density. Differently, the Paris Courthouse results to a medium close visibility and high remote visibility, which underlines the dominant presence of this building on both aspects, figuratively, for its legal function, and physically, because it is inserted in an urban area characterized by low-medium rise building blocks. Furthermore, the presence of a large urban park in front of the building emphasizes the visibility of the PV systems on the south façade for both close and far from the building.

4.7. PV as Peculiar Element

The examples of the Kaohsiung National Stadium, the Umwelt Arena and the Copenhagen International School represent the cases of total PV integration into the dominant building elements, roofs and façades. In these cases, the object size plays an important role, because the integrated PV modules give an impression of an outer material texture applied to entire objects. Considering the current worldwide trend of Low Energy Buildings and the European Directives regarding the

construction of nearly Zero Energy Buildings, the buildings constructed in the future will have to contain systems for producing part of their own energy demand. Among these, PV systems will play a major role in new or refurbished buildings. The seven architectural performance parameters should be considered when designing buildings with integrated or applied photovoltaic systems.

The main solutions to be considered for installing the PV systems are:

- Installed on the roof/façades;
- Opaque/transparent PV modules;
- Different shapes and colours.

5. Conclusions

Landmark buildings are architecturally convenient for application of PV systems for many reasons. Their size and shape are larger than of neighbour objects, and their architectural appearance does not necessarily need to be in accordance with that of the surrounding buildings. Since landmark buildings are built with larger budgets, they are often authored by renowned architectural offices and well-known architects. Design of these objects allows participation of many disciplines and sometimes presumes some technological developments and advancements. It is important to stress that the aim of landmark objects equipped with PV system is mainly their impact on society. Such impact is sometimes related to advanced aesthetics (Novartis Campus), environmental neutrality (Maracanã Stadium), technological advantage (Apple Headquarter) and energy production (Copenhagen International School, Kaohsiung National Stadium, Powerhouse Brattørkaia, Umwelt Arena).

Furthermore, the examined samples have shown several other parameters of architectural performance: definition and articulation of the fifth façade, PV emphasizing distinctive geometry of architectural buildings, PV contributing to specific geometry of architectural buildings, PV as architectural accent, total integration of PV into the building skin and peculiar PV elements.

Since the examined samples were different, the general conclusions could be applied to many other similar landmark buildings. The results of this study, i.e., the systematization of selected landmark buildings according to the seven architectural performance parameters, might also be a starting point, as emblematic examples, of the fruitful collaboration between architects and engineers when designing a PV equipped building. The high architectural quality of the PV integration in the selected landmark buildings has been confirmed by the analysis of the architectural integration quality, context sensitivity and system visibility conducted with the LESO-QSV method [24].

Building a landmark object with an integrated PV system can be an affordable option as it obtains the energy independence for the institution that owns the object and sometimes for its neighbourhood. It also represents the idea of sustainability and environmental responsibility, sending a strong message to its surroundings. Finally, it brings new aesthetics and contributes to the architectural performance of the PV equipped object.

Author Contributions: Conceptualization, M.D., B.-G.B. and D.D.; methodology, M.D. and G.L.; sample analysis, M.D., D.D. and M.R.; investigation, G.L.; writing—original draft preparation, M.D., M.N.; writing—review and editing, A.K.-F., B.-G.B., G.L. and G.M.; supervision, G.L. and G.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors wish to thank the Schlaich Bergermann Partner, Apple, Ivar Kvaal, Sergio Grazia, CECI Engineering Consultant Inc. for both photos and data consents. This publication is based on work from COST Action CA16235 PEARL PV (<https://www.pearl-pv-cost.eu/>) supported by COST (European Cooperation in Science and Technology, <https://www.cost.eu>).

Conflicts of Interest: The authors declare no conflict of interest.

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