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## **PV Grid-Connected Systems: Performance and Architectural Integration Aspects**

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Considering the high global rates of carbon dioxide emissions, there is a great concern about renewable energy especially solar energy in buildings. Despite its growth, there has been limited acceptance of architects and stakeholders concerning the use of solar energy technologies in buildings, and subsequently, insufficient architectural integration. Here, the research aims to develop better understanding of architects for the design stages, considerations, and possibilities regarding solar PV grid-connected systems in buildings using inductive methodology, thus analyzing the technology specifications and good integration practices. The research determines the factors that influence the early design and conception phase of the building. It develops a framework for architects concerning the technical and physical aspects affecting the design process, through building needs, cell types, system performance, site conditions, space and environmental requirements, and BIPV integration possibilities. In conclusion, this study will help in the implementation of PV grid-connected powered buildings in new projects by addressing previous design challenges and providing data for architects and researchers on the system design and performance.

**Keywords:** solar energy, photovoltaics, grid-connected system, architectural integration, BIPV.



## 1. Introduction

Considering that the major component of greenhouse gases (GHGs) is carbon dioxide, there is a global concern about enhancing renewable energy especially solar energy to reduce building's carbon footprint. Solar energy total installed capacity at the end of 2015 was 227 GW with more than 50 GW installed just in 2015. Despite this growth only about 1.3% of the world's electricity is produced by PV [1].

At regional scale, efforts are made to develop solar energy solutions or to bridge the gap of limited acceptance from architects through sharing knowledge between architects and specialists of the photovoltaic sector. Surveys reveal that one of the main barriers to the spread of solar power systems is the high cost, perceived by architects and contractors, who are considered the main stakeholders. On the other hand, the drastic cost breakdown of solar energy over recent years has decreased system prices. Thus, it is essential to build trust of architects, investors, and financial stakeholders in solar power. The language how the technology components are presented physically and virtually is one of the main keys to this acceptance.

The study aims to develop better understanding of architects for designing solar PV grid-connected systems in architectural integrated buildings, that act as micro energy hubs consuming and generating energy with a reduced carbon footprint. Therefore, the objectives of this paper include;

- To explore the solar technologies and needs.
- To understand types of photovoltaics (PV) cells.
- To study the factors affecting PV energy yield, space requirements, and on-site conditions.
- To study architectural integration solutions of BIPV systems.
- To conclude a framework for architects regarding the factors affecting the design process.

The methodology of this research implies an inductive approach, through exploring the various design solutions and investigating the factors affecting it, focusing on the technical and physical aspects.

## 2. Photovoltaics Technology

Today, solar technologies have fulfilled various needs in buildings, ranging from passive technologies and active technologies (Figure 1.). In the case of active systems, solar energy can be transformed into heat using solar thermal collectors, or into electricity using photovoltaic (PV) modules [2]. Solar thermal collectors can provide domestic hot water (DHW), space heating, and recently transform solar heat into cold to fulfil building cooling needs; while PV modules can provide building cooling, light, and electricity needs [3].

Solar thermal collectors include two systems depending on the medium used for energy transformation; air collector systems, and hydraulic collector systems. Hydraulic collectors are more cost effective, and require more sophisticated technology. Furthermore, hydraulic collectors are divided into three types; glazed flat plate collectors, unglazed flat plate collectors, and evacuated tubes collectors [4]. However, the research only covers the photovoltaics technology in further detail.

### 2.1. PV cell types

A PV system is formed by a number of cells combining to make a module, and modules combining to

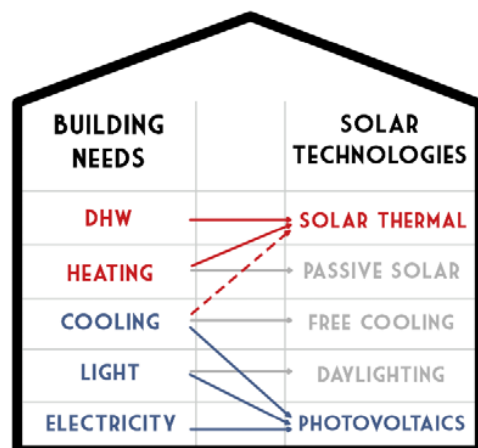





Figure 1: Different solar technologies covering different building energy needs [3]

make an array. Cells can differ according to their manufacturing process. Basically, they can be divided into three main categories; crystalline silicon cells, thin film cells (Table 1), and third generation cells [3]. The third category is still emerging with less sufficient data and results, while the first two categories are the main established technologies that the research would focus on.

Table 1. PV cells categories[2, 3].

Category	Crystalline silicon solar cells		Thin film cells
Types	Monocrystalline silicon	Polycrystalline silicon	<ul style="list-style-type: none"> <li>Amorphous or micromorphous silicon</li> <li>Gallium- Arsenide (GaAs)</li> <li>Cadmium-Telluride (CdTe)</li> <li>Copper-Indium-Diselenide (CIS)</li> </ul>
Photo Example			
Description	They are cut into thin wafers from a singular continuous crystal grown for this purpose, and has uniform colour, ranging from blue to black. The cells may be fully round or they may be trimmed into other shapes.	They are melted and poured into a mold. As the material cools, it crystallizes in an imperfect manner, forming random crystal boundaries. This forms a square block that can be cut into square wafers.	They have a low-cost potential because its manufacture requires only a small amount of material and less energy. They are available in range of colors.
Average production in European weather	900-1000 kWh per each kW installed	750-850 kWh per each kW installed	600-800 kWh per each kW installed

## 2.2. PV systems

Photovoltaic systems can be either stand-alone or grid-connected systems. Stand-alone/off-grid systems are more suitable for isolated or desert settlements without access to the government electricity grid [5]. They supply energy independently and thus, energy must be balanced and energy surplus must be stored in batteries. On the other hand, grid-connected systems can be a very efficient solution that avoids costly batteries and reduce high losses, therefore, it is the simplest and cheapest solar power setup available [6].

In this system, electricity is generated using PV modules as direct current (DC), and as the electricity supply in the grid is alternating current, an inverter is used to convert DC to AC (Figure 2.). Whenever the electricity generation from PV modules does not cover the building consumption, the shortage is compensated from the public grid. However, if generation exceeds consumption, the excess energy goes to the grid [3],[6]. The study will focus on grid-connected systems performance and applications.

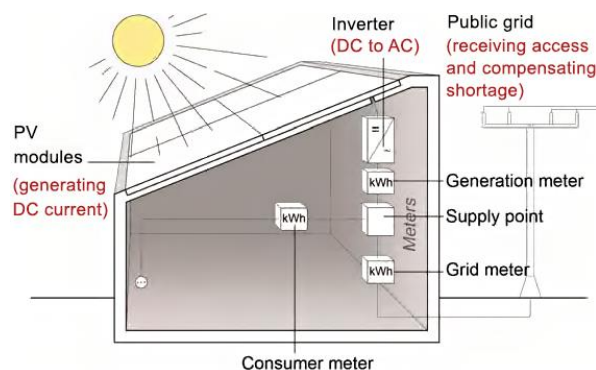


Figure 2: Scheme of a common grid-connected PV installation. [2] edited by researcher.

### 3. PV Performance

For designing a solar system, it is crucial to study its production and the energy required to fulfil the building needs, as well as the factors affecting the production and causing efficiency losses. The study of the technical side on the early design phase leads the architect to design the optimum conditions for the system to deploy the most out of the it.

#### 3.1. Energy yield

The production of a PV system can be roughly estimated through a simple calculation in predesign stage, as followed [3];

- $FinalYield = G [kWh/ m^2] \cdot OrientationFactor[\%] \cdot Area[m^2] \cdot eff [\%] \cdot PR[\%]$

**G:** Global irradiation is the amount of solar energy on the horizontal surface. Irradiation maps can be found online, and they calculate the irradiation for specific locations as an annual long-term average (Figure 3.).

**OrientationFactor:** The orientation factor is the effective radiation reaching the PV modules and is determined by the module's orientation.

**Area, eff:** Cell efficiency depends on the technology of the cell types, and it is specified in the PV module datasheet provided by manufacturer. By multiplication of it with module area, the nominal power of the system is obtained.

**PR:** The performance ratio of the systems depends on the ratio of losses due to other factors like type of installation, poor ventilation... etc.

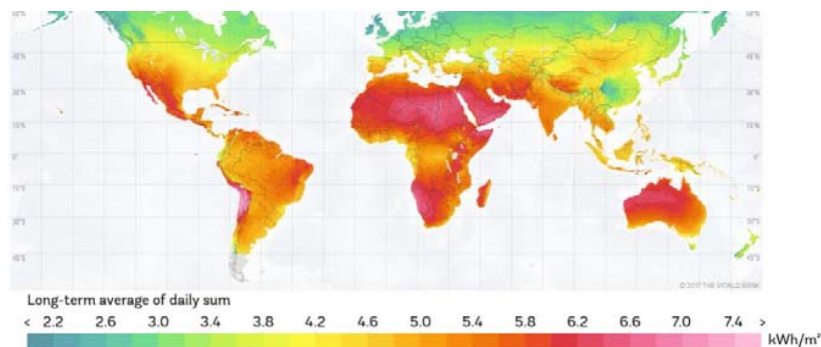


Figure 3: Global horizontal irradiation map [7]

#### 3.2. Space requirements

The space required ( $S_r$ ) to install 1 kWp PV system can be obtained with a simple calculation depending on cell efficiency, as follows [3];

- $S_r [m^2] = 1/eff$

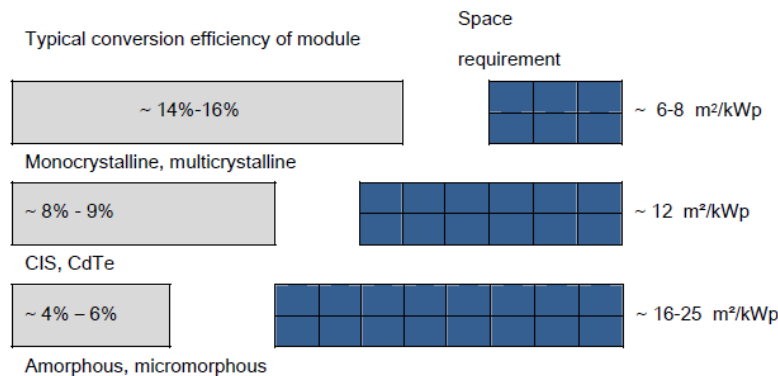


Figure 4: How cell efficiency affects the modules space required [3]

### 3.3. On-site considerations

**3.3.1. Orientation and tilt.** Solar power gain is affected by on the module orientation and tilt for each site. The best orientation (azimuth angle) is south facing at the northern hemisphere, and north facing at the southern hemisphere. While, the tilt (elevation angle) is influenced by the latitude, as it is found that the best module tilt is facing the equator with a tilt equal to the latitude angle [1]. Studies has showed that a system installed at the vertical façade gained an annual solar energy with 30% losses compared to a system installed at the altitude angle. While a system installed at horizontal angle losses were as high as 10%. [8]

**3.3.2. Temperature dependency.** Losses in the cell performance highly depend on the module temperature, especially mono- and multi-crystalline cells. Depending on the cell technology (Table 2.), each have a different temperature coefficient (%/°C); which is defined as “the dependence of the electrical characteristics of PV on the operating temperature”[1]. It indicates the percentage of efficiency loss for every degree Celsius temperature above STC conditions -Standard Test Conditions; a radiation of 1 kW/m<sup>2</sup>, a cell temperature of 25°C, and 1.5 air mass- (Figure 5.), and can be found at the module datasheet as well.

Table 2. Temperature coefficients for different photovoltaic technologies.[1]

Technology	Temperature coefficient (%/°C)
Mono-c-Si	-0.40
Multi-c-Si	-0.45
a-Si	-0.20
a-Si/μc Si	-0.26
CIGS	-0.36
CdTe	-0.25

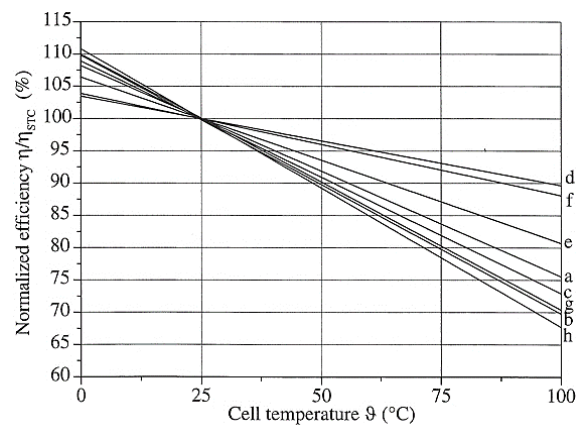


Figure 5: A representation of the influence of cell temperature on the normalized efficiency of the modules for different cell technologies. (a) high efficiency crystalline silicon; (b) monocrystalline silicon; (c) polycrystalline Silicon; (d) amorphous silicon; (e) "micromorph" tandem; (f) CdTe; (g)-(h) CIGS. [3]

**3.3.3. Self-shading.** Shading greatly affects solar PV production. Shading the bottom part of the module causes losing the entire module production as they are interconnected ribbons (Figure 6.- Left), while side shades only causes losing those particular cells production (Figure 6.- Right). [9] Strategies to minimize self-shading require careful design and placing of the modules (Figure 7.). The calculation of row inter-spacing can be simplified as follows;

- $d = (h \div \tan a)$

d: minimum distance between rows

h: height differential between the top of the panel and the ground

a: solar altitude angle

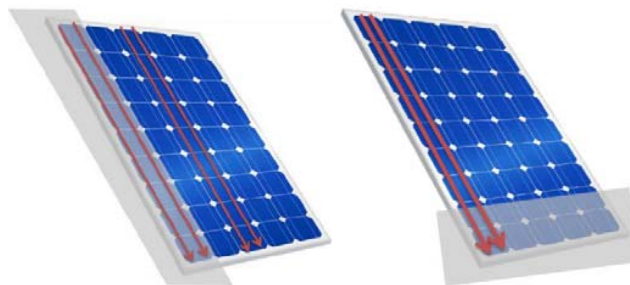


Figure 6: Interconnect cell ribbons, (Left: side shading, Right: bottom shading). [10]

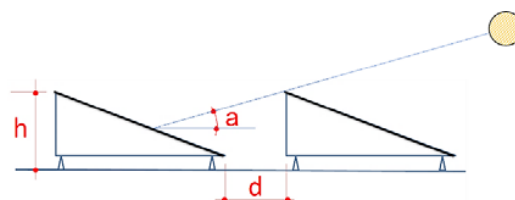


Figure 7: Design of modules inter-spacing. [9] edited by researcher

The solar altitude angle can be calculated using online software can be used, such as NOAA Solar Calculator (<https://www.esrl.noaa.gov/gmd/grad/solcalc/>) [10], using the following steps;

- Firstly, the location is determined by online map, or by entering latitude and longitude values,
- Also, the time zone, specific date and time are determined (Figure 8.),

- Eventually the software calculates the altitude angle for the time and area.

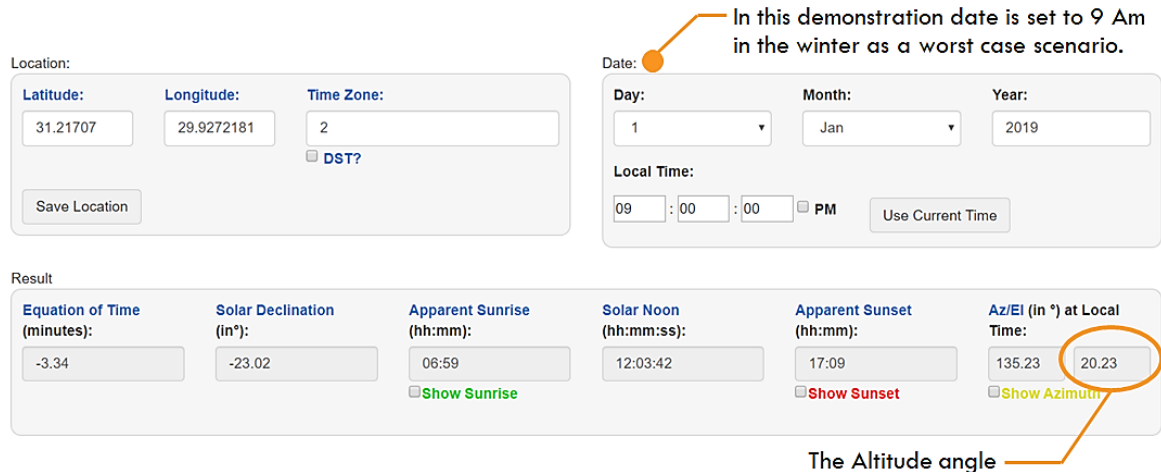


Figure 8: An implementation of NOAA Solar Calculator  
Source: Researcher, 2019

**3.3.4. Soiling and system losses.** Soiling indicates dust accumulation above the surface of PV modules (Figure 9.). It is a factor of losses of the system performance depending on the dust type, time period since previous rainfall, and the cleansing schedule. To overcome soiling issues, studies are exploring solutions such as developing soiling sensors, cleaning strategies, and anti-soiling coatings.

A study that has taken place in Egypt compared three PV systems production; a clean PV module, a module that was exposed to dust for a year, and a module that was exposed to dust as well but was cleaned every two months. Results showed that the one-year soiled module and the two-months soiled module produced 35% and 25% less energy, respectively, when compared to the clean module. [1]



Figure 9: Interconnect cell ribbons, (Left: side shading, Right: bottom shading). [1]

Other system losses can be caused by inverters, wires, glass reflection, snow, deviation from STC, ...etc. (Table 3.). All these parameters have an influence on the final Performance Ratio (PR) of the system. [3]

Table 3. Common losses percentage [3]

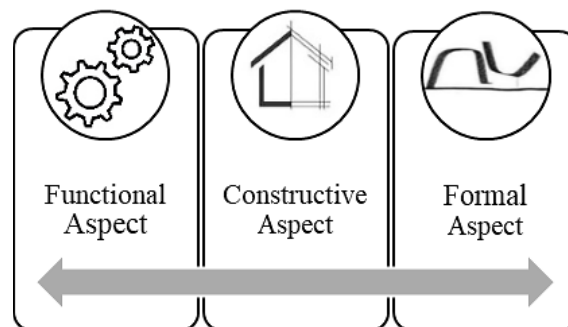
Common losses factors	Mean losses
Glass reflection losses	2 – 4%
Deviation from STC	2 – 4%
Temperature effect	3 – 6%
Snow. Dust/soiling	1 – 2%
Shadows	≥ 0%
Tolerance and mismatching	2%



Inverter losses	$\geq 5\%$
Cables and line losses	1 – 2%

#### 4. Architectural integration

The architectural integration quality is defined as the result of a controlled and coherent integration of the solar system simultaneously from all architectural points of view, functional, constructive, and formal (aesthetic) [3]. This implies that the PV system that would replace a building element shall carry out its functional and constructive quality, while being be in good composition and aesthetically pleasing (Figure 10.).



**Figure 10.** Architectural integration aspects.  
Source: Researcher, 2019

##### 4.1. Integration terminology

- Building added photovoltaics (BAPV); In this type the modules are only added on top of the building envelope without replacing any building elements. Therefore, there are no savings of materials nor cost, but furthermore, additional mounting systems are used. [2]
- Building integrated photovoltaics (BIPV); Photovoltaics modules are integrated within the building envelope to be used as an architectural element and for energy generation. This could result in savings when the cost of the PV elements is below the traditional elements. [2]

There are various advantages of integrating photovoltaics into buildings [11];

- No need for additional land, as PV is installed on a part of the building, which is optimum for dense cities.
- The cost of PV elements is offset against the cost of the replaced building elements.
- Avoiding losses during distribution as the power is generated on-site.
- Architectural elegant, which helps increasing the market acceptance (Figure 11.).



Figure 11: Inclined PV integrated glazed façade of Vocational College in Tirol, Austria [12]

**4.2. BIPV solutions**

In case of BIPV, the relationship between the system and the building envelope can be categorized into three main categories (Table 4.); roof, façade, and external elements solutions. Roofs usually are the most efficient solution to achieve the optimum angle. They can be tilted roofs, flat roofs, or skylights. Façade solutions can be in the form of cladding or glazing PV panel. Furthermore, external elements can take the form of shading canopies and louvers, or the form of railing and parapet systems.

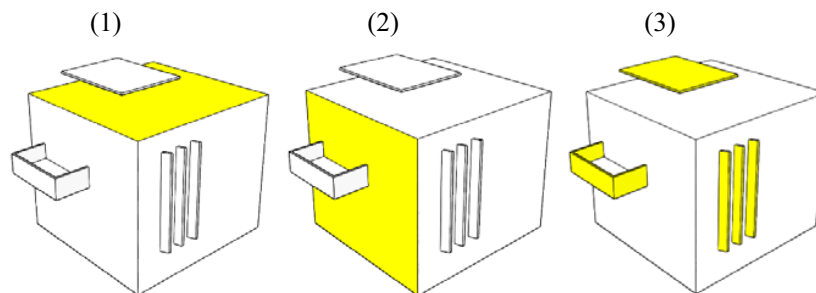


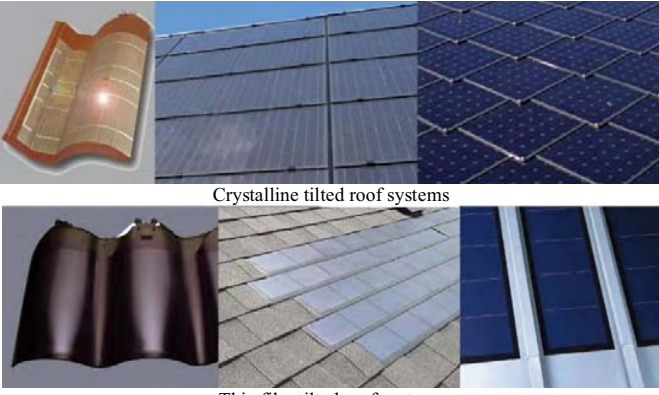
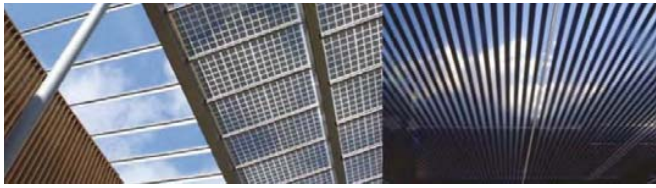






Figure 12: PV integration within the building envelope. (1) Roof solutions. (2) Façade solutions. (3) External devices solutions. Source: Researcher, 2019

Table 4. Solutions of PV integration within the building envelope[2, 3]

Category	Solution	Description
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<p><b>(1) Roof</b></p>	<p>Flat roof modules</p>	<p>Special racks might be used to create tilt angles. Crystalline modules may also be used on plastic substrates and with adhesive backing. Another trend is using thin film laminates above waterproof membranes.</p>  <p>Crystalline modules for flat roof. Left: standard module on rack mounting system. Right: special rack system for thin film cells on stainless steel substrate.</p>  <p>Integration of PV laminates on plastic substrates in flat roof. Left: mono-crystalline modules. Right: thin film modules.</p>
<p><b>(1) Roof</b></p>	<p>Tilted roof tiles</p>	<p>There have been many products developed for roof tiles, shingles, and slates; using both crystalline and thin film cell technologies. They can match traditional products with great aesthetics.</p>  <p>Crystalline tilted roof systems</p> <p>Thin film tilted roof systems</p>
<p><b>(1) Roof</b></p>	<p>Skylights</p>	<p>In case of skylights, PV modules could be the only element covering the roof. Mostly, semi-translucent crystalline modules are custom made so the architect must ask for a simulation or a test about the performance. While for thin films, translucent modules are standard with detailed datasheets available.</p>  <p>Semi-translucent skylights. Left: crystalline modules. Right: thin film modules.</p>
<p><b>(2) Facade</b></p>	<p>Cladding</p>	<p>PV modules can be used as cladding installed on a load-bearing wall. The modules are usually back ventilated to avoid efficiency loss due to temperature. Both crystalline and thin films can be used, with various fastening systems.</p> 



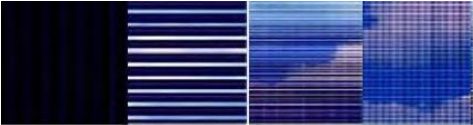


		Façade cladding solutions
	Glazing	<p>Translucent PV modules could be integrated into curtain wall systems; post-beam structure, structural glazing, and spider system. It also can be used for the outer layer of double façades. PV glazing solutions can greatly affect indoor climate, and can transfer heat into the space. Therefore, products with good thermal insulation have been developed with low-E value, which could be used as double or triple glazing elements.</p>  <p>Façade glazing solutions. Left: Translucent thin film module curtain wall. Middle: Frameless modules with spider glazing system. Right: Double glazing module with thermal insulation.</p>
(3) External devices	Shading devices	<p>PV modules can be used as sun shades in a form of canopies, louvers, or movable shutters. They can be semi-translucent crystalline or thin film modules. Also, opaque modules are used, which require that the upper part is made without cells to avoid shading.</p>  <p>Shading devices solutions. Left: sliding shutters. Right: shading louvers.</p>
	Railings	<p>PV can be integrated in railing and parapet systems as well. There are mostly semi-translucent modules that are made with security glass (SSG).</p>  <p>Railing and parapet solutions</p>

#### 4.3. Physical characteristics of PV cells

For the design and implementation of PV technology in buildings, it is important to take the aesthetic value into consideration. This requires from the architect to harmonise the physical and visual characteristics of the PV modules with the architectural language in the building [13]. Various products have been developed for the sake of integration within the buildings with many physical properties that provide variety in solutions. It is essential to explore these properties which include; colour, texture/pattern, translucency/reflection, and flexibility.

Table 5. Physical properties in BIPV and their characteristics

Property	Characteristics
----------	-----------------

Colour	<p>There are many colour variations for PV modules. Polycrystalline cells are usually black or dark blue, but other colour variations can be produced by changing the thickness of the anti-reflective coating [13]. Darker cell colours maximize sunlight absorption and are the highest in efficiency, so the change in colours must compromise the efficiency [14]. Thin film cells provide various ranges of colours as well. Amorphous silicon cells or CIS are usually available in black, grey, or dark brown, while CdTe cells have greenish shades [15].</p>  <p>Coloured crystalline silicon cells manufactured by Solartec[13]</p>
Texture and pattern	<p>The cells texture varies depending on the technology they are made of. Monocrystalline cells have a solid finish and a homogenous texture, while polycrystalline cells have a marble-like texture and multifaceted reflections [18]. Variations of patterns of polycrystalline cells can be produced by the grey metallic grid which collects the produced energy [13]. Amorphous silicon cells mostly have a homogenous texture with fine lines, but it is also possible to produce semi-transparent cells with a variety of patterns by laser cutting (point, stroke, stripes).</p>  <p>Variations of the pattern of metallic grid on polycrystalline cells [3]</p>  <p>Thin film modules with different pattern and level of translucency [3]</p>
Translucency and reflection	<p>Both crystalline silicon cells and thin film cells can be produced as translucent or semi-transparent cells [16]. There is a variety of products in the market with different transparency rates such as 10%, 20% and 30%. These products maximize sunlight indoor spaces and avoid infrared radiation [6]. The module cover is commonly made of glass, which has a reflective surface causing annoying glare. Some products overcome this by sandblasting the glass cover creating a matt finish [15].</p>  <p>Semi-transparent c-Si cells with 22% transparency [17]</p>
Flexibility	<p>Thin film technologies provide flexible solar cells which creates PV foil as thin and lightweight building element for architectural integration [18]. The flexible CIGS and CdTe cells can be laminated to the building elements as the flat roof membranes or tiles without adding an extra weight which highly reduces the cost and extend the opportunities for new PV concepts and applications [19].</p>  <p>Flexible thin film solar cells integrated in a curved rooftop [20]</p>

## 5. Conclusion and recommendations

The early study of the design process and possibilities of the photovoltaics system has a huge effect on avoiding future challenges and achieving a cost-effective system. The research investigated the technical and physical aspects of the design phase that would be affected by the architectural decisions. The paper concluded four design determinants that shall be considered by the architect during the design of the solar system which are; cell type (technical), the position of the modules in the building, the integration solution, and cell type from a physical/ visual aspect. Figure 13. illustrates a framework for the design determinants of PV grid-connected solar systems.

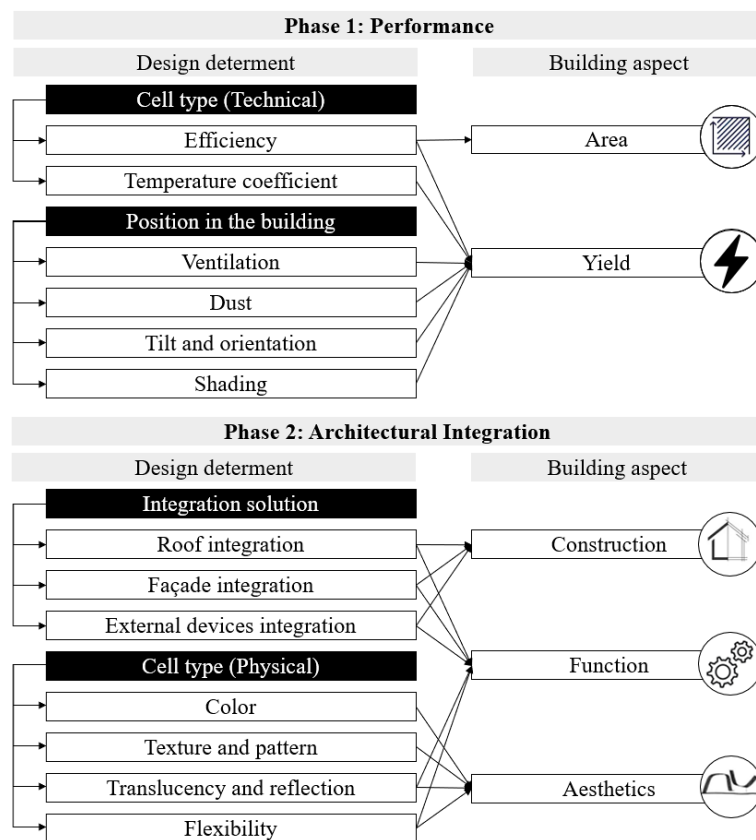


Figure 13: A framework for the design determinants of PV grid-connected solar systems  
 Source: Researcher, 2019

Phase 1 concludes the design determinants by the technical characteristics of the solar system. The first determinant is the technical cell type, where the architect chooses the optimum efficiency and temperature coefficient that affects the facing building aspects. The second determinant is the position of the solar system in the building, where the architect studies ventilation, dust, tilt, orientation, and shading results. The building aspects that are affected in phase 1 are the area of the building space needed to place the system, and the final yield produced by the system to fulfil the building needs.

On the other side, phase 2 concludes the design determinants by architectural integration of the solar system. The first determinant is the integration solution, where the architect determines the relationship between the system and the building envelope; roof solutions, façade solutions, or external devices solutions. The second determinant is the cell type in terms of physical and visual characteristics; where the architect chooses the cell that suits the desired design in terms of colour, texture and pattern, translucency and reflectivity, and flexibility. The building aspects that are affected in phase 2 are construction, function, and aesthetics.

The research concludes some recommendations for architects, as follows:

- Starting to direct awareness towards PV grid-connected solar systems for proving to be the best cost-effective and less complicated system.
- Making preliminary estimated building electrical need analysis using simplified equations or software, and estimating the required area in early design phase.
- Studying the precise location of the PV system and analysing various alternatives to check on ventilation, dust, solar angle, and shading of the panels.
- Reviewing the products in the market with various efficiencies to make a cost-effective analysis.

- Reviewing the products in the market that are developed for roof and façade integration, as well as external devices products.
- Experimenting with different design solutions for asuitable architectural quality in terms of colour, texture and pattern, translucency and reflectivity, and flexibility.
- Co-operating with manufacturers regarding the desired architectural needs and visions for developing more state-of-art products.

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