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TILT AND ORIENTATION: A PREFERENCE FACTOR AMONG PHOTOVOLTAIC ROOF SYSTEMS

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Abstract:One of the most abundant renewable energy resources is solar energy. In the construction sector, buildings are the largest human fabric intercepting solar radiation; they are a driving sector for developing solar energy uses especially those for generating electricity; Photovoltaics (PV). PV can produce on-site electricity with no harmful emissions. Generally, PV modules (PVs) are placed as a lay-on or additive solution to the building external envelope. Initially, they were secured to the roof or onto a facade using a metal structure with the sole function of generating energy. Afterwards, PVs were thought of as buildings components "part of the building external envelope", thus becoming multifunctional construction materials bringing “added value” to building materials. Hence, the idea of integrating PVs in buildings arose and the Building Integrated Photovoltaic systems (BIPVs) concept was introduced.

There are various typologies of BIPVs and vast number of factors/constraints affects the dual usage of PVs as electrical elements and architectural ones. There is a lack of consensus in the methodologies used for the BIPV implementation; there is a minority of tools connecting these factors in a way that enables stakeholders analysing BIPVs alternatives, thus choosing the most appropriate one. Hence, it is obvious that designing with BIPVs requires a much more holistic perspective than what has been typically applied for decision-making in the past. This approach focuses on the interaction between BIPVs basics/characteristics, and the constraints affecting their suitability for application. The paper will focus on one factor (tilt and orientation) and its effect on one BIPV typology (roof systems). At the end of this paper, a preference matrix will be conducted which resembles the interrelationship between PV roof systems and tilt and orientation factor. The aim of paper is to provide architects with an effective supporting tool to analyse different BIPV alternatives for any building within a specific location, to choose the most appropriate BIPV system.

Keywords: Photovoltaics, Building integration, Tilt, Orientation, Roofs, Preference.

I. INTRODUCTION

PVs offer enormous potential to building designers, but it has to be done right from the start, they shouldn’t be an afterthought. To do this, factors affecting the suitability of PVs for building integration should be carefully considered from the beginning[1]. The key factors are related primarily to the building, PVs and the surrounding environment; such as tilt and orientation, shading, temperature and ventilation, PV technologies "materials", and building type/design. As part of the design process, the tilt and orientation of the building surfaces that will incorporate PV elements is a starting point[2]. The tilt and orientation factor is among the most influencing factors specifying BIPVs suitability for application; as it generally affects almost all other factors, and specifically affects the building’s external envelope design. Accordingly, this paper will focus on this critical factor.

As for Egypt, it lies among the Sun Belt countries in the northern hemisphere. Recent studies concluded that Egypt has great incentives for applying PV systems; it occupies the fourth position among Middle East countries for PV applications opportunities [3].

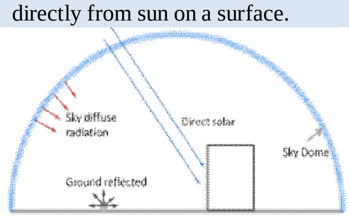
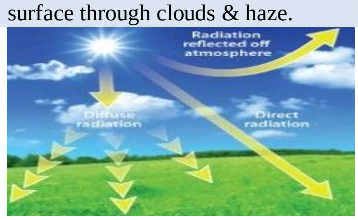
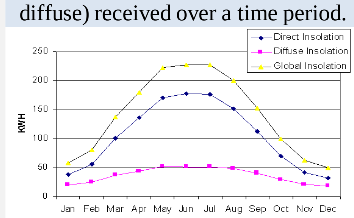
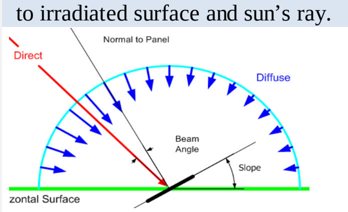
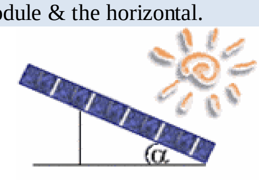
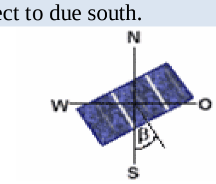
II. LITERATURE SURVEY

PV systems and factors affecting their integration in buildings have been the subject of many studies. In 2004, Ellison presented a simple study on the heat impact of a BIPV system installed on a house roof [4]. Later, in 2005, Alzoubi conducted a study on optimizing the buildings façades performance using PV cells [5]. Afterwards, in 2007, Yang and Lu discussed the effect of tilt and azimuth angles of a PV array on the amount of incident solar radiation exposed on the array, hence the PV performance [6]. The effect of shading on the PV efficiency and output losses of a BIPV facade have been analysed and calculated by Catani [7], while Ikedi introduced a method for assessing the impacts associated with the installation and use of BIPV technology in buildings [8]. Unfortunately, the presence of a preference tool to choose the convenient BIPV system with respect to influencing conditions was a missing issue.

III. TILT AND ORIENTATION

The performance of BIPV systems is highly influenced bythe modules' tilt angles and orientations.First of all, in order to understand the significance of tilt and orientation, we need to appreciate how light reaches building surfaces [2], refer to Table 1.

TABLE 1
TERMS AND DEFINITIONS

T.	Description	T.	Description	T.	Description
Irradiance	The amount of light arriving directly from sun on a surface. 	Direct irradiance	The amount of light arriving at a surface through clouds & haze. 	Solar Insolation	Total amount of light (direct and diffuse) received over a time period. 
Angle of incidence	The angle between the line normal to irradiated surface and sun's ray. 	Tilt angle	The angle between the plane of the module & the horizontal. 	Azimuth angle	The angle of orientation with respect to due south. 

Source: Adapted by the researcher

As for tilt angle,it is well-known that the sun's angle of elevation changes during the year, thus the tilt angle of the array should be chosen so that maximum energy production is guaranteed [9].It is worth mentioning that, in most locations, winter is typically cloudier than summer. Besides, the average morning and afternoon insolation is not symmetric. Consequently, the tilt angle should be selected so as to satisfy the energy demand for the critical design month [10], as shown in Fig. 1.Favoured tilt angle conditions to obtain maximum energy output are shown in Fig. 2.

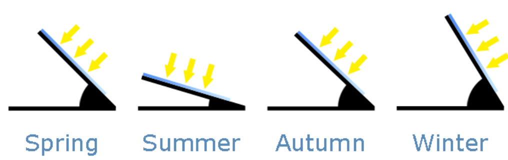


Fig.1Tilt angles with respect to seasons
Source:www.solarsecuritysolutions.co.uk

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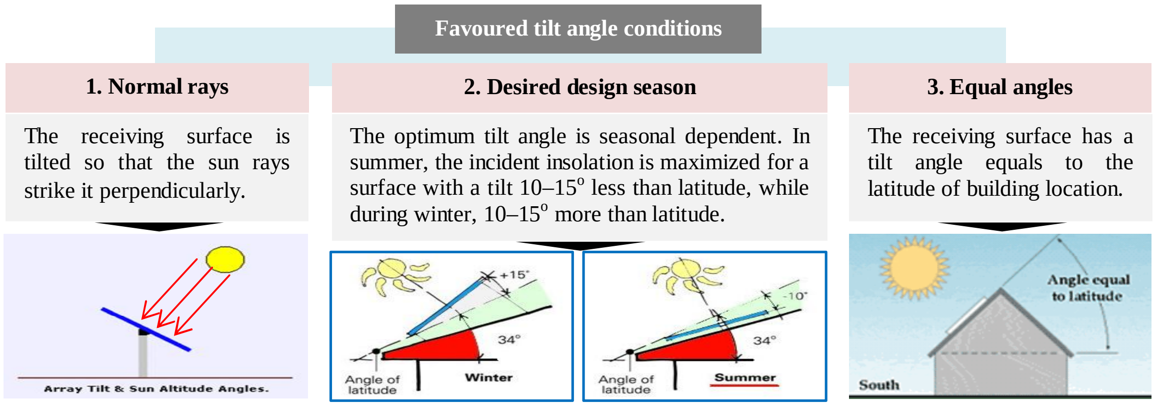

Fig. 2 Favoured tilt angle conditions
Source: Adapted by the researcher

As for orientation, in the Northern Hemisphere, PV arrays should be oriented to face south to receive maximum solar insolation [11].However, exact orientation is not critical; the vertical angle (tilt) has a much important effect on performance. Many studies indicated that surface tilt angles and azimuth angles (orientations) can be varied over a considerable range without significantly reducing the amount of annual incident solar radiation [6],refer to Fig. 3.

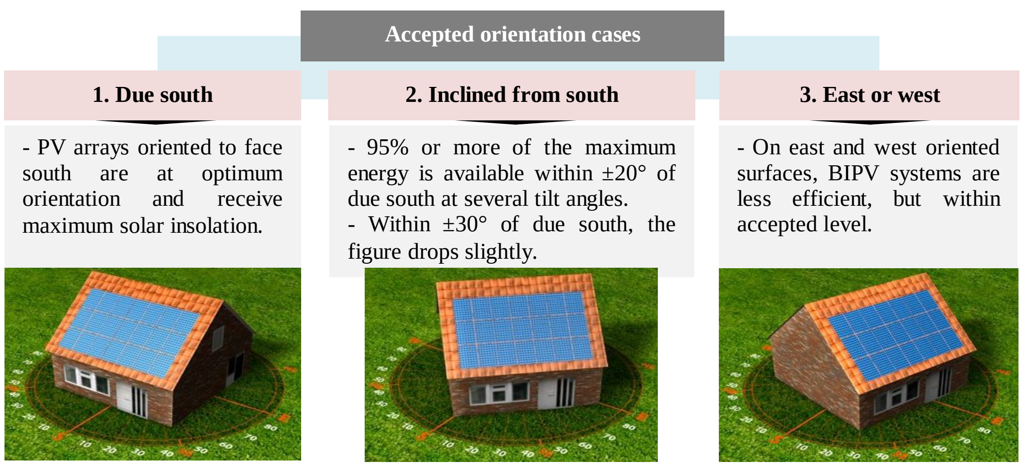

Fig. 3 Possible accepted orientation cases
Source: Adapted by the researcher

In comparison to a system oriented south at latitude angle, Table 2 shows expected losses due to unfavourable tilts and orientations [12].

TABLE 2
LOSSES FOR UNFAVORABLE TILTS/ORIENTATIONS

Tilt and orientation	Losses %
Vertical installations oriented south	30%
Horizontal installations oriented south	10%
Vertically mounted BIPVs with east/west orientation	40%

Source: Adapted by the researcher

It is obvious from the previous table that a good amount of power can be produced in non-optimal tilts and orientation. Moreover, in overcasting conditions, a good power yield can still be achieved, provided that the characteristics of PV

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modules allow this. Thin-film (TF) modules possess these properties and regularly generate higher yield compared to crystalline (C) ones (see Fig. 4), which prefer directly high solar radiation. Advantages of TF modules are [13]:

- They perform better in weak light(cloudy and dull weather), even north facing facades can be included.
- They are recommended in situations where there is a significant proportion of diffuse light due to reflection and light-scattering (by water vapour, dust and soot particles).

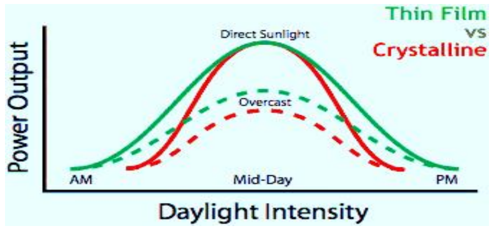


Fig. 4: TF/C-Si output comparison with respect to weather conditions
Source: www.modernoutpost.com

IV. BIPV Roof Systems

In the "BIPV vision", PVsare not only technical device producing electricity,but it is supposed to be a building component that is able to generate energy when exposed to the sun (a multifunctional product).In principle, BIPV can be appliedon all parts of the building envelope. Consequently, there is a large variety of possible PV integrations in and on buildings [13].A general approach for classification is according to the building part they are integrated into [14]. Accordingly, BIPVs can be classified into four major types (Fig. 5), each type comprises sub-systems beneath.

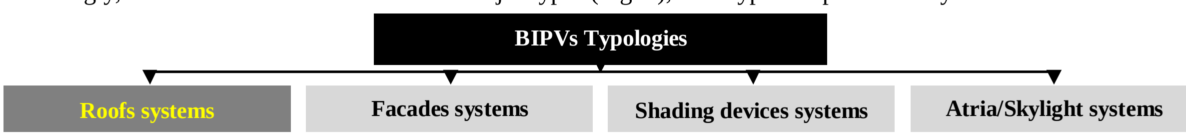
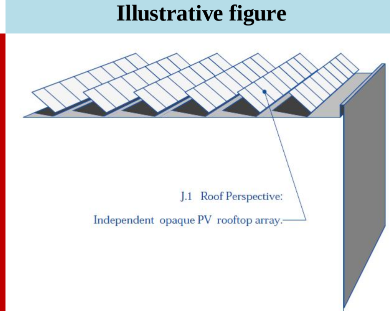
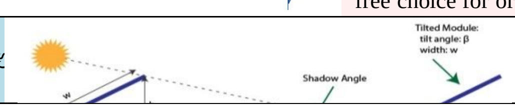


Fig. 5Broad classifications of BIPVs.
Source: Adapted by the researcher.

- The research will focus on BIPV roof systems,as roofs offer the most attractive opportunity for BIPV installations since roofs usually have the most substantial solar access due to the reason of being free from overshadowing[1].
- Table 2 introduces BIPV roof sub-systems. Each sub-system will be described as follows:
  - System name.
  - Short description.
  - An illustrative figure.
  - Distinguishing features and characteristics.
  - A project example.

TABLE 2
BIPV ROOF SYSTEMS

<table>
<tr><th rowspan="3">Flat Rooftop system (RS. 1)</th><th></th><th>Illustrative figure</th><th>Description</th><th>Project</th></tr>
<tr><td></td><td>
</td><td>Flat roofs present the least degree of engineering difficulty for BIPVs. Flat roofs are roofs with slope less than 11° [15]. They are opaque PVs which can either substitute the external layer of the roof (cladding "A"), or they can be mounted "B" on an inclined structure fixed on the roof [16]. They reduce heat load by providing shading on rooftops. Claddings ones provide a free choice for orientation [17].</td><td>
Shenzhen Horticultural Exposition, Japan.</td></tr>
<tr><td>Characteristics</td><td colspan="2">
</td><td>The inclined arrays give maximum efficiency due to proper tilt angle, and provide shading on the rooftop [15].</td></tr>
</table>

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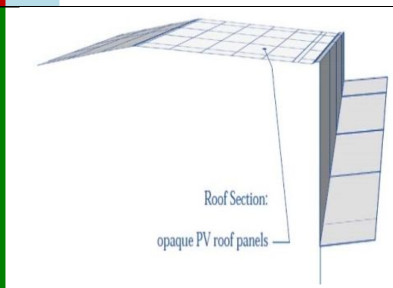
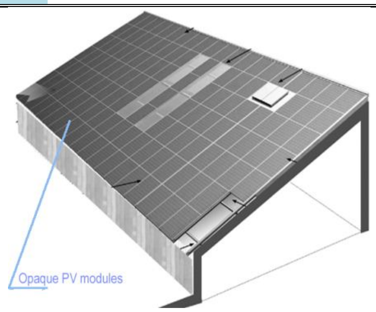
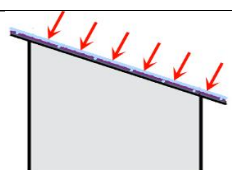
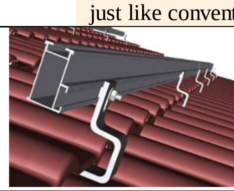
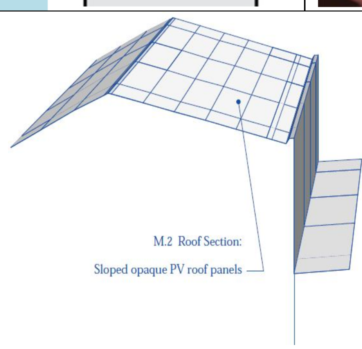
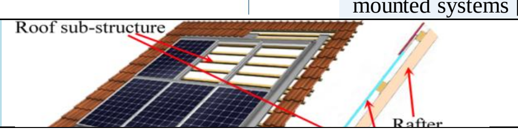
				The distance between arrays should be carefully adjusted with respectto angle of incidence to avoid self-shadings [17].
Flat PV Roof Panels system (RS. 2)			These systems provide dual function; generating electricity and totally replacing conventional roofing material. They should have good rear ventilation so that efficiency is not decreased due to high temperatures [18]. Proper water-tightness, drainage, and structural load considerations should be carefully considered [19]. Frameless PVs can be used for aesthetic appearance[16].	 Sunshades, Kanazawa bus Terminal, Japan
	Characteristics			Opaque PVs act as standard roof combined with roof structure "PVs and roof structure sizes should be compatible" [20]. Cables at the back should be hidden and invisible from final appearance "usually in the mullions and frames" [21].
Sloped Rooftop system (RS. 3)			PVs can either be merely applied on top of the building skin, or properly replace/combine with the roof covering. Installers often choose the technically less complex first approach. The second approach is in general more appealing for architects; PVs substitute the external layer of the roof [16].A more elegant way is to seamlessly integrate PVs into the roof, following the roof's contours, just like conventional tiles [18].	 Edward BIntercultural centre, Washington
	Characteristics	 		Sloped roofs perform better than flat roofs; amount of solar radiation on tilted surfaces is higher than that for flat ones [19]. PVs are fitted using metal rails; allowing an air space "about 10 cm" for ventilation. Framed/frameless PVs can be used [15].
Sloped PV Roof Panels system (RS. 4)			Unlike flat roof systems, sloped ones are visible to the public, thus should be aesthetical. This urged the market to provide PVs that match with common roof products, such as PV tiles and shingles [16]. Here, PVs combine with roof structure. PVs should be rainproof between the modules and at the edges. Sufficient ventilation behind the modules must be guaranteed. However, ventilation space is generally smaller with roof-mounted systems [15].	 Am Schlierberg neighbourhood, Germany
	Characteristics			Frameless modules give more aesthetical view than framed onesandthey are preferable for cleaning and water drainage [22].

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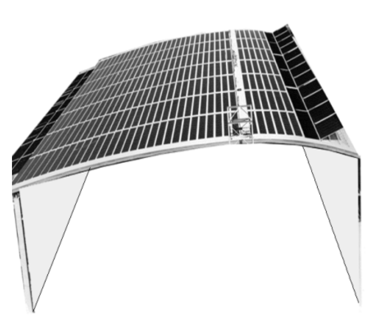
The entire roof or partial areas is covered with PVs that should be less visually intrusive and conform to conventional roof materials [17].

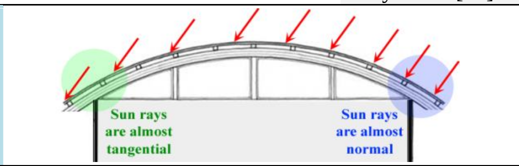
Curved Rooftop system (RS. 5)



Curved systems Extended design possibilities by introducing some flexibility to the field of installing PVs [22].Standard typical rigid modules can be used and installed row by row, following the roof's curve, just like conventional roof tiles. Most installations are usually applied on Metal roofing "aluminium and stainless steel" [1].Like other cladding systems, PVs add insulation value and protect the roof area that they cover [17].

Adam Joseph Lewis Centre, Oberlin College, Ohio, USA.

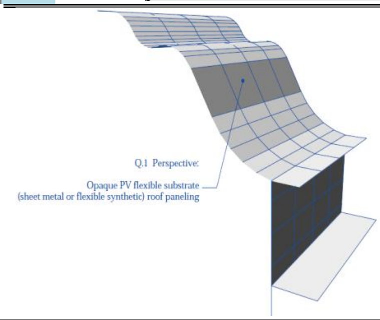
Characteristics



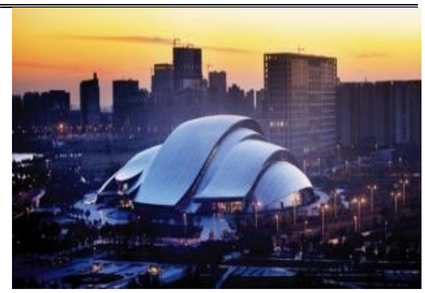
Have reduced performance due to the non-uniformity of sunlight intensity over PVs surface[23].

Opaque PVs are fitted on roof using a metal substructure. They are fixed on rails with system-specific fixing elements [15].

Curved PV Roof Panels System (RS. 6)

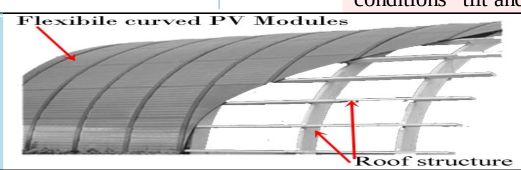


Opaque PV flexible roof panels act as the building skin combined with rooftop structural system [20].When installing a PV system in such curved roofs, the manufacturers usually customize PV modules "tailor made panels" to comply with the roof shape, geometry and dimensions [2].PVs grouping and zoning should be carefully considered as the modules experience different conditions "tilt and orientation" [11].



Hefei's Grand Theatre, Anhui, China.

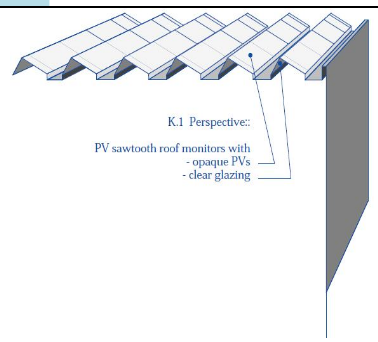
Characteristics



Curved PVs provide roof design with flexibility, light-weight and can be seamlessly integrated on the roof structure [21].

Flexible PVs are fabricated commonly from thin-film modules, shingles and tiles fastened directly to the roof structure [23].

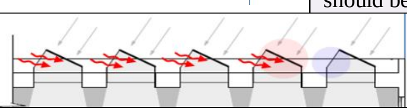
PV Sawtooth Roof system (RS. 7)



Saw-tooth structures are one of the most interesting places to install PVs. They combine the advantage of light diffusion in the building while providing an unobstructed surface for installing PVs [22].PVs can either be mounted over roof covering or can replace the tilted side of saw-tooth towards south. Saw-tooth tilt angle should be adjusted to receive normal sun rays as possible for optimum output. Besides, water drainage should be carefully considered [18].

University of Gloucestershire Sports Hall, UK

Characteristics



North glazing providesdaylighting and supports the rear ventilation of PVsto keep efficiency as high as possible [21].

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	PV sawtooth roof monitors with - opaque PVs - clear glazing	PVs are oriented towards south for capturing sunlight, with a proper tilt angle to avoid partial shading on other PVs [20].

Source: Adapted by the researcher

V. THE PREFERENCE MATRIX

After what has been discussed above, a preference matrix will be conducted and introduced (see Table 3). This matrix acts as a supporting tool that helps architects and designers choose among various PV roof systems the most convenient one with respect to tilt and orientation factor, taking into account the building and environmental conditions/constraints.

TABLE 3
BIPV AND TILT/ORIENTATION PREFERENCE MATRIX

■ RELATION □ NO RELATION

				BIPV Roof Systems															
				RS. 1															
				A		B		RS. 2		RS. 3		RS. 4		RS. 5		RS. 6		RS. 7	
PV material				C	TF	C	TF	C	TF	C	TF	C	TF	C	TF	C	TF	C	TF
Tilt and Orientation factor	Tilt	PV tilt angle	Site latitude: PVs tilt equals to site latitude			■	■			■	■	■	■					■	■
			Solar angle of incidence			■	■			■	■	■	■	■	■	■	■	■	■
			PVs perpendicular to sun rays			■	■			■	■	■	■					■	■
			PVslope angle: Horizontal (0°)	■	■			■	■							■	■		
			(10°)	■	■	■	■	■	■					■	■	■	■		
			(20°)			■	■			■	■	■	■	■	■	■	■	■	■
			(30°)			■	■			■	■	■	■	■	■	■	■	■	■
			(40°)			■	■			■	■	■	■	■	■	■	■	■	■
			(50°)			■	■			■	■	■	■	■	■	■	■	■	■
			(60°)							■	■			■	■	■	■		
			(70°)											■	■	■	■		
			(80°)											■	■	■	■		
			Vertical (90°)																
		Desired season/month (peak demand)	Season: Summer	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
			Winter			■	■			■	■	■	■	■	■	■	■	■	■
			Spring / Autumn (year round)			■	■			■	■	■	■	■	■	■	■	■	■
			Monthly insolation: Direct insolation amount	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
			Diffuse insolation amount		■		■		■		■		■		■		■		■
			Average daily insolation	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
			Average month insolation	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Orientation	Azimuth Angles	S: Due south (angle equals 0°)			■	■			■	■	■	■	■	■	■	■	■	■
			Inclined from south: ±20° of due south			■	■			■	■	■	■	■	■	■	■	■	■
			±30° of due south			■	■			■	■	■	■	■	■	■	■	■	■
			From ±30° to ±75° of due south			■	■			■	■	■	■	■	■	■	■	■	■
			From ±75° to ±90° of due south			■	■			■	■	■	■	■	■	■	■	■	■
			E / W: East/West ±90° of due south			■	■			■	■	■	■	■	■	■	■	■	■
			N: All north east, north & north west angles (non-favoured orientations)				■				■		■		■		■		■

Source: The researchers

After the systems have been filtered from the above matrix, the appropriate ones should be subjected to software simulation to examine their output power, hence taking the highest available yield output.

VI. CONCLUSION

Based on the research objective, factors analysis, systems description, and conducted preference matrix, the following points have been obtained and concluded:

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- A building orientated to the south for daylighting, passive solar gain and free of overshadowing is eminently suitable for PVs.
- In non-optimal orientations, specifically in north directions, thin film modules are the preferable.
- From the matrix, it is obvious that slopped, curved, and saw-tooth systems are moreappropriate with various tilt angles than flat ones.
- Flat mounted roof systems have more flexibility for tilt angles than flat cladding and flat PV roof panels.
- Orientation has no effect on flat mounted and flat PV roof panels systems.
- It is clear from the matrix that tilt is a more critical preference factor than orientation.

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