Performance Evaluation of a Building Integrated PV (BIPV) at Heriot-Watt University Malaysia

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Abstract. Building Integrated Photovoltaics (BIPV) is a promising technology that combines the generation of energy into the building structure where the modules act as building material or blend completely with architectural design. This study analyses the performance characteristics of a proposed BIPV system for Heriot-Watt University Malaysia building, the system is designed with aim to utilize the curved roof area of the building. The available roof area of 7725 m² is curved with varying tilt angles from 1.5° to 26°. The environmental plugin Ladybug integrated within Grasshopper was used to visualize and estimate the energy potential from the roof surface in Rhinoceros 3D modeling software. Additionally, detailed system simulations are conducted with PVSyst software. Eight proposed system variants of different PV technologies and modules types are studied with capacities of 411.8 kW to 1085.6 kW. The recommended system has a size of 1085.5 kW and utilizes Thin-film CdTe PV modules. The system generates 1415 MWh annually with a performance ratio of 84.9%, which saves 62.8% of the electricity bill and has an estimated cost of 901 thousand USD. Installation of the proposed system should preserve the aesthetical value of the building’s roof and satisfy BIPV rules.

1. Introduction
As reported by the International Energy Agency (IEA), the global consumption of energy has risen by roughly 40% between 1990 and 2007, and it is estimated to continue rising be 8-10% every 5 years until 2035 [1]. Burning of fossil fuels is an essential source of CO₂ emissions, which is considered a Green House Gas (GHG) affecting the global warming and climate change. This environmental impact of GHGs became a strong motive to use the renewable sources of energy [2]. Solar energy has emerged as one of these sources due to its many features; available everywhere, free, no or little need for maintenance and most importantly inexpensive. This paper focuses on the application of Solar PV technology in buildings where the panels combine the function of building material with electrical energy generation [3]. This application is called Building Integrated Photovoltaics (BIPV) which is one of the heavily researched field in PV technology along with cost reduction, efficiency enhancement and energy storage [4]. BIPV has gained an increased global interest due to many factors; it has superiority over conventional PV in that no dedicated land or facility is needed for the system, the cost is reduced as some materials are replaced, and also the need for mounting system is eliminated [5]. Moreover, BIPV conserves the aesthetical view of building. BIPV products are widely varied and were heavily examined in literature including Tripaty, Sadu and Panda [6], Shukla, Sudhakar and Baredar [3] and Cerón, Caamaño-Martín and Neila [7]. Various researchers analysed the performance of BIPV systems, most noticeably Li et al. who assessed the performance of a grid-connected system installed at an institutional building in terms of energy, environmental and economic views. The 40 kW system generated between 10 to 360 kWh daily and 116.3 kWh on average, efficiencies were close to manufacturer’s data [2]. A 22 array grid-connected system of 142.6kW was investigated by Wittikopf et al., they have analyzed in detail the impact of different parameters such as orientation, tilt angle,
shading, and the temperature of PV cells on BIPV installation performance [8]. The unique design of HWUM building with curved roof oriented in an east-west direction enables a high possibility of BIPV application. This is the first proposed design in Malaysia of this type to include the foil type BIPV products on a curved surface, and to use Grasshopper software with Ladybug plugin to simulate the performance parameters. This paper aims to design a grid-connected BIPV system to fit on the curved roof of Heriot-Watt University Malaysia building and evaluate its feasibility in Malaysia’s climate. The goal of this system is to save energy by reducing utility bill. The solar radiation resource potential was assessed at this location using Tilt and Orientation factor. The performance of the proposed system was analysed by simulation for 8 different scenarios of the design.

2. Background

Building Integrated Photovoltaics (BIPV) is the field that is related to PV systems that include products that makes part of the building structure to replace the traditional building materials and integrate in an architectural way [5]. The products come in a variety of shapes, roof, window or façade component serves the building exterior. BIPV has gained increased global interest due to many factors; it is superior to conventional PV in that it does not need a dedicated land area or any facility for the system, and the cost is reduced as some materials are replaced and the need for mounting system is eliminated. The aesthetical value of Building Integrated Photovoltaics (BIPV) is improved with the variety of technical available options that aim to attract architects and end user attention, these options include colours, patterns, textures, also modern integration techniques such as prefabrication, multifunctional components, low maintenance and so on [9]. From another side, the market of BIPV is likewise witnessing rapid growth recently. The estimated global market in 2015 was 2.3 GW which increased from 1.5 GW in 2014, that is almost 50% rise[10]. The total capacity of installed BIPV is forecasted to exceed 11 GW by 2020.

3. Methodology

The design and analysis of the BIPV system at HWUM building will be carried out following the steps below.

1) Assessing the site of the building by looking into the available solar insolation/irradiation and energy potential, Ladybug software is used to calculate the incident radiation on the roof.
2) Evaluating the curved roof surface for electricity generation using Tilt and Orientation Factor (TOF).
3) Analysis of 8 configuration options of the PV system. Initially, Ladybug will be utilized to obtain an estimate of the photovoltaic electricity production.
4) A detailed simulation of systems is obtained with PVsyst to generate performance parameters and compare energy with data from Ladybug.

Assumptions were made throughout this study, there are no obstacles around the building to cause shading. System components other than panels and inverters are used from defaults of PVsyst. The site of this study is the building of Heriot-Watt University Malaysia located in Putrajaya. The location’s coordinates are N 2° 53' 57.912'' and E 101° 40' 21.3204''.

3.1. PV Modules Selection and Inverters

Many PV modules on the market are compatible with the BIPV system. Adding to the BIPV specific modules, Standard PV modules can also be used if they do not present much of interference with the building’s architecture, taking into consideration that, they may be installed level or flush with the roof or have a cell/module colour that matches or similar to the surrounding material. In the case of curved surfaces, flexible PV foils or laminates are the most suitable option. These panels can follow the exact curve of the surface and are usually water resistant. Some products include PV as a part of water proofing membrane for roofs, such as Alwitra products. Ease and speed of installation are attractive feature of this type of BIPV products [6]. Inverters perform the function of converting DC power into AC electricity [11]. For the system options to be analysed, three-phase SMA inverters of 20-25 kW
capacities are used, except in the case of amorphous silicon modules where transformer-less inverters are not compatible as this might damage the TiO2 layer [12]

3.2. PV System Configurations
The BIPV system for HWUM was designed according to scenarios as listed in Table 1. Scenarios 6, 7, and 8 use a mix of panels from the first five scenarios. Mixing configurations seems to be an advantage in the case if high efficiency panels are used on the top side of the roof which is not visible to public, and the tilted part would include flexible modules that provide enhanced aesthetical integration. Another aspect would be using modules with higher performance on the tilted part to compensate for the lower energy received.

| No. | PV Manu.   | Model          | Cell Tech. | Modules Qty | Nom. Power [W] | Tot. DC Power [kW] |
|-----|------------|----------------|------------|-------------|----------------|--------------------|
| 1   | Global Solar | PowerFlex BIPV 300 | TF CIGS    | 1820        | 300            | 546                |
| 2   | Uni-Solar  | PowerBondePVL-144 | TF a-Si    | 3280        | 144            | 411.8              |
| 3   | First Solar | FS-4122A-3     | TF CdTe    | 8862        | 122.5          | 1085.6             |
| 4   | Yingli Solar | YL340D-36b | c-Si Mono  | 3173        | 340            | 1078.8             |
| 5   | Sunrise    | SR-P672330     | c-Si Poly  | 3173        | 330            | 1047               |
| 6   | 1+3        | -              | CIGS - CdTe | 834+4152   | -              | 758.8              |
| 7   | 1+5        | -              | CIGS - Poly c-Si | 834+1486 | -          | 750.6              |
| 8   | 3+4        | -              | CdTe - Mono c-Si | 4710+1486 | -          | 1082.2             |

3.3. Simulation Methodology
The system simulation will be conducted by 2 phases. The first phase involves modelling the building geometry, the subject surfaces then can be analysed to estimate energy generation. This workflow is demonstrated in Figures 1 & 2.

![Figure 1: Phase 1 of the simulation with LB and GH.](image1)

![Figure 2: Phase 2 of the simulation. PVsyst is used.](image2)

The Solar radiation and PV energy simulation is performed using Ladybug software plugin. LB can be used as tool to make quick estimation of PV electricity generation of a surface when the 3D model is
available. This is specifically important for BIPV as the system is often installed on unconventional surfaces such as facades or curved roofs, this point differentiates it from the other software options that can basically perform estimates for a roof system from an aerial map image. Compared to LB, the traditional modelling tools only provide simulation of irradiance and electrical performance for flat planar surfaces [13].

3.4. Performance Evaluation
The analysis of BIPV system performance parameters is conducted according to the standard 61724 of IEC [14] [15], and the results were obtained from PVsyst simulation. BIPV system suitability depends on the building and environment features; such as tilt and orientation, temperature, PV technology, shading, ventilation and building design. Of these factors, Tilt and orientation factor is considered one of the most important factors to determine the BIPV suitability [16]. Waseef has also summarised some of the studies that investigated the factors affecting PV system integration with buildings [16]. Tilt and Orientation Factor (TOF) expresses the amount of radiation incident on the subject surface as a percentage of the radiation incident on a surface with the optimal tilt and orientation for the same specific location. Various studies have identified the optimum tilt and orientation for many countries globally, Hafez et al., have reviewed those studies extensively and summarized the results [17]. Elhub et. al. have concluded that the optimum tilt angle for Kuala Lumpur, Malaysia is 10 degree [18]. Regarding the BIPV application, the tilt and orientation will follow the roof’s or facades’ shape and orientation, even though it may not be the optimum setting, the architectural aesthetics remains as the main constraint.

4. Results and Discussion
4.1. Estimation of Solar Radiation Potential
The calculated total incident radiation was 1.2736x10^7 kWh. The software also plotted the radiation gradient over the roof surface which can be seen in Figure 3 & 4. It can be noticed that variation of irradiation along the roof surface is not significant, the irradiation at the tilted curved part (west side) is only 10% lower than the nearly horizontal side (east side). This is can be related to the large component of diffuse radiation which is a feature of solar radiation in tropical countries [8]. Tilting the modules toward the sun is not critical in the tropics compared to areas where the direct radiation is more dominant [8]. Designers and engineers can use LB in a similar matter to obtain a quick visual and numerical estimation of solar radiation and PV output from unconventional roof surfaces.

![Figure 3: The solar radiation gradient on HWUM roof.](image)

4.2. Tilt and Orientation Factor
For the curved roof to be treated as a flat surface, it was divided into 8 planar segments, the tilt and orientation factors were determined for each surface using Ladybug. It was found that even the section with the highest tilt still receives good amount of radiation of TOF = 92.7%. Segments from 4 to 8 has almost the optimum value and can be represented as a flat horizontal surface as shown in Figure 4 which summarises the results of TOF simulation in LB.
4.3. Energy Yield
This part is conducted using PVSyst software to conduct performance simulations in detail. The results are represented in Figures 5 & 6. It can be noticed that the temperature losses in GLOBAL SOLAR scenario 1 made a large portion of the total losses, 12.3% of the generated energy was lost due to temperature effect. a-Si module model selected for scenario 2 has a very low efficiency that cannot compete with other configurations. PR (Performance ratio) for the systems analysed ranged between 78% for Uni-Solar to 84.9% for scenario 3 (First Solar). Mixed configurations that contain First solar performed better especially when FS module made the largest portion (scenario 8). From the efficiency side, First Solar configuration also had the highest system efficiency. CdTe cells are least affected by temperature as can be seen from the results, First Solar configuration had the lowest temperature losses, while global solar was the worst.

Figure 4: TOF simulation on rood which is divided into 8 segments.

Figure 5: Final Yield, Capture loss and System loss for the studied scenarios.
5. Conclusions
In this work, a novel simulation methodology was presented for the estimation of solar energy potential and calculation of electrical energy generated from different proposed system configurations. The methodology was applied on the curved roof of Heriot-Watt University Malaysia Building in Putrajaya, Malaysia. Through TOF analysis, it was determined that the roof has good energy potential even at the part with highest tilt on the west side, this due to the nature of radiation in tropical countries whose diffuse component is significant. Eight proposed configurations of the roof system were compared from energy perspective. It is found that the system using CdTe Thin film modules from First Solar proved to provide the highest energy output of 1240 MWh/year saving 53% of the electricity bill, while the most aesthetic scenario with flexible laminates modules generated only 596 MWh/year. This means that flexible thin film technology used widely in BIPV applications still needs improvements in efficiency to compete with the non-flexible silicon modules of higher performance.

References
[1] International Energy Agency, “Worldwide Trends in Energy Use and Efficiency,” 2008.
[2] D. H. W. Li, S. K. H. Chow, and E. W. M. Lee, “An analysis of a medium size grid-connected building integrated photovoltaic (BIPV) system using measured data,” Energy Build., vol. 60, pp. 383–387, 2013.
[3] A. K. Shukla, K. Sudhakar, and P. Baredar, “Recent advancement in BIPV product technologies: A review,” Energy Build., vol. 140, pp. 188–195, 2017.
[4] M. Raugei and P. Frankl, “Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks,” Energy, vol. 34, no. 3, pp. 392–399, 2009.
[5] B. P. Jelle, C. Breivik, and H. D. Røkenes, “Building integrated photovoltaic products: A state-of-the-art review and future research opportunities,” Sol. Energy Mater. Sol. Cells, vol. 100, pp. 69–96, 2012.
[6] M. Tripathy, P. K. Sadhu, and S. K. Panda, “A critical review on building integrated photovoltaic products and their applications,” Renew. Sustain. Energy Rev., vol. 61, pp. 451–465, 2016.
[7] I. Cerón, E. Caamaño-Martín, and F. J. Neila, “‘State-of-the-art’ of building integrated photovoltaic products,” Renew. Energy, vol. 58, pp. 127–133, 2013.
[8] S. Wittkopf, S. Valliappan, L. Liu, K. S. Ang, and S. C. J. Cheng, “Analytical performance monitoring of a 142.5kWp grid-connected rooftop BIPV system in Singapore,” Renew. Energy, vol. 47, pp. 9–20, 2012.
[9] E. Delponte, F. Marchi, F. Frontini, C. Polo, K. Fath, and M. Batey, “BIPV in EU28, from niche to mass market: an assessment of current projects and the potential for growth through
product innovation,” in 31st Eur. Photovolt. Sol. Energy Conf. Exhib, 2015, pp. 3046–3050.

[10] M. Tabakovic et al., “Status and Outlook for Building Integrated Photovoltaics (BIPV) in Relation to Educational needs in the BIPV Sector,” Energy Procedia, vol. 111, pp. 993–999, Mar. 2017.

[11] A. (Antonio) Luque and S. Hegedus, Handbook of photovoltaic science and engineering / edited by Antonio Luque and Steven Hegedus., 2nd ed. Hoboken, N.J. : Chichester: Hoboken, N.J. : Wiley , 2011.

[12] PVsyst SA, “PVsyst 6 Help,” 2014. [Online]. Available: http://files.pvsyst.com/help/.

[13] J. Hofer, Z. Nagy, and A. Schluetter, “Electrical Design and Layout Optimization of Flexible Thin-Film Photovoltaic Modules,” 2016.

[14] International Electrotechnical Commission (IEC), “International Standard IEC 61724: Photovoltaic System Performance Monitoring—Guidelines for Measurements, Data Exchange and Analysis,” 1998.

[15] J. B. Lee, J. W. Park, J. H. Yoon, N. C. Baek, D. K. Kim, and U. C. Shin, “An empirical study of performance characteristics of BIPV (Building Integrated Photovoltaic) system for the realization of zero energy building,” Energy, vol. 66, pp. 25–34, Mar. 2014.

[16] A. Waseef, TILT AND ORIENTATION: A PREFERENCE FACTOR AMONG PHOTOVOLTAIC ROOF SYSTEMS, vol. 3. 2014.

[17] A. Z. Hafez, A. Soliman, K. A. El-Metwally, and I. M. Ismail, “Tilt and azimuth angles in solar energy applications – A review,” Renew. Sustain. Energy Rev., vol. 77, pp. 147–168, Sep. 2017.

[18] B. Elhub et al., Optimizing tilt angles and orientations of solar panels for Kuala Lumpur, Malaysia, vol. 7. 2012.