Energy and Buildings 130 (2016) 676–691

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A verification study for energy analysis of BIPV buildings with BIM

Hang-Jung Kuo (Ph.D.)[a], Shang-Hsien Hsieh (Professor)[a,*], Rong-Chin Guo (Chief Executive Officer)[b], Chi-Chang Chan (Project Manager)[c]

[a] Department of Civil Engineering, National Taiwan University, Taipei, Taiwan
[b] Research Center for Building & Infrastructure Information Modeling and Management, Department of Civil Engineering, National Taiwan University, Taipei, Taiwan
[c] Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan

ARTICLE INFO

Article history:
Received 6 May 2016
Received in revised form 20 July 2016
Accepted 13 August 2016
Available online 22 August 2016

Keywords:
Building integrated photovoltaics
Building information modeling
Building energy analysis

ABSTRACT

This paper investigates the energy analysis process of Building-Integrated Photovoltaics (BIPV) buildings using a case study and explores its accuracy. Building Information Modeling (BIM) software tools are used for modeling BIPV buildings and carrying out energy analysis. The case study simulates electricity production from four BIPV panel systems of the BIPV Experiment Demonstration House located in the Industrial Technology Research Institute (ITRI), Hsinchu, Taiwan, and compares the simulated results with three-year measured data. It is shown that a reasonably good estimate of the electricity production of a BIPV building at the building design stage was obtained in the case study.

1. Introduction

The production of clean energy is one of the most important and pressing technological challenges facing the human race today. Considerations about global warming and restrictions on carbon emissions necessitate the need to actively search for alternative or new energy sources and developing technologies for renewable clean energy. One of the most popular of these technologies is solar energy, which uses photovoltaic panels to collect sunlight and convert it into direct-current (DC) electricity and then uses inverters to convert it into alternating-current (AC) electricity for common use [1]. Its performance depends on the solar radiation, solar spectrum, module temperature, electrical properties of the solar cell, *etc.* [2].

Building-Integrated Photovoltaics (BIPV) [3] is a typical solar energy technology that has great potential for reducing carbon emissions from building energy consumption. It uses an architectural design method to integrate photovoltaic cells, which generate electric power from solar radiation, into the building envelope as part of the building materials [3]. However, there are currently some obstacles in the general adoption of this technique. Firstly, the cost of photovoltaic panels is still high. Secondly, a better design approach is required for architects to effectively explore different BIPV applications in building design and arrive at a good BIPV solution for electricity efficiency. Thirdly, more evidence is needed on the effectiveness of the energy-efficient design of BIPV buildings as well as the benefits of BIPV to convince owners to opt for BIPV buildings.

In order to quantify the benefit of BIPV design, it is required to estimate BIPV electricity production first. Comparing BIPV electricity production with predicted building energy consumption, the energy saving can be calculated. Building energy consumption can be predicted using historical data or energy simulation results. Multiplying energy saving with energy price, the predicted cost saving can be obtained. This process is energy analysis. Considering BIPV investment and predicted cost saving, the payback period can be formulated for owners to evaluate the strategy to use BIPV in their projects.

Several studies have been conducted to address some of these issues. Concerning design aspect, Peng et al. [4] discussed the features of BIPV in architectural design in China, and proposed new BIPV structure for easy maintenance. Therefore, in the future, a BIPV panel with higher conversion efficiency can replace the existing BIPV panel. It indicates that design of BIPV building can have important impact in building life cycle. Maturi et al. [5] compared electricity production simulation results using a PV simulation software called PV*SOL with the measured data of a BIPV system in northern Italy. The simulation results and measured data are

* Corresponding author.
E-mail addresses: alaric@caece.net (H.-J. Kuo), shhsieh@ntu.edu.tw (S.-H. Hsieh), rongchin@gmail.com (R.-C. Guo), arcadia@itri.org.tw (C.-C. Chan).

http://dx.doi.org/10.1016/j.enbuild.2016.08.048
0378-7788/

recorded for a single day period. They reported that predictions of the irradiation of a PV array and the average temperature of the modules were obtained with good accuracy (−2% and +0.2%, respectively), while the electricity production was underestimated by around 20%. Although the overall prediction of irradiation and temperature of module are close to the measured value, there are still some underestimation of irradiation and overestimation of temperature of module in specific time periods. This results in uncertain prediction of electricity production and more data are needed to conduct verification. Sung et al. [6] compared electricity production simulation results using a PV simulation software called PVsyst with the measured data of a BIPV building in Hsinchu. There were 4 kinds of BIPV module systems in this case. The simulation results and measured data were recorded for one year. Three kinds of solar radiation source were used as simulation software input to conduct electricity production simulation. The relative error of simulation results is ranging from −2.35% to 8.91%. Although overall simulation results seem close to measured values, it is required to analyze the contribution of each BIPV systems in electricity production to avoid compensation error.

Nowadays, it is generally accepted by the construction industry that Building Information Modeling (BIM) [7] is the most promising technology for enhancing the performance and quality of construction. BIM is a technology that is used to integrate a three-dimensional building model with building information through the life cycle of the building [8]. One of the features of BIM is that building geometry can be extracted from a BIM model to aid the assessment of alternative sustainable design principles [9]. Using this feature, some calculations like rainwater harvesting, solar access, and recycled content can be calculated automatically. There are studies using BIM on BIPV research. For example, Xuan [10] applied BIM technology for modeling and analyzing the tilt angle of a BIPV panel. Dixit et al. [11] developed an API program in Autodesk Revit to calculate insolation which was compared with the measured insolation and ±10% error was obtained. Both Xuan and Dixit et al. developed specific PV electricity production simulation functions in Revit. Gupta et al. [12] developed a conceptual framework for PV simulation using an open BIM standard format. The framework was web-based and required a IFC file as input to perform PV simulation. It seems increasing number of analysis tools are developed with BIM interoperability or based on BIM platform. Also, measured data are still needed for different analysis tools to verify simulation result as simulation benchmark [13].

Although the emerging BIM technology has provided a better design platform in a 3D digital space, there is still a lack of BIM components and robust design procedures to facilitate design and energy analysis of BIPV buildings. Once a BIM model of a BIPV building can be used to carry out energy analysis with reasonable simulation results, the benefits of the BIPV building can be evaluated without additional modeling effort.

Our case study uses the BIPV Experiment Demonstration House of the Industrial Technology Research Institute (ITRI, Taiwan) to investigate the reliability of BIM-based energy analysis at the conceptual design stage. This study compares the simulated values with the actual measured data of electricity production.

2. BIM and energy analysis procedure

In the traditional drawing-based building design process, architects put a great deal of effort in developing conceptual designs in the early stages of project. At this stage, decisions about the building's geometry and orientation have a big impact on the building's energy performance. Energy analysis is a science to analyze how building systems affect building performance [9]. The baseline energy load is set for the building project in the beginning. Energy analysis can be conducted to use simulation method to evaluate and compare the energy performance of different conceptual designs with baseline energy load. The energy use of conceptual design can be optimized. This analysis of the design process can also be outsourced to energy consultant.

Energy analysis requires the creation of 3D building models from 2D drawings for the simulation, which requires considerable effort. Therefore, it is difficult to quickly integrate it in the conceptual design stage. As the cost of energy analysis is high, it is typically carried out at the final building design stage instead. If the energy analysis process can be better integrated with the building design process, then the benefits in terms of delivering design information in an efficient way are obvious.

BIM technology deals with the generation and management of the virtual representation of a building/facility in a virtual environment. In a BIM-based building design process, architects can apply BIM technology to explore different design concepts in a short time. With the creation of a BIM model, the building geometry and information within the BIM model can be extracted to enable energy simulation and analysis. When the conceptual design has been finalized, architects can continue to develop the BIM model into the schematic design and design development stage.

For adapting BIM into the design process, the Information Delivery Manual (IDM) [14] can provide an integrated reference for people who use BIM to carry out the building design and construction process. The IDM document for Building Energy Analysis (BEA) [15] developed by the General Services Administration (GSA) and the Open Geospatial Consortium (OGC) is a preliminary reference for this study. There are three roles (design staff, client staff, and consultant) in the IDM for BEA. The process map of the IDM is illustrated in the Business Process Model and Notation [16] format and is shown in Fig. 1.

The analysis process in Fig. 1 commences with the design. When the conceptual design BIM model is complete, the next step is to prepare and adjust the BIM model for energy analysis. The BIM model is a kind of database that can export information for analysis. The design staffs use energy tariffs, weather data, analysis methods, and energy analysis inputs, which are exported from the BIM model as inputs for analyzing energy demand and consumption. The energy analysis results are then reviewed. After the results are accepted by the design staff, the results are submitted to client staff to validate the BIM model for energy analysis. Consultants can help client staff analyze energy demand and consumption and review energy analysis results. The analysis report prepared by the consultant is used to evaluate energy performance, operating costs, and capital costs. This process runs in a loop until the energy performance is accepted. Finally, the process moves to the design development stage.

Following the trend of BIM, this study intends to introduce BIPV into the architectural design process using BIM. In general, the planning of BIPV module and the simulation of BIPV electricity production require the expertise of electrical and mechanical engineers. Architects cannot easily evaluate the benefits of BIPV in the building conceptual design stage, but BIPV needs architects to design buildings with façades that can receive sufficient solar radiation. With good solar radiation, BIPV module can achieve good performance in terms of electricity production. Since the process of BIPV design is related to building physics and energy, the BIM process of BEA can be combined with BIPV planning and analysis process. According to the Exchange Requirements for Energy Simulation Input, which is the exchange information required by BEA, this information which should be included in BIM model is related to BIPV planning and analysis and is listed in Table 1.

In Table 1, there are four types of information related to PV analysis. "Site" information includes global coordinates, site elevation, and 3D geometry. These are important in describing the

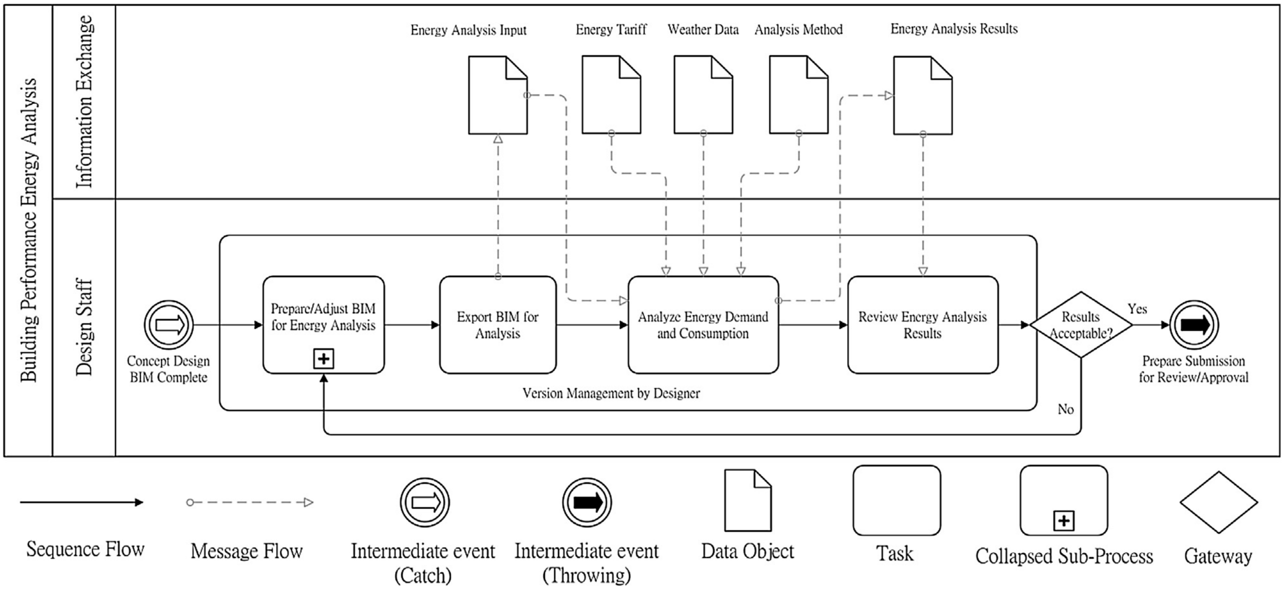


Fig. 1. Process map for building energy analysis (The Object Management Group, 2011).

Table 1
Information for the PV simulation (The Object Management Group, 2011).

Type of Information	Information Needed	Data Type	Units
Site	Global Coordinates	(2) triples	deg/min/sec
	Site Elevation (datum) (relative to sea level)	Real	M
	3D Geometry	IFC Geometry	Varies
Site Context	Identification	String	n/a
	3D Geometry	IFC Geometry	M
Building	Identification	String	n/a
	Global Coordinates	(2) triples	deg/min/sec
	Orientation (deviation of building grid from true north, clockwise)	Real	Angular Degrees
	Elevation (relative to the site datum)	Real	m
Photovoltaics	Photovoltaics	Boolean	
	Host Building Element (required if 'Photovoltaics' = TRUE)	Relationship	n/a
	Active Area Fraction (fraction of host element with PVs) (required if 'Photovoltaics' = TRUE)	Real	%
	DC to AC Inverter Conversion Efficiency (required if 'Photovoltaics' = TRUE)	Real	%
	PV Surface Integration (Decoupled, Integrated, Integrated w/Ventilation) (required if 'Photovoltaics' = TRUE)	Enum	n/a
	PV Cell Efficiency (required if 'Photovoltaics' = TRUE)	Real	%

surrounding environment of the building design. "Site Content" is the adjacent buildings, which may block sunlight from reaching the target building. "Building" is the target building category. Global coordinates, orientation, and elevation are important factors in "Building" in order to locate the building so that it receives sunlight. "Photovoltaics" contains basic information about the PV active area, inverter conversion efficiency, PV surface integration, and PV cell efficiency. As regards the differences between PV and BIPV, it is noted that BIPV incorporates both building material and PV. This obviates the need for a separate PV panel attached to the building.

A more convenient and easier design approach is needed for BIPV building design. BIM technology can be adapted as a design approach to help architects grasp the material features of BIPV module. This case study focuses on investigating electricity production simulation in the BIM-based energy analysis process. The research process uses a BIM model to simulate the electricity production of an as-built BIPV building with measured data. After the accuracy of the simulation is evaluated, cost–benefit analysis of BIPV can be incorporated in the early design stage. The final conceptual design with BIPV can be further developed by experts in the following design. The BIM modeling and energy analysis procedure of this study is divided into three major steps, and the process map is shown in Fig. 2.

Step 1: data collection

In the beginning, data are collected for creating a BIM model and carrying out energy analysis. In our study, the 2D CAD shop drawings and the building environment information of the BIPV Experiment Demonstration House were collected for creating the BIM model. The 2D CAD shop drawings include architectural plans, structural plans, mechanical plans, electricity plans, and plumbing plans. The building environment information includes Site information, Site Content information, and Building information. The BIPV information is product information that is modeled in the BIM model. Solar radiation data are recorded for the reference software

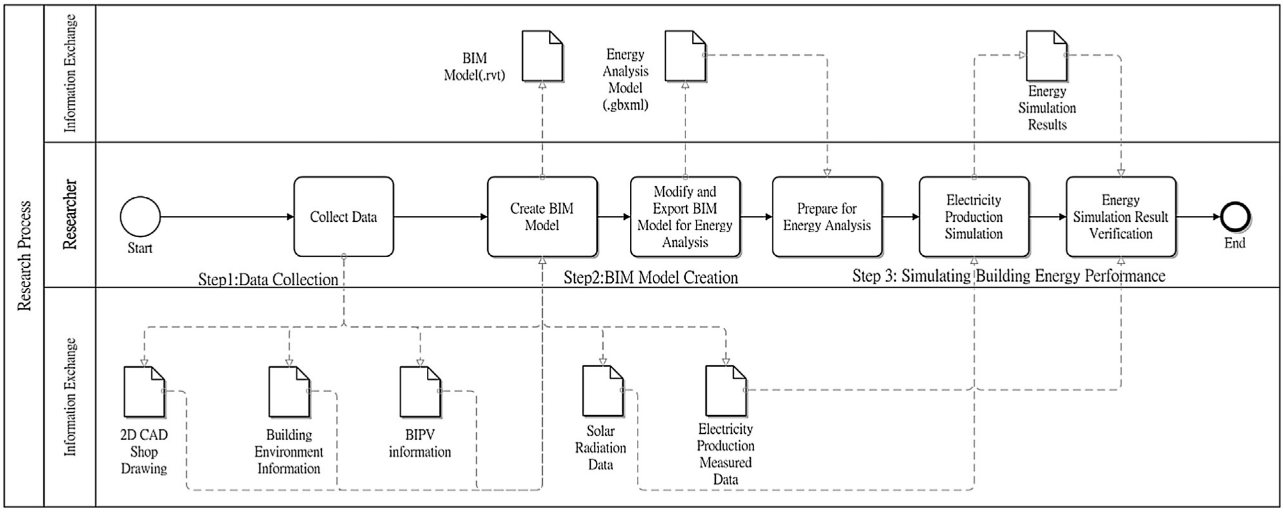


Fig. 2. BIM modeling and energy analysis procedure for the current study.

input of energy analysis, and the measured electricity production data are recorded for verifying the simulation result.

Step 2: BIM model creation

For a building designed using BIM, the model is constructed as the design evolves. Some existing buildings like the BIPV Experiment Demonstration House do not have a BIM model at the design and construction stage. Therefore, the BIM model for the existing building is created based on the 2D CAD shop drawings and BIPV information. The building environment information of the target building needs to be set in the BIM model. Then, the building information and building geometry, which are needed for energy analysis, are extracted from the BIM model. However, the following interoperability problem may arise in transferring the file. When the BIM model exports to a 3D CAD format like DXF or 3DS, it can split a surface polygon of the 3D model into a triangular area. Information of the area of BIPV module, which is a critical factor in solar analysis, can be lost in this format. A commonly used file format for the energy analysis software is gbXML (Green Building XML), an open XML (eXtensible Markup Language) schema for facilitating the transfer of green building properties in 3D BIM models to energy analysis software [17]. The gbXMLformat can retain the building space and area information of the BIM model, and this model of the BIPV Experiment Demonstration House is exported in the gbXML format to the energy analysis software.

Step 3: simulating building energy performance

For carrying out energy analysis, the building model and solar radiation data are required as inputs for the software. The software loads the energy analysis model file (gbXML), and the building environment information recorded in the energy analysis model is verified with the BIM model. The solar radiation data is needed as an input source to simulate electricity production. In this study, monitoring equipment of the BIPV Experiment Demonstration House measured solar radiation data over a three-year period. Therefore, the solar radiation data can be used to transfer the weather data format for energy analysis. Finally, the measured data of electricity production of the BIPV Experiment Demonstration House can be compared with simulated values in a spreadsheet. This is done to assess the accuracy of the simulated results and perform a sensitivity study on the parameters.

3. Case study

The BIPV Experiment Demonstration House of the ITRI (Fig. 3) is used to study the BIM process for modeling and conducting energy analysis of BIPV buildings and confirming the accuracy of the analysis. It is located in Hsinchu, Taiwan and is a reconstruction of a part of ITRI's Building No. 46. The reconstruction was completed in November 2010. Table 2 provides basic information about the House. The goal of this reconstruction was to create a demonstration space for BIPV research and development and display its potential. The BIPV Experiment Demonstration House has five pyranometers (Fig. 4) to record solar radiation. Its monitoring and demonstrating system (Fig. 5) includes monitoring of PV module electricity production, cooling loading, energy saving, and environment control [18].

Researchers at the ITRI collected data on power generation conditions, solar radiation, light, temperature, humidity, and CO_2 concentration. There are four different BIPV module systems in different parts of the BIPV Experiment Demonstration House (Table 3). From Fig. 6, it can be seen that the interior configuration is divided into two rooms, a south room for simulating an office setting with four people, and a north room for discussion and exhibition space.

4. Modeling and energy analysis

Concerning about energy analysis for BIPV buildings, analysis software that can work with BIM software to perform PV simulation and building energy simulation is the best choice. To help selecting software to design and analyze PV systems, the International Energy Agency called Solar Heating and Cooling Programme (SHC) provides a list of available solar design software as shown in Table 4 [19]. The list indicates that most simulation software lack of 3D environment or sufficient visualization function for integrating whole building design with PV systems. Among the software listed, Ecotect Analysis and eQUEST are the only two software that can perform both energy analysis of an entire building and PV simulation.

When the BIM model file is transferred from the BIM software to the energy analysis software, the aforementioned interoperability problem may result in information loss and faulty geometry. Reeves et al. [20] published a guideline for using BIM in energy analysis. The guideline indicates that Ecotect Analysis scores higher than eQUEST in terms of interoperability. The input file format of Eco-

Table 2
BIPV module information.

System Number	1	2	3	4
System Position	Sloping Roof	Right Side	Transom	Sun Shield
System Capacity (Wp)	4200	1890	750	1200
Module Type	Light-Through (Glass–Cell–Glass)	Frameless opaque modules (Glass–Cell–White Tedlar)	See-Through High-Color Rendering (HCRI) Frameless module (Glass–Cell–Glass)	Frameless opaque modules (Glass–Cell–Glass)
Conversion Efficiency	11.19%	12.79%	5.24%	8.39%
Module Size (mm) L × W × H	1760 × 1066 × 11	1657 × 991 × 5	1300 × 1100 × 7	1300 × 1100 × 6.8
Rated Power (Wp)	210	210	75	120
Number(set)	20	9	10	10

Table 3
Basic information of the BIPV Experiment Demonstration House.

Location	Building 46, No. 195, Sec. 4, Zhongxing Rd., Zhudong Township, Hsinchu County 310, Taiwan (R.O.C.)
Coordinates	Latitude 24.775° N; Longitude 121.0453° E
Floor Areas	65 square meters
Dimensions	42.20°
Operation Hours	Monday to Friday 8:00–17:00
Altitude	121 m
Working Temperature	27 °C

Table 4
Available PV and solar thermal simulation software [19].

Simulation Software	Description
DPV	• PV and solar thermal collectors will be implemented in following releases.
Ecotect Analysis	• The optimum position and orientation for active solar components can be identified by solar analysis diagrams. • The estimated electricity consumption of building design can be compared with electricity production by solar components.
ENERGIEplaner	• It is an additional module of Polysun technology. • It provides simple PV-simulation for calculation based on EnEV 2009.
eQUEST	• Its PV module supports active solar design to determine voltage, angle, dimension and temperature between the cell and the back surface. • The solar thermal systems cannot be modelled.
IDA ICE	• It can conduct calculations on active solar systems with PV and solar thermal components in the model. However, this function is not yet available for early planning phases.
LESOSAI	• Its system templates are based on the Polysun database. • It provides internal software interface to transfer parameters to the Polysun simulation engine.
Polysun	• It can be used for the design and simulation of energy systems such as active solar components. • In early design phase, it can be used for prediction of system profit ratio and system optimization for the later design phase. • It supports both PV and solar thermal simulation.
PV*SOL	• It can determine the PV size and system configuration used for the design and simulation of PV systems. • Its economic module can be used to assess the capital value of the PV systems, the electricity production cost and the amortization period. • 3D-environment is not supported.
PVsyst	• It is used at preliminary design for pre-sizing systems and evaluates the monthly production and performance of systems. • The preliminary economic evaluation of the PV system can be performed at preliminary design stage, and detailed simulations according to several dozens of variables can be performed at project design stage. • Shading of diffuse radiation is considered.
T*Sol	• It can perform dynamic simulation. • It is designed for the sizing of solar thermal heating systems including hot water preparation, space and swimming pool heating.
VisualDOE	• Its active solar system calculation uses PVWATT which takes simple inputs such as sq. Ft., AC-DC derating, location (latitude) and mounting declination angle. • PVWATT can be used for obtaining the full annual energy contribution instead of hourly increments.

Fig. 3. The BIPV Experiment Demonstration House.

Fig. 4. The pyranometers of the BIPV Experiment Demonstration House.

tect Analysis includes DXF and gbXML, allowing Ecotect Analysis to work well with BIM software such as Revit and ArchiCAD. With PV simulation and whole building energy simulation functions plus high BIM interoperability, Ecotect Analysis is a common choice by architects for solar analysis in the conceptual design stage [21].

In this study, Autodesk software was selected to demonstrate the modeling and energy analysis process: Autodesk Revit was used to create a BIM model of the BIPV Experiment Demonstration House and Autodesk Ecotect Analysis 2011 was adopted to analyze the model. After the building environment information and the 2D CAD shop drawings of the BIPV Experiment Demonstration House were collected, the CAD files were imported into Revit as a reference to create a BIM model, and building environment information was set into the BIM model.

The 2D CAD shop drawings can be used to create a BIM model with detailed geometry and building information. After initializ-

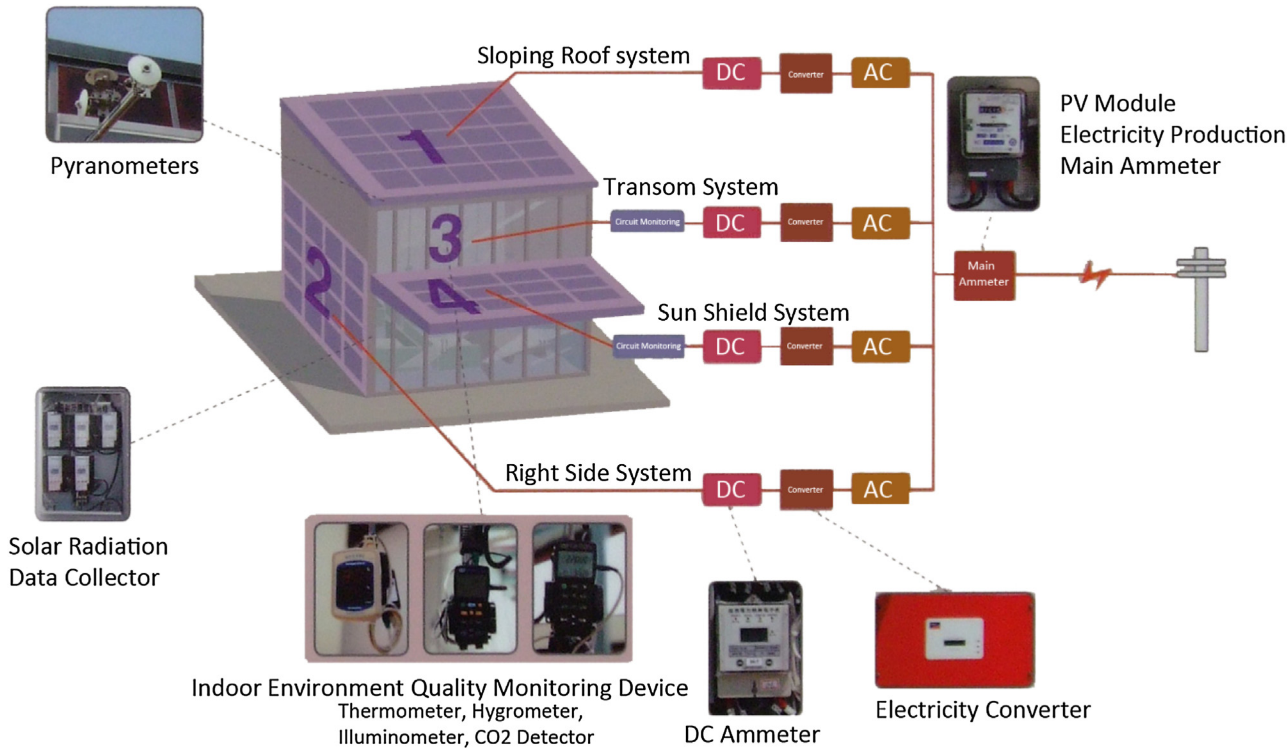


Fig. 5. System framework of the BIPV Experiment Demonstration House.

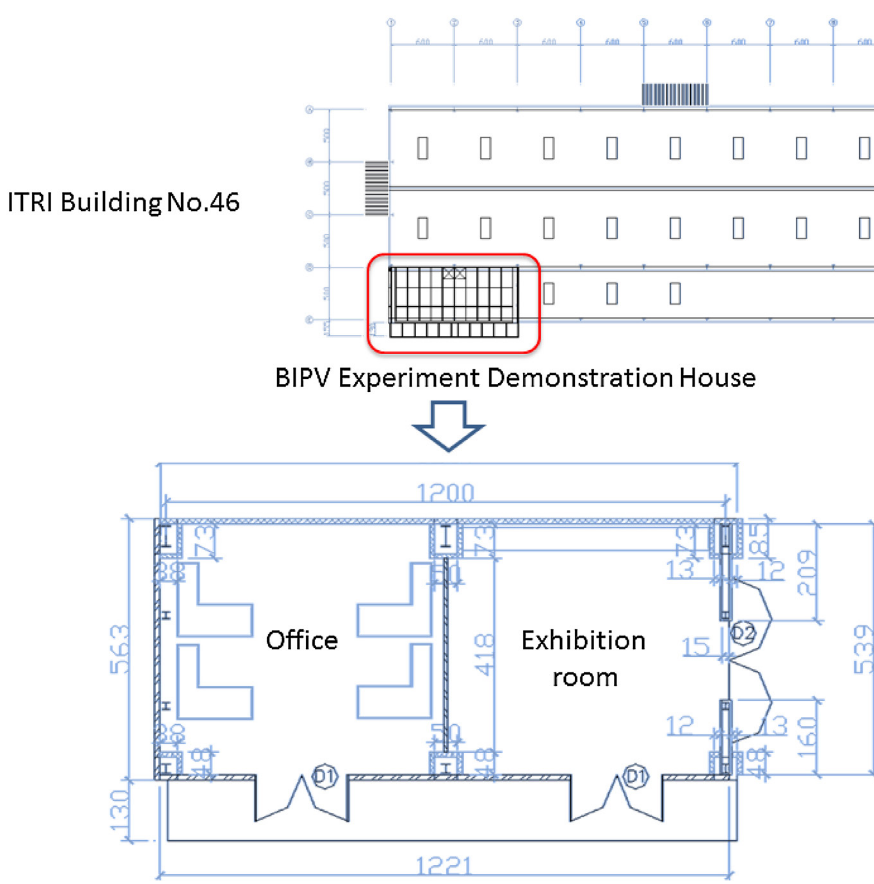


Fig. 6. Floor plan of the BIPV Experiment Demonstration House.

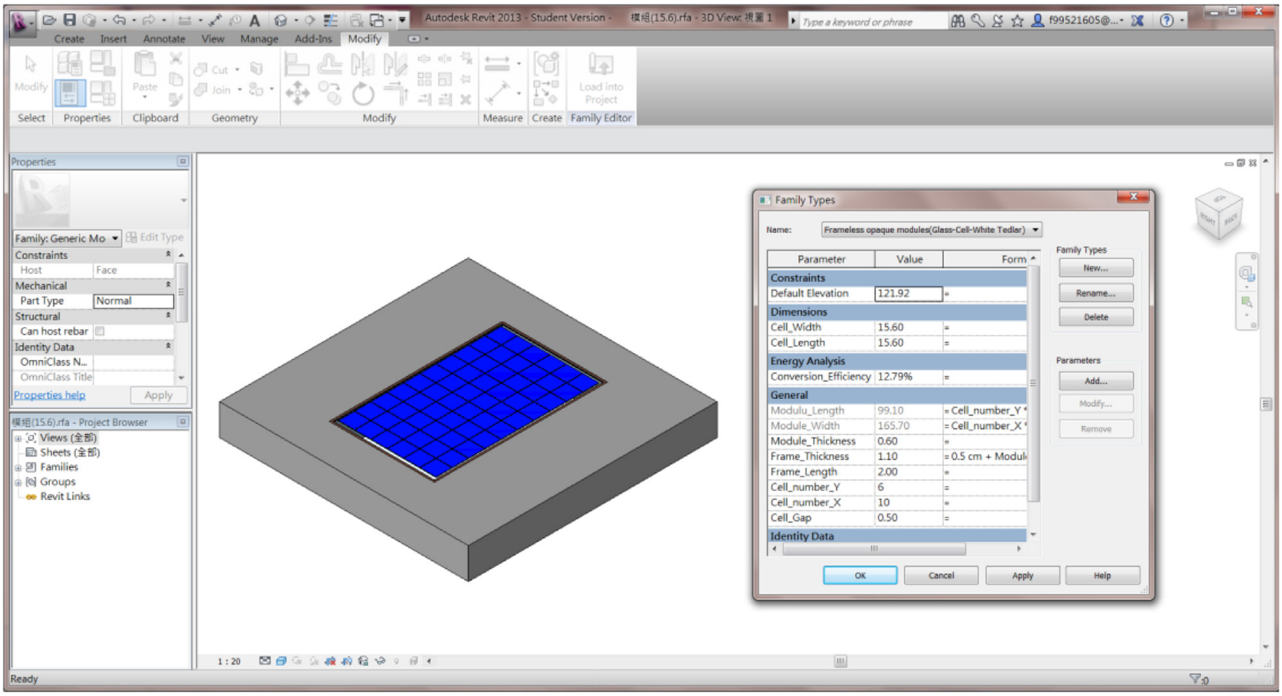


Fig. 7. BIM component model of the BIPV module.

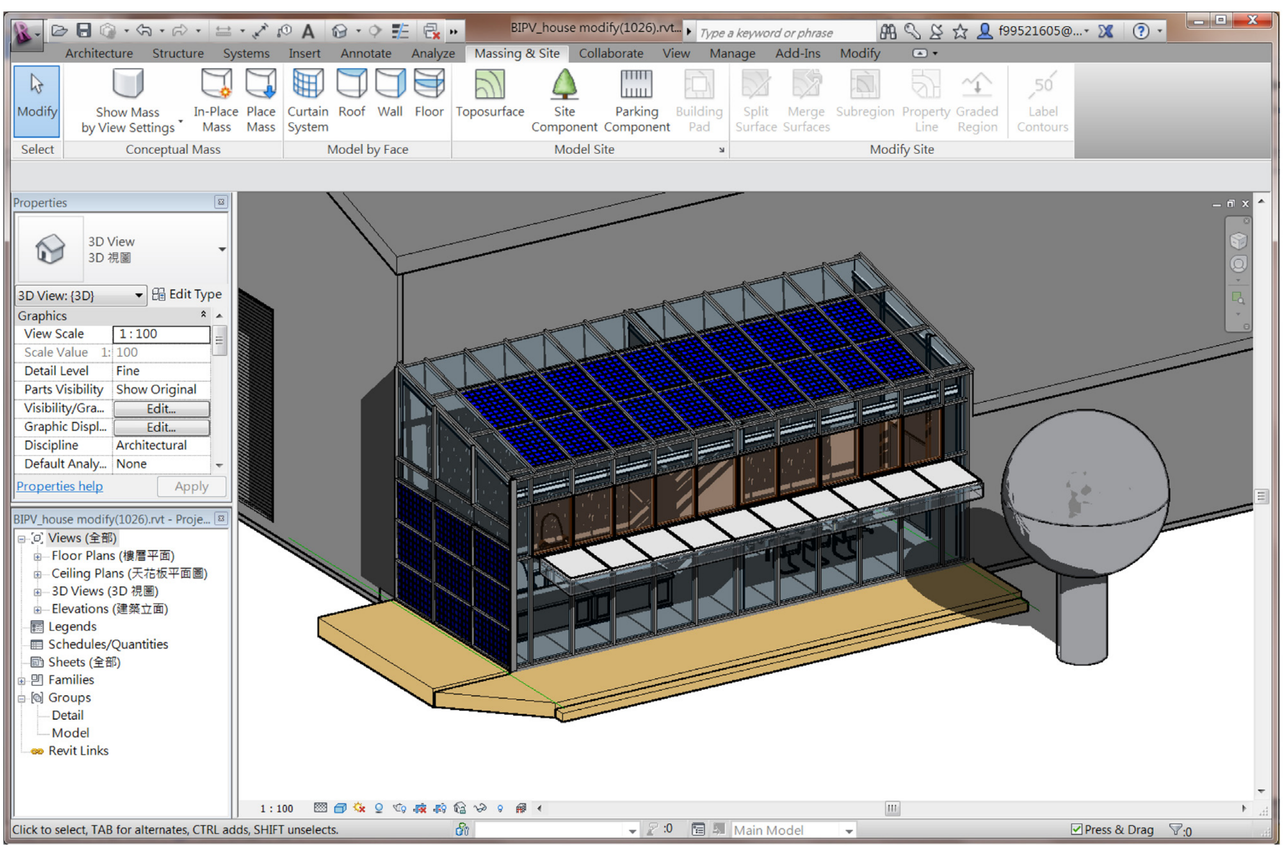


Fig. 8. BIM model of the BIPV Experiment Demonstration House.

ing the BIM project environment, this study created the wall, floor, column, and furniture reference from the 2D CAD shop drawings. Besides the general building components, the corresponding BIM component model of the BIPV module with module information was customized in the model (Fig. 7). The BIM component model of the BIPV module is composed of a PV cell, which is the basic parametric model unit. Neighboring buildings that do not produce shade at the BIPV module are not used in energy analysis to reduce computation complexity. However, there is a tree in front of the BIPV Experiment Demonstration House. Including a detailed tree model will cause very heavy loading in the simulation process, so this study used a sphere and a cylinder to represent the tree for modeling its shading effect (Fig. 8). To create a precise BIM model of the BIPV Experiment Demonstration House, not only 2D CAD shop drawings are used but also the actual size of the house is measured and double checked by visiting the site.

For exporting the model in the gbXML format, some modifications to the model are needed. The model should be divided into several room spaces using the "Room" label function in Revit. When choosing the function to check the result of the model and the export model in gbXML, it is found that the BIPV module cannot be transferred to gbXML. Because the family category of BIPV module is categorized as "Electrical Equipment", Revit cannot transfer this object into gbXML. Thus, this study uses "Curtain Grid" function to enclose area of BIPV module to deal with this problem. While exporting the BIM model, the BIPV modules area can be recognized as a window area in the gbXML format (Fig. 9). This modification is used for transferring the BIM model into the energy analysis model. Although it shows manually operation in dealing BIM model, it keeps consistent information in design process. Once the simulation results show feedback building design, the BIM model contained component of BIPV module can be easily modified to a new design with better energy performance.

After exporting and saving the model in the gbXML format, it is imported into Ecotect Analysis. Besides the building model, the tree model, which represents the shading factor, is also exchanged via the dxf format. When the model is loaded into Ecotect Analysis (Fig. 10), it is important to check its building information, such as longitude, latitude, and orientation, in the current file property. The model modifies the building space into several enclosed "zones", and building materials are assigned (Fig. 11) to the corresponding part of the building model and zone properties are set to satisfy the model requirements of Ecotect Analysis.

5. Solar radiation data processing

Solar radiation is the most important factor in the simulation of BIPV electricity production. Data about solar radiation is required for Ecotect Analysis weather data. In this study, solar radiation data is used as input data. The data resource is collected from the pyranometer of the BIPV Experiment Demonstration House and is recorded in an hourly format. The BIPV Experiment Demonstration House has four pyranometers in which the tilting angle is parallel to each BIPV module systems and one horizontal pyranometer. The solar radiation data collected from the horizontal pyranometer is used to input weather data in Ecotect Analysis, and the data collected from the other four pyranometers are used as a reference. A few hours of data were lost in recording as a result of unstable power supply. The measured data of electricity production are also referenced to these conditions, and the corresponding data are eliminated to carry out a precise comparison.

The Ecotect Analysis weather data format acquires input from direct solar radiation and diffuse solar radiation. The pyranometer recorded data comprises only total solar radiation data. In order to validate the accuracy of the simulation, this study evaluates the effect of diffuse solar radiation. In a previous study, the Bouguer–Lambert–Beer law in Formula (2) and the Berlage formula in Formula (4) [22] were applied to divide the recorded solar radiation values into two parts, namely direct and diffuse, like so:

$$I_{\text{suntot}} = I_d + I_{\text{diff}} \tag{1}$$

$$I_d = I_0 \cdot P^m \cdot \cos i \tag{2}$$

$$\cos i = \cos\theta \cdot \sin h + \sin\theta \cdot \cos h \cdot \cos\varepsilon, \text{ and} \tag{3}$$

$$I_{\text{diff}} = \frac{1}{2} I_0 \cdot \sin h \cdot \frac{1 - P^m}{1 - 1.4\ln P} \cdot \cos^2\left(\frac{\theta}{2}\right) \tag{4}$$

where I_{suntot} is the total solar radiation; I_0 is the solar constant (1353 W/m^2); I_d and I_{diff} are the direct and diffuse solar radiations, respectively; and P is the atmospheric transmission factor, whose value ranges from 0 to 1. A value of 1 indicates that the sky is very clear and the total solar radiation is only direct solar radiation, while a value of 0 indicates complete diffuse solar radiation. A value of P between 0 and 1 denotes that the total solar radiation is allocated to direct solar radiation and to diffuse solar radiation in different proportions. The value P is set to 0, 0.25, 0.5, 0.75, and 1 for testing the parameter sensitivity in this study. Furthermore, $m = 1/\sin h$, h is the sun's altitude angle, which can be obtained by using astronomical algorithms [23], θ is the angle between the measurement surface and the horizontal, and ε is the wall solar azimuth. Since the measurement surface is horizontal, θ is zero. Therefore, cos i is equal to sin h. By dividing Eq. (2) with Eq. (4), Eq. (5) can be obtained:

$$I_d / I_{\text{diff}} = P^m \frac{1}{2} \cdot \frac{1 - P^m}{1 - 1.4\ln P} \tag{5}$$

With the use of Eq. (1) and (5), the solar radiation for the electricity production simulation can be obtained.

After dealing with direct and diffuse radiation data, this study uses the data to construct the weather data for Ecotect Analysis and carries out the electricity simulation (Fig. 12).

This study examines the accuracy of the simulation results for solar radiation with different P values. Considering the practical design process, architects can only use historical weather data to carry out the simulation. The simulation results are compared with currently measured data.

6. Results and discussions

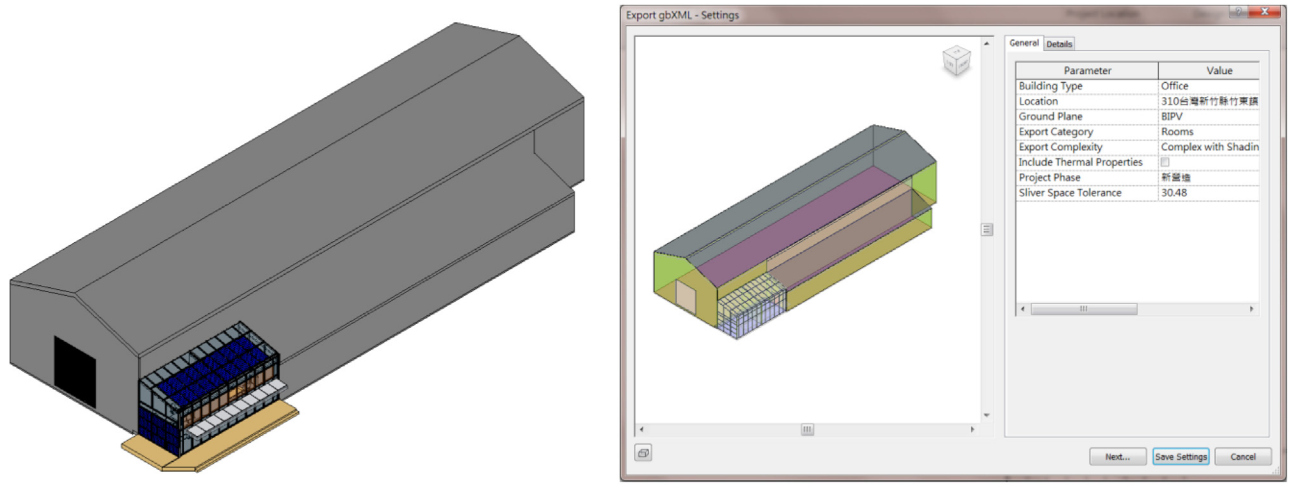
This study simulates the electricity production of four BIPV module systems for a three-year period from 2011 to 2013. In order to choose an appropriate P value to carry out the simulation and make comparisons, this study analyzes the P value using measured data in 2011. After a P value is chosen, it is used to run a simulation on the data for the years 2012 and 2013. Some data for the measurement records of 2011, 2012, and 2013 were lost (Table 5). All the data, including solar radiation at different angles and electricity production data, are recorded hourly. This study deals with horizontal solar radiation and electricity production data. The corresponding lost data are removed from each record for consistent comparison. There are 438 invalid records for 2011, 274 invalid records for 2012, and 2347 invalid records for 2013. As the invalid records are distributed randomly in these three years, it is not possible to directly compare electricity production for these years.

1) Sensitivity analysis of the P value using whole-year data (2011):

- Sloping roof system electricity production (Fig. 13):

For the year 2011, the measured data is higher than the rest of the simulation results. The simulation results increase directly with an increase in the P value. The trends of measured data and simulation results are the same and they almost match each other. Electricity production tends to increase from spring to summer, and decreases from fall to winter. The months of March and May are exceptions to this rule, as they show less electricity production compared to previous months for the rainy season.

The sloping roof system tilts at an angle of 13°, which allows a large quantity of sunshine to reach the panel. A comparison of simulation results shows that the simulation of electricity production yields conservative results. The trend of simulation results, which use data from the pyranometer, shows that electricity production has a direct relationship with solar radiation.



(a) BIM model in Revit (b) Preview of output model in gbXML

Fig. 9. Transfer of the BIM model of the BIPV Experimental House to gbXML format (a) BIM model in Revit (b) Preview of output model in gbXML.

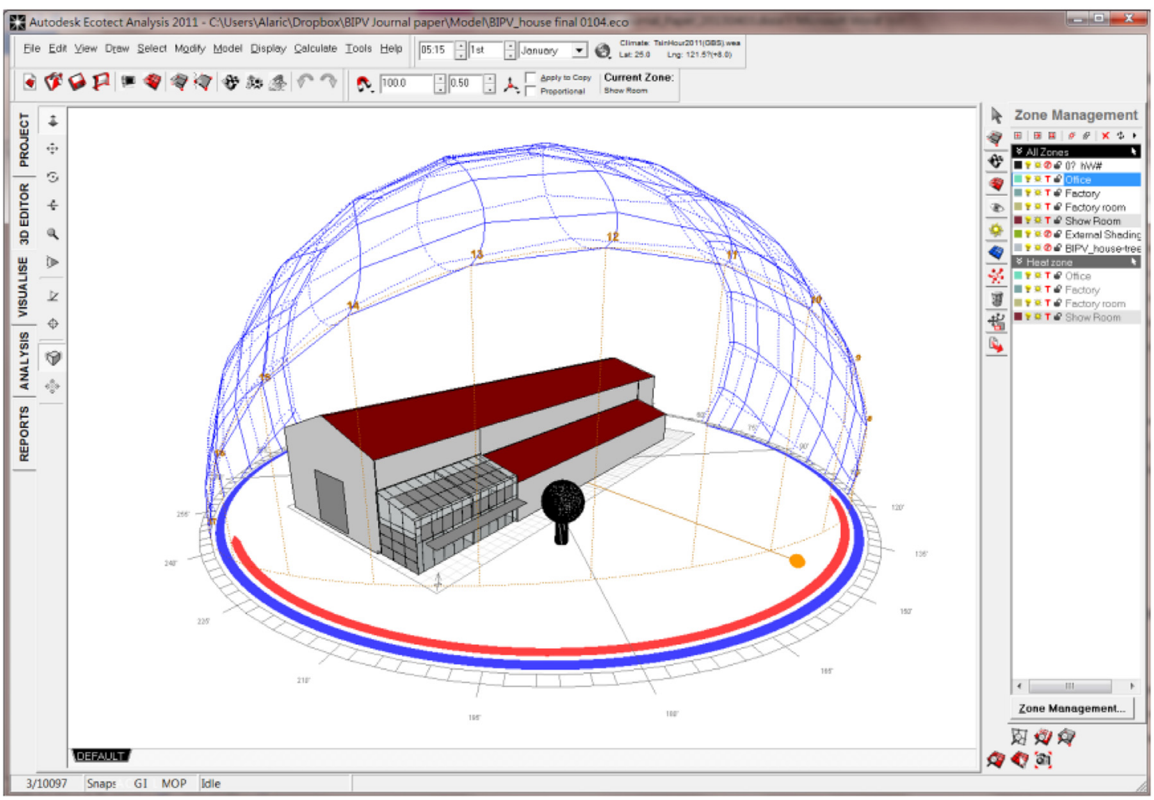


Fig. 10. Energy analysis model imported into Ecotect Analysis.

Table 5
Record of lost data (recording frequency is in hours).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2011	53	0	6	0	0	0	58	0	12	266	43	0	438
2012	56	75	0	2	0	15	20	10	0	95	1	0	274
2013	0	1	31	576	402	254	0	621	348	26	7	81	2347

- Right-side system electricity production (Fig. 14):

The simulation results are higher than the measured data when the P value is 0, and they are close when the P value is 0.25. The trend for the simulation results is similar; simulation results with P values of 0 and 0.25 have a higher electricity production in summer. The right-side system is vertical to the ground, which makes it hard

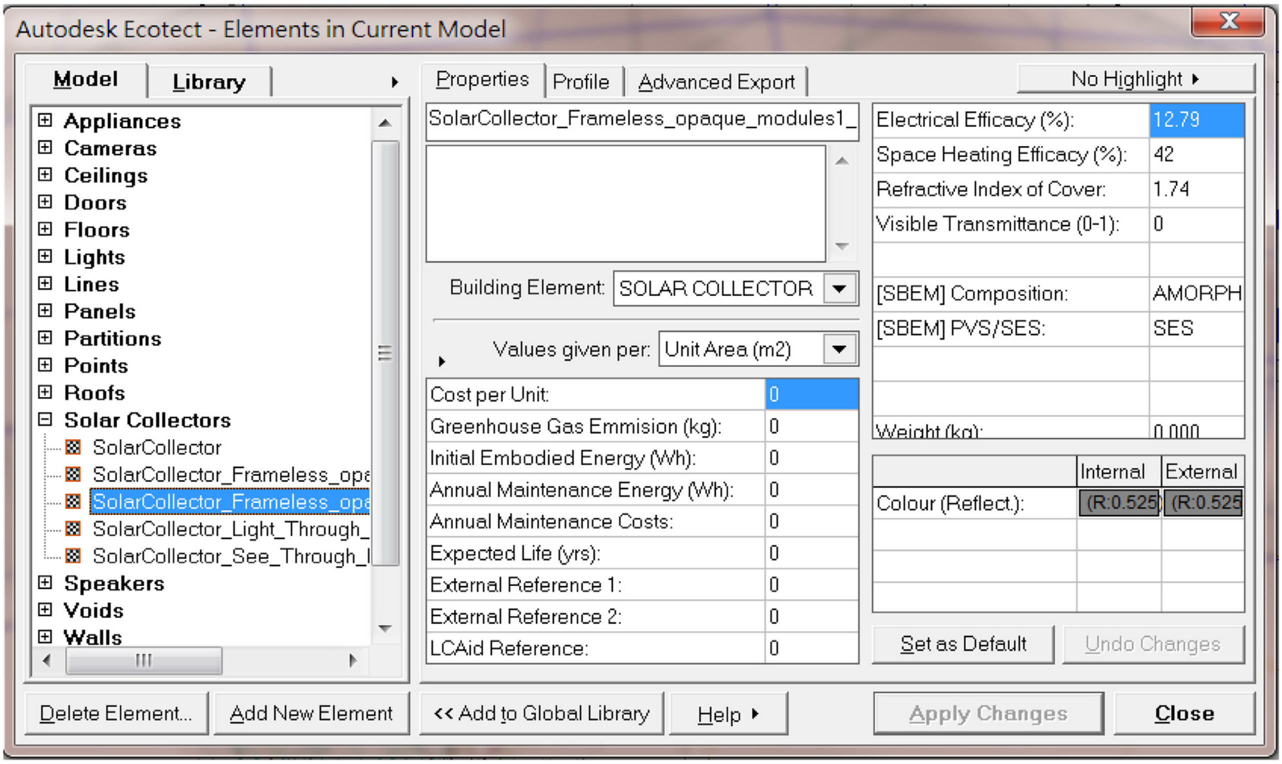


Fig. 11. The material library in Ecotect Analysis.

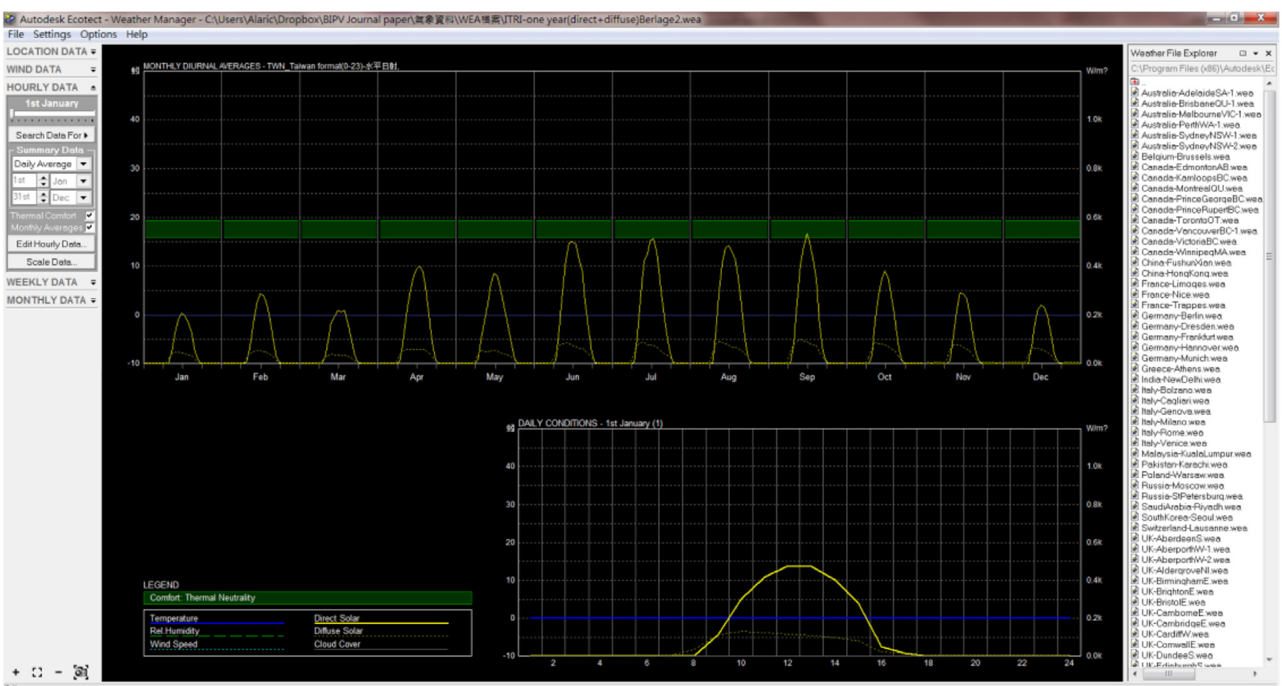


Fig. 12. Importing solar radiation data into the weather tool in Ecotect Analysis.

for it to receive direct solar radiation. Therefore, it needs diffuse solar radiation to produce electricity. In this case, there are some differences from the simulation results, especially in the summer period. Complete results show that the measured data are within the same range as the simulation results.

- Transom system electricity production (Fig. 15):

The general trends of the simulation results for different months are similar, except for January, February, November, and December. Simulation results with a *P* value of 0 have a significantly higher electricity production during April to September. The measured data shows a similar trend for the period of May to August. As the transom system is a type of power window that can be opened, it is not always kept in a vertical position during operation. Using Eco-

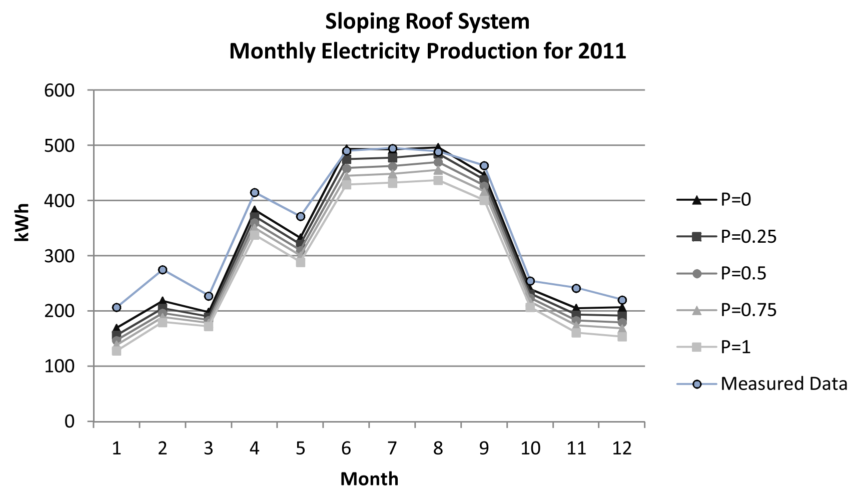


Fig. 13. Comparison of sloping roof system electricity production.

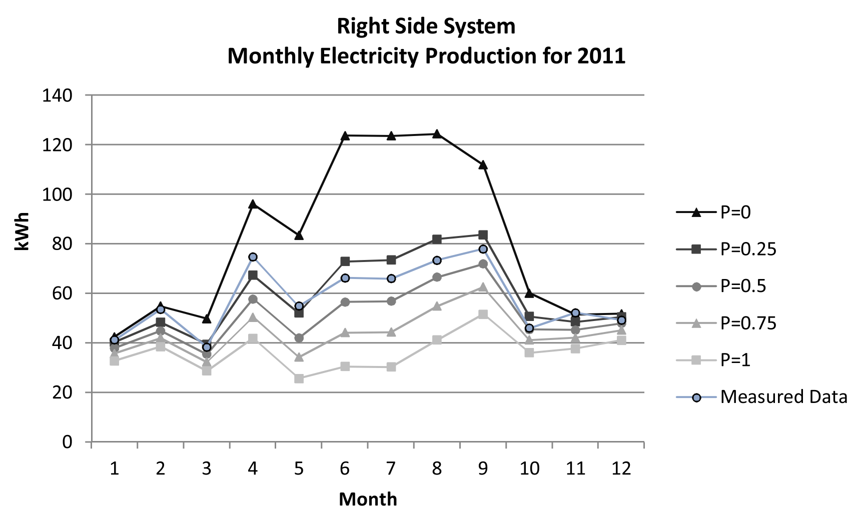


Fig. 14. Comparison of right side system electricity production.

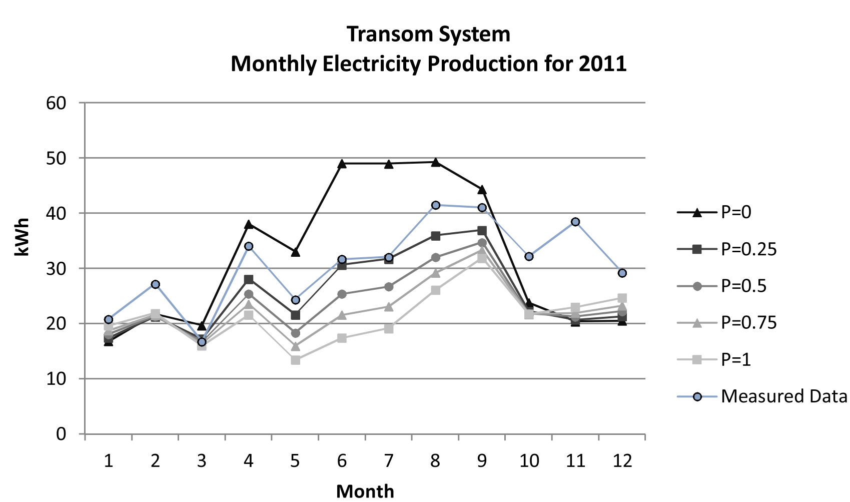


Fig. 15. Comparison of transom system electricity production.

tect Analysis, this study can only simulate the electricity production of solar panels at a fixed angle at a given time. The moveable mechanism of the transom system causes the measured data to show a different pattern to the rest of the simulation results in fall and winter.

- Sun shield system electricity production (Fig. 16):

For this system, the trends of the simulation results are almost the same. According to the figure, the electricity production from the measured data is lower than that from all the simulation results.

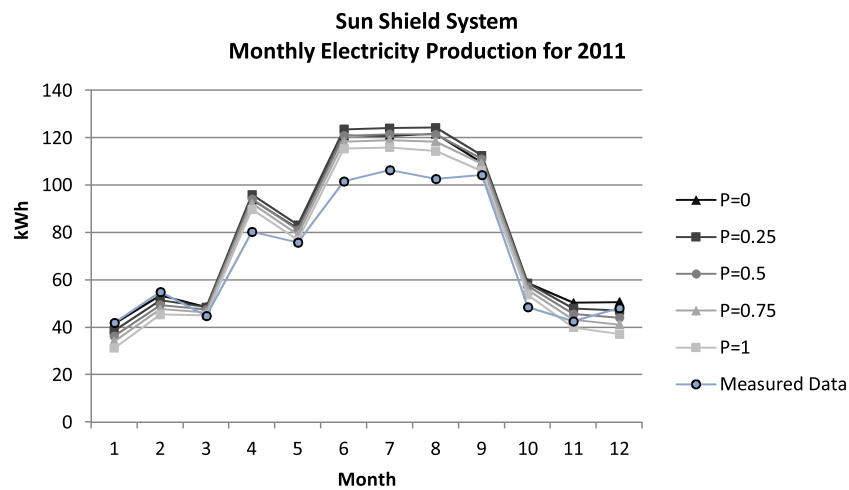


Fig. 16. Comparison of sun shield system electricity production.

As mentioned earlier, a part of the sun shield system is shaded by the tree. But this is not the case for the pyranometers. Therefore, solar radiation received by sun shield system is lower compared with solar radiation data recorded by the pyranometers. The sun shield system is also easily covered with leaves and dust. Furthermore, the panels of the sun shield system can sometimes reach a temperature of 80 °C. Depending on the physical properties of the solar panel, the conversion efficiency decreases when the panel has a high temperature. This study verified the maintenance record with the manager of the BIPV Experiment Demonstration House and found that the sun shield system was cleaned in April. Consequently, the measured data of the sun shield system increases in May but decreases in summer, owing to the high temperature. When simulating the behavior of the solar panel, the software assumes that the conversion efficiency is constant and is not affected by temperature. This results in the measured data being lower than the simulation results.

In order to find an appropriate *P* value, Table 6 lists the simulation results for P values ranging from 0 to 1 to compare with the measured data. The "Results (Wh)" column is electricity production accumulated for the whole year (2011). The "Error (%)" column represents the simulation result minus the measured data, divided by the measured data. The "Error (%) to total" represents the error contributed to the total simulation results. Table 6 shows the obvious trend that the simulation results increase when *P* has a relatively small value in the range 0–1. In the sloping system, the error ranges from −19.78% to −6.47%. In the right-side system, the error ranges from −37.17% to 40.35%. When *P* is negative, it shows that the simulation value is higher than the measured value. In the transom system, the error ranges from −30.51% to 4.36%. In the Sun Shield system, the error ranges from 2.19% to 11.68%, which shows that the measured data is lower than the rest of the simulation results. In this case, it shows that different *P* values have different impacts on the simulation. The following validation is carried out when *P* is 0.5.

2) Validation of simulation results with three-year record and TMY3 data:

This study focuses on the trend of the differences between the simulation results and measured data in each year. In the sloping roof system (Fig. 17), the difference between the simulation results and measured data is small for 2011–2013. Although the energy simulation underestimates the actual electricity production, the error is decreased. The errors when the *P* value is 0.5 are −13.22% in 2011, −1.36% in 2012, and −2.09% in 2013 (Tables 6–8, respectively). In the right side system (Fig. 18), the energy simulation overestimates the results compared to the measured data, ranging from −12.27% to −10.55% when the *P* value is 0.5 (Tables 6–8, respectively). In the transom system (Fig. 19), the simulation result is generally lower than the measured data by −23.08% to −31.95% during a three-year period (Tables 6–8, respectively). In the sun shield system (Fig. 20), the simulation result is higher and the error ranges from 9.12% to 25.59%.

When an architect commences a new building design, there is no measured data to begin with. The typical-meteorological-year (TMY3) data can be used as a weather data source for energy analysis. The TMY3 data for Hsinchu [24] is employed in this study, and it deals with the invalid data for the three years mentioned earlier. After carrying out the energy simulation, the results that use TMY3 data are consistent with the simulation results using measured solar radiation as the weather data input. It is shown that simulation results using TMY3 data have higher values for the systems, except the transom system (Tables 6–8).

7. Conclusions

This study has verified the accuracy of BIM-based energy analysis of BIPV buildings in electricity production simulation. The design procedure of BIM-based energy analysis of BIPV buildings follows the process map provided by the IDM document for BEA, and the scenario for energy analysis starts from conceptual design to the following design stage. In conducting electricity production simulation of BIPV building, information contained in BIM model such as correct building location, building orientation, weather data, the area of BIPV module system and system conversion efficiency is required as simulation input.

In this paper, a BIM model is built using Revit and the energy analysis is conducted using Ecotect Analysis for BIPV building. This study collects building data and 2D CAD shop drawings to create the BIM model of the BIPV Experiment Demonstration House, which is exported into the energy analysis model in a gbXML format. The BIM components of BIPV module were created as part of the BIM model, and the model transferring between BIM software and energy analysis software were tested. After loading the model into Ecotect Analysis, building information for the model, like longitude, latitude, and orientation, is checked in the file property information. The model needs to be divided into several enclosed zones, assigning building materials with the corresponding parts of the building model. However, an interoperability problem may arise in

Table 6
Comparison of electricity production data in 2011.

2011		P = 0	P = 0.25	P = 0.5	P = 0.75	P = 1	TMY3	Measured Value
Sloping Roof	Results (Wh)	3888519	3742414	3607978	3486696	3335050	4148686	4157519
	Error (%)	−6.47020	−9.98444	−13.218	−16.1351	−19.7826	−0.21245	
Right Side	Results (Wh)	974193	709736	608935	529330	436153	884852	694137
	Error (%)	40.3459	2.24725	−12.2745	−23.7427	−37.1661	27.4751	
Transom	Results (Wh)	386196	305695	284655	270783	257174	365458	370078
	Error (%)	4.3553	−17.3971	−23.0824	−26.8308	−30.5081	−1.24838	
Sun Shield	Results (Wh)	952557	956458	930722	905131	871656	1037443	852950
	Error (%)	11.6779	12.1353	9.118	6.11771	2.19309	21.63	
Total	Results (Wh)	6201465	5714303	5432290	5191940	4900033	6436439	6074684
	Error (%)	2.08704	−5.93250	−10.5749	−14.5315	−19.3368	5.95512	

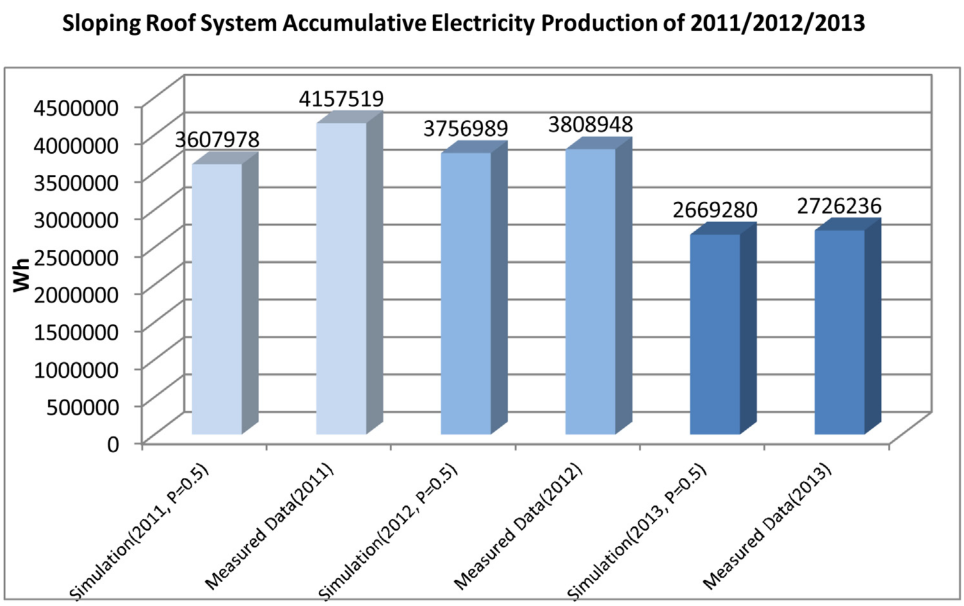


Fig. 17. Comparison of sloping roof system electricity production over three years (accumulative).

Table 7
Comparison of electricity production data in 2012.

2012		P = 0	P = 0.25	P = 0.5	P = 0.75	P = 1	TMY3	Measured Value
Sloping Roof	Results (Wh)	4037582	3892578	3756989	3633022	3476174	4300582	3808948
	Error (%)	6.00255	2.19562	−1.36413	−4.61875	−8.73663	12.9073	
Right Side	Results (Wh)	1011540	735629	626947	540717	439918	915288	700944
	Error (%)	44.3111	4.94833	−10.5567	−22.8587	−37.2392	30.5793	
Transom	Results (Wh)	401002	322593	302691	289756	277112	381615	436432
	Error (%)	−8.11810	−26.0840	−30.6441	−33.6079	−36.5051	−12.5602	
Sun Shield	Results (Wh)	989074	995161	970099	944449	910254	1075916	792023
	Error (%)	24.8795	25.648	22.4837	19.2451	14.9277	35.844	
Total	Results (Wh)	6439198	5945961	5656726	5407944	5103458	6673401	5738347
	Error (%)	12.2135	3.61801	−1.42237	−5.75780	−11.0639	16.2948	

Table 8
Comparison of electricity production data in 2013.

2013		P = 0	P =0.25	P = 0.5	P = 0.75	P = 1	TMY3	Measured Value
Sloping Roof	Results (Wh)	2897565	2775381	2669280	2573908	2457788	2993345	2726236
	Error (%)	6.28445	1.80267	−2.08918	−5.58748	−9.84683	9.79772	
Right Side	Results (Wh)	725928	555725	483910	426156	359194	652557	544368
	Error (%)	33.3524	2.08627	−11.1060	−21.7154	−34.0163	19.8742	
Transom	Results (Wh)	287778	243707	233527	227579	222301	278543	343177
	Error (%)	−16.1429	−28.9850	−31.9514	−33.6846	−35.2226	−18.8340	
Sun Shield	Results (Wh)	709806	704766	683645	662847	636524	747526	544366
	Error (%)	30.3913	29.4655	25.5855	21.765	16.9294	37.3205	
Total	Results (Wh)	4621077	4279579	4070362	3890490	3675807	4671971	4158147
	Error (%)	11.1331	2.92034	−2.11115	−6.43693	−11.5998	12.357	

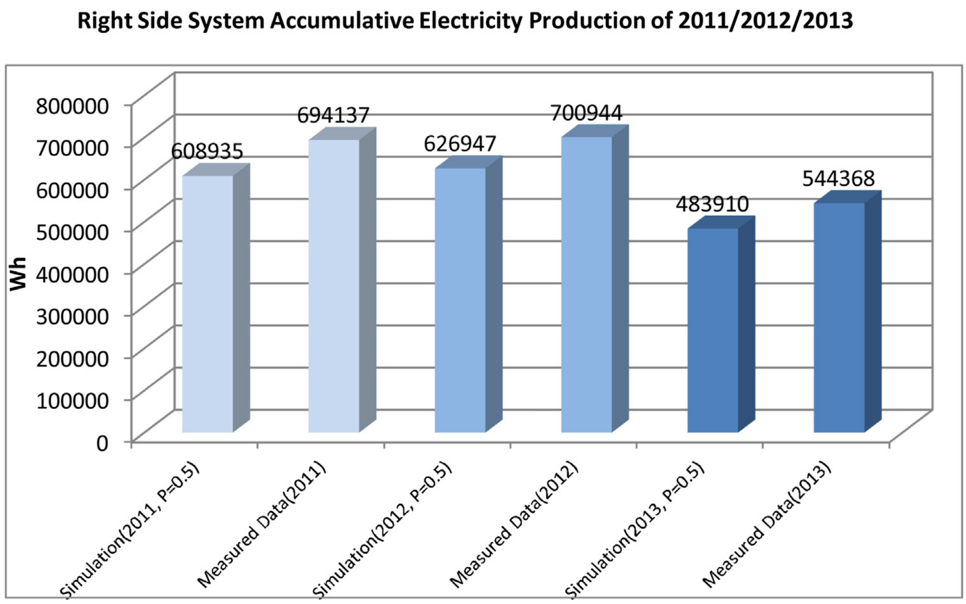


Fig. 18. Comparison of right-side system electricity production over three years (accumulative).

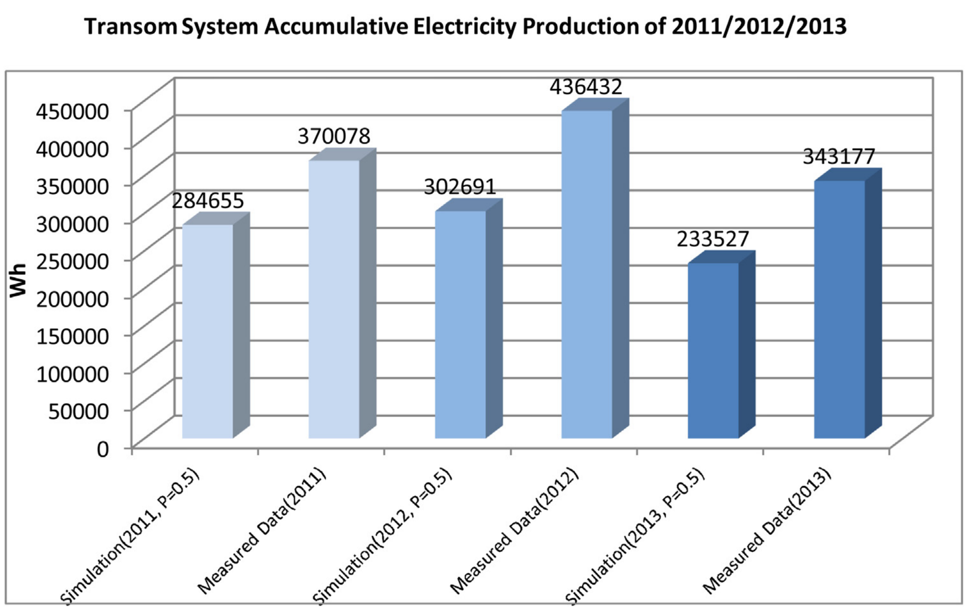


Fig. 19. Comparison of transom system electricity production over three years (accumulative).

transferring the building model between software packages. Modification of conceptual design BIM model is required for energy analysis, but rework to rebuild overall building model in energy analysis software can be greatly reduced. Also, conceptual design BIM model can be easily modified with feedback of energy analysis to improve energy performance and boost design procedure.

In energy analysis, choosing appropriate weather data source result in better energy prediction. Solar radiation is the most important factor of weather data in the simulation of BIPV electricity production. Since pyranometers of study case collected whole solar radiation, this study uses the Bouguer–Lambert–Beer law and the Berlage formula to divide whole solar radiation into direct and diffuse solar radiation for the three-year measured data. The atmospheric transmission factor (P) ranging in the Berlage formula controls division of solar radiation. With more solar radiation allocated in diffuse solar radiation, higher simulation results are shown among all BIPV module systems based on the case study examined.

There are practical factors found in case study related to BIPV design. In design stage, designer can only obtain historical data such as typical-meteorological-year (or TMY3) weather data as software input to conduct energy analysis. The accuracy of simulation results using TMY3 weather data was investigated and it was found that it underestimates electricity production for the BIPV module systems, except for the transom system. Comparing simulation results using measured solar radiation with simulation results using TMY3 weather data, measured solar radiation has more conservative simulation results than TMY3 weather data. Besides weather data, it is needed to concern many practical factors in BIPV design. It was found that the performance of BIPV module systems may be affected by the presence of leaves, dust, and the shade of trees in this case study. The temperature and angle of the BIPV module system also affect electricity production.

BIM-based energy analysis is demonstrated workable in this paper and its reliability has been shown through the verification

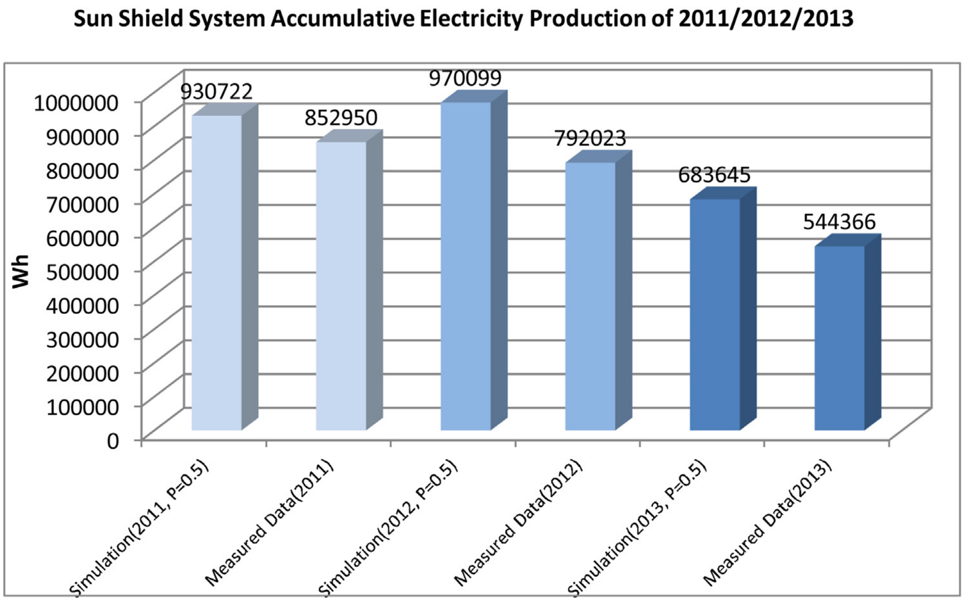


Fig. 20. Comparison of sun shield system electricity production for three years (accumulative).

study on the accuracy of the electricity production simulation results of four BIPV module systems with three year measured data. How a designers can use BIM-based energy analysis to simulate BIPV performance has been demonstrated. For future work, more analysis tools can be tested and more study cases of BIPV using the BIM modeling and energy analysis procedure presented in this study can be collected. The verification results can be used as simulation benchmarks among analysis tools to help further development of analysis tools.

Acknowledgements

The authors would like to acknowledge the financial support from the Industrial Technology Research Institute (ITRI) and thank Mr. Chao-Yang Huang and Mr. Chun-Ming Shu of ITRI for their suggestions and help in the case study. Thanks also go to Mr. Chien-Hsun Huang and Mr. Meng-Hsin Wang for instruction on Ecotect Analysis applications.

References

[1] S. Kubba, Chapter 9—Impact of Energy and Atmosphere, 2010. http://dx.doi.org/10.1016/b978-1-85617-691-0.00009-6.

[2] D.L. King, J. a Kratochvil, W.E. Boyson, Photovoltaic array performance model, Online 8 (2004) 1–19, http://dx.doi.org/10.2172/919131.

[3] A. Henemann, BIPV: built-in solar energy, Renew. Energy Focus 9 (14) (2008) 16–19, http://dx.doi.org/10.1016/S1471-0846(08)70179-3.

[4] C. Peng, Y. Huang, Z. Wu, Building-integrated photovoltaics (BIPV) in architectural design in China, Energy Build. 43 (2011) 3592–3598, http://dx.doi.org/10.1016/j.enbuild.2011.09.032.

[5] L. Maturi, W. Sparber, B. Kofler, W. Bresciani, Analysis and Monitoring Results of a BIPV System in Northern Italy, 2006.

[6] H.C. Sung, G.W. Chang, K.L. Yen, An empirical study of the power generation performance in a BIPV building, in: GTEA Green Technol. Eng. Appl. Conf., 2012, 2012.

[7] C.M. Eastman, BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors, 2008.

[8] National Institute of Building Sciences, National Building Information Modeling Standard, 2007.

[9] E. Krygiel, B. Nies, Green BIM. Successful Sustainable Design with Building Information Modeling, 2008 http://books.google.com/books?hl=en&lr=&id=2Nia6A4G0uQC&oi=fnd&pg=PP11&dq=Green+BIM:+Successful+Sustainable+Design+with+Building+Information+Modeling&ots=tFnnZLutfF&sig=Ih4PIChfduYy35nZjAnYB6nQJUI.

[10] X.D. Xuan, Application of building information modeling in building integrated photovoltaics, Adv. Mater. Res. 171–172 (2010) 399–402, http://dx.doi.org/10.4028/www.scientific.net/AMR.

[11] M.K. Dixit, W. Yan, BIPV prototype for the solar insolation calculation, in: Proc. 29th Int. Symp. Autom. Robot. Constr. ISARC, 2012, 2012, pp. 2–5 http://www.scopus.com/inward/record.url?eid=2-s2.0-84893319273&partnerID=tZOtx3y1.

[12] A. Gupta, A. Cemesova, C.J. Hopfe, Y. Rezgui, T. Sweet, A conceptual framework to support solar PV simulation using an open-BIM data exchange standard, Autom. Constr. 37 (2014) 166–181, http://dx.doi.org/10.1016/j.autcon.2013.10.005.

[13] Y.H. Wen, H.J. Kuo, S.H. Hsieh, A test bed for verifying and comparing BIM-based energy analysis tools, in: Comput. Civ. Build. Eng., American Society of Civil Engineers, Reston, VA, 2014, pp. 211–218, http://dx.doi.org/10.1061/9780784413616.027.

[14] BuildingSMART, Information Delivery Manual Guide to Components and Development Methods, 2010.

[15] R. See, Information Delivery Model for Building Energy Analysis, 2011.

[16] Object Management Group (OMG). Business Process Model and Notation (BPMN) Version 2.0, 2011, http://dx.doi.org/10.1007/s11576-008-0096-z.

[17] B. Dong, K.P. Lam, Y.C. Huang, G.M. Dobbs, A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments Geometry information, in: Proc Build. Simul., 2007, 2007, pp. 1530–1537.

[18] H.J. Kuo, Y.W. Chen, C.H. Yeng, W.Y. Chien, R.C. Guo, S.H. Hsieh, et al., A case study on BIM energy analysis of BIPV buildings, in: Int. Conf. Constr. Appl. Virtual Reality, 2011, 2011.

[19] M.C. Dubois, M. Horvat, State-of-the-art of digital tools used by architects for solar design task 41 – sol. energy archit, Energy Procedia 41 (122) (2010), http://dx.doi.org/10.1016/j.enbuild.2012.05.031.

[20] T.J. Reeves, S. Olbina, R.R.A. Issa, Guidelines for using building information modeling for energy analysis of buildings, Buildings 5 (2015) 1361–1388, http://dx.doi.org/10.3390/buildings5041361.

[21] J. Kanters, M. Horvat, M.C. Dubois, Tools and methods used by architects for solar design, Energy Build. 68 (2014) 721–731, http://dx.doi.org/10.1016/j.enbuild.2012.05.031.

[22] Z. Wang, Y. Lu, Q. Peng, Z. Jiang, H. Zhu, An infrared image synthesis model based on infrared physics and heat transfer 2. The fundamentals of heat transfer and infrared physics, J. Syst. Simul. 19 (2000) 1661–1669.

[23] E.S.R.L. US Department of Commerce, NOAA ESRL Global Monitoring Division – Global Radiation Group, 2015. http://www.esrl.noaa.gov/gmd/grad/solcalc/ (accessed 11.04.16).

[24] M.C. Ho, K.T. Huang, J.C. Wang, The development and research on hourly typical meteorological years (TMY3) for building energy simulation analysis of Taiwan, 2013.