DEVELOPMENT OF A SOLAR RADIATION AND BIPV DESIGN TOOL AS ENERGYPLUS PLUGIN FOR GOOGLE SKETCHUP

Stephen K Wittkopf[1,2], Ashwin Kambadkone[3], He Quanhui[3], Ng Poh Khai[2]
[1]Department of Architecture, [2]Solar Energy Research Institute of Singapore,
[3]Department of Electrical and Computer Engineering
National University of Singapore, Singapore

ABSTRACT

This paper describes the development of a BIPV design tool that integrates the building and PV simulation capabilities of EnergyPlus building performance simulation software and Google SketchUp 3D drafting software. The BIPV design tool builds on the OpenStudio plugin by Peter Ellis to include solar radiation analysis and PV simulation features that can be done from inside SketchUp. The BIPV design tool is an improvement in the BIPV design workflow in EnergyPlus that normally requires the user to manually input text-based files. Firstly, the solar and PV modelling capabilities in EnergyPlus are analyzed and validated by comparing with measured data. Next, the structure and features of the BIPV design tool are introduced. Finally, the features that are marked for future development are highlighted.

INTRODUCTION

Building Integrated Photovoltaics (BIPV) has gained considerable attention as an efficient method to implement distributed generation using photovoltaic powers systems in the built environment. BIPV design software has traditionally focused only on the PV system and not on the integration into the building and the building energy consumption profile.

EnergyPlus is a whole building energy analysis software program developed by the US Department of Energy. Originally designed for HVAC system sizing, EnergyPlus has evolved into a comprehensive building simulation tool capable of modelling heating, cooling, lighting, ventilating and other energy flows in buildings. EnergyPlus can run at sub-hourly time steps and is usually used to perform annual energy simulations. However, EnergyPlus is only a simulation engine and comes without a graphical user interface. Users are required to input text-based descriptions of buildings and EnergyPlus displays its output in text-based files.

Google SketchUp is a popular 3D drafting tool that is capable of drafting complex 3D models. SketchUp, through its built-in Ruby interpreter, allows third party plugins to add additional functionality using Ruby scripts. The OpenStudio plugin [1] developed by Peter Ellis of the National Renewable Energy Labs is a SketchUp plugin that is mainly designed to be geometry editor for EnergyPlus. The work presented here builds on this plugin to include BIPV design functionality into SketchUp, while using EnergyPlus as a building simulation engine.

In this paper we introduce the capability of the BIPV design plugin, the current stage of development and the proposed capabilities in the future. In addition, the solar and photovoltaic modeling functions in EnergyPlus are reviewed and validated.

BIPV SIMULATIONS IN ENERGYPLUS

EnergyPlus is a very useful tool for BIPV simulations because it has excellent solar and photovoltaic performance computational models that are highly relevant to BIPV design. Incident solar radiation analysis can be carried out using the detailed solar and shading models. In EnergyPlus, each building surface is defined by the three dimensional Cartesian coordinates of its vertices. The direct beam, diffuse and reflected solar radiation is calculated based on the geometry of each surface. Direct beam solar radiation is calculated using the ASHRAE clear sky solar model and diffuse solar radiation is calculated using the Perez anisotropic sky model [2]. Reflected solar radiation from the ground and neighbouring buildings are also accounted for using geometry and absorption/reflection coefficients.

Actual measured solar radiation data can be used in EnergyPlus to obtain accurate assessments of the incident solar radiation. The EnergyPlus website [3], maintained by the US Department of Energy, provides a comprehensive database of hourly weather data of more than 1000 locations from all around the

world. The shading models take into account shading caused by attached building surfaces and neighbouring obstructions such as buildings and trees. Shading reduces incident solar radiation over the entire surface even though only a small part of the surface is affected by shading. Overlapping shadows are also accounted for using the Walton [2] model.

There are three types of photovoltaic performance simulation models in EnergyPlus. The simple model is trivial and simply uses a user-defined conversion efficiency to calculate the energy produced. The equivalent one diode model is more detailed and is based on an equivalent circuit that comprises of a DC current source connected in parallel with a diode and two resistances. This equivalent circuit is derived from the semiconductor physics of silicon PV cells but they can also be used for PV cells that are made of different materials such as CdTe and CIGS. The inputs for this model, such as open circuit voltage and short circuit current, can usually be obtained from datasheets provided by the manufacturer. This model takes into consideration the effect of the PV cell operating temperature on the current-voltage characteristics by including the temperature coefficients of the short circuit current and open circuit voltage. There are two methods used to calculate the cell operating temperatures. The first method assumes that the cell is isolated from the building and there are no thermal interactions between the two objects. The next method assumes that the cell temperature is identical to the ambient air temperature, which is useful for simulating ventilated BIPV installations.

The third model is the Sandia photovoltaic array performance model [4] developed by Sandia National Labs. This model is based on both theoretical and empirical measurements of PV modules in actual operating conditions. A whole set of empirical coefficients is derived from regression analysis of the measurements and it describes the variation of the module I-V characteristics with incident solar radiation and module temperature. This model has been verified to be accurate to within 10% of actual module performance [4].

The solar models in EnergyPlus were validated by comparing the results of a simulation using weather data obtained from the EnergyPlus weather database against actual weather data from the Singapore Meteorological Service. The comparisons show that the simulations results agree to within 10% of the measured data as shown in Figure 1. The photovoltaic performance models were validated by comparing the predicted efficiency of a Siemens

SP75 monocrystalline module against the actual measured efficiency of the same module in a study conducted by Fan Jiang *et al.* [5] in Singapore. The predicted average efficiency was 9.83% while the measured figure was 9.05%.
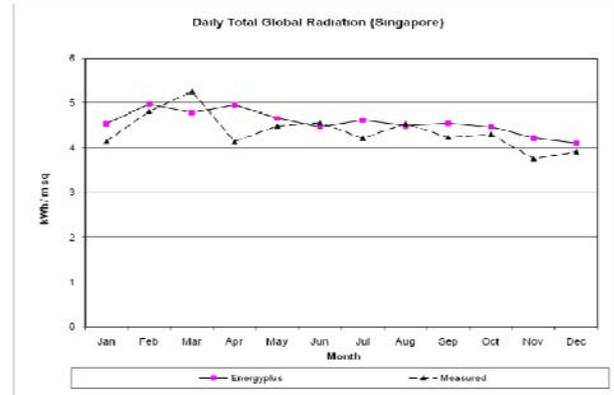

Figure 1: Comparison of EnergyPlus simulation results with measured solar radiation data

OPENSTUDIO: INTEGRATING SKETCHUP AND ENERGYPLUS

OpenStudio is a SketchUp plugin developed by Peter Ellis initially as a geometry editor for EnergyPlus files. The plugin is scripted in the Ruby language, a relatively new and powerful object-oriented language. OpenStudio is a great starting point for the BIPV design plugin due to its ability to integrate with EnergyPlus. OpenStudio is structured as a series of objects that integrate a part of EnergyPlus functionality into SketchUp. In this section, the following objects that implement EnergyPlus functions are described:

- Data dictionary
- Input file
- Simulation Manager
- Dialog Manager
- Results Manager
- Interfaces
- Observers
- Command and menu managers

Data Dictionary

Data Dictionary is the object in OpenStudio that contains the EnergyPlus IDD definitions. It is initialized when OpenStudio plugin is loaded. In the initialization process, it parses through the EnergyPlus IDD file and creates a local database of EnergyPlus object and field definitions. Currently, 98% of the objects in the IDD file can be imported into the database.

Input File

Input File is the object in OpenStudio that is similar to the IDF input file in EnergyPlus. There is an IDF file template located in the OpenStudio folder where the material, construction and other EnergyPlus objects are defined. The Input File object opens this template and appends user-defined EnergyPlus objects at the end of the template file.

Simulation Manager

Simulation Manager is the object in OpenStudio that allows SketchUp to run EnergyPlus simulations directly without leaving SketchUp. It allows the user to define the weather file to be used, run period, output variables and template reports available in EnergyPlus.

Dialog Manager

Dialog Manager is the object in OpenStudio that handles the dialog windows. SketchUp allows the communication of variables from web dialog windows to the Ruby scripts using action callbacks. This feature forms the backbone of the graphical user interface in the BIPV design plugin.

Results Manager

Results Manager is the object in OpenStudio that parses the EnergyPlus output files and allows the output variables to be represented visually in SketchUp. This object is very important because it is one of the ways to communicate simulation results back into SketchUp. This file can be expanded in future to post-process and create all kinds of reports and visualizations in SketchUp.

Interfaces

Interfaces are objects that describe the geometry in EnergyPlus. These interfaces are created whenever a user draws an item in SketchUp. The interfaces are then appended onto the end of the IDF template file by the InputFile object.

Observers

Observers are objects that observe the user's actions and the items that are drawn. It can identify the type of surface based on its orientation and position and assign it to its respective EnergyPlus object.

USING SKETCHUP FOR ENERGYPLUS SIMULATIONS

To run an EnergyPlus simulation in the non user-friendly interface, the user is required to manually write the IDF input file and launch the simulation using the EP-launch program. This process is not only tedious and time consuming but also very prone to errors. An IDF input file is a text-based file that describes EnergyPlus objects in terms of their name and parameters in the following format:

```
BuildingSurface:Detailed,
Zn001:Wall001, !- Base Surface Name
Wall,EXTERIOR,  !-  Class  and  Construction
Name
ZONE 1 @ 200 601 0 T, !- Zone
Outdoors,, !- Outside Boundary Condition
SunExposed, !- Solar Exposure
WindExposed, !- Wind Exposure
0.5000000 , !- VF to Ground
4, !-Rectangle
0.0000000E+00, 0.0000000E+00, 3.048000 ,
0.0000000E+00, 0.0000000E+00, 0.0000000E+00,
6.096000 , 0.0000000E+00, 0.0000000E+00,
6.096000 , 0.0000000E+00, 3.048000 ;
```

One can immediately see how difficult and time consuming it would be to manually write an IDF input file for a large building. OpenStudio provides a much simpler interface to create IDF input files and launch EnergyPlus simulations. The data flow between SketchUp, OpenStudio and EnergyPlus is illustrated in the data flow diagram in Diagram 1.

As shown in the diagram, OpenStudio can be divided into two parts. The first part consists of the observers that run in the background and monitor user input for geometry information. The observers identify the drawing objects such as zones and surfaces and call up the corresponding interfaces. The interfaces create input objects that can be described as the OpenStudio representation of an IDF input file object. These objects are stored internally within OpenStudio and can be accessed using the object info dialog. This dialog allows the user to change certain parameters and view the actual text that is written into the IDF input file.

Post processing Visualisation

Sketchup

User Drawings — User Commands

Observers

Command/Menu Manager

Surface Type

Results Manager

Interfaces

Dialog Manager

Geometry information

Data Dictionary

Input Object

Simulation Dialog

IDF text — IDF text

IDF input file
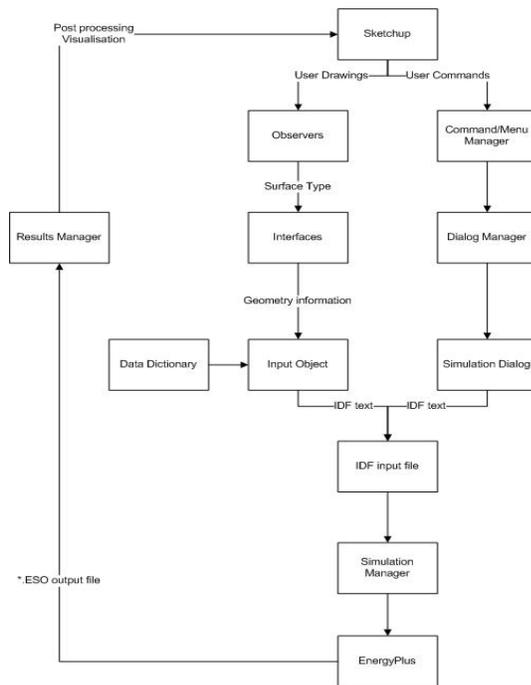
*.ESO output file

Simulation Manager

EnergyPlus

Diagram 1: Data flow diagram of OpenStudio plugin

The second part consists of the managers that make up the rest of the plugin. The command and menu managers make up the interface of the plugin and control user interaction. In this case, when the user clicks on the "Run Simulation" command, this request is processed by the Command/Menu manager, which passes on the request to the dialog manager. It then calls up the "Run simulation" dialog, in which the run period, the report variables and the weather file path are defined. Once the user clicks on "OK", the input objects are written to the IDF input file and simulation manager will start the EnergyPlus simulation.

At the end of the simulation, the results are available in the *.eso EnergyPlus output file. The Results Manager object post-processes the data in the output file and makes it available inside OpenStudio, where it can then display the results onto the building model as a colour scale rendering on the surface. This allows the user to easily visualize the results. In the current version of the OpenStudio plugin, the results manager can only display the raw data in the output file but further post processing functionality can be added easily.

BIPV DESIGN AND SIMULATIONS IN SKETCHUP

The BIPV design plugin utilises OpenStudio as a front end to pre and post process data from EnergyPlus simulations. At this stage of development, the plugin consists of the following functions:

- Sketching simple building mass models
- Surface incident solar radiation analysis
- Add small sensor surfaces onto corners of main surfaces for detailed radiation analysis
- Attach PV objects onto surfaces

Sketching simple building mass models can be done easily using the various drafting tools available in SketchUp. These tools are commonly found in most 3D architectural drafting tools such as AutoCAD and most people who have done 3D modelling before should have no problems with the tools. Detailed step-by-step tutorials on how to use SketchUp can be found on the SketchUp website [5]. In order for EnergyPlus to recognise the building mass models, all building surfaces must be created inside an EnergyPlus zone as shown in Figure 2. Once an EnergyPlus zone has been created, all building surfaces created inside it will be automatically classified as *floor, wall, roof* surfaces based on their orientation and position. Windows are automatically recognised if the user creates a surface inside an existing surface and doors are also automatically recognised if the surface shares a common edge with a floor surface in addition to being inside an existing surface. A simple building mass model of a house is shown in Figure 3.

Solar radiation analysis is one of the most important stages in the BIPV design and is usually done at the first step. The designer must fully understand the amount of solar radiation available on the surfaces of a building before he/she can design the PV system. The BIPV design plugin utilises the solar simulation capabilities of EnergyPlus to obtain the incident solar radiation on each surface. It then uses the OpenStudio results manager to display the results on the SketchUp model.
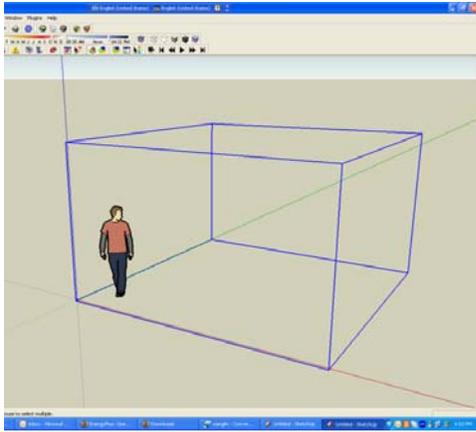
Figure 2: EnergyPlus Zone in SketchUp (blue edges). Double click on the edges to open the zone (dashed lines).
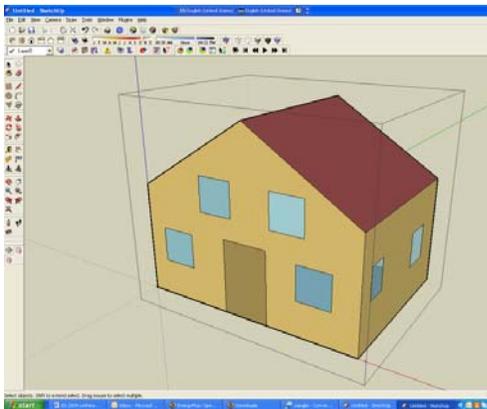

Figure 3: Simple building mass model of a house using SketchUp

The solar radiation models in EnergyPlus are used in the BIPV design plugin and they provide a large number of output variables for incident solar radiation analysis. The Report Manager object allows the user to select the specific output variables that are required and it consists of template reports that include commonly required data used in incident solar radiation analysis. At the current stage of development, the Report Manager object can only handle the output variables relevant to solar radiation analysis and PV array performance analysis.

In order to perform an EnergyPlus simulation from SketchUp, the user has to click on the "Run simulation" command. This displays the dialog window that allows the user to select various run control options and launch the simulation. The weather file can also be selected using this dialog window. At this stage of development, the plugin is unable to ensure that there are no errors or missing data in the EnergyPlus input file. The user is required

to ensure that he/she has input all the necessary building descriptions before clicking on the "Run simulation" command. The "Run Simulation" dialog box is shown in Figure 4.

If the EnergyPlus simulation was successful, the simulation results can be viewed directly in SketchUp. The "Rendering settings" command launches the dialog window that allows the user to select the output result to display. The user can also select the run period if there were multiple run periods specified in the input file. Once that has been selected, the simulation results will be displayed as a colour scale rendering on the building surfaces as shown in Figure 5. The time period can be adjusted by dragging the control sliders to the specific date and time. Another useful feature available in OpenStudio is the ability to animate and playback the rendering, allowing the user to visualize the change of solar radiation with the change of time.

Further detailed analysis on the incident solar radiation can be performed on a surface by attaching small surfaces measuring 3ft x 3ft to each vertex of the surface. Using these surfaces as sensors, the incident solar radiation at the vertices of the main surface can be analyzed. This allows the user to obtain a more detailed understanding of the incident solar distribution on the surface and be more able to position the PV panels to get a higher energy yield. The BIPV plugin is currently still unable to display the results of this detailed simulations but work is in progress to display the results as a colour gradient on the surface. Other than colour gradients, work is also in progress to display the output values on the surface so that the user can obtain a clearer understanding of the simulation results.

The PV models in EnergyPlus are used in the BIPV design plugin. After analyzing the results of the simulation, PV arrays can easily be added onto the surfaces using the "Add PV" command. The "Add PV" dialog window allows the user to select the EnergyPlus PV performance model and input the module characteristics. It also determines which surface the PV array is attached to. The various modes of integration to determine the module operating temperatures can also be selected in this dialog window. A limitation in this feature is that the dialog window is unable to verify that the area of the PV array is smaller than the surface it is attached to. The user has to ensure that the module characteristics are free of errors.

As mentioned above, the Report Manager object can be used to select the output variables that are relevant to PV performance analysis and the EnergyPlus simulations is re-run with the PV array object and the new output variables. Work is currently in progress to display the results of the PV performance analysis in SketchUp.

The flowchart in Appendix A gives a summary of the BIPV design and simulation workflow and the various steps involved that were described in this section.
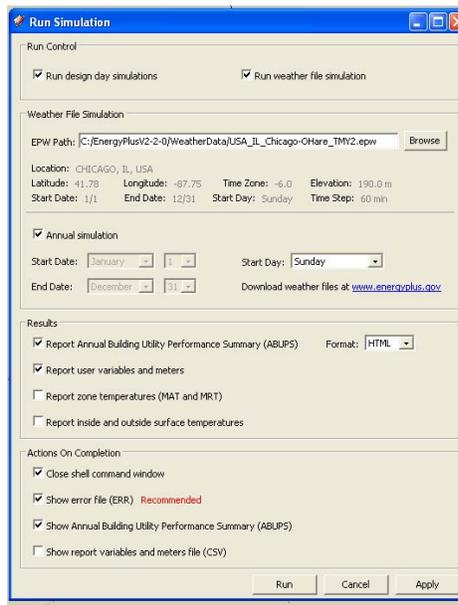

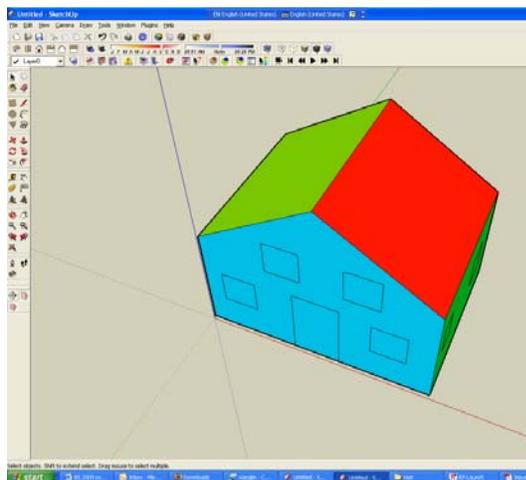*Figure 4: Simulation parameters in the "Run Simulation" dialog box*

Figure 5: Colour scale rendering of incident solar radiation simulation results

MODIFICATIONS MADE TO OPENSTUDIO

Minimal modifications were made to the original source code of OpenStudio. Due to the object-oriented nature of the Ruby language, most of the BIPV design functions are structured as individual objects. The changes made to OpenStudio are listed below:

-       Managers:
    -   Addition of report manager to create output variables in the EnergyPlus IDF file in order for the simulation to generate output results

-       Interfaces:
    -   Addition of PV interface to create a PV input objects in the IDF file.
    -   Addition of PV performance interface to create PV performance input objects in the IDF file.

-       Commands:
    -   Addition of ADD_PV command for user to add PV object onto a surface
    -   Addition of ADD_SENSORS command for user to add sensors onto a surface
    -   Modification of Command manager and Menu manager files to incorporate ADD_PV and ADD_SENSORS commands.

FUTURE DEVELOPMENT

Rendering of graduated incident solar radiation on a surface

Using the incident solar radiation on the sensor surfaces, the gradient of distribution of the solar radiation on a surface can be rendered as a colour-scale along the edges of the surface. This will give the user a better understanding of the solar radiation distribution.

Displaying of values of simulation results onto surfaces

The simulation results are displayed as numbers that are attached to the building surfaces. This allows the user to see both the absolute value of the simulation results and also the colour scale rendering that shows the results relative to the other surfaces.

Displaying of simulation results of PV performance simulations

The results of PV performance simulations can be displayed as both colour scale rendering and numbers. In addition, output variables such as energy generated, current and voltage at MPP can be displayed as charts that can be used to design the balance of system components in a BIPV system.

Semi-automated splitting of surfaces for detailed analysis of incident solar radiation

Building on the sensors tool, this tool will allow the user the easily split up the surface for further solar radiation analysis. The tool will detect large gradients between the sensors and alert the user to split up the surface for detailed analysis. This tool is especially ideal for large surfaces, i.e. Roofs of industrial buildings, facades of skyscrapers, etc.

CONCLUSION

This paper has presented a BIPV design tool that focuses on the integration of the PV system into the building, using Google SketchUp with the OpenStudio plugin as the interface and EnergyPlus building simulation software as the simulation engine. The detailed solar and PV performance models in EnergyPlus were reviewed and validated against actual measured data and it was found that there is good agreement between the two. EnergyPlus is an excellent simulation software for BIPV simulations

The structure and data flow with OpenStudio was presented and the major components were described. OpenStudio is an excellent starting point for integrating full BIPV simulation capabilities into SketchUp. The BIPV design plugin is still undergoing development and more new features are being implemented.

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APPENDIX A
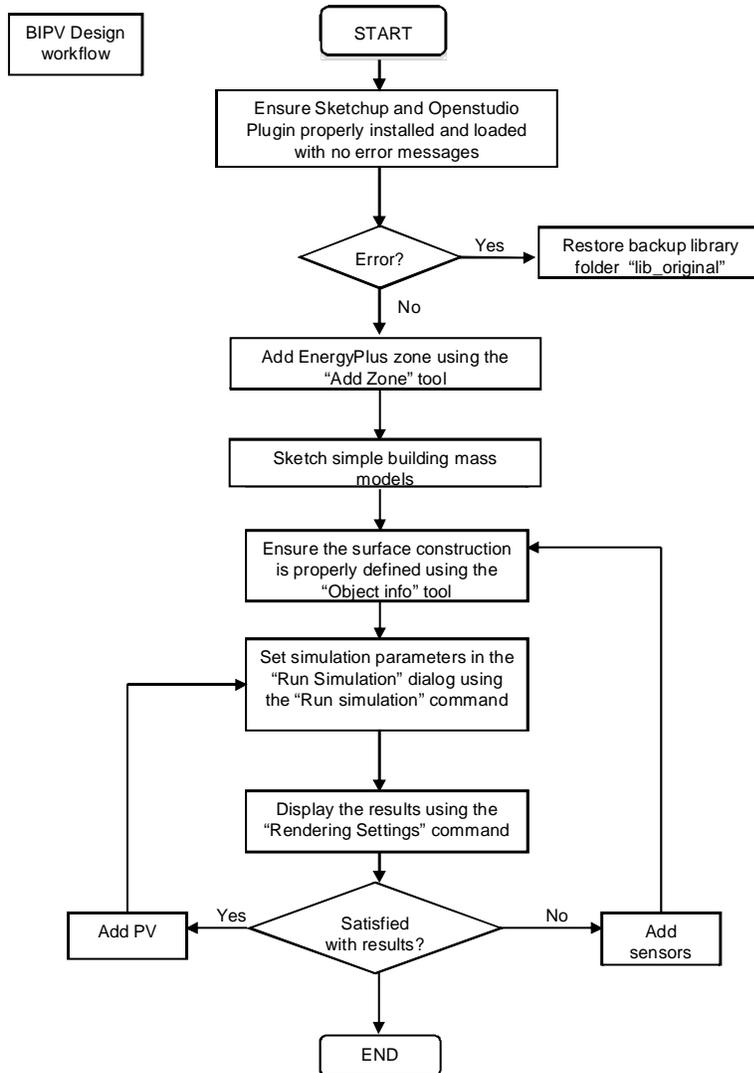
Flowchart of BIPV design workflow