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Professional PV Design and Management Systems: Effects of PV on the Cooling Load of Buildings

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Abstract

Solar PV power as a renewable energy source has recently become a much more popular topic of discussion as we begin to consider its impact on the future of energy and reduction of CO_2 emissions. The solar PV panels can be put on rooftops and integrated into building designs. Currently, the most widely promoted PV products in Australia are rooftop solar PV systems, which are used to generate electricity from rack-mounted PV panels on a roof. Also, there's a development of integration of solar PV panles into the building roof and envelope to generate 'free' energy from sunshine. PV panels generate both heat and electricity when exposed to sun. Application of PV modules in to building fabric could change the thermal properties of the building envelope through natural convection and shading effects. The building envelope impacts the indoor air temperature, radiant temperature and humidity. As a result of PV integration could affect the thermal comfort of the building occupants. Therefore, it is necessary to identify the effect of PV systems on the building indoor environment not just the energy generation and cost/benefits associated with the PV system design. There are number of professional PV design and development tools on the market. This study has analysed 27 PV design and development tools to identify the gaps in the current PV system design in relation to its effect on building cooling load. Further, a questionnaire survey was carried out to identify the users' perspective on identifying PV system impact on building cooling load. The findings show that there's a necessity to analyse the impact of PV systems on building cooling loads.

1. Introduction

There is an unprecedented growth in Australia's greenhouse gas emission levels in the past few years (Organisation for Economic Co-operation and Development OECD, 2017). According to Climate Council Australia (2018), Australia's greenhouse gas emission levels have reached to 556.4 $MtCO_2^e$ in December 2017 which is 1.5% increase from 2016. The electricity sector is responsible for the highest GHG emissions (33%) in 2017 (Climate Council Australia , 2018). Therefore, there is an urgent need to explore the renewable energy resources such as solar PV which not only meet the increasing energy requirements but also are environmental friendly (Kibria et al., 2016). Australia has excellent solar resources in terms of both land mass and solar exposure, with the highest solar radiation per square meter of any continent (Geoscience Australia, 2017). Therefore, there is great potential for expanding solar power generation in the Australian building sector.

Although households have dominated Australia's solar PV market over the last decade, commercial (100kW-1MW) and industrial scale (large-scale systems 1MW or more) solar PV installations are taking off on airports, mines, healthcare facilities and businesses (Yang and Zou, 2016; Johnston and Egan, 2016; Climate Council of Australia, 2017). The increased demand in PV integrated roofing and façade trends are leading to changes in urban building environments (Scherba et al., 2011). Solar transmission through the building envelope can affect both indoor thermal comfort and visual comfort (López and Sangiorgi, 2014). When PV modules are integrated in building envelope, the thermal resistance of the building envelope is changed (Akata et al., 2015). The change in the thermal resistance of the building envelope has the potential to impact the building indoor air temperature, radiant temperature and relative humidity.

2. Impact of PV modules on Building Thermal Environment

There are six primary thermal comfort variables in case of indoor environment: Ambient temperature (air temperature), radiant temperature (the temperature of the surfaces around us), relative humidity (measurement of the water vapor in an air -water mixture), air motion (the rate at which air moves around and touches skin), metabolic rate (amount of energy expended), and clothing insulation (materials used to retain or remove body heat) (Raish, 2008). These six variables play an important role in building thermal environment especially peformance of the Heating Ventilation and Air Conditioning (HVAC) system. HVAC is one of the most popular modes of maintaining building thermal comfort and is generally responsible for a significant proportion of total building energy consumption. A typical system accounts for approximately 40% of total building consumption in Australia (Department of Environment and Energy, 2013). Thus, reduction of cooling load in a building helps saving energy spend for HVAC and in turn CO_2 emissions.

Both building attached PV (BAPV) modules and BIPV modules can have variety of impacts on the building cooling load. PV modules produce heat, while generating electricity. According to Honsberg and Bowden (2018), for a typical commercial PV module operating at its maximum power point, only 10 to 15% of the incident sunlight is converted into electricity, with the remainder being converted into heat. A study done by Mei et al. (2003) for buildings at three different locations reported that the cooling loads are marginally higher with the PV facade for all locations considered. Therefore, the heat generated by PV modules can modify the thermal resistance of building envelope which has the potential to increase the cooling load of the building.

In contrast, the shading offered by the non-integrated or integrated PV panels have an obvious impact on reducing the building cooling load (Macia et al., 2008). For example, the combination of PV and ventilated roofs could decrease the cooling load of the building through the roofs (Wang, 2006). A study done by Kotak et al. (2014), demonstrated that the energy required for roof-induced cooling load decreased between 73% and 90% after installation of the PV system. They pointed out that the shading offered by the PV array aid in reducing the cooling load. A study done by Yang et al. (2001), showed that the cooling-load component through a PV roof with the ventilation gap is about 35% compared with the load of a conventional roof.

The findings of the afore mentioned studies indicate different types of BAPV and BIPV have various influences on the building cooling loads. Such impact on the cooling load may vary based on the material, mode of construction and other factors, such as insulation level, solar absorptivity, local climate, etc. (Wang et al., 2006).

To find the cooling load, an energy simulation is required. It calculates the heating and cooling energy required to keep the building at a comfortable temperature throughout the year. The simulation needs to define the attributes of each room in terms of their adjacency, internal loads, occupancy scheduling, and the material properties of the room (Perkins and Will, 2017). To facilitate this calculation software tools are used. However, studies of PV design tools for identifying the impact of PV systems on building cooling load are limited. Therefore, this study has conducted an extensive review to identify the characteristics of the available professional PV design and management software to identify the gaps in the current system design. The characteristics will be discussed in the following section with review of software.

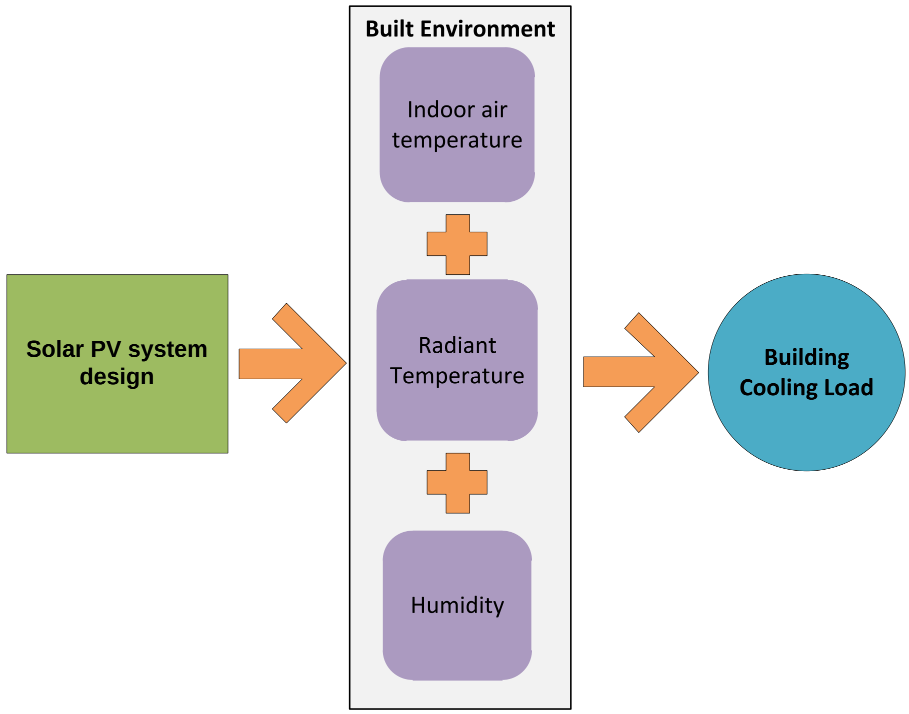

Figure 1 Impact of Solar PV system on building cooling load

3. Previous Studies on Professional PV Design and Management Systems

When considering BAPV and BIPV, each project is unique and therefore requires careful and meticulous planning to increase the efficiency and cost-effectiveness of the design (Klise and Stein,2009; Gridscape, 2013). There are various solar design tools currently available in the market. These tools can be found online, PC based and as smart phone/tablet applications. Many studies have used the solar PV design tools for calculating solar irradiance, shading loss, energy output, financial viability and 3D modelling of potential PV installations/projects. For example, a study done by Axaopoulos et al. (2014), focuses on six tools, i.e. TRNSYS, Archelios, Polysun, PVSyst, PV*SOL and PVGIS, to compare the energy generation results with the actual data on a grid connected 19.8 kW PV installation. A similar study has been done by Freeman et al., (2014) which validated and compared the energy production result accuracy within SAM, PVsyst 6.1.1, PV*SOL, PVWatts and RETScreen for nine PV systems. However, only several studies can be found which discuss the use of software to show the effect of PV systems in the building cooling load.

Mei et al. (2003) have used TRNSYS to present a dynamic thermal model, for a building with an integrated ventilated PV façade/solar air collector system. The study has calculated the heating and cooling loads for the building with and without such a ventilated façade and investigated the impact of climatic variations on the performance of such buildings. However, they have stated in their study that when calculating the cooling load in TRNSYS the maximum and minimum room temperature limits are user-set constants. Therefore, it is difficult to set out the temperature setpoints for occupied and unoccupied periods. Thus, the estimations will not be accurate.

Wang et al., (2006), have explored significant influence of BIPV on the heat transfer through the building envelope by simulating PV performances and building cooling-and-heating loads under four different roofs: ventilated air-gap BIPV, non-ventilated (closed) air-gap BIPV, closeroof mounted PV, and the conventional roof with no PV and no air gap in Tianjin, China. They have used Sandia electrical performance model and Radiant time series (RTS) load-model in excel spreadsheet. However, using spreadsheets for complex designs sometimes might not be practical especially for large projects.

Peng and Yang (2016) have used EnergyPlus to investigate the effects of PV panels on rooftop temperatures in China. The results show that heat transfer by convection, radiation, and conduction in the air gap between the PV panels and the building envelope, such as roofs and walls, can be simulated in the EnergyPlus environment when these air gaps are within the "air conditioning zone." However, the simulated effect that the PV panels have on rooftop temperature was not accurate when the air gaps between the PV panels and the building envelope cannot be set as the "air conditioning zone". This shows that a PV specific tool rather than whole-building energy simulation program could facilitate such analysis.

A comprehensive study was done within the framework of IEA SHC Task 41 – Solar Energy and Architecture (Dubois and Horvat, 2010). The study compares 56 software grouped under computer aided architectural design (CAAD) tools, visualization tools and simulation tools. The study has analysed the selected tools in terms of aesthetic aspects, technical aspects and economic aspects in Solar projects. As per the study, CAAD tools with a simple user interface and rapid modelling such as Google SketchUp were used extensively in the early design phase. More complex tools such as Revit Architecture and AutoCAD were used in the later project phases. Under simulation software, some tools were preferred in the early design phase (e.g. Ecotect, RETScreen) and more specific and complex tools such as Polysun, PVSol were used heavily in later stages. Their study noted the followings in terms of analysing building thermal performance;

- CAAD tools such as BIM applications offer the most interesting possibilities for energy simulations including passive solar gains predictions (e.g: Allplan, ArchiCAD, DDS-CAD PV, MicroStation, Revit and Vectorworks).
- Google SketchUp, which is not a BIM application, also integrates many plugins: IES VE-Ware, OpenStudio, and Google SketchUp Demeter, which allow performing thermal simulations based on IES VE, EnergyPlus and Green Building Studio.
- None of the visualization software reviewed includes any form of algorithm for the prediction of passive solar gains.
- There are many simulation software which can be used for the prediction of passive solar gains. In most cases, the estimation of passive solar gains is considered in the calculation of the whole building thermal balance calculation (e.g.: bSol, DesignBuilder, DPV (Design Performance Viewer), Ecotect, EDGII, ENERGIEplaner, eQUEST, IDA ICE, IES VE, LESOSAI, VisualDOE).

Further, several past studies such as Klise and Stein (2009), Lalwani et al. (2010), Sharma et al. (2014), Nebojsa Jakica (2017) have been conducted to compare the key features of professional PV related tools. However, none of the studies have addressed the impact of PV systems on the cooling load of the building. There is no clear understanding on to what extent PV design and development software would help the PV system designers and other stakeholders understand to which extent PV systems impact the indoor environment thermal load of a building. Clearly, there are not enough studies in this area. Therefore, this study has conducted an extensive review to identify the characteristics of the available PV design and management software to identify the gaps in the current system design in the following section.

4. Objectives and Methodology

The aim of the review is to understand the current features and functions in the current solar PV design and management tools in relation to the indoor environment thermal load of a building, and propose an integrated solution for PV design and development. The main objectives of this study are:

- Describe the current features and functions of current solar PV design and management tools in relation to the indoor environment thermal load of a building;
- Illustrate the limitations;
- Propose potential improvements for an integrated solution for PV design and development.
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The paper's methodology uses data collected through an extensive literature survey and a questionnaire survey which was carried out with 15 PV professionals who are working in the Austrialian PV industry. A worldwide search was made for providing diagnosis of photovoltaic design and management systems. Out of many software tools found in the literature review 23 software and 4 mobile apps were selected as follows,

- 13 major standalone PV software packages: SAM Version 2017.1.17, RETScreen Expert, Solarius-PV, Homer Pro, PV *SOL Expert, PV Scout 2.0, Solar F-Chart, Sunulator, Pvsyst, Helos3D solarparkplanung, Polysun, INSEL, SolarPro;
- 4 CADD/BIM plugins: Google Sketchup, Autodesk Revit, Honeybee and Ladybug tools for Grasshopper;
- 6 online tools: ArcheliosPro, PVwatts, PVGIS, CalculationSolar.com, PV*SOL Online, EasyPV;
- 4 smart phone/tablet applications: EasySolar, Onyx Solar, PVOutput, SMA Sunny Portal

The selection of the standalone software and the online tool PV-GIS was based on their usage in the current Solar PV literature where tools that were common in the past studies such as Klise and Stein (2009), Lalwani et al. (2010), Sharma et al. (2014) and Nebojsa Jakica (2017). Further, several online tools (Calculation solar, PV*SOL online, Easy-pv and Easysolar) CAAD/ BIM plugin and smart phone/tablet apps were selected based on the studies Nebojsa Jakica (2017), photovoltaic-software.com (2017) and Nault et al. (2015). In addition, a questionnaire survey was carried out with 15 PV professionals who are working in the Austrialian PV industry. All professionals supported the selection and added Sunnulator, Homer, PV watts and PVsyst to the list which were reviewed as well.
Although the listed tools still cannot cover across the world, we endeavor to include the major ones based on their accessibility and relevancy for BAPV/BIPV design and management. Also, tools which were developed specifically for single company PV products such as Fronius Solar Configurator, The Redback app etc. were not considered in this review. Each solar design and management tool and app which were free to download for a trial version or where the demo or educational version was available were tested with simulation exercises whereas for software tools with limited access, web sites, product manuals, white papers and demo videos etc. were used. The selected tools and the key findings from the review are presented in Table 1 and will be explained in the following subsections.

5. Discussion

The first phase of the work done was to review and analyze the current software related to photovoltaic design and management available for architects, engineers and other stakeholders of a PV project with a focus on decisions of PV attached or integrated building projects. The results show that only CADD/BIM tools currently facilitate simulation of building thermal performance with respect to PV system designs (See Figure 2).

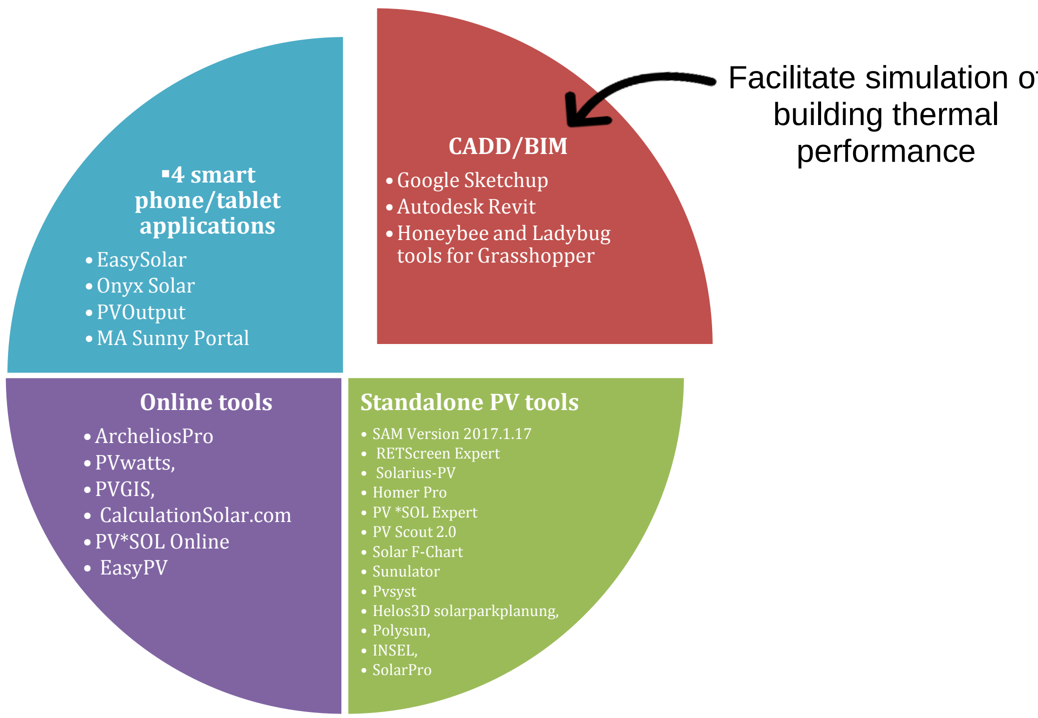
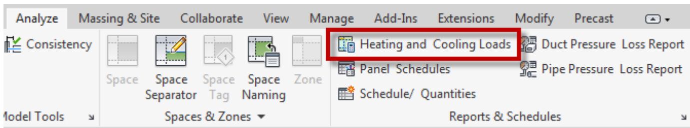


Figure 2: PV design and Management Software

The Revit platform is Autodesk's purpose-built solution for building information modeling (Autodesk, 2018). Within Revit components of a PV attached or integrated building project such as roof, floor, windows, glazing, PV modules, mounting systems, shading, internal loads can be modelled. Further, factors such as solar heat gain in site and outdoor temperatures can be defined. Once model is created and spaces and zones of the building are defined, Revit provides the option either to model the cooling loads within the programme (See Figure 3) or to export the space load data via gbXML file or EnergyPlus to an external simulation software programme such as Green Building Studio Autodesk® (GBS). Advantages of using Revit for cooling load simulation of PV projects are designers can introduce both building attached and integrated PV product details to the BIM model; the analysis takes in to account building type, geometry, climate, active systems and envelope properties; design changes made are automatically updated throughout the model; model can also be exported to third-party applications for further analysis; and the information provided in Revit models allow architects , engineers, designers, contractors and other stakeholders in a PV project to take decisions collaboratively. Disadvantages are the software can be costly; expert knowledge is required for building the model and it is more suitable for detailed design phase of PV projects and cannot be used in early design phase



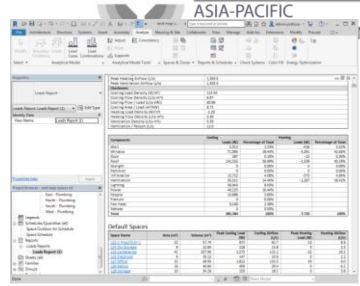


Figure 3: Revit: Cooling/heating load simulation
Source: Prakoso (2017)

Google Sketchup is a powerful software which can be used for conceptual design stages of PV projects. Using Sketchup, a building model with PV modules attached or integrated can be created. Then, using Energy Plus OpenStudio plug-in the indoor cooling load of the building model can be simulated. Sketchup require basic skills to learn and easy to use. Therefore, PV project stakeholders such as contractors, installers, engineers, researchers etc. could easily simulate the impact of different PV designs on the cooling load of the building.

Rhino Grasshopper simulates the cooling load of buildings using details of the spaces, building constructions, and weather data. It calculates the temperature inside each room for every hour of the year to calculate the heating and cooling energy required to keep the temperature inside each room comfortable when people are using each room (Perkins and Will, 2017). Honeybee and Ladybug components for Grasshopper interface to OpenStudio component and EnergyPlus facilitate cooling load simulation (See Figure 4). In contrast to Google Sketchup, Rhino Grasshopper require expert knowledge to run its applications.

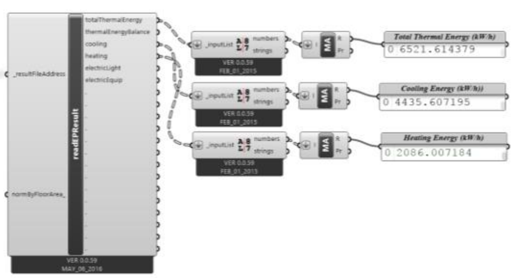


Figure 4: Honeybee: Cooling/heating load simulation
Source: Perkins and Will (2017)

The findings in the above section show that most of the PV design and development tools does not consider the impact of PV systems on the indoor environmental thermal loads. The tools that facilitate this feature such as Honeybee and Ladybug components for Grasshopper, Sketchup and Revit require substantial knowledge to operate the software. Therefore, it is impractical especially for residential owners and those who are not familiar with the software. Thus, it would be beneficial if the current PV design tools could provide a platform or framework on how the proposed design will affect the indoor thermal load of the selected building.

The second phase of the project aimed to learn from users, i.e. engineers, architects, PV installers etc. A questionnaire survey was used find out the limitations and improvements of the currently available tools for solar design and its impact on the building thermal environment.

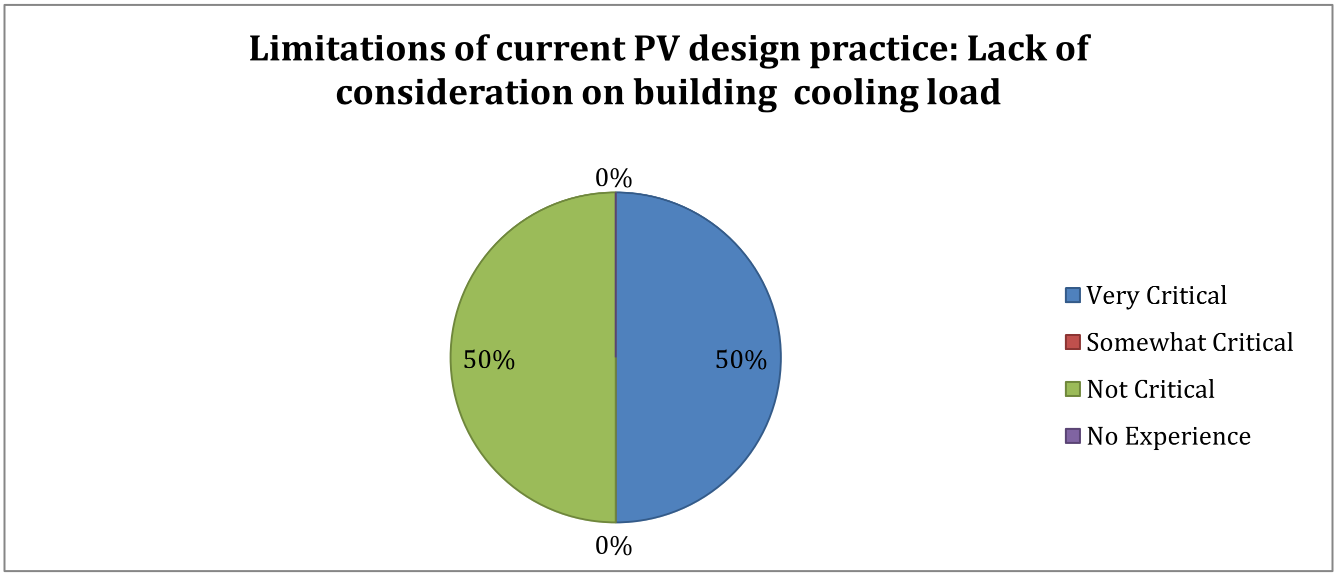


Figure 5: Limitations of current PV design practice: Lack of consideration on building cooling load

Respondents were asked to choose the limitations of the current PV design tools and rate the criticalness of the selected limitation. Half of the survey responses indicated that building cooling load is not critical for designing a PV system and half of the survey responses agreed that building cooling load should be considered in designing PV systems (*See* Figure 5). The Respondents were then asked about the needs for improvements required and in total 60% have agreed that it is important to have an indoor environmental impact analysis when designing a PV system. However, 20% have considered this option to be not important (See Figure 6).

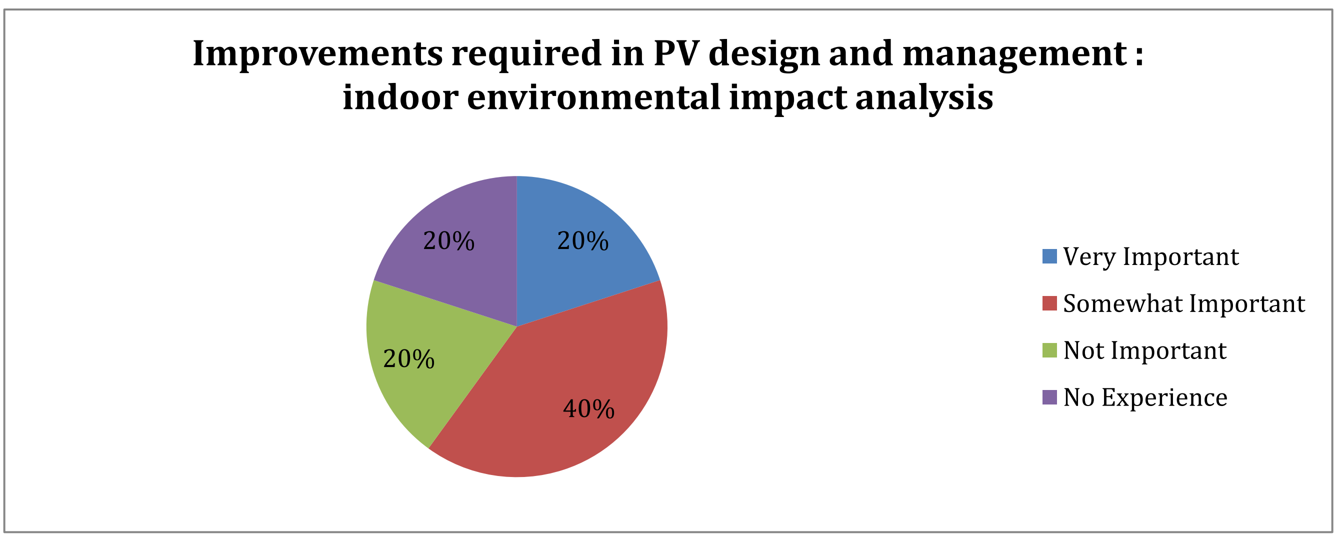


Figure 6: Improvements required in PV design and management: indoor environmental impact analysis

This survey results indicate that current PV design software should consider the impact of PV design on the building thermal environment. The above survey results indicate that there's a necessity to understand the impact of PV design on the building thermal environment. However, relatively little research has been published on the impact of attached and integrated PV on the buildings cooling load. Further, not many PV design tools facilitate simulation or calculation of the impact of PV systems on building cooling load. Therefore, there should be an integrated solution to facilitate this process. The proposed solutions can be identified under information and simulation and analysis options as shown in the Table 1 below;

Table 1: Proposed solutions for an integrated platform for PV design and development

Category	Proposed Improvements
Information	▪ Detailed local meteorological data and local geographic/terrain data with minimum time intervals ▪ Localised PV system product database (e.g. panel, storage, BOS) ▪ Localised cost data on PV system products and installation ▪ Localised energy price data ▪ Accurate energy consumption data ▪ Information on local building regulations and codes ▪ Information on local government incentives and policies ▪ Information on financial modes and contract arrangements ▪ Database on previous project examples ▪ Information on product performance in previous projects ▪ Information on commissioning and O&M procedures
Simulation and analysis options	▪ Efficient 3D model creation of the physical environment ▪ Generation and comparison of alternative PV module designs ▪ Visualization of shading impact and losses ▪ Automatic PV system configuration and optimization ▪ Anlysing the building cooling load ▪ Accurate energy consumption data simulation ▪ Matching and optimizing energy outputs with fluctuating demands and electricity prices ▪ Balancing revenue against cost to optimise PV module and storage sizes ▪ Lifecycle cost-benefit analysis and comparison from different stakeholders' perspectives ▪ Sensitivity analysis by changing simulation and assessment factors

6. Conclusion

Solar PV design and management is a complex process which span across the interests of multidisciplinary stakeholders. A PV project decision is not only based on the amount of power generated. It also should consider the impact of the installation to the indoor environment thermal loads. 23 PV design and management software and 4 apps were examined on their capability for calculation of building cooling/heating load before installation and after installation. The findings of this review showed none of the examined software except Google Sketchup, Rhino grasshopper and Autodesk Revit can be used to identify the impact of BAPV/BIPV system on the building indoor cooling/heating load. Additionally, the questionnaire survey findings indicated that there's a requirement for analyzing indoor environmental impact with PV designs. Therefore, studies on the impact of PV designs on the building thermal environment are required to upgrade the current PV design tools. Further, an integrated solution which consider the informational requirements and simulation andanalysis requirements should be established to calculate the impact of PV on the indoor thermal load of buildings.

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