International Energy Agency
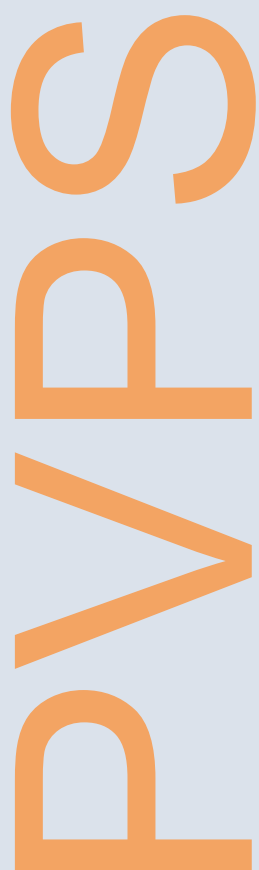**Photovoltaic Power Systems Programme**

Task 15 Enabling Framework for the Development of BIPV

PVPS

BIPV Digitalization: Design Workflows and Methods – A Global Survey
2022

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance (SEPA), the Solar Energy Industries Association, the Solar Energy Research Institute of Singapore and Enercity SA are also members.

Visit us at: www.iea-pvps.org

What is IEA PVPS Task 15?

The objective of Task 15 is to create an enabling framework to accelerate the penetration of BIPV products in the global market of renewables, resulting in an equal playing field for BIPV products, BAPV products and regular building envelope components, respecting mandatory issues, aesthetic issues, reliability and financial issues.

Authors

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COVER PICTURE

Picture of a BIPV façade conceptual design in a digital tool. Source: Rebecca Yang

BIPV Digitalisation: Design Workflows and Methods – A Global Survey

**IEA PVPS
Task 15
Enabling Framework for the Development of BIPV**

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ACKNOWLEDGEMENTS

LIST OF ABBREVIATIONS

AEC	Architecture, Engineering & Construction
BAPV	Building Attached Photovoltaics
BIPV	Building-integrated Photovoltaics
BOS	Balance of System
CAD	Computer-aided Design
CO_2	Carbon Dioxide
CSV	Comma-separated Values
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
DPB	Discounted Payback Period
EPW	Energy Plus Weather
ESD	Environmentally Sustainable Design
GHI	Global Horizontal Irradiance
GIS	Geographical Information System
IEA	International Energy Agency
IP	Internet Protocol
IRR	Internal Rate of Return
JSON	JavaScript Object Notation
LCOE	Levelized Cost of Energy
LiDAR	Light Detection and Ranging
NPV	Net Present Value
O&M	Operation and Maintenance
PB	Simple Payback Period
PI	Profitability Index
POA	Plane of Array
PV	Photovoltaics
ROI	Return on Investment
SAM	System Advisory Model
SHGC	Solar Heat Gain Coefficient
TMY	Typical Meteorological Year

EXECUTIVE SUMMARY

Building integrated photovoltaic (BIPV) technology is one of the most feasible means of supporting the built environment's energy requirements. BIPV systems consist of electrical, mechanical, and structural elements that have a direct impact on the performance of a building. However, the design process of BIPV projects can be complex compared to traditional building envelopes or Building Attached Photovoltaic (BAPV) systems. The complexities of BIPV projects are identified as one reason for slow uptake of BIPV projects globally. Therefore, there's a need to investigate a suitable process for BIPV design that would provide the best outcome as a building element and as a renewable energy technology.

Currently, BIPV design process involves various methods, approaches and workflows practiced by professionals in both the Architecture, Engineering, and Construction (AEC) and BIPV industries. The aim of this study is to investigate the BIPV simulation and modelling methods, approaches and workflows used in BIPV design and analysis globally. The study uses a questionnaire survey targeting 10 professional groups which included professionals related to both building envelope design and BIPV design and management process in Europe, Asia, Oceania, North America and South America. The professional categories included: Architect, Façade engineer, Electrical engineer, Mechanical/Structural engineer, Fire engineer, Environmentally Sustainable Design (ESD) consultant, Academia, research, and development, PV consultant, BIPV system installer, Developer and Property management. The study evaluated findings from eighty AEC and BIPV professionals in Europe, Asia, Oceania, North America and South America.

The survey findings identified methods, approaches and workflows in BIPV design and analysis under four key areas: 1. **solar irradiation** 2. **BIPV power output** 3. **building performance** and 4. **financial and design outcome**.

The key take-aways of this study are:

- **Preference workflows and methods**: Similar preference for the workflows and methods employed in the BIPV design process were found across the five regions. Further, there's a lack of awareness among the respondents on the methods and models used to estimate POA, power output, embodied emissions, heat island impact, thermal, daylighting, structural and fire requirements of BIPV projects. Therefore, research and development are required for the above methods for BIPV design and analysis.

- **Requirement for BIPV-specific components in digital design platforms**: BIPV specific software or a design process can facilitate BIPV design and analysis which would improve the uptake of efficient and cost effective BIPV projects. Therefore, BIPV product database, BIPV system design documentation, shading on BIPV projects, embodied energy in BIPV, customer requirements and decision support models should be considered in future BIPV specific software/design processes.

- **BIPV in urban context**: The current BIPV design methods and workflows can be applied in building context. However, the impact of BIPV can be explore in urban scale. Therefore, further investigation on the methods and workflows need for identification of the impact of BIPV on the urban environment could provide designers and end users a comprehensive knowledge on the feasibility of BIPV applications in a metropolitan setting.

1 INTRODUCTION

Buildings are one of the largest consumers of the global energy. Renewable energy sources such as solar photovoltaic plays a big role in reducing the fossil fuel based energy production. Solar photovoltaic (PV) can be applied in buildings as building attached PV (BAPV) and building integrated PV (BIPV). BAPV is the traditional photovoltaic solutions where the PV modules are fitted on existing surfaces such as the roof. On the other hand, in BIPV, the PV modules replace the traditional building envelope materials. Therefore, the advantage of BIPV is that it not just produces energy it also plays the functions of the building material. However, BIPV design, engineering, construction and management is a complex process which spans the interests of multidisciplinary stakeholders and different phases of the BIPV project life cycle. Therefore, the design and development of a BIPV system cannot be done in isolation. A cross-functional inter-phase approach should be adopted. The BIPV system, similarly to other multifunctional and complex building envelope technologies, is considered as part of an ecosystem consisting of many networked and interconnected functional and construction elements of different life cycles, from raw materials to end user consumption, and from physical and technical systems to environmental and economic systems.

There are four domains under BIPV designing and integration: geophysical, technical, economic and environmental (Wijeratne et al. 2019, Jackia et al. 2019). Sub-factors are found under each domain. These factors can directly impact the successful implementation of the BIPV system. For an example, BIPV is designed to a high degree according to customers or the project's needs (Yang, 2015; Kuhn et al. 2021). Thus, aesthetical issues are to a very high degree the origin and the driving factor to consider BIPV (Awuku et al. 2021). Otherwise, if only cost and energy output is the driving factor, most likely conventional addon PV is being used. To ensure that informative decision is made, we need to look at geophysical, technical, economic and environmental aspects of the BIPV design. Therefore, operative approaches, methods, and workflows relevant to geophysical, technical, economic and environmental aspects of BIPV design and integration need to be identified and applied.

In general, the BIPV design process involves the use of various digital tools. However, digitalization and adoption of 3D tools in the construction sector develops very slowly and is led by technology suppliers and not the builders themselves, except for technical building like hospitals where the costs of the building materials are marginal. Even with a perfect design and coordination along the value chain, too often (sub)contractors do not have the skills or would make last minutes decisions based on cheaper alternatives, hence adding to the overall "project failure" costs because the actual construction usually has to be adapted/repaired on the spot. Therefore, it is important to know which approaches, methods, and workflows would be most feasible for reaching the correct BIPV design decisions.

This report explores the workflows and methods used in BIPV digital design through a questionnaire survey distributed globally. It provides information on methods and workflows that can be used for designing BIPV envelopes under four domains: 1. solar irradiation; 2. solar power output; 3. building performance and 4. financial and design outcome. The BIPV digital design methods and workflows presented in this report can assist building construction professionals, BIPV professionals and anyone interested in BIPV to improve their knowledge on BIPV design and simulation. Thereby improving the uptake of BIPV projects which in return reduce the use of electricity generated with fossil fuel and associated carbon emissions.

Section two of this report presents the aim of this study. The third section discusses the research methodology used in this study. The findings under the literature review are presented in section four. The fifth section discusses the survey findings. The sixth and final section presents the conclusions.

2 AIM OF THE STUDY

The design process of a BIPV envelope is more complex to a regular building envelope due to its construction and electrotechnical aspects. Further, the implementation of a BIPV projects involves multiple professionals from architecture, engineering, construction (AEC) and BIPV industries. To make the right BIPV project decisions, geophysical, technical, economic, and environment factors need to be assessed and evaluated at the design phase of the project. Therefore, it is essential to identify what procedures or methods are used to assess and evaluate BIPV projects by AEC and BIPV industry professionals. Hence, the aim of this study is to investigate the operative methods and workflows relevant to BIPV envelope digital design process utilized by the AEC and BIPV industries through information and data collected from existing BIPV projects and engineering experts.

3 METHODOLOGY

To achieve the study aim, this study used a questionnaire survey. First, a preliminary literature review on workflows and methods in BIPV design was conducted. The following sections discuss the research process used in the study.

3.1 Research process

A survey for the study is developed with two main sections. The first section is regarding the respondents' background. The background information included country, profession, and level of experience. The information helps to gain a general understanding of their experience related to BIPV design and contributes to the data analysis process. To gain insights from a global perspective, the survey was translated into different languages for distribution. The second section is based on the literature review (see Section 4), which concentrates on approaches, methods and workflows applied in building envelope/BIPV design. There are four subsections that cover different perspectives from solar modelling to financial performance. Participants are allowed to select one or more than one section according to their own experience and understanding of the specific areas. The complete copy of the questionnaire survey is attached in Appendix A. The online survey was distributed to target population of the ten categories in Europe, Asia, Oceania, and in American continents. This study did not include Africa because of insufficient information on BIPV activity in Africa to provide meaningful survey input/results. Further, there were no participants in task 15 from the African continent and therefore, there was a difficulty to collect data.

3.2 Data collection

Eighty valid responses were received globally. Figure 3.2.1 shows the continent wise number of responses. Figure 3.2.2 displays the professions of the 80 respondents who completed the questionnaire survey. The targeted population for the study is the key professionals in the BIPV value chain to support decision making of the property developers. In total, 11 categories are chosen for the survey, which are: (1) Architect, (2) Façade engineer, (3) Electrical engineer, (4) Mechanical/Structural engineer, (5) Fire engineer, (6) Environmentally Sustainable Design (ESD) consultant, (7) Academia, research, and development, (8) PV consultant, (9) BIPV system installer, (10) Developer and (11) Property management. Meanwhile, all respondents

are categorized by 5 major regional groups: (1) Europe, (2) Asia, (3) Oceania, (4) North America and (5) South America.
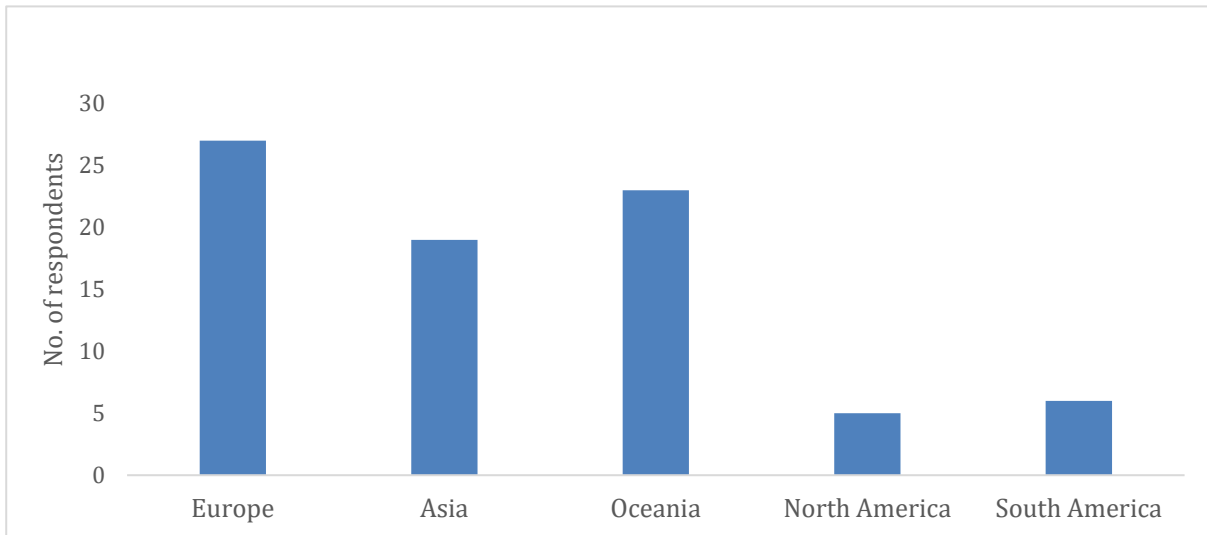
Figure 3.1 Total valid responses according to regions
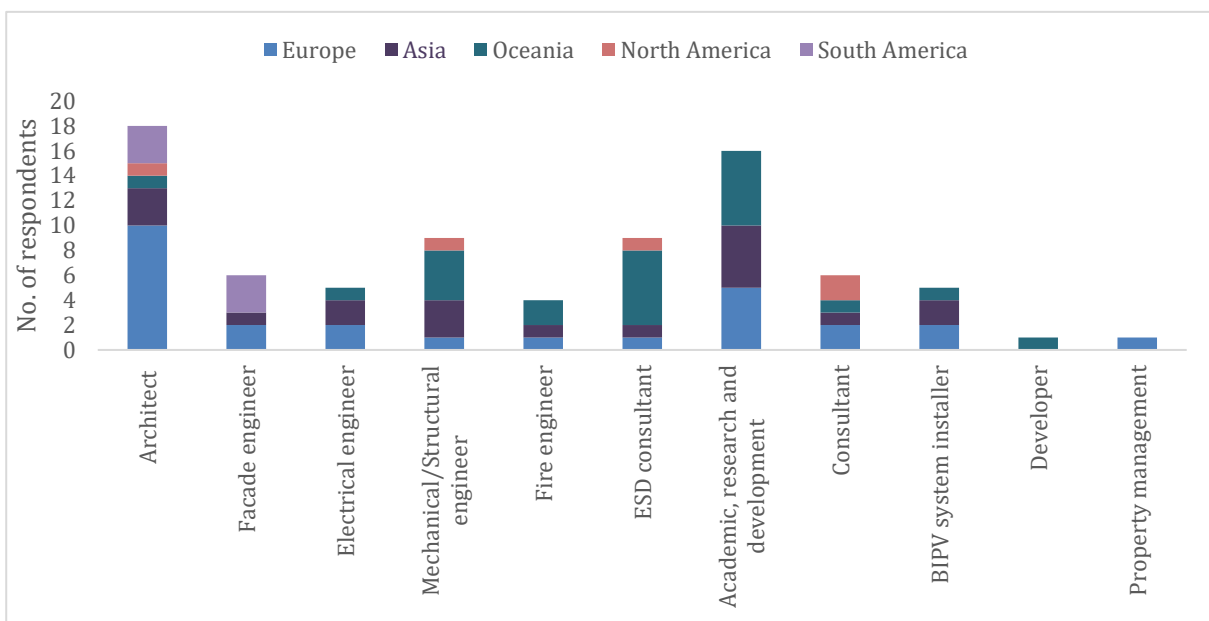
Figure 3.2 Total valid responses according to profession

Figure 3.2.3 shows the involvement of the respondents in building envelope (façade & roof) simulation and analysis and BIPV designs related simulation and analysis. As the figure shows, the majority of the respondents have experience related to building envelope simulation and analysis and not much in BIPV design simulation.
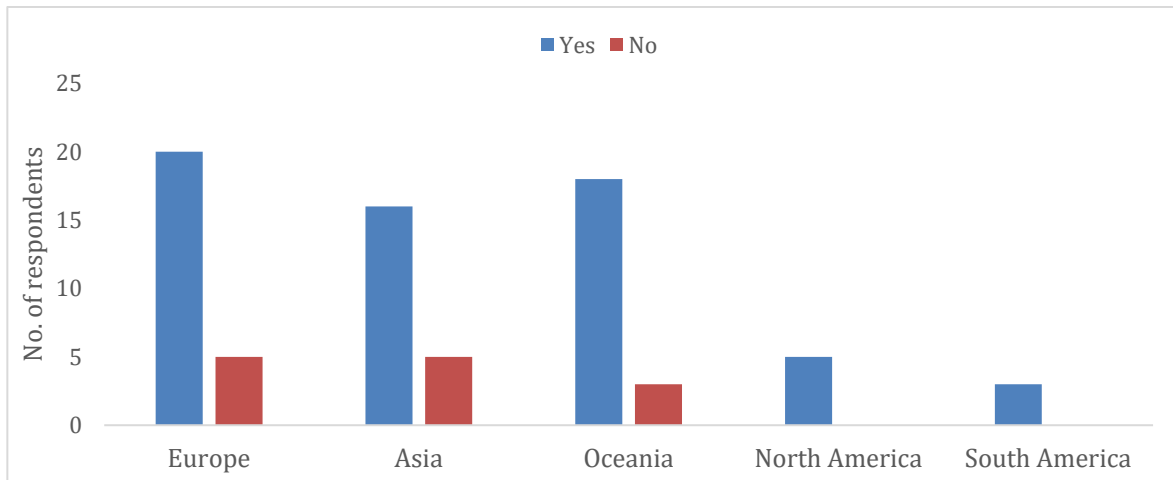
(a) experiences in building envelope (façade & roof) simulation and analysis
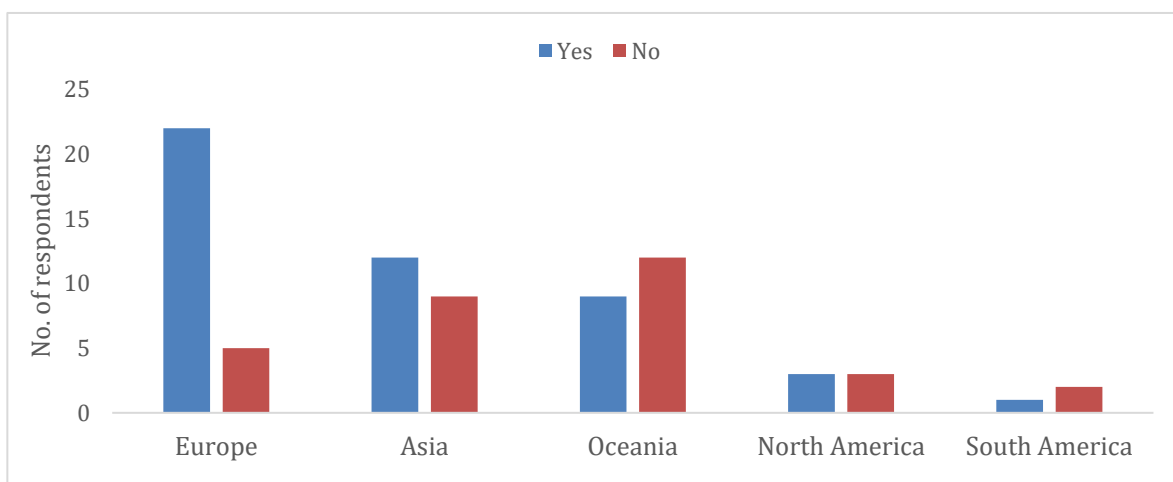
(b) experiences in BIPV simulation and analysis

Figure 3.3 Involvement of the respondents in building envelope (façade & roof) simulation and analysis and BIPV designs

3.3 Data analysis

The surveys responses were exported to Microsoft Excel for data screening. To obtain insightful findings from the survey, the answers were analysed based on: (a) region, and (b) profession. The survey responses were grouped into four categories and each subsection under the four categories consist of two figures demonstrating the result (a) region, and (b) profession. The regional results were sorted by 5 major groups. The profession results were sorted by 11 professions in the building, construction and BIPV industry. Based on the regional results and profession results, the difference and similarity of respondents from different groups can be distinguished. The noticeable findings from the two graphs are highlighted, which helps to understanding the digital design process of BIPV projects and make contribution to the further study of design and analysis for BIPV projects.

4 LITERATURE REVIEW ON WORKFLOWS AND METHODS USED IN BIPV DESIGN

In BIPV, the PV modules are integrated to the building elements. Therefore, both construction and electrotechnical elements need to be correctly designed which makes the design process of a BIPV system becomes more complex than a conventional building element. The BIPV design simulation and analysis process can be done using various operative approaches, methods, and workflows. As shown in Figure 4.1, these operative approaches, methods, and workflows relevant to each domain of BIPV design and integration can be divided into four categories: Workflows and methods used in

a. solar irradiation modelling and simulation

b. solar power output modelling or simulation

c. building performance modelling or simulation

d. financial, environmental and design outcome

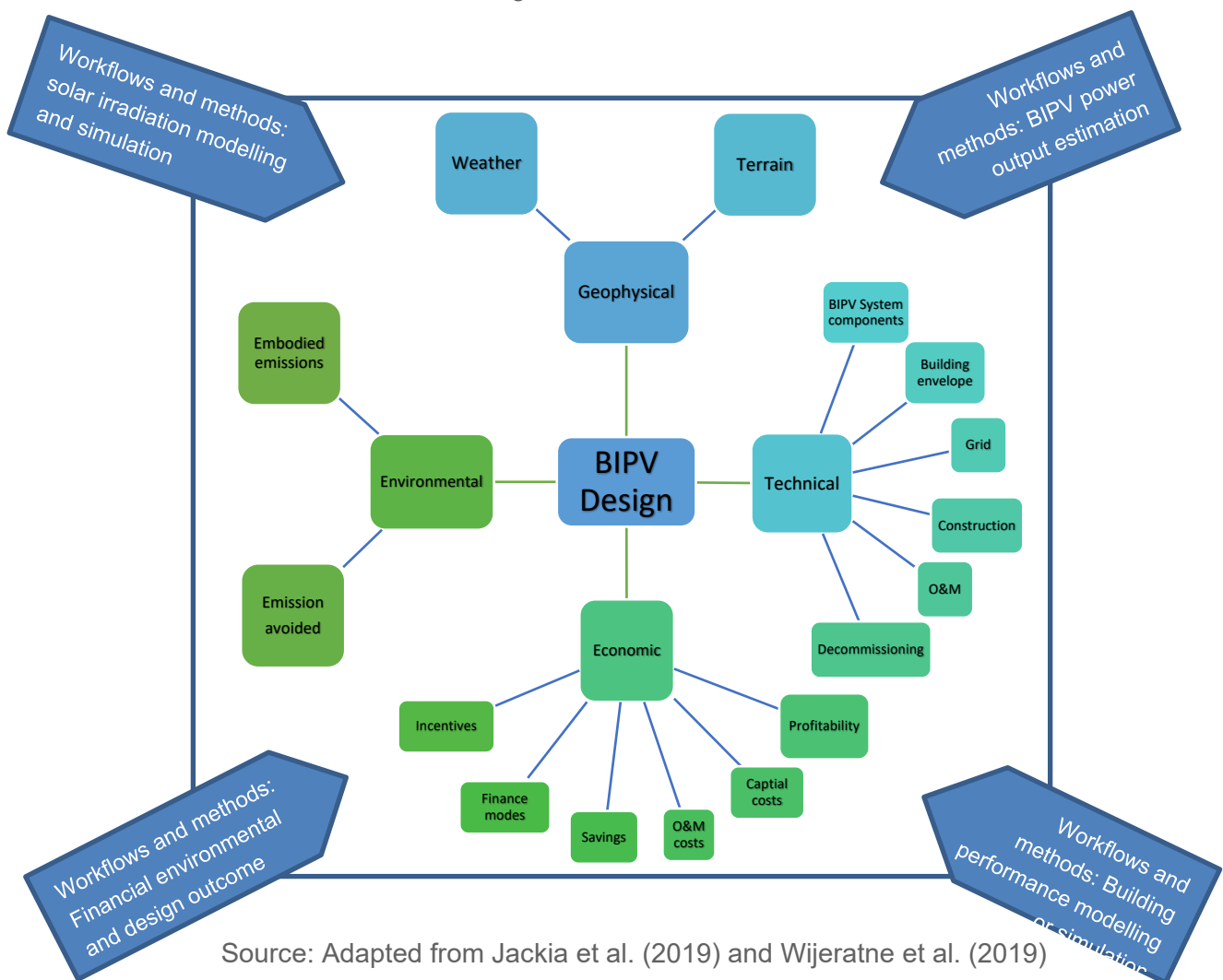Source: Adapted from Jackia et al. (2019) and Wijeratne et al. (2019)

Figure 4.1 Mapping of workflows and methods for BIPV design and simulation

4.1 Workflows and methods used in solar irradiation modelling and simulation

This section discusses approaches, methods and workflows used in modelling or simulating the BIPV project in a specific location and solar irradiation simulation.

4.1.1 Tools used for modelling building envelopes/BIPV envelopes

As the first step of designing a BIPV system, the building parameters such as building's location, orientation, energy consumption, roof and façade layout etc. should be identified. Often, architectural design software tools such as AutoCAD, Autodesk Revit and Sketchup etc. are used (Jakica, 2018, Wijeratne et al., 2019). All of them provide support for architectural design. Also, they consist of simple solar irradiation simulation tools. Such software can be used to generate a 3D model of the building and related envelope elements that will host BAPV or integrate BIPV components. The 3D model can provide information such as walls/roofs dimensions, shape of walls/roofs, surface tilt angles, structural characteristics, and thermal characteristics that can be necessary for developing the BIPV project. Further, the above software has the option to set up the building location which can help to identify the azimuth of the roof or wall surfaces.

4.1.2 Tools used for simulating solar irradiation in BIPV designs

There are many solar Photovoltaics (PV) design tools available for calculating solar irradiance and energy output. TRNSYS, Archelios, Polysun, PVSYST, PV*SOL, PVGIS, System advisory model (SAM), PVWatts and RETScreen (Axaopoulos et al., 2014, Freeman et al., 2014) are examples for software that are used often in the industry. However, BIPV is, in contrast to conventional PV, very prone to inhomogeneous irradiation. Therefore, identification of the impact of shading in BIPV designs are important. Yet, none of the tools listed consider shading which is very likely in BIPV applications. According to Stamenić and Erban (2021), BIPV systems can encounter three types of shading: 1. Micro - shading caused by the components of the BIPV module; 2. Mezzo - shading caused by the components of the BIPV system and building and 3. Macro – shading caused by external objects, adjacent building and trees. However, the tools used for simulating solar irradiation in BIPV do not differentiate between the impact of micro, mezzo or macro shading (Stamenić and Erban, 2021).

4.1.3 Methods used for identifying building location (i.e., longitude and latitude) in simulation tools

- **Google maps**: Google Maps is a web mapping service developed by Google. It offers satellite imagery, aerial photography, street maps, and 360° interactive panoramic views of streets. It can be used to identify the coordinates such as longitude and latitude (Google, 2020) and helps to identify weather information in BIPV design simulations.

- **IP addresses**: An Internet Protocol address (IP address) is a numerical label assigned to each device connected to a computer network that uses the Internet Protocol for communication. An IP address serves two main functions: host or network interface identification and location addressing to identify weather information in BIPV design simulations.

- **Select from software's own database**: Some software consists of a weather database where the users can select the relevant weather file from a drop-down list.

- **What3words app**: what3words app is like google maps and it helps to find precise locations easily (What3words, 2022).

4.1.4 Methodology for modelling the geometry of the building and surrounding environment of a BIPV project

The geometry of the building and surrounding environment of a BIPV project can be created two-dimensional (2D) and three-dimensional using various tools or techniques, as discussed below.

- **2D CAD**: 2D drafting and drawing is the process of creating and editing technical drawings, as well as annotating designs. Drafters use computer-aided design (CAD) software to develop floor plans, building permit drawings, building inspection plans and landscaping layouts (Autodesk, 2020).

- **3D CAD**: 3D CAD, or three-dimensional computer-aided design, is technology for design and technical documentation, which replaces manual drafting with an automated process (Jakica, 2018). Building information modelling (BIM) is a specialized field of 3D modelling which includes detailed information attached to every single component of 3D model.

- **GIS based modelling**: GIS-based modelling is when Geographical Information System (GIS) is used in the process of creating building and/or terrain models (Imam, 2019). GIS information can be incorporated into 2D and 3D building designs.

- **Point-cloud data using LiDAR**: LiDAR stands for "Light Detection and Ranging" (Reutebuch et al., 2005). This technology can be mounted to aerial vehicles to send laser pulses to the earth's surface and once the laser returns back to the sensor, the LiDAR system will record data based on information received. A point cloud is a collection of data points defined by a given coordinates system which can be created using LiDAR. The LiDAR point cloud data can be used to create 3D models of buildings and its surrounding environment.

- **Photogrammetry**: Photogrammetry is the technology for obtaining information about buildings and the environment through recording, measuring, and interpreting photographic images (Aber, Marzolff and Ries, 2010). Photogrammetry can generate 3D models of buildings and their surrounding environment in the BIPV design process.

4.1.5 Photorealistic visualization of BIPV envelope

Photorealistic architectural visualization can help architects communicate with their clients and provide a better presentation of their ideas. Photorealistic visualization helps to understand the aesthetic appearance of the BIPV project. It could eliminate the negative conceptions of BIPV appearance and encourage clients to accept BIPV projects. Therefore, photorealistic visualization could improve the uptake of BIPV and ultimately help create energy efficient and sustainable buildings. There are several commercial software tools that can be used to graphically represent the aesthetic appearance of a BIPV envelope. Rendering tools enable the use of photorealistic representations of solar installations, including simulation of colour, materiality and reflectivity (e.g., 3DS MAX, Maya, Revit, Autodesk rendering. Enscape, Lumion etc.)

4.1.6   3D formats for data exchange between collaborators or data import

A 3D file format is used for storing geometrical information about 3D models. In BIPV project designs, several 3D files formats can facilitate interoperability between BIPV design and simulation software such as proprietary formats:

- Trimble® SketchUp®.skp

- AutoDesk® .dwg, .rvt or. fbx

- Rhinoceros® .3DS

In addition, open formats, such as:

- o STL
- o OBJ
- o COLLADA
- o STEP

In addition to 3D file formats, there are file formats capable to retain not only the geometrical information about the 3D model but also building component informative parameters. Examples of these file formats are:

- Open BIM (ISO) .ifc

- GreenBuilding XML(gbXML) .xml

- EnergyPlusTM format .idf

- AutoDesk® REVIT®.rvt

- AutoDesk® REVIT®family.rfa

4.1.7   Weather parameters for identifying plane of array irradiation

The solar irradiance can be categorized into several parameters such as:

- **Beam/Direct normal irradiance (DNI)**: irradiance that comes directly from the solar disk

- **Diffuse Horizontal Irradiance (DHI)**: Scattered and reflected irradiance that is sent to the earth surface from all directions (reflected from other bodies, molecules, particles, droplets, etc.)

- **Global Horizontal Irradiance (GHI)**: Total irradiance from the sun on a horizontal surface on Earth. Sum of direct irradiance (after accounting for the solar zenith angle of the sun z) and diffuse horizontal irradiance

For BIPV system sizing or prediction of electricity generation, the main parameter to measure or determine is **Plane of Array (POA) irradiance**, or in-plane irradiance, which is the total irradiance (solar radiant flux incident per unit area) on the module's surface. POA irradiance includes direct plus diffuse irradiance. POA irradiance is measured with a pyranometer or a reference photovoltaic cell.

While irradiance is an instantaneous measurement of solar power over the area of the BIPV system, in watts per square meter, solar irradiation, or insolation, measures the cumulative solar energy density of over that area for a defined period of time, e.g., **annual, monthly, or daily irradiation**. Irradiation is commonly measured in kilowatt hour per square meter.

Apart from the POA irradiance, temperature and wind speed also play a role in BIPV design.

4.1.8   Type of weather data for designing BIPV

Weather data such as solar irradiance, temperature, wind speed etc. are obtained from different types of observing stations around the world. The main methods used to collect weather data are:

- Ground mounted meteorological stations

- Satellite based meteorological data

- Measured at site

- Hybrid method (i.e., combination of ground mounted meteorological data and data measure at site)

- Long-term averaged data

4.1.9   Type of weather file formats

Data formats commonly encountered in climate research fall into 2 categories.

- Typical Meteorological Year (TMY): A typical meteorological year (TMY) is a set of meteorological data with data values for every hour in a year for a given geographical location. The data are selected from hourly data in a longer time period (normally 10 years or more). Since, weather conditions can vary significantly from year to year, typical meteorological year (TMY) is commonly used for simulations. Since Hall et al. developed the first method for generating TMY, many different approaches are found in the literature to generate weather files [Hall, I J, Prairie, R R, Anderson, H E, and Boes, E C. Generation of a typical meteorological year. United States: N. p., 1978.]. Hall's method used statistical calculation to select one typical meteorological month from a period of years of data and concatenating the 12 months to form a TMY.

- Typical Meteorological Year 2 (TMY2) developed by the National Renewable Energy Laboratory (NREL) use synthetic year to represent the temperature, solar radiation, and other variables, based on improved solar models to more closely match the long-term average climatic conditions. The TMY3 are constructed using more recent data than the TMY2 (1991-2005 against 1961-1990 respectively). Many other countries have their own set of TMYs. The Joint Research Centre (JRC) of the European Commission supplies TMYs through its PVGIS tool [https://re.jrc.ec.europa.eu/pvg_tools/es/#TMY], using satellite data and following the procedure described in ISO 15927-4 for the month selection. Commercial software packages supporting simulations using TMY data include TRNSYS, PV*SOL, PVscout and PVSYST.

- EPW files from the EnergyPlus website: Weather data file saved in the standard EnergyPlus format. It is used by EnergyPlus energy simulation software and was developed by the U.S. Department of Energy (DoE) (Sabunas and Kanapickas, 2017). It can also accommodate TMY weather data which can be used for running energy usage simulations.

The most used file formats for TMY are CSV (comma-separated values), EPW (Energy Plus Weather File), and JSON (JavaScript Object Notation). CSV and EPW usually include a header with the information of the site (latitude, longitude and elevation), and the list of the years used for each month to construct the TMY.

4.1.10 Software used to estimate plane of array (POA) irradiation

Various POA irradiance estimation software available for the users to choose from. Klise and Stein (2009) have identified this software under five categories:

- PV Models Developed and Used by Sandia National Laboratories: PVSS, SOLCEL, Evans and Facinelli Model, PVForm, PVSIM, Sandia Photovoltaic Array Performance Model, Sandia Inverter Performance Model, PVDesignPro, Solar Advisor Model

- Other PV Performance Models: Parameter Array Performance Model, PVWatts, PVSYST, PV F-Chart, RETScreen Photovoltaic Project Model, PV*SOL, Polysun, INSEL, SolarPro

- Simplified PV Performance Models: Clean Power Estimator, PVOptimize, OnGrid, CPF Tools Solar Estimate

- Hybrid System Models Developed and Used by Sandia National Laboratories: SOLSTOR, HybSim, Hysim

- Other Hybrid System Models: HOMER, Hybrid2, UW-Hybrid (TRNSYS), RETScreen, PVToolbox, RAPSIM, SOMES, IPSYS, HySys, Dymola/Modelica

4.1.11 Models in software to estimate POA irradiation

There are several methods that can be used to estimate Plane of array (POA) irradiation.

- POA (Beam only): The plane of array (POA) beam component of irradiance is calculated by adjusting the direct normal irradiance by the angle of incidence (Sandia National Laboratories, 2018)

- POA with shading and ground reflected (Albedo): The plane of array (POA) irradiance on a tilted surface with shading impact caused from neighbouring objects and irradiance on a tilted surface that is reflected off the ground

- Ray tracing with radiosity: Ray tracing follows all rays from the eye of the viewer back to the light sources and radiosity simulates the diffuse propagation of light starting at the light sources (Yu, 2010). This can be used to identify and visualise the POA irradiation. Software such as EDSL TAS, DIAL+Suite and Autodesk 360 rendering engine used in INSIGHT (Solar analysis tool) for Revit use this approach (Jakica et al., 2019).

- Ray tracing with rasterization: A hybrid approach that combined the speed of rasterization with the visual accuracy of ray tracing (HAR-EVEN, 2018)

4.1.12 POA sky diffuse model to estimate POA irradiance

- Isotropic Sky Diffuse Model: The isotropic sky diffuse model is the simplest of the POA sky diffuse models and forms the foundation upon which more accurate models build. The isotropic sky diffuse model assumes that the diffuse radiation from the sky dome is uniform across the sky (Sandia National Laboratories, 2018).

- Simple Sandia Sky Diffuse Model: This is an empirical model calculating diffuse sky irradiance developed at Sandia National Laboratories (Sandia National Laboratories, 2018)

- Hay and Davies Sky Diffuse Model: The Hay and Davies model divides the sky diffuse irradiance into isotropic and circumsolar components to calculate the plane of array irradiance (Hay and Davies, 1980).

- Reindl Sky Diffuse Model: Reindl sky diffuse irradiance model consists of diffuse radiation on the POA, including isotropic, circumsolar brightening, and horizon brightening (Reindl, Beckman, and Duffie, 1990).

- Perez Sky Diffuse Model: BIPV models will often use non-isotropic sky conditions (Snow and Prasad, 2005). The Perez model, accounts for non-isotropic sky characteristics such as variations in clouds, and variations in sky due to atmospheric thickness (Perez et al., 1987)

4.1.13 Models to estimate impact of shading in BIPV

As discussed in section 4.1.2, BIPV can be impacted by micro, mezzo and macro shading. There are several shading modelling methods used in PV simulation tools to identify the impact of shading on the level of irradiance receive by the BIPV system such as far-field shading horizon map, far field shading factor, near-field shading factor, shading percentage, reduction of incident irradiation, shading index, sky view factor and ray tracing (Mermoud 2010; Zomer and Rüther 2017; Jakica et al., 2019).

4.1.14 Weather data interval for solar irradiation data

Weather data interval values can be by Minute, Hourly, Daily, Monthly or Annually. The weather data interval can differ based on purpose of use. For example, for conceptual design stage, monthly and annual values can be considered whereas, in detailed design stage, minute or hourly data is more useful.

4.1.15 BIPV module performance with higher spatial resolutions

The BIPV module performance with higher spatial resolutions (PV cell level or higher) is simulated for complex building envelope installations. Currently, Ladybug tools can simulate BIPV performance on PV cell level when coupled with external script in MATLAB (Hofer et al., 2016).

4.2 Workflows and methods used in solar power output modelling or simulation

This section discusses the approaches, methods and workflows used in modelling or simulation of the BIPV power output.

4.2.1 Importing properties of the technical components of BIPV modules and other BIPV related components to the simulation.

There are several methods that can be used to extract BIPV product information:

- Database of components such as PV modules and inverters which automatically load the items to the simulation program

- Online platforms to import product data

- Specific exchange format to import products

- Adding properties manually

4.2.2 Methods used for calculating the electric DC output of BIPV

There are several methods for calculating BIPV system power output. Most of them are based on different PV module models relating the I-V characteristics and the module temperature:

- Cell Temperature Model (Faiman 2008; Trinuruk, Sorapipatana and Chenvidhya, 2009)
  - Sandia Cell Temperature Model
  - PVSYST Cell Temperature Model
  - Faiman Cell Temperature Model
- Single Diode Equivalent Circuit Models
  - De Soto "Five-Parameter" Module Model (De Soto, 2006)
  - PVSYST Module Model
- The two-diode model
- Point-value models
  - Sandia PV Array Performance Model
  - Loss Factor Model
- Power model by Heydenreich et al. (2008)

4.2.3 Software for calculating the electric DC output of BIPV

There are various models and software which can be used to calculate the electric DC output (Klise and Stein, 2009; Jakica, 2018; Jakica et al., 2019; Wijeratne et al., 2019):

- PV Models developed and used by Sandia National Laboratories: PVSS, SOLCEL, Evans and Facinelli Model, PVForm, PVSIM, Sandia Photovoltaic Array Performance Model, Sandia Inverter Performance Model, PVDesignPro, Solar Advisor Model
- Simplified PV Performance Models: Clean Power Estimator, PVOptimize, OnGrid, CPF Tools Solar Estimate
- Other PV Performance Models: Parameter Array Performance Model, PVWatts, PVSYST, PV F-Chart, RETScreen Photovoltaic Project Model, PV*SOL, Polysun, INSEL, SolarPro, Aurora Solar, Helioscope, BIMSolar, Skelion, Archelios, PVGIS
- Hybrid System Models developed and used by Sandia National Laboratories: SOLSTOR, HybSim, Hysim
- Other Hybrid System Models: HOMER, Hybrid2, UW-Hybrid (TRNSYS), RETScreen, PVToolbox, RAPSIM, SOMES, IPSYS, HySys, Dymola/Modelica

4.3 Workflows and methods used in building performance modelling or simulation

This section discusses the approaches, methods, and workflows to identify BIPV related building dynamics such as energy consumption, thermal load, structural load and fire safety.

4.3.1 Method used for identifying building energy consumption

If not designed properly, most buildings can consume far more energy than they produce with BIPV. An efficient BIPV system could reduce the energy consumption of the building as well

as supply excess energy to the grid. Therefore, BIPV systems need to be accurately sized. For that, we need to understand the energy consumption of the building and the energy offset potential of a BIPV system. There are several methods to identify the energy consumption of a building, such as measuring real-time data via smart meter or sensors or simulating the building energy performance and building energy systems' demand. In the survey, the methods considered are listed as below:

- Calculate total watt-hours per day for each appliance used in the building/project
- Calculate the percentage of monthly energy consumption based on habitual use and use during weekends and holidays
- Use historical information from electricity bills
- Measure building energy consumption real time
- Simulate using a building energy simulation software: data of building consumption can be generated by building energy simulation software such as EnergyPlus, DeST, DOE2 or Ecotect (Amasyali et al. 2018)
- Definition of the building type and utilization of Energy Use Intensity (EUI) data based on building type. This data is published for US buildings by the U.S. Energy Information Administration (EIA) ref. eia.gov

4.3.2 Energy consumption data interval

Interval data is simply energy data collected at defined intervals, typically every 15 minutes or hourly (gridium, 2012). Generally, energy data intervals can be taken annually, monthly, daily, hourly, sub-hourly, one minute and in seconds. However, in BIPV design, the required interval may differ depending on the software time resolution or based on whether the design is done in the conceptual design phase or detailed design phase.

4.3.3 Type of data file formats for storing building energy consumption data

Building energy consumption data can be stored in file formats such as:

- Text file
- MS Excel spreadsheet
- Comma Separated Values (CSV file)

4.3.4 Thermal load

The photovoltaic effect in BIPV produces a substantial amount of heat, while generating power. Consequently, BIPV has significant influence on the amount of heat transfer through the building fabrics, and could affect the indoor air temperatures, cooling load and the comfort of the occupants, as it changes the thermal properties of the building envelops (Toledo et al. 2020). Although BIPV heats up the glass and the envelope, it also blocks light from entering the envelope. Given that most envelopes are protected by an air gap within an insulated glass unit, the heat of the BIPV unit does not pose a detrimental threat to the envelope's cooling load. The benefit of solar technologies absorbing the sunlight and converting it into electricity likely far outweighs this risk due to the thermal break. Therefore, the SHGC for BIPV glass is typically lower than that of conventional glass, despite the BIPV being hotter (Olivieri et al. 2015; Moralejo-Vázquez et al. 2015; Kapsis, Athienitis and Harrison 2017). Therefore, understanding the SHGC of BIPV glass is important due to the energy savings potential. Various thermal models of BIPV system have been proposed and examined to achieve a good

thermal prediction of BIPV systems (Assoa et al. 2017). This can be done by calculating solar heat gain manually or simulate using a building energy simulation software such as IES-VE, EnergyPlus.

4.3.5 Heat island impact of BIPV systems

According to Genchi et al. (2003), if PV panels are installed over a large area, the surface heat balance of the city will be altered. There are not many methods to explore heat island effects of BIPV systems. A study by Thomas (2014) have explored heat island effect using a Revit 3D model and EnergyPlus simulation. Further, the CitySim thermal models was used by Thomas et al., (2014) to simulate the target building to identify the heat island effect. Boccalatte, Fossa, and Ménézo, (2020) created a method with EnergyPlus model with OpenStudio plug-in and the Urban Weather Generator (UWG) to simulate the heat island impact of a BIPV system. Further, there are studies which have used various methods/tools to simulate the impact of BAPV on heat island effect. For example, Taha (2013) used a method with the albedo and the solar conversion efficiency to estimate the heat island impact of solar PV. Masson et al. (2014) have used Town Energy Balance (TEB) model to simulate roof top BAPV related heat island effect on the Paris metropolitan area.

4.3.6 Methods to identify the impact on daylighting in BIPV design

When implementing a semi-transparent BIPV façade, natural daylighting can be affected because of opacity of the solar cells in the glass panes. Therefore, the impact needs to be calculated manually or use simulation software such as DIVA for Rhino, Sefaira, Revit Insight (Yi He and Schnabel, 2018). Further, a multitude of online tools provided by glass manufacturers such as Pilkington, Saint-Gobain, AGC can be used for analysing the daylighting in BIPV projects.

4.3.7 Structural loads

As part of building elements, structural load analysis needs to be considered for the selection of BIPV products. However, like other building envelope elements, poor design or lack of design standard of structural loads could lead to technical flaws on BIPV projects (Yang 2015). According to Bernalillo County (2017), dead load, wind load, earthquake (seismic) load, live load, rain load, snow loads need to be identified in BIPV Engineering.

4.3.8 Methods and software for the structural impact of BIPV designs

Not many PV simulation tools have the option for analysing the structural impact of BIPV designs. For instance, Easy PV provide options for structural load calculations. Easy PV offers a simple calculation for the dead load and the wind load based on roof structure types (such as flat, truss, rafters, roof with hips and valleys, asymmetric pitched roof etc.) (Wijeratne et al., 2019). However, the majority of all BIPV panels are made from glass any glass calculation software can do the job (e.g., SJ-Mepla, Glasstik). According to local norms on construction sector, the structural engineering of BIPV systems (e.g., roof, facades, balustrades, etc.) usually follows the building design code practices. Therefore, building design software already has this capability through the use of a BIPV plugin.

4.3.9 Methods and software to identify the fire related impact in BIPV designs

As BIPV consist of construction and electrical parts, it is necessary to check whether the selected BIPV design comply with building fire regulations, which is crucial to the safety. There is no international fire safety harmonization. Furthermore, there is a lack of fire-related

international standards and building codes specific for BIPV systems (Yang 2015). However, some countries have their national fire safety standards (e.g., Europe - EN 13501, Germany - ENV1187 or DIN4102). In some countries, the practice is based on separated standards for construction and conventional PV systems (Bonomo, 2018). For this fire testing process, there is no straightforward technique. Some new methods for fire testing in BIPV are proposed by Jol et al. (2009) and Parolini (2020) such as conventional fire test with burning brands and radiant heat, and self-developed test protocol for fire behaviour. With the development of computer technology, simulation software can facilitate the numerical analysis of smoke and heat transport from fires, such as Fire Dynamics Simulator (McGrattan et al. 2010).

4.4 Workflows and methods used in financial, environmental and design outcome

This section discusses the approaches, methods and workflows used for identifying the economic impact of BIPV designs.

4.4.1 Economic feasibility indicator(s) of BIPV designs

The cost- benefits is important for decision making in BIPV adoption. The indicators used to identify the economic feasibility of BIPV projects could help the evaluation process of the decision makers such as property developers. For renewable energy technologies and projects, there are a variety of economic indicators (Short et al. 1995). Sommerfeldt and Madani (2017) investigated studies regarding PV generation and summarized the popularity of different economic indicators. Some extensive references investigating BIPV cost competitiveness and real case-studies are already available in literature (SUPSI-Becquerel Institute, 2020; BIPVBOOST, 2021). The selection of economic indicators should depend on the emphasis of the economic analysis and the need of audience. The following 6 indicators are included:

- **Net Present Value (NPV)**: The difference between the present value of cash inflows and the present value of cash outflows over a period of time. When NPV is above zero, the BIPV project can make profit during its lifespan.

- **Simple Payback Period (PB)**: Payback period refers to the time required to recoup the funds expended in an investment, or to reach the break-even point.

- **Discounted Payback Period (DPB)**: Similar to PB, DPB is the amount of time it takes to recover the cost of an investment. The difference is DPB considered the time value of money in the calculation.

- **Internal Rate of Return (IRR)**: Discount rate that makes the NPV of all cash flows equal to zero in a discounted cash flow analysis. If the IRR is higher than a particular interest rate or the discount rate used, the BIPV project can be financially feasible.

- **Profitability Index (PI)**: Measure of a project's or investment's attractiveness. The PI is calculated by dividing the present value of future expected cash flows by the initial investment amount in the project

- **Return on Investment (ROI)**: Return on investment or return on costs is a ratio between net income and investment. A high ROI means the investment's gains compare favourably to its cost.

- **Levelized cost of energy (LCOE)**: The levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the average net present cost of electricity generation for a generating plant over its lifetime.

- **Incremental Cost (IC)**: The incremental cost of a BIPV system is the cost of the components that are additional to the elements that would otherwise be intrinsic to the built environment. The IC serves as a cost basis for the financial analysis of BIPV systems.

4.4.2 Capital cost (initial costs) of BIPV designs

Capital costs are fixed, one-time expenses incurred on installing a BIPV system. Total capital cost of a BIPV project consists of (Norton et al., 20011; Fu et al., 2016; Yang et al., 2019 Weerasinghe et al. 2021):

- Solar PV module costs

- Solar PV mounting structure cost

- Solar PV installation cost

- Costs of electrical devices (Balance of System) and installation costs

- Contingency

4.4.3 Operations and maintenance costs

The Operation and Maintenance (O&M) costs of BIPV system is the cost associated with operating and maintaining of the BIPV system throughout its lifetime. O&M costs of a BIPV system can include the following (Agrawal & Tiwari 2010; Gholami et al. 2020; Frischknecht et al. 2020; Weerasinghe et al. 2021):

- Cleaning costs

- Repair of solar PV modules

- Repair of electrical devices (Balance of System)

- Repair of mounting system

- Replacement of solar PV modules

- Replacement of electrical devices (Balance of System)

- Replacement of mounting system

- Insurance

- Depreciation

4.4.4 Life cycle income of BIPV system

Life cycle income of BIPV systems refers to the profit generated by the BIPV system throughout its lifetime. The benefits from BIPV systems that can be considered as life cycle income are listed below (Agrawal & Tiwari 2010; Bonomo et al. 2017; Gholami et al. 2020):

- Saving from energy self-consumption

- Income from feed in tariffs

- Salvage value at the end of BIPV system life

- Savings from reducing building cooling load

4.4.5 Incremental cost

One benefit of BIPV modules is that they completely replace traditional building materials. Therefore, the overall system costs should reflect the corresponding cost offset in the design evaluation (Eiffert, 2003). However, there is limited research regarding the material cost offset brought by different BIPV applications (Yang et al., 2019). Moreover, according to Wijeratne et al. (2019), none of the available software and apps have considered building material cost offsets in their PV system design platforms or in financial analysis.

4.4.6 CO_2 emissions associated with BIPV designs

The environmental impact of BIPV systems can be evaluated considering different approaches and indexes. The most common approaches allow calculating the reduction of CO_2 emissions and/or embedded emissions.

- Reduction of the CO_2 emissions/CO_2 emissions avoided: Avoided emissions are emission reductions that occur as a result of free electricity generation of the BIPV system during the operational phase of BIPV system (Seng et al. 2008). Usually, the CO_2 emission avoided can be calculated by the reduction in CO_2 emission by the electricity production of the conventional power plants, which should consider the local utility sectors.

- Calculating the embedded emissions: Embedded emission of BIPV system is the emissions that occur in BIPV during the manufacturing, construction, and decommissioning phase, which is used for the calculation of energy payback period (Hammond et al. 2012; PAYET and Moreau, 2016).

4.4.7 Optioneering/ decision making methods in BIPV design

Designing BIPV envelopes is a complicated task where you are required to balance various antagonistic parameters. Several key factors impact the decision of choosing a BIPV system design to a building. Besides the initial investment costs, amount of energy saved, annual maintenance costs, reduction of greenhouse gases and profitability of the overall project are considered. There are several methods that can be used to evaluate BIPV design options:

- Multiple solution comparisons using parametric workflows: This includes use of parametric software to generate feasible BIPV design options

- Multiple solution comparisons using traditional workflows: The traditional workflows consider use of 2D design drawing and use of basic software such as MS excel or manual calculation methods to identify the feasible BIPV design options.

- Integrated optimization: Integrated optimisation uses advanced methods such as machine learning techniques such as genetic algorithms, neural networks etc. to identify the feasible BIPV design options.

4.4.8 Factors that impact optimum BIPV design options

When identifying the most suitable design option, designers can determine and fix any variables that meet their design priorities/preferences. Among them, some parameters are high on the list of priorities for any BIPV project from diverse perspectives, such as (Erban and Ley 2020; Samarasinghalage et al. 2022):

- Aesthetic appearance (size, shape, colour and transparency)

- Design and functionality (flexibility, cell coverage and combination with other building functions)

- Cost

- Energy generation

- CO_2 emissions avoided

- Thermal impact

5 QUESTIONNAIRE SURVEY RESULTS

## 5.1 Workflows and methods used in solar irradiation modelling and simulation

5.1.1 Tools used for modelling building envelopes/ BIPV envelopes

The Figure 5.1.1 shows the survey results on tools used for modelling building envelopes and BIPV envelopes. Overall results show that AutoCAD is used by most respondents followed by Sketch-up and Autodesk Revit. AutoCAD is commonly used for 2D drafting (Gindis and Kaebisch, 2017). However, the AutoCAD platform can be used to create 3D models. Sketch-up and Autodesk Revit are used for 3D modelling and building information modelling (Jakica, 2018). It can be seen that regionally (Figure 5.1.1a), AutoCAD and Sketchup is highly used by the respondents from Asia and Europe compared to other regions. Autodesk Revit is also prefered in Australia, Asia and Europe. Other design software such as Rhinoceros and ArchiCAD are also used by the respondents in Europe.

As shown in Figure 5.1.1b, AutoCAD, Sketchup and Autodesk Revit are mostly used by Architects and Academic research and development for modelling building envelopes and BIPV envelopes. However, other professions such as Electrical engineers and Façade engineers also use Sketchup and Mechanical/structural enginners use AutoCAD and Autodesk Revit. The resutls show that AutoCAD, Sketchup and Autodesk Revit can cater many professions for modelling building/BIPV envelopes.
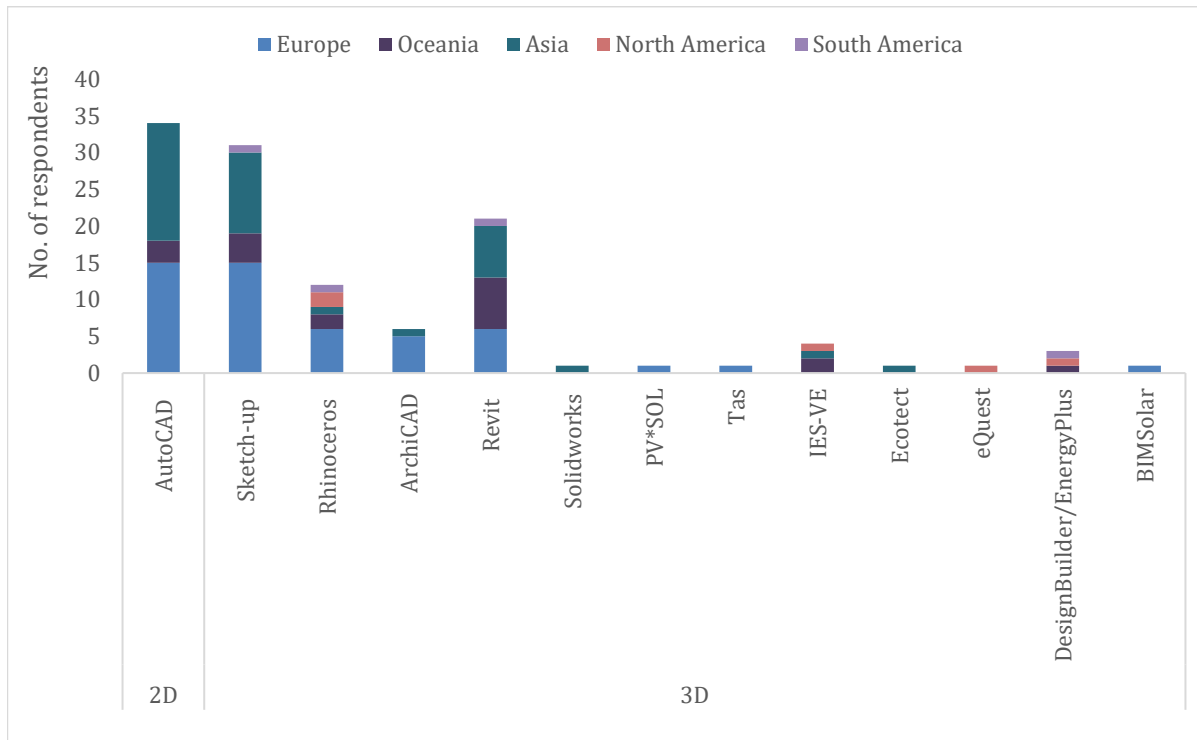
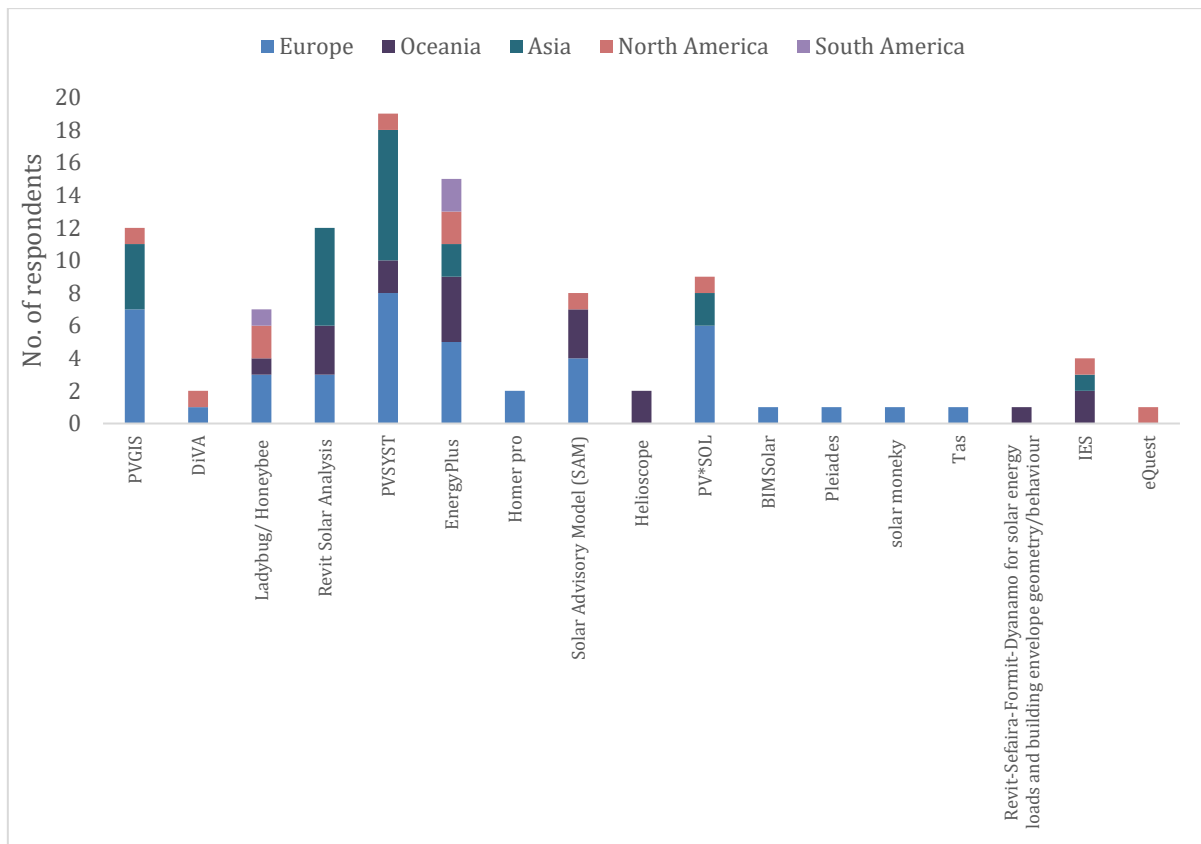(a) Survey results by region
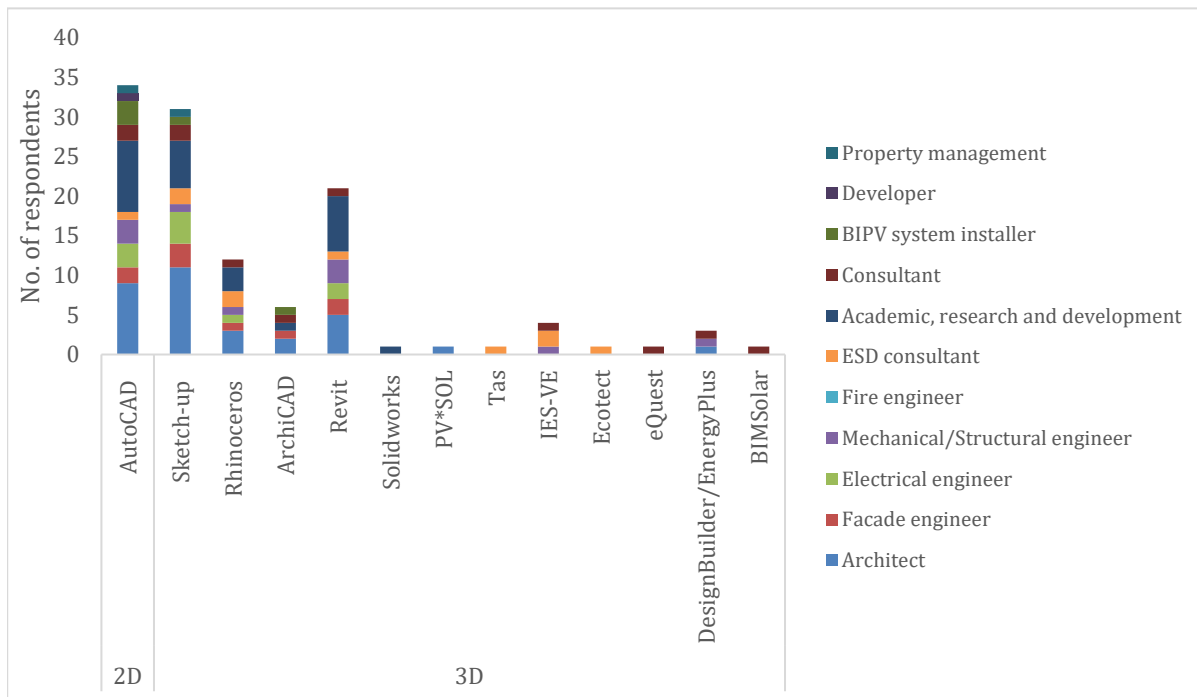
(b) Survey results by profession

**Figure 5.1 Tools used for modelling building envelopes/ BIPV envelopes**

5.1.2 Tools used for simulating solar irradiation in BIPV designs

Figure 5.1.2 illustrates the survey results on tools used for simulating solar irradiation. In total, the number of respondents who use PVSYST is relatively high. Further, EnergyPlus, Revit Solar Analysis, PVGIS, PV*SOL, SAM and Ladybug/Honeybee are also used by many respondents. In terms of the region of the respondents, PVSYST is highly used by the respondents from Europe and Asia. Compared to Europe and Australia, Revit solar analysis is used more in Asia. However, the respondents who use Energyplus for PV simulation is high in Europe and Australia. Compared to other regions the use of PVGIS and PV*SOL is higher in Europe. Although PVGIS calculator covers solar data in America, Europe, Asia and Africa, it is more popular with the respondents from Netherland.

On the other hand, PV*SOL is popular with the respondents from Germany. The reason for the popularity is that PV*SOL was developed by a German-based software company and the software has been available since 1998 (International Solar Energy Society, German Section, 2013). Professional wise, Architects and Academics use EnergyPlus and Revit Solar Analysis for solar PV simulation. PV*SOL is also considered by Architects. The respondents from professions such as electrical engineering, façade engineering, academic and consultancy use PVSYST for solar PV simulation. Overall, the results show that building design professionals prefer PV simulation tools which can be used with CAD or BIM software whereas professions such as BIPV system installers and PV consultants use solar PV simulation software that are more devoted to technical parameters such as SAM, PVSYST and PVGIS.
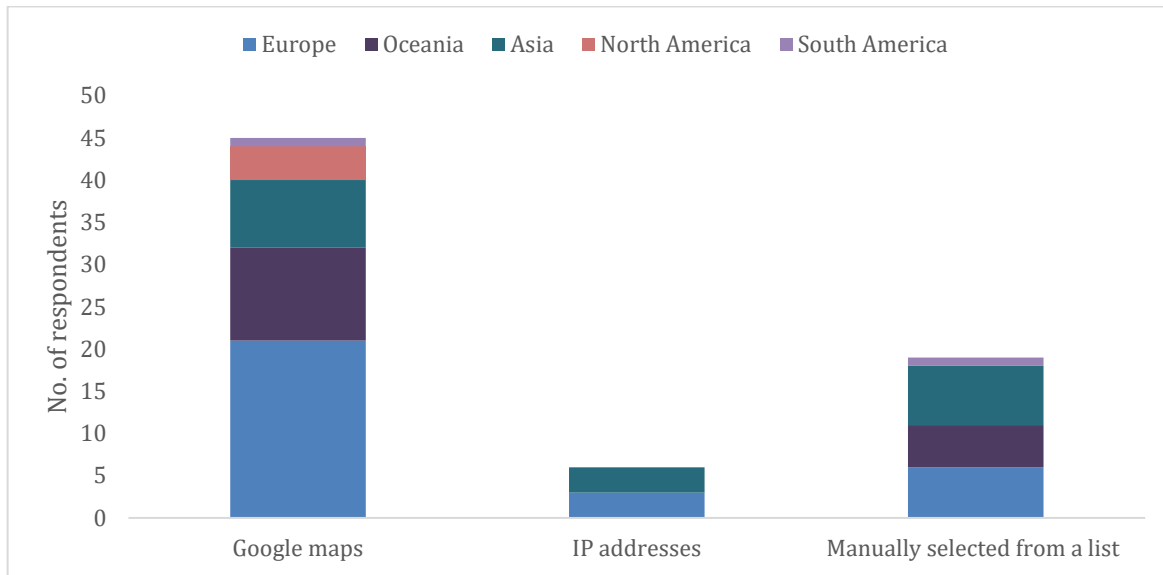

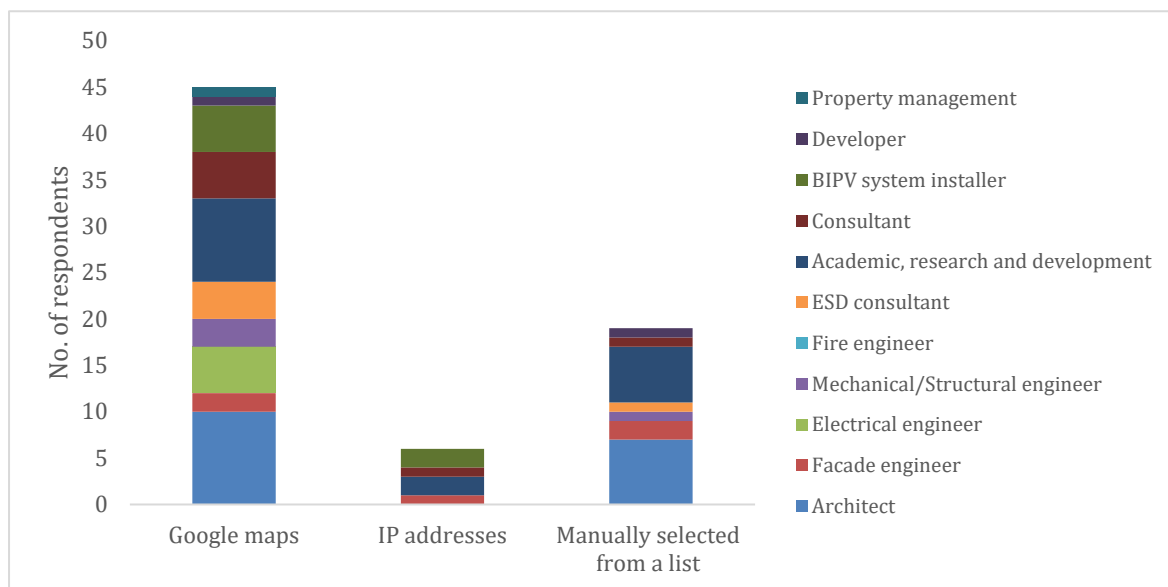(a) Survey results by region
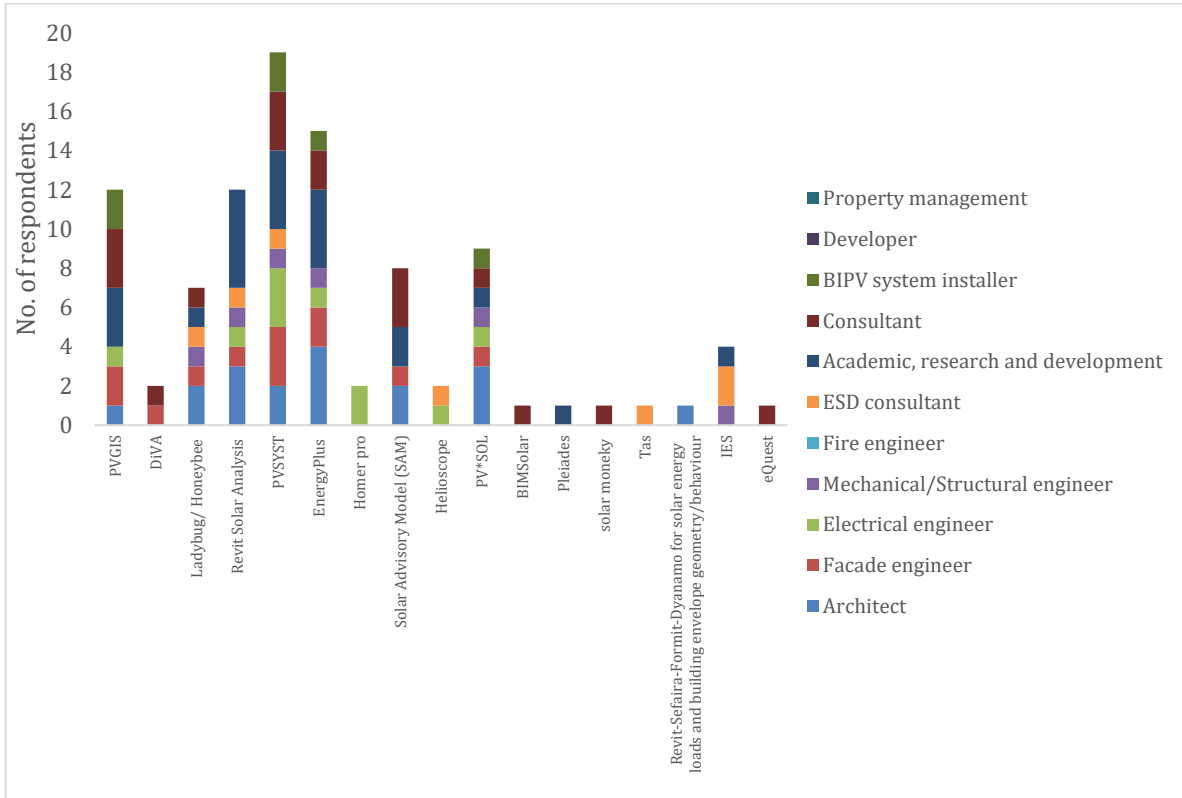
(b) Survey results by profession

Figure 5.2 Tools used for simulating BIPV

5.1.3 Methods used for identifying the location for BIPV design in simulation tools

As discussed in Section 4.1.3, simulation tools typically require the user to identify the location (i.e., longitude and latitude) of the building to collect local weather data parameters. There are three common ways to identify the building location in simulation tools. Figure 5.1.3 a and Figure 5.1.3 b shows the survey results on the methods used in simulation tools to identify the building location. Overall, most of the respondents have selected the use of google maps to determine the location. Compared to methods such as identifying the location manually from a list or use of IP addresses for identifying location, higher number of respondents from Europe, Oceania, Asia and North America are using google maps to determine the location of the project in the simulation tools. The same pattern can be observed in the professional wise responses. Most professions use google maps to select the location of the BIPV project in the simulation tool. It can be seen from the survey results that the use of maps to identify the location and weather data is a suitable approach for BIPV design in simulation tools.

(a) Survey results by region

(b) Survey results by profession

**Figure 5.3 Methods used for identifying the location**

5.1.4 Methodology for modelling the geometry of the building and surrounding environment

Generally, there are five common methods for modelling the geometry of the building and surrounding environment as discussed in Section 4.1.4. Figure 5.1.4 shows the survey results on the methods used for modelling the geometry of the building and surrounding environment by region and by profession. In total 3D CAD is the most popular method, accounting for about 50% of all choices. 2D CAD takes the second place, making up 21% of total respondents.

Compared with CAD-based methods, GIS-based modelling and Point-cloud data are less adopted.

In addition, Photogrammetry is used for developing the geometry of building models. Eight survey respondents have mentioned that they do not model building geometry and surrounding environment in BIPV related simulation. Regionally, higher number of respondents from Europe, Oceania, Asia and North America use 3D CAD. 2D CAD is also considered in Europe, Oceania, Asia. Although there's a low use of GIS-based modelling, the methods are used in all the regions under consideration. In contrast, photogrammetry has been considered for modelling the geometry of buildings only in Europe. Furthermore, use of point cloud data with LiDAR 3D scanning is used in Europe, Oceania, and America. Professionally, higher number of Architects uses 3D CAD and 2D CAD for modelling buildings. Professions such as Engineers, ESD consultants, BIPV installers and Academics prefer to use 3D CAD compared to other methods. The overall results suggests that 2D CAD and 3D CAD are popular methods for developing the geometry of building models. However, 3D CAD is more suitable for BIPV designs as it provides a more realistic visualisation of the building model.
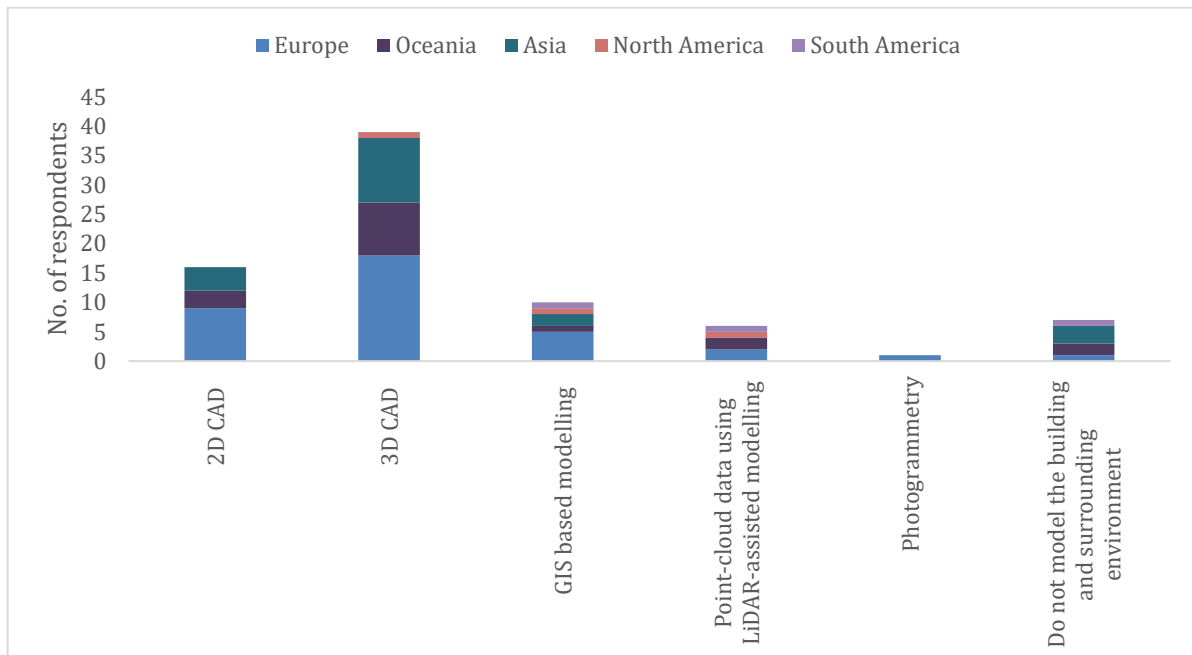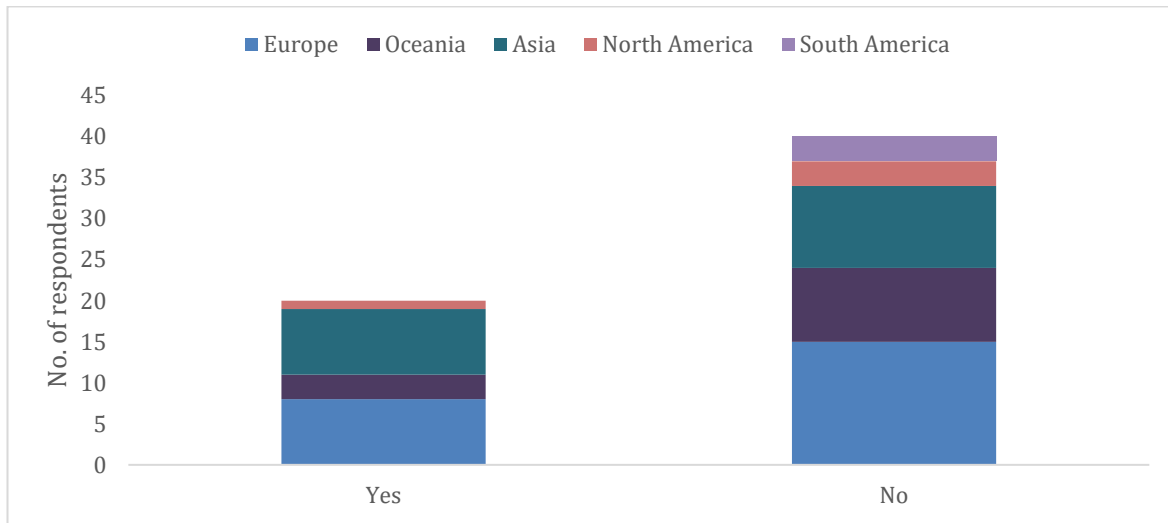

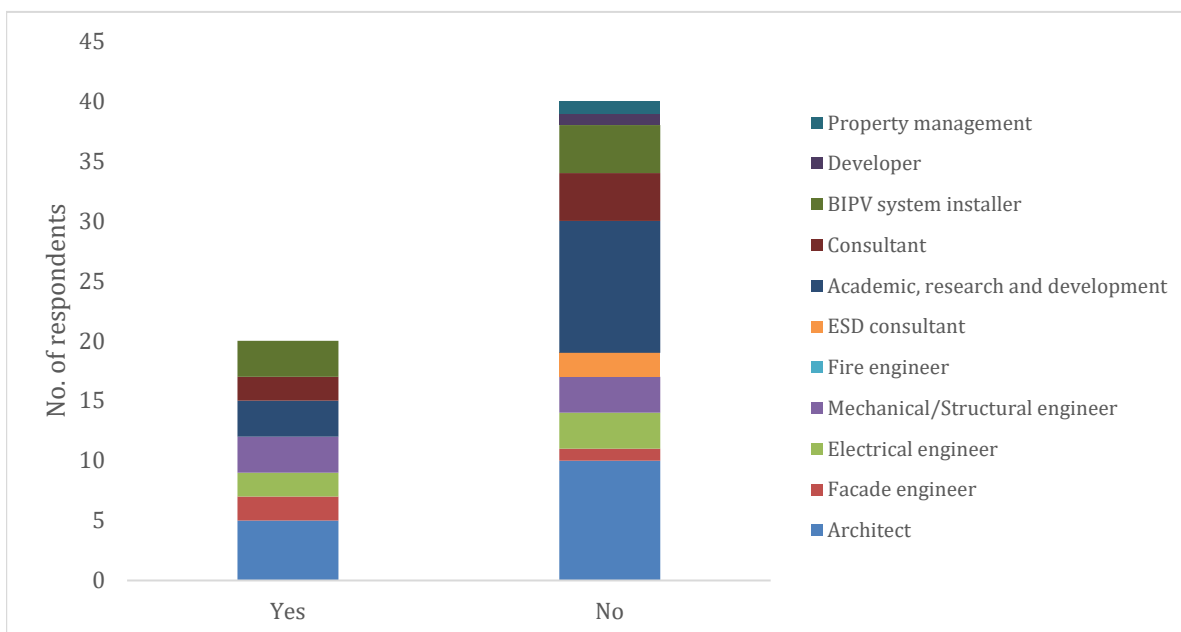(a) Survey results by region
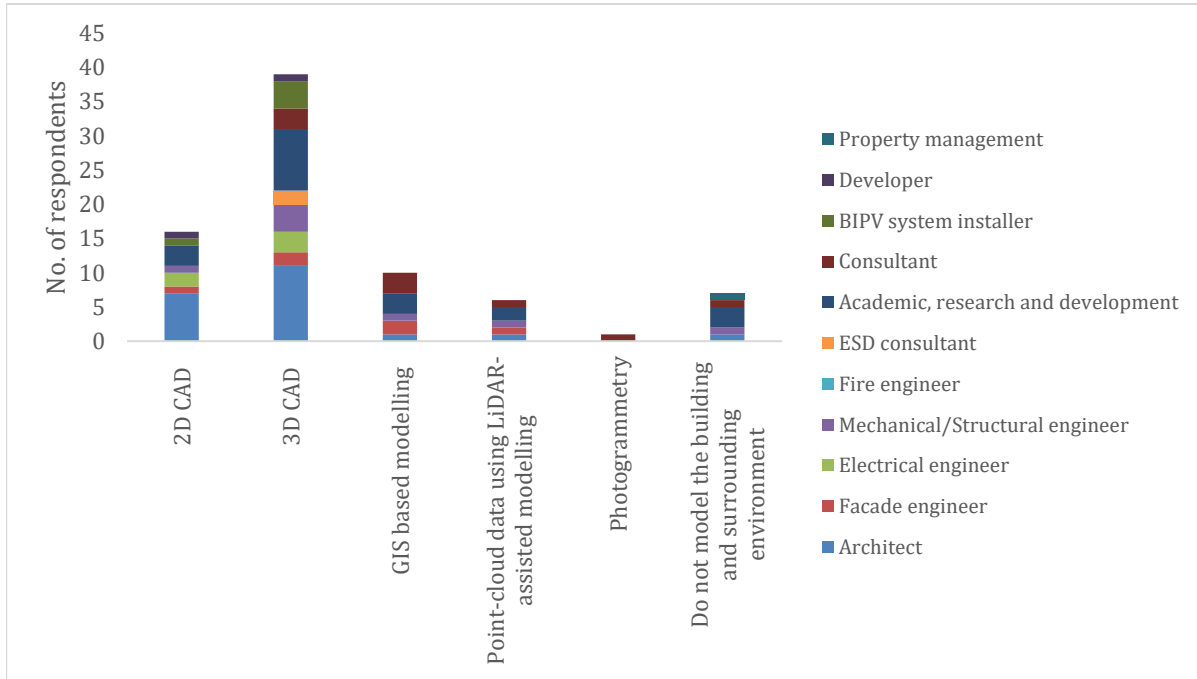
(b) Survey results by profession

Figure 5.4 Methodology for modelling the geometry of the building and surrounding environment

5.1.5 Methods for photorealistic visualization of building/BIPV envelope designs

The visualization of 3D BIPV envelope models provide great support for evaluating BIPV designs. Figure 5.1.5 shows the survey results on whether photorealistic visualization is considered in building/BIPV envelope designs. Out of all the respondents, only twenty have used photorealistic visualization in building/BIPV envelope designs. It can be seen that a higher number of respondents who have used photorealistic visualization methods are from Europe and Asia. Professionally, higher number of Architects uses photorealistic visualization methods compared to other professions who have used photorealistic visualization methods in building/BIPV envelope designs. Architects are responsible for creating aesthetically pleasing building envelope designs. Therefore, photorealistic visualization methods are useful for Architects to demonstrate the realistic views of the building model. The survey responses revealed that Autodesk Revit, Sketchup, Rhino and Autodesk Maya, 3D studio max, Lumion, SU Podium rendering plugin for SketchUp, MicroStation and KeyShot software are employed to generate photorealistic building/BIPV envelope designs.

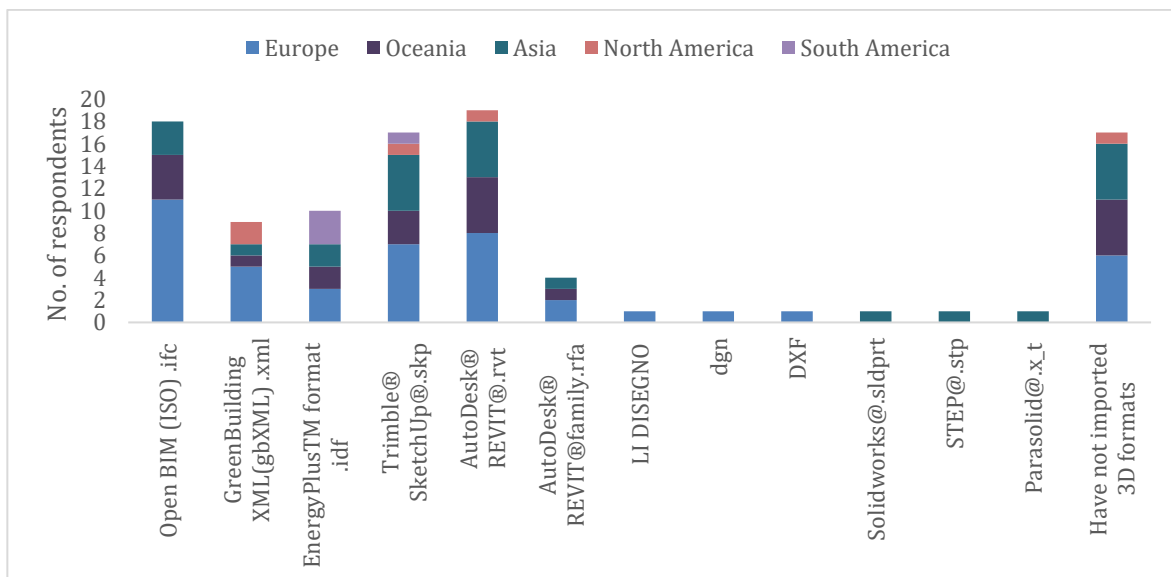(a) Survey results by region

(b) Survey results by profession

Figure 5.5 Methods for photorealistic visualization of building envelope with solar panels

5.1.6 Commonly used 3D format for data exchange between collaborators or data import

Figure 5.1.6 presents the common 3D formats adopted for the data exchange between collaborators in BIPV projects, which mainly depend on the software/tools they used. 18% of respondents are not used to share 3D file whereas most respondents mainly deal with 3D data formats such as Autodesk Revit.rvt (20%), Open BIM (ISO).ifc (19%) and SketchUp.skp (18%), which are the most popular. In terms of the region, Open BIM (ISO) format (.ifc) is highly used

in Europe, especially by the respondents from Germany and France. Autodesk Revit.rvt format is more popular in Asia and Oceania. Compared to BIPV industry professionals, more building professionals use the 3D format for data exchange between collaborators and data import. Among the building professionals a higher number of Architects use SketchUp.skp, Autodesk Revit.rvt and Autodesk Revit family.rfa files. On the other hand, Open BIM (ISO).ifc is used by a higher number of Academic research and development professionals. It's quite interesting to highlight that most BIPV system installers, electrical engineers and PV consultants stated that they do not import 3D formats.

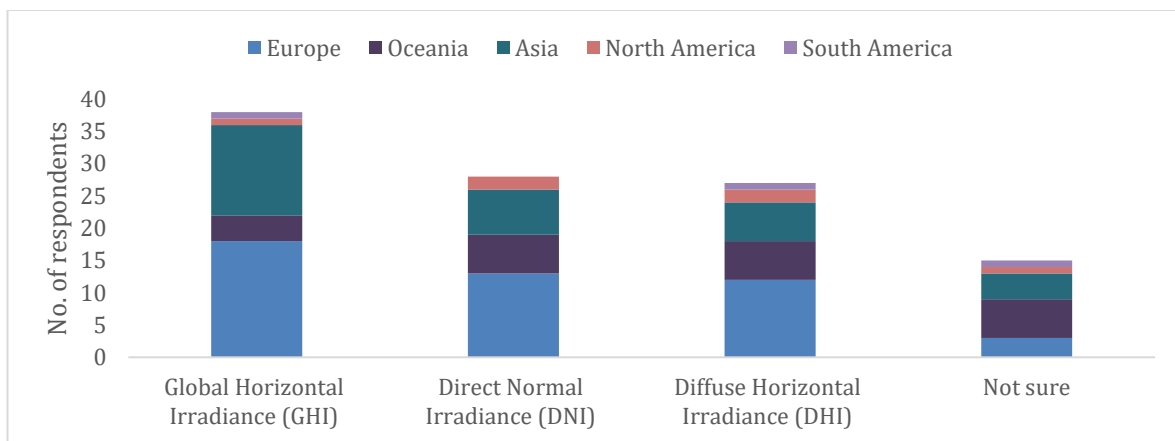

(a) Survey results by region
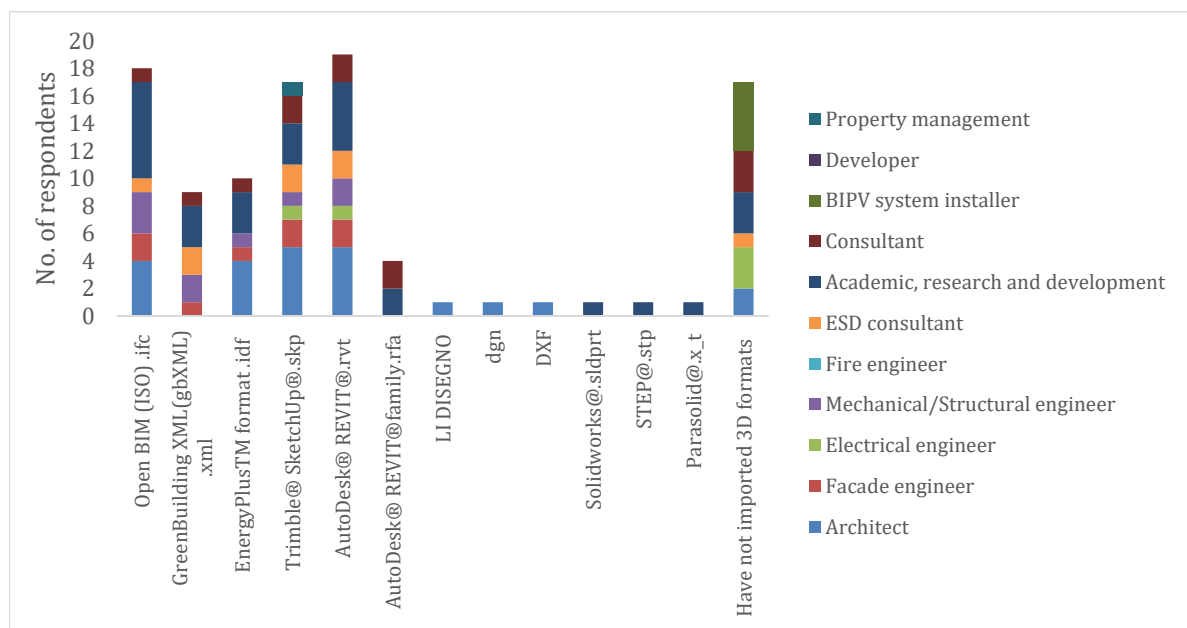
(b) Survey results by profession

Figure 5.6 3D format for data exchange between collaborators or data import
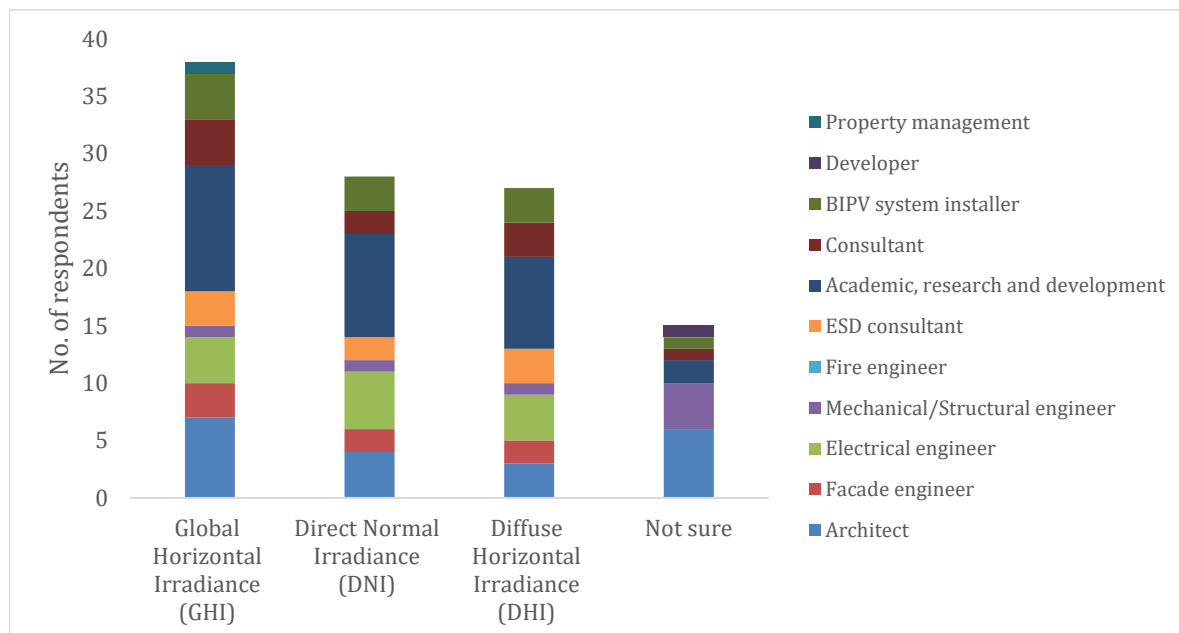
5.1.7 Weather parameters for identifying plane of array irradiation

As discussed in Section 4.1.7, estimation of POA irradiation need to consider solar irradiation data such as beam/direct normal irradiance, diffuse horizontal irradiance, and global horizontal Irradiance. As shown in Figure 5.1.7, the beam/direct normal irradiance, diffuse horizontal irradiance, and global horizontal irradiance components have been confirmed by the survey respondents in terms of region and profession. Overall, the most common parameter used for estimating plane of array irradiation is GHI in region-wise results and in professional results. However, DNI and DHI can also be used to determine the plane of array irradiation.
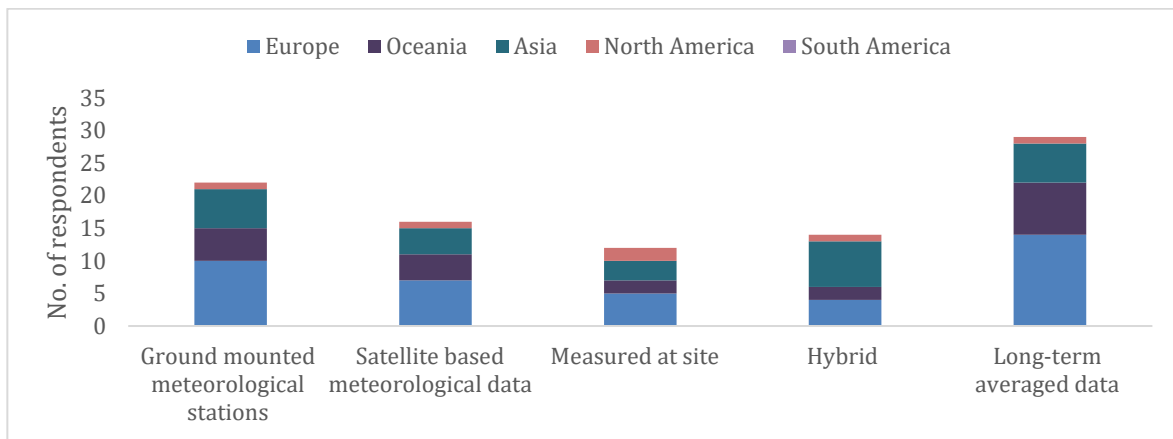

(a) Survey results by region

(b) Survey results by profession

**Figure 5.7 Weather parameters for identifying solar potential (Plane of array irradiation)**

5.1.8   Type of weather data for designing BIPV

As show in Figure 5.1.8, long-term averaged data is the most popular type of weather data for designing BIPV, followed by data from ground mounted meteorological stations as well as hybrid weather data. Long-term averaged data and ground mounted meteorological data is popular among respondents in Europe, Oceania, Asia, and North America. However, country wise, Australia has the highest usage rate of long-term averaged data. In China, hybrid data is the most common choice. Furthermore, respondents from France self-adjust the solar data based on their experience on past BIPV projects. Long-term averaged solar data is the most popular type among most of the professional groups. However, many respondents from Academic research and development also uses solar data ground mounted meteorological stations. The results show that long-term averaged data and ground mounted solar data is suitable for simulating BIPV designs.

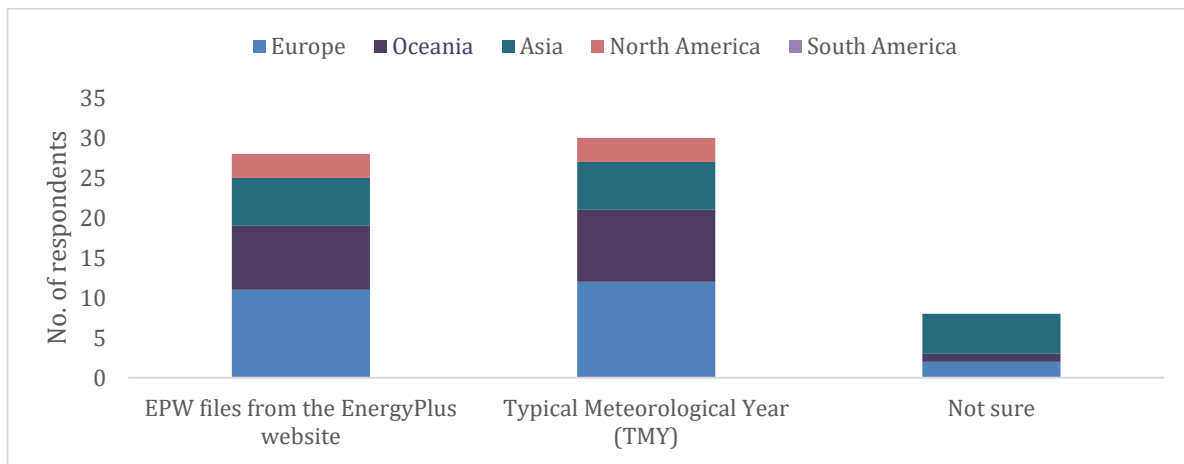

(a) Survey results by region
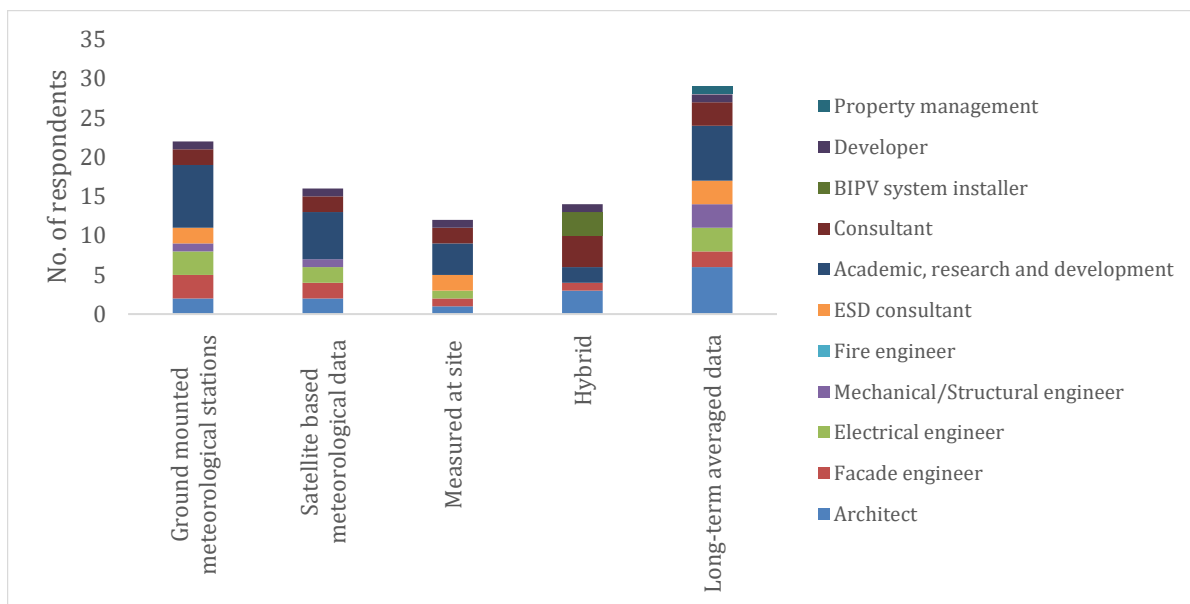
(b) Survey results by profession

**Figure 5.8 Type of weather data for designing BIPV**

5.1.9   Type of weather file formats

As discussed in Section 4.1.9, TMY and EPW files from the EnergyPlus website are weather data file formats commonly used in BIPV simulations. As shown in Figure 5.1.9 both EPW and TMY are widely used regionally and professionally, accounting for 85% of all respondents. It can be seen that TMY weather data is preferred in Europe, Oceania, Asia, and North America. Although TMY weather data is used by most of professional categories, a higher number ESD consultants, Façade engineers and PV consultant have used EPW. As EnergyPlus can be used with building design software, use of EPW weather data is makes the BIPV simulation process easier.
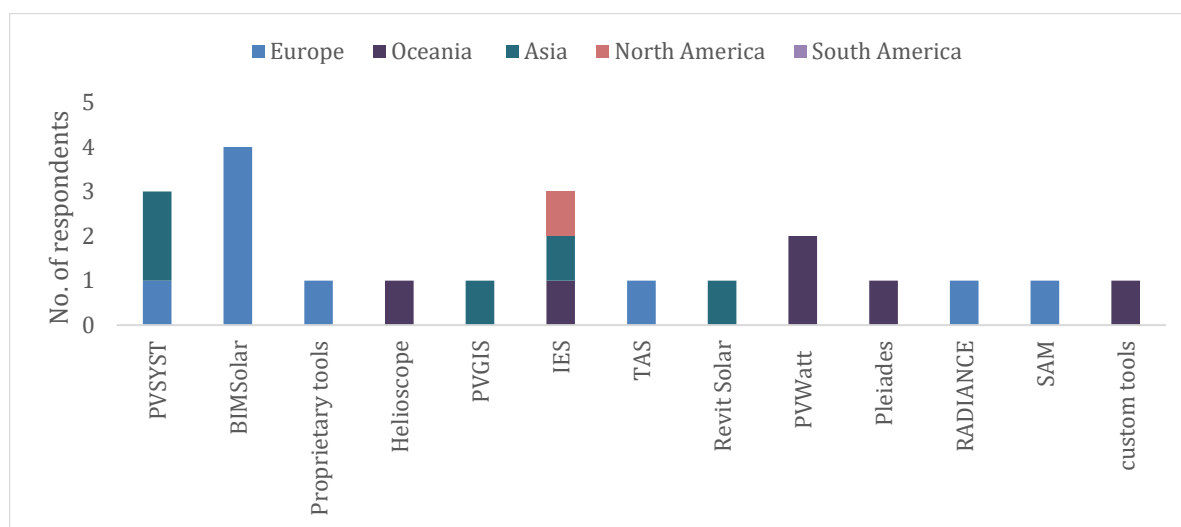

(a) Survey results by region
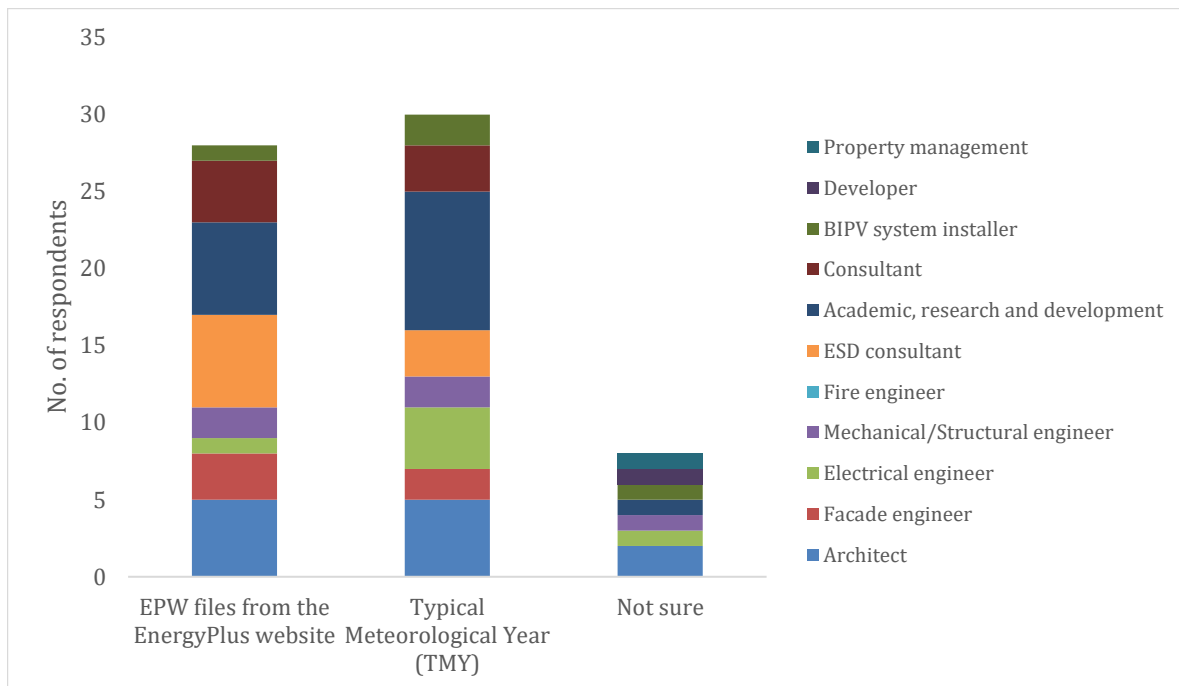
(b) Survey results by profession

**Figure 5.9 Type of weather file formats**

5.1.10 Software used to estimate Plane of array irradiation (POA)

As discussed in Section 4.1.10, various software can be used for estimating POA irradiance. Figure 5.1.10 demonstrates the survey responses on the software used to estimate POA irradiation. Overall, the survey results identified twelve tools which can be used to estimate POA by region and profession. Among all tools, BIMSolar is widely used in European countries such as France, Belgium, and Switzerland. IES considered in Oceania, Asia (Singapore) and North America. PVSYST is more popular in Asian countries and professions such as Façade engineers, Electrical engineers and BIPV system installers use it. ESD consultants seem to prefer IES, TAS and Revit Solar whereas Academics have used PV watts, Pleiades, Radiance and SAM to estimate POA irradiation. The results also show that that there are custom-made tools to estimate POA irradiation used by PV consultants.

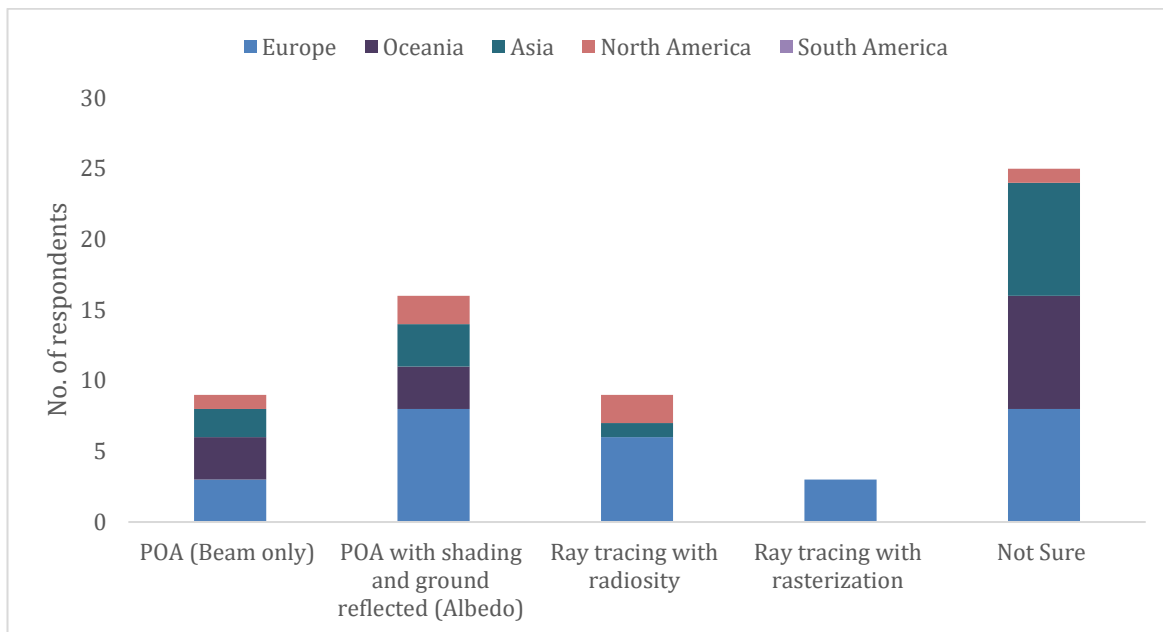(a) Survey results by region
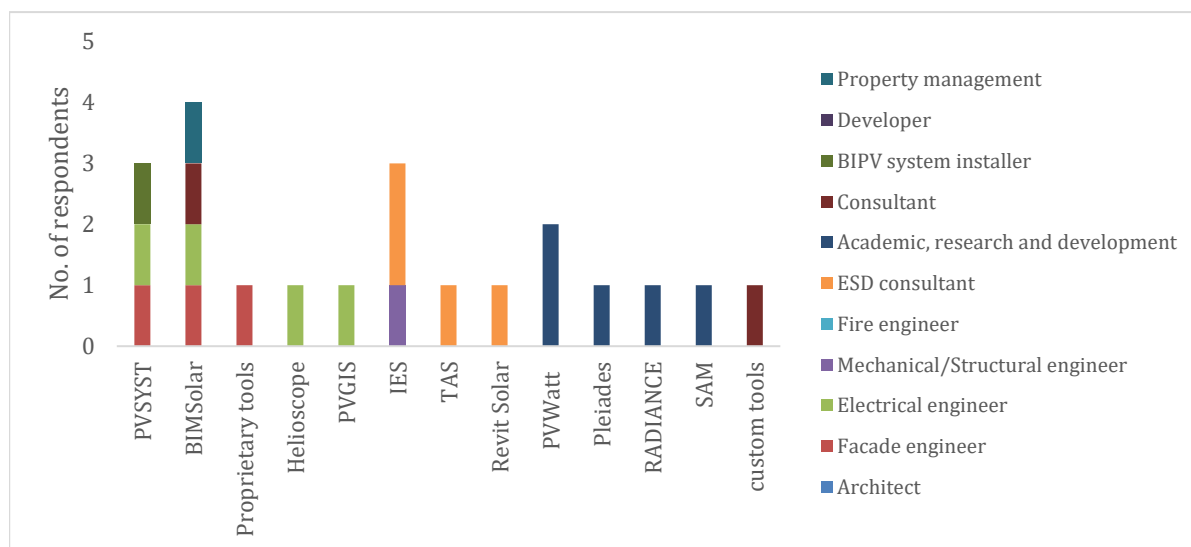
(b) Survey results by profession

**Figure 5.10 Software used to estimate Plane of array irradiation (POA)**

5.1.11 Models in software to estimate POA

Section 4.1.11 described that POA can be estimated using several methods such as POA (Beam only), POA with shading and ground reflected (Albedo), POA sky diffused, Ray tracing with radiosity and Ray tracing with rasterization. The survey results on models to estimate POA are demonstrated in Figure 5.1.11. Overall, 42% of the respondents that are not sure about model used for POA estimation. The reason for the respondents to reply as "not sure" could be because the estimation of POA irradiance consists of complex mathematical concepts which the respondents may not be specialised in to provide a direct answer.

However, the survey results show that POA with shading and ground reflected (Albedo) is widely used in Europe, Oceania, Asia and North America followed by POA (Beam only). POA with shading and ground reflected is applied in software used by Architects, façade, electrical, mechanical, and structural engineers. ESD consultants, Academics and PV consultants. Ray tracing with radiosity is considered in Europe, Asia and North America and Ray tracing with rasterization is used only in Europe and applied in software used by Façade engineers and Academics. The results indicate that further improvement on the knowledge and training of the methods to estimate POA in BIPV projects is required to improve the awareness of building construction professionals.
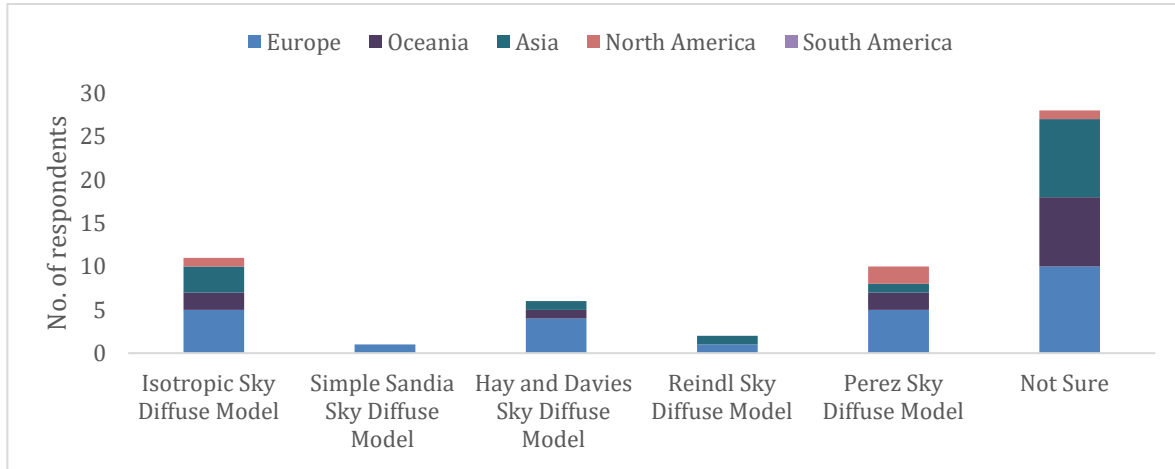

(a) Survey results by region
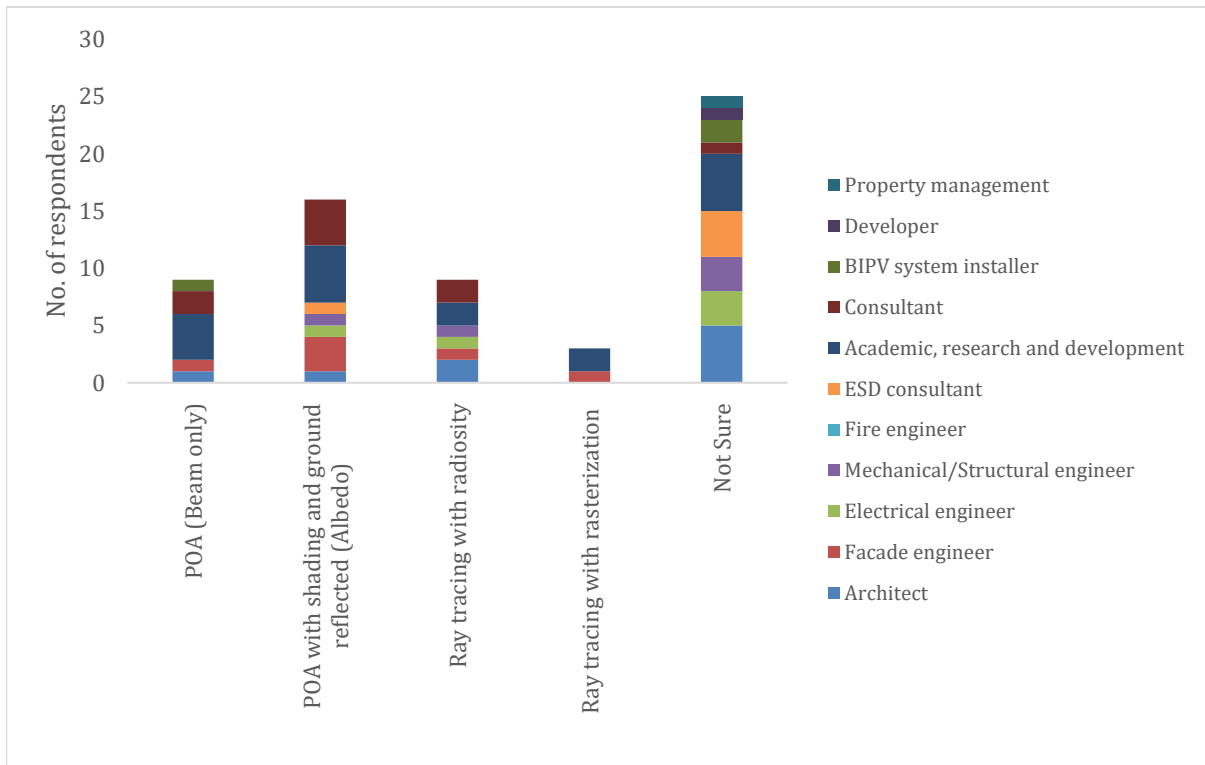
(b) Survey results by profession

**Figure 5.11 Models in software to estimate POA**

5.1.12 POA sky diffuse model to estimate POA irradiance

Figure 5.1.12 shows the survey results on sky diffuse model used to estimate POA irradiance. The results show that the respondent use Isotropic Sky Diffuse Model, Simple Sandia Sky Diffuse Model, Hay and Davies Sky Diffuse Model, Reindl Sky Diffuse Model, Perez Sky Diffuse Model to estimated sky diffuse irradiation. However, 24 out of 40 respondents are not sure about which POA sky diffuse model can be used for POA estimation in BIPV projects. This indicates that more investigation is required to identify which sky diffuse irradiation model is suitable for BIPV projects.

In Europe and Oceania both Isotropic Sky Diffuse Model and Perez Sky Diffuse Model is preferred. However, Isotropic Sky Diffuse Model is considered in Asia and Perez Sky Diffuse Model is considered in North America. Profession wise, Academics prefer both Isotropic Sky Diffuse Model and Perez Sky Diffuse Model. However, BIPV installers and PV consultants use Isotropic Sky Diffuse Model. Hay and Davies Sky Diffuse Model is preferred by Architects. The results show that the use of sky diffuse models may vary based on the region and profession. Therefore, more research investigations are required to identify the suitable model for BIPV projects.
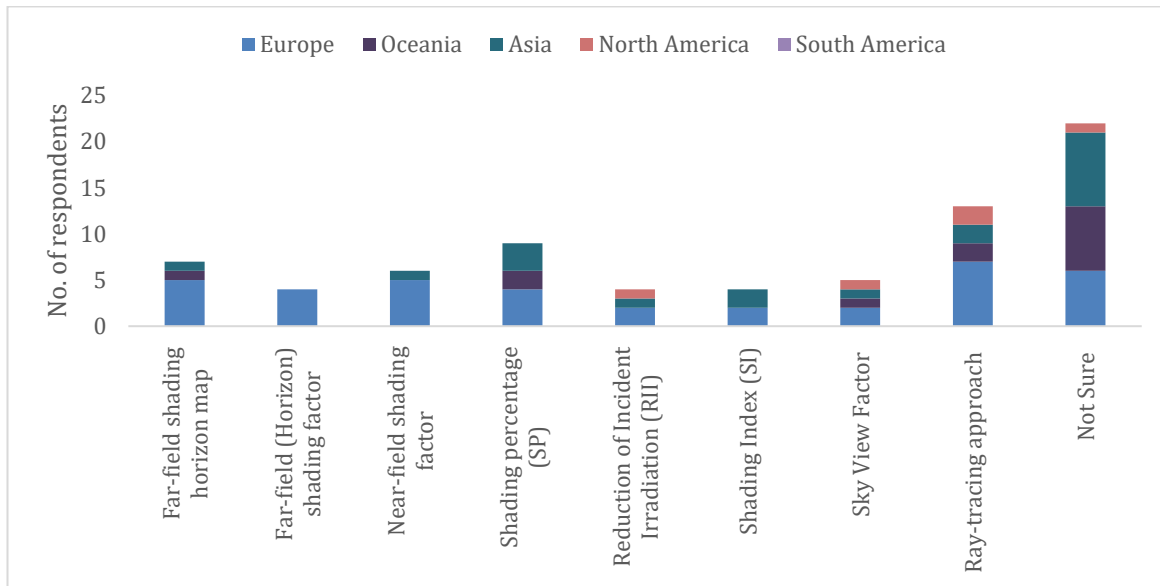
(a) Survey results by region
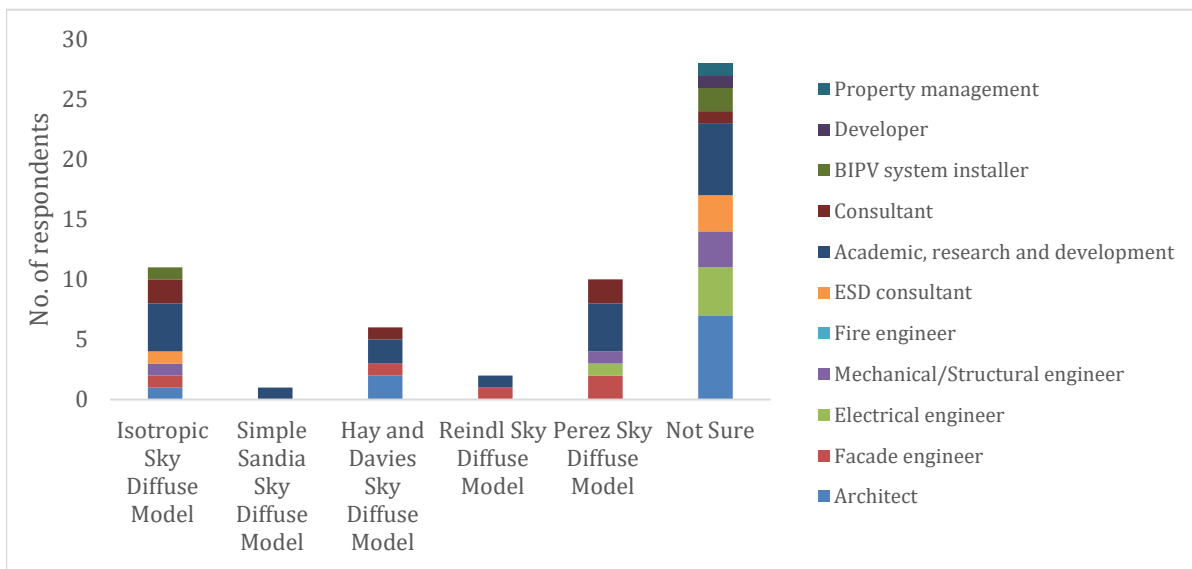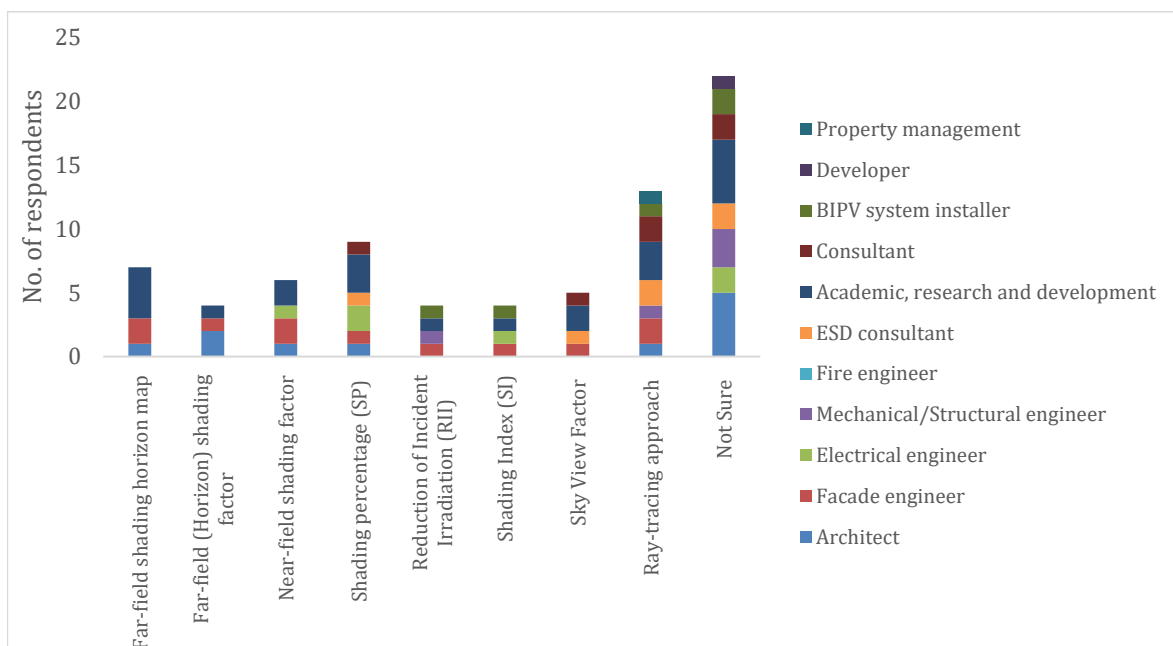

(b) Survey results by profession

Figure 5.12 POA sky diffuse models

5.1.13 Methods for shading approximations

As identified in Section 4.1.13, there are several methods that can be used to estimate the impact on shading in BIPV projects. As shown in Figure 5.1.13, the survey results show the methods employed for to estimate the impact on shading. In total the most popular method region wise and professional wise for shading approximation is ray tracing approach which is used in most building simulation software. Furthermore, use of shading percentage is popular in Europe, Oceania, and Asia among Electrical engineers and Academics. However, there are many respondents who are not sure on the suitable for method for estimating shading in BIPV projects. Therefore, a study which investigates the suitability of the above methods could facilitate these professionals to select the appropriate method for BIPV projects.

(a) Survey results by region

(b) Survey results by profession

Figure 5.13 Methods for shading approximations

5.1.14 Weather data step values used for solar irradiation data

As discussed in Section 4.1.14, weather data interval values can be by Minute, Hourly, Daily, Monthly or Annually. It may vary based on the stage of design in BIPV project. As shown in Figure 5.1.14, the survey results show that annual weather data is used at the conceptual design phase most widely in all regions and all by most professional categories. However, the

hourly data is more used at the detailed design stage of the project in all regions and professions.
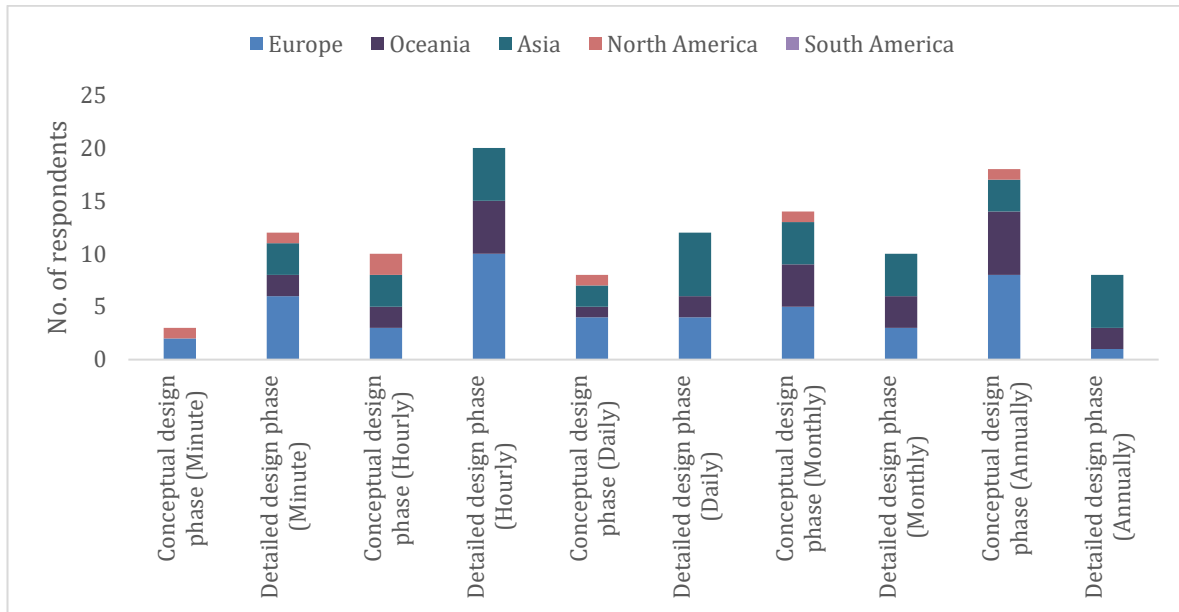
(a) Survey results by region
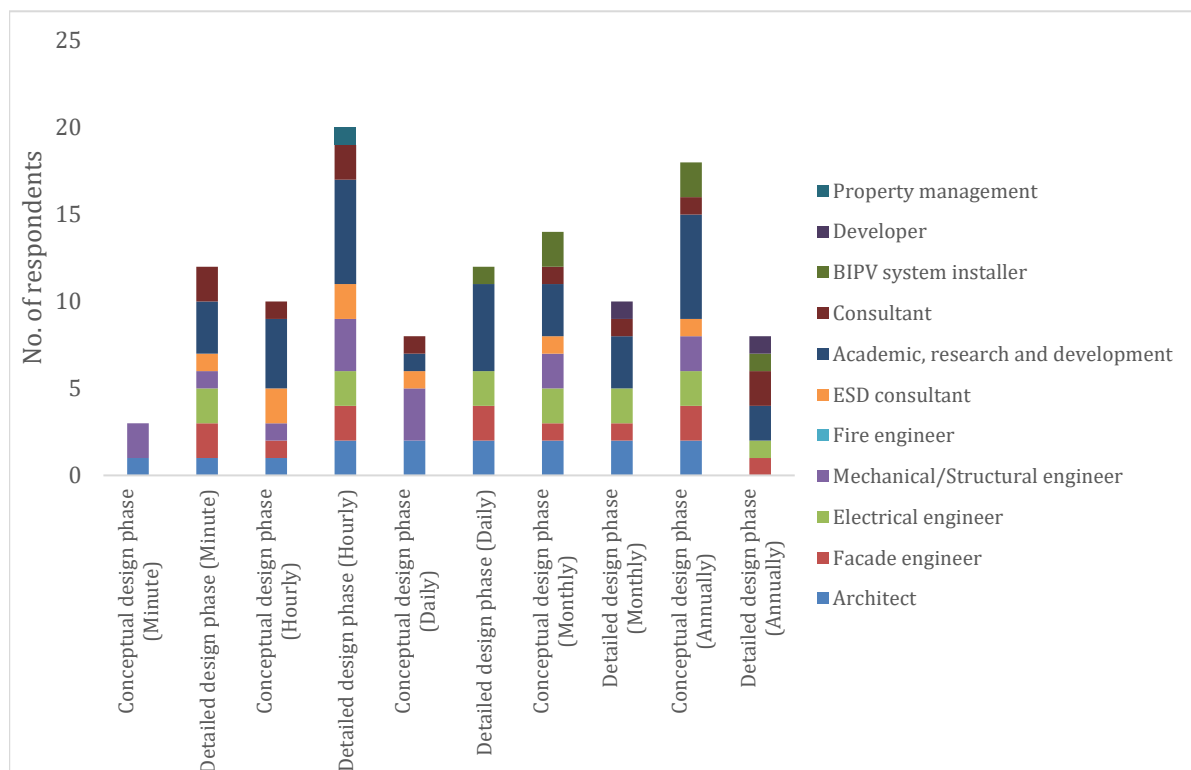
(b) Survey results by profession

Figure 5.14 Weather data step values used for solar irradiation data

5.1.15 Models used for simulating higher spatial resolutions (PV cell level or higher)

Figure 5.1.15 shows the survey results on the use of models for simulating higher spatial resolutions in BIPV projects. In total, 11 out of 19 respondents mentioned that they do not perform simulation of higher spatial resolutions in BIPV projects. The respondent who simulates the higher spatial resolutions in BIPV projects include respondents from North America, Europe, Oceania, and Asia. The survey results show Academics and PV consultants used custom made tools to perform simulation on higher spatial resolutions.
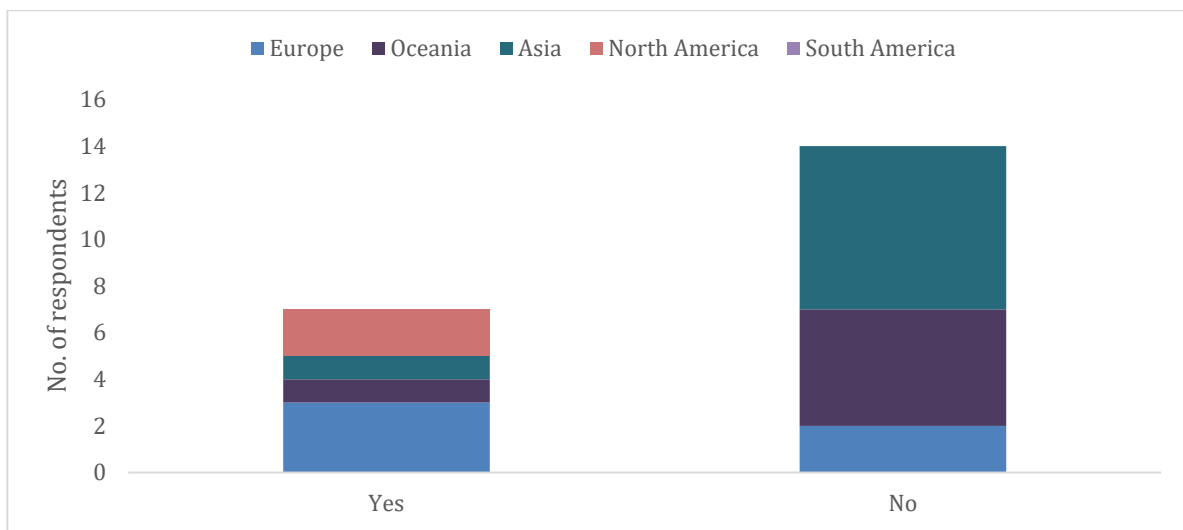
(a) Survey results by region
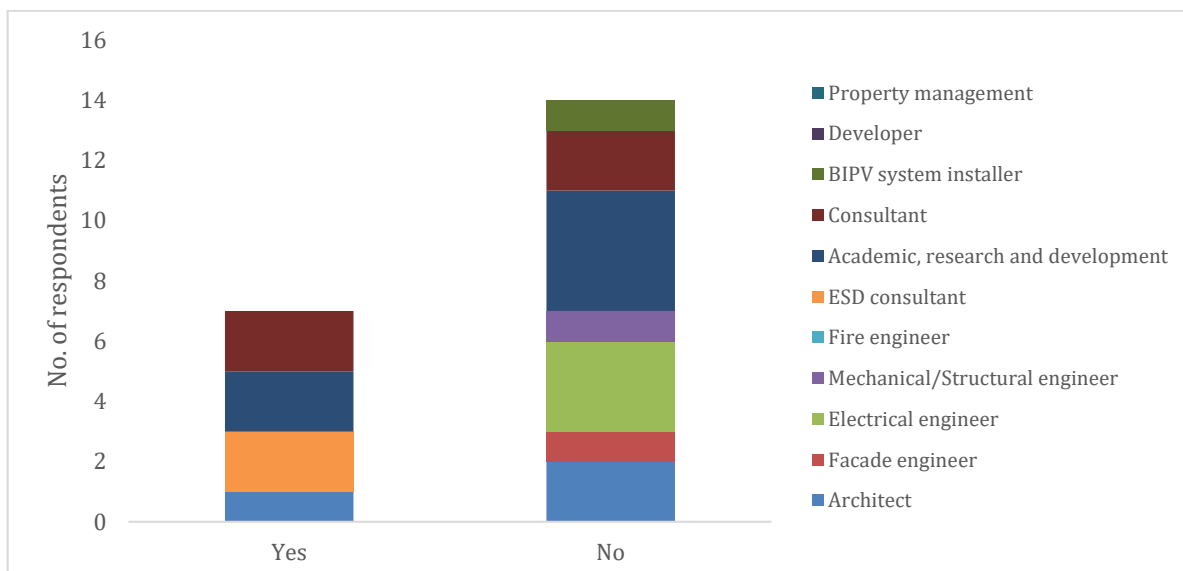
(b) Survey results by profession

Figure 5.15 Models suitable for simulating higher spatial resolutions (PV cell or higher)

5.2 Workflows and methods used in solar power output modelling or simulation

5.2.1 Methods used to import properties of the technical components of BIPV modules

As discussed in the Section 4.2.1, it is important to select the appropriate BIPV module and related components to accurately estimate the BIPV power output. Figure 5.2.1 a and Figure 5.2.1 b show the survey results on methods used to import properties of BIPV system components. In total, a higher number of survey respondents use the databases available in the software to import the BIPV system properties. Respondents from Europe, Oceania, Asia and North America added BIPV properties manually. Higher number of Architects and Electrical engineers added BIPV properties manually. Moreover, a very low number of respondents from Asia and Oceania imported the BIPV product properties from online databases of BIPV products. The results show that having a BIPV product database within the BIPV simulation tools is preferred by both Building design professionals and BIPV professionals.
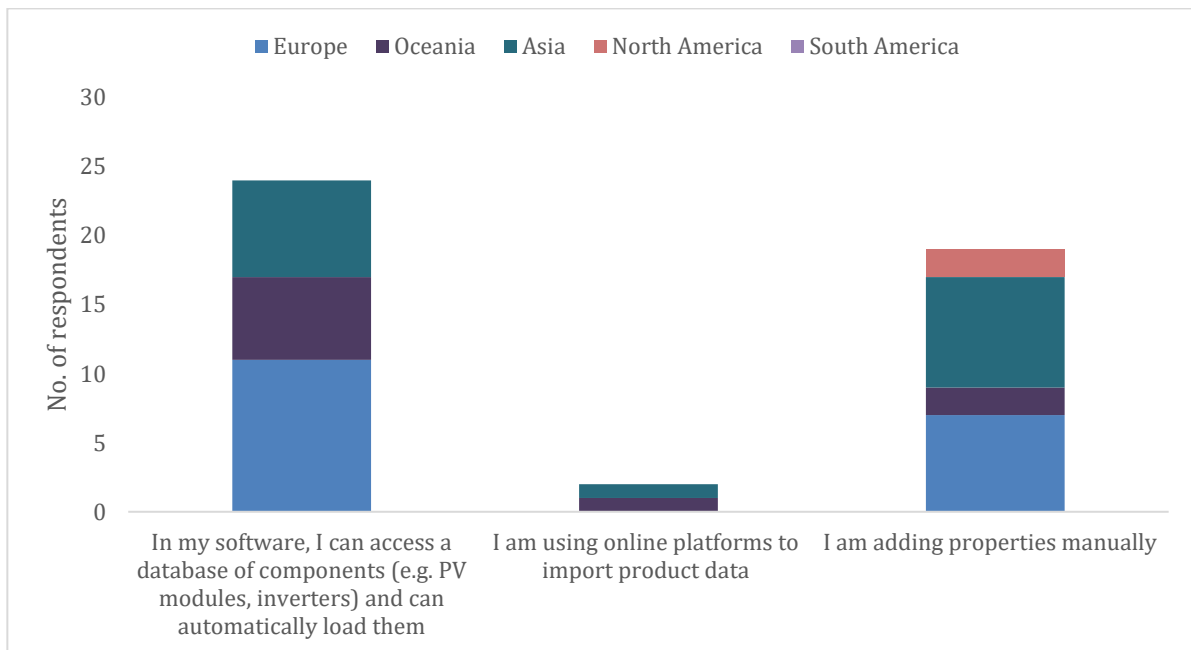
(a) Survey results by region
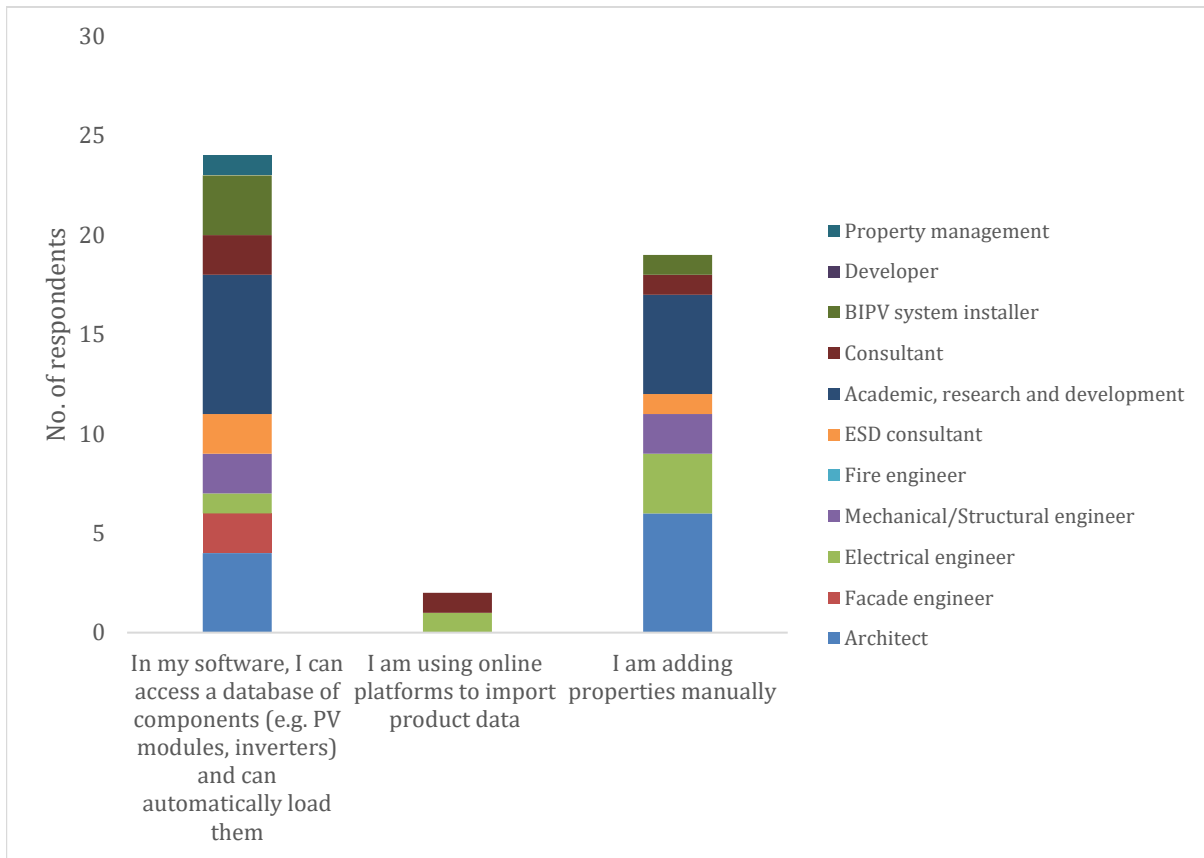
(b) Survey results by profession

Figure 5.16 Methods used to import properties of the technical components of BIPV modules

5.2.2 Methods used for calculating the Electric DC output of BIPV

As discussed in Section 4.2.2 several methods are available for estimating the amount of electricity produced by a BIPV system such as PV cell temperature model, power model by Heydenreich et al. (2008), the Sandia PV Array Performance Model (SAPM), loss factors model (LFM), single diode model, the two-diode model etc. Figure 5.2.2 a and Figure 5.2.2 b shows the survey results on the above methods by region and by profession.

Twenty-seven respondents have mentioned Not sure about the model used for estimating the electric DC output of BIPV. The reason could be because these methods consist of complex mathematical concepts which the respondents may not be specialised in or aware of to provide a precise answer. However, seventeen survey respondents from Europe, Asia, Oceania and North America have selected forecasting the BIPV power output with PV cell temperature model. Compared to other methods, Architects, Façade engineers, Electrical engineers and Academics use the PV cell temperature model to forecast the power output.
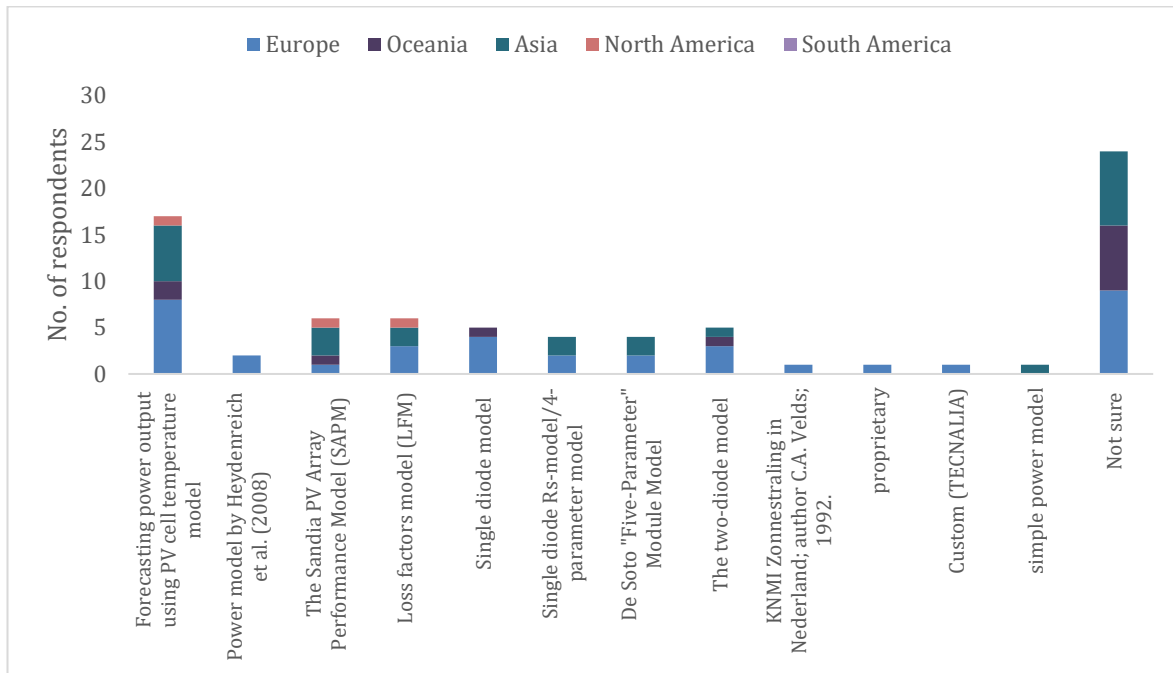
(a) Survey results by region
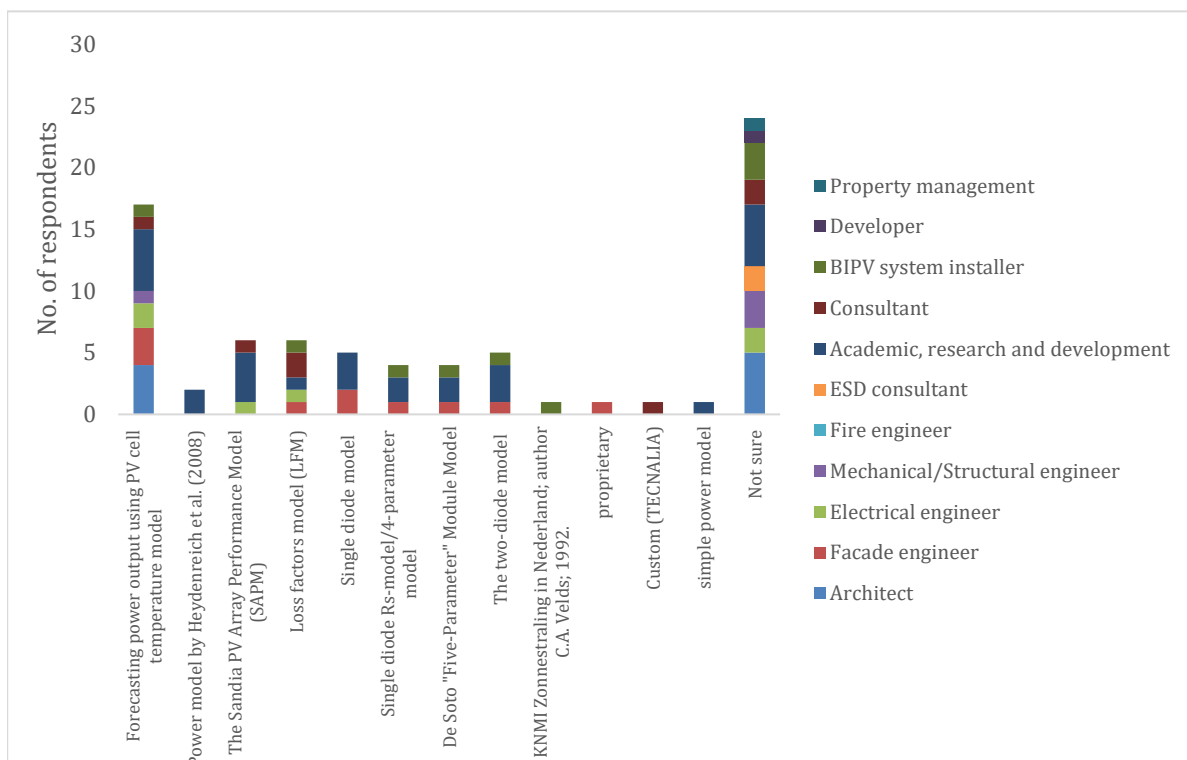
(b) Survey results by profession

Figure 5.17 Methods used for calculating the Electric DC output of BIPV

5.2.3 Software for calculating the Electric DC output of BIPV designs

As discussed in the Section 4.2.3, software can be used to estimate the electric DC output of BIPV designs. Figure 5.2.3 a and Figure 5.2.3 b show survey results on use of software to estimate the electric DC output. A higher number of respondents from Europe use software to estimate the BIPV DC output. It can be seen that a higher number of PV consultants, Academics and Electrical engineers prefer to use software to estimate the BIPV DC output. Figure 5.2.3 c and Figure 5.2.3 d show survey results on the software used to estimate the BIPV DC power output. BIMsolar and PV*SOL are mostly used in European countries. PVSYST is considered in Europe, Oceania, and Asia. SAM and PVwatts is used in North America.

In terms of the profession, Electrical engineers prefer PVSYST. PV*SOL and Retscreen are considered by Architects. PV*SOL and SAM are popular with Academics. BIM solar is popular among a variety of professionals such as Façade engineers, Electrical engineers, PV consultants, and Property managers. Overall, the results show that not many respondents are aware of the use of software for estimating BIPV power output. Therefore, further research in this area is required.
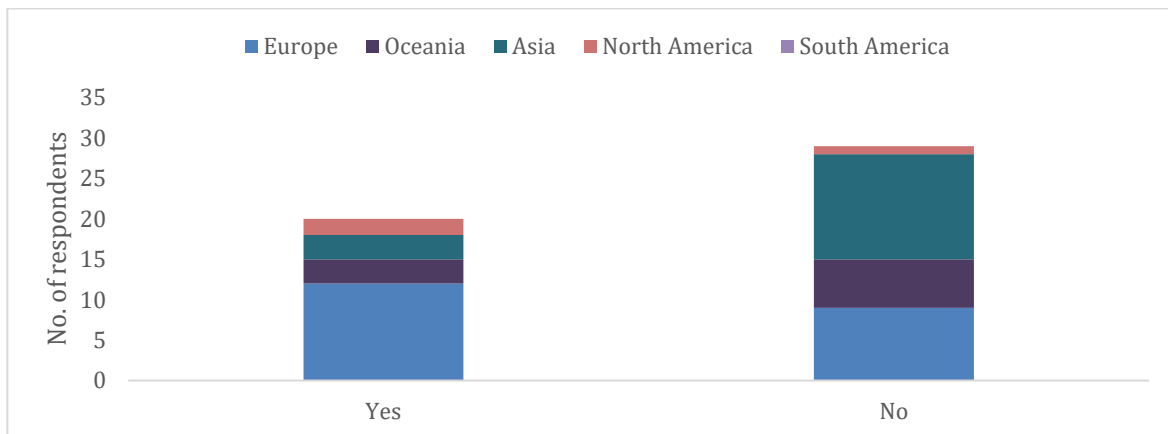
(a) Survey results by region
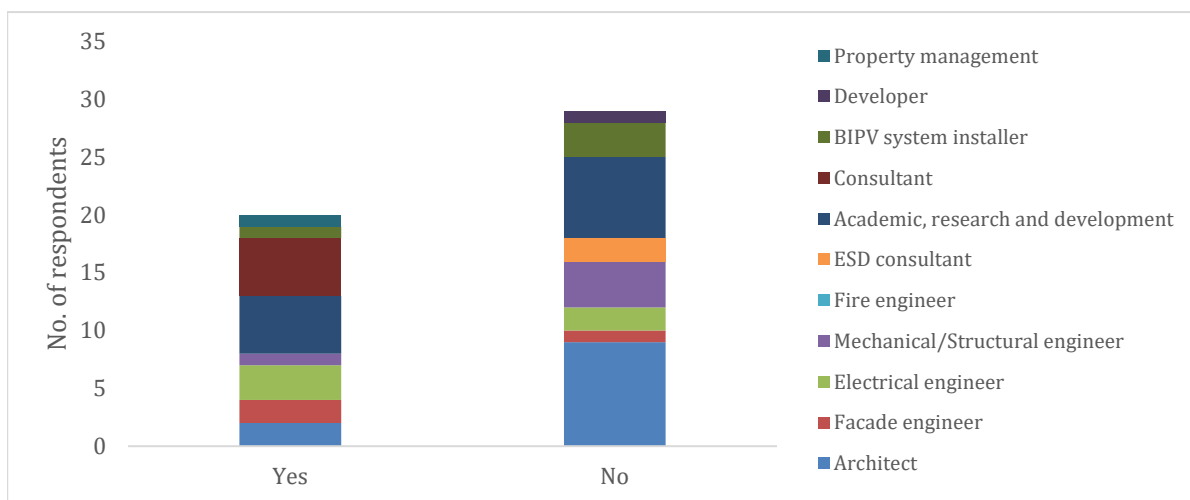
(b) Survey resutls by profession
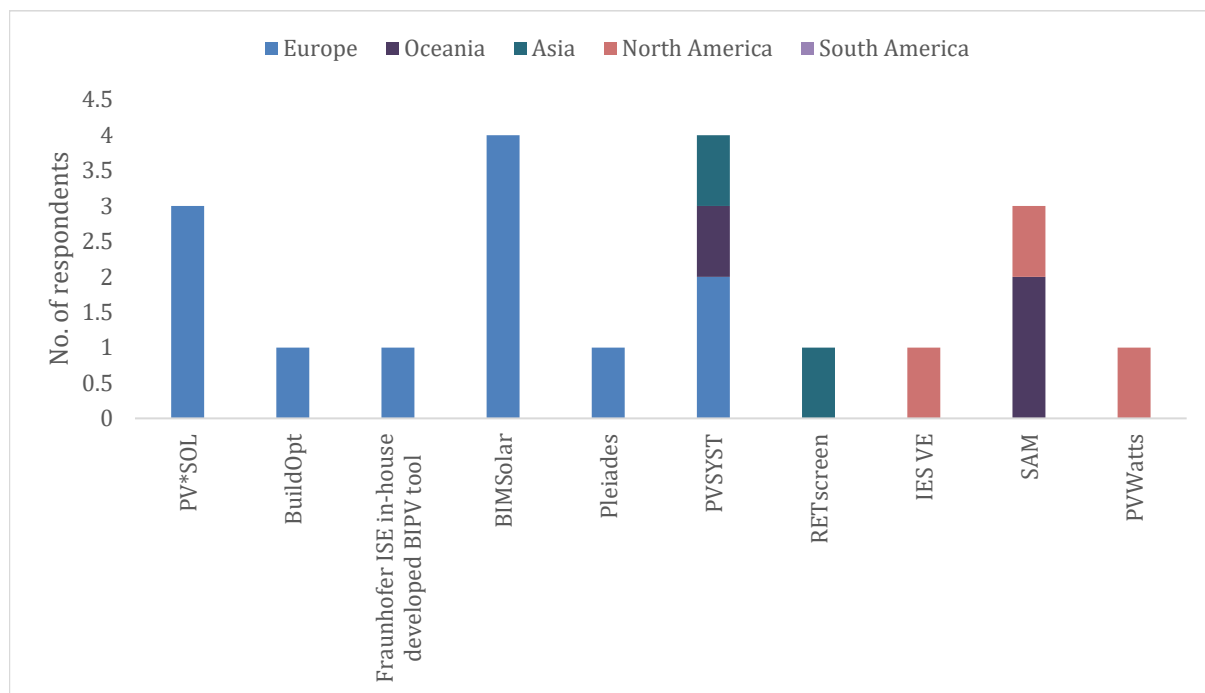
(c) Software: Survey resutls by region
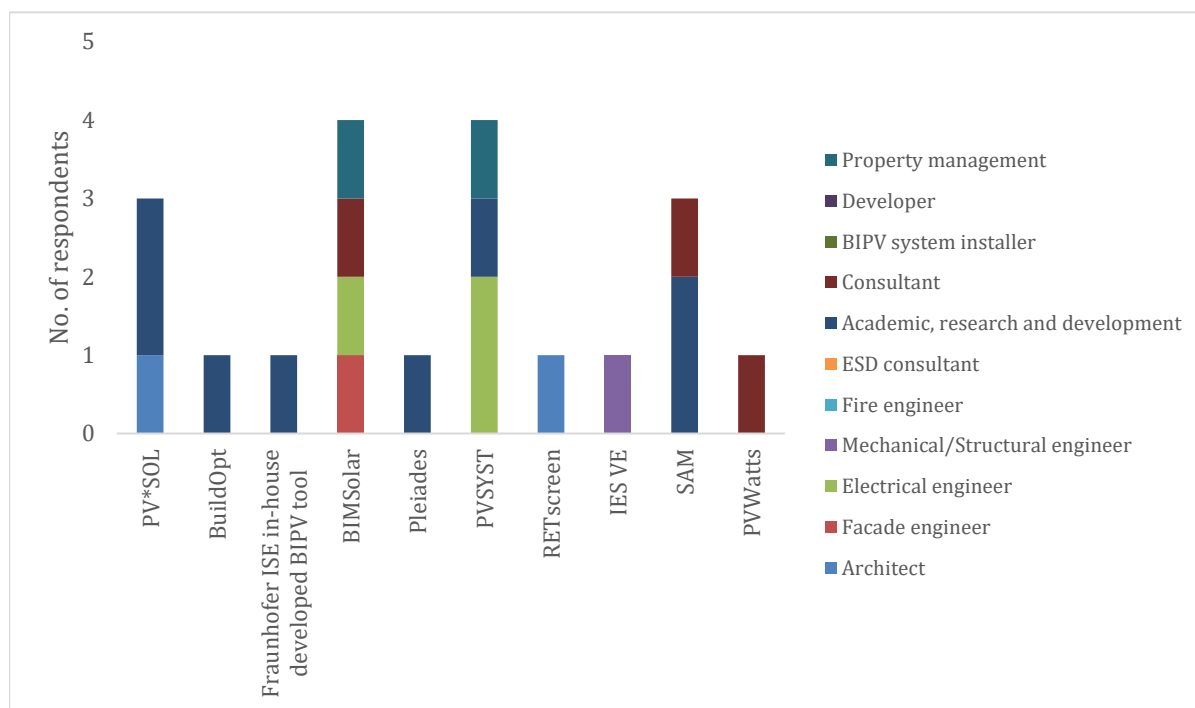
(d) Software: Survey resutls by profession

Figure 5.18 Software for calculating the Electric DC output of BIPV designs

5.3 Workflows and methods used in building performance modelling or simulation

5.3.1 Method used for identifying the energy consumption patterns of a building

Building energy consumption is required to identify the amount of BIPV system energy fed to the building. As discussed in Section 4.3.1, here are several ways to identify the energy usage of a building. Figure 5.3.1 a and Figure 5.3.1 b show the survey results on the method used for identifying the energy consumption patterns of a building. The most popular method selected by the respondents is the historical information from energy bills to identify the energy consumption patterns of a building, followed by calculating watt hour per day for each appliance used in the building/project and the use of simulation software to identify building energy demand.

The survey results show that the calculation of watt-hour data is applied most commonly in Europe while the use of historical information is most popular in Asia and Oceania. Architects and Mechanical/ Structural Engineers prefer calculating the watt hour data and using historical information. Consultants and BIPV system installers prefer to use historical information. ESD consultants and Academics prefer the use of simulation software. Figure 5.3.1 c and Figure 5.3.1 d shows survey results on the software used for the energy consumption simulation. A higher number of respondents from Oceania and North America use IES VE. IES VE software is popular among ESD consultants and PV consultants. EnergyPlus is preferred by many respondents from Europe. Both EnergyPlus and Design builder are preferred in Asia. EnergyPlus is more popular among Architects, Academics, and consultants.
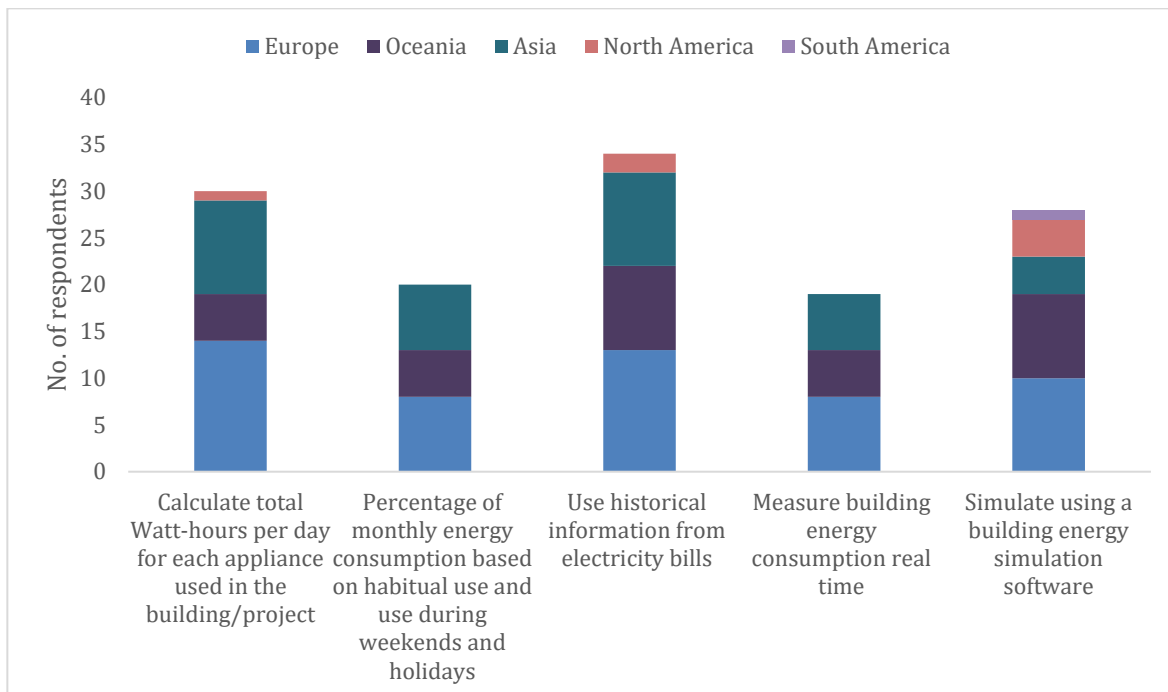
(a) Method: Survey results by region
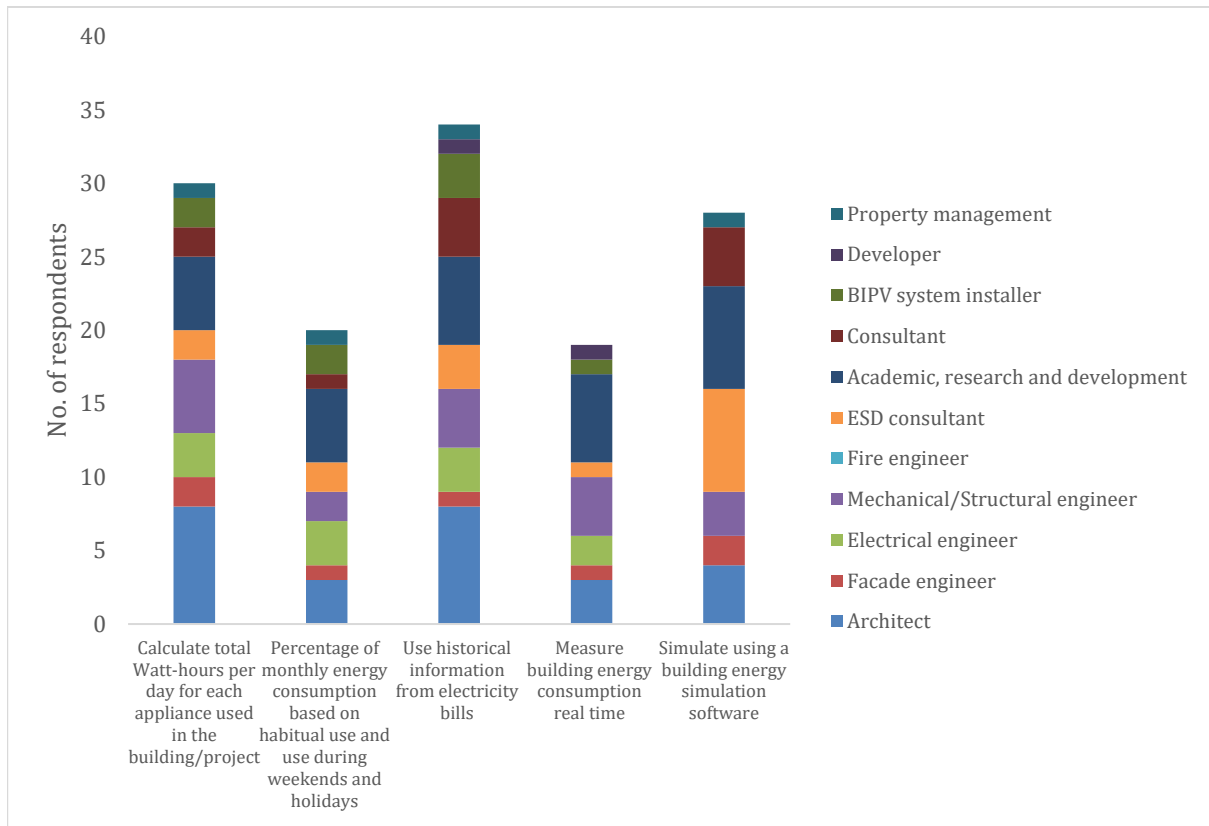
(b) Method: Survey results by profession
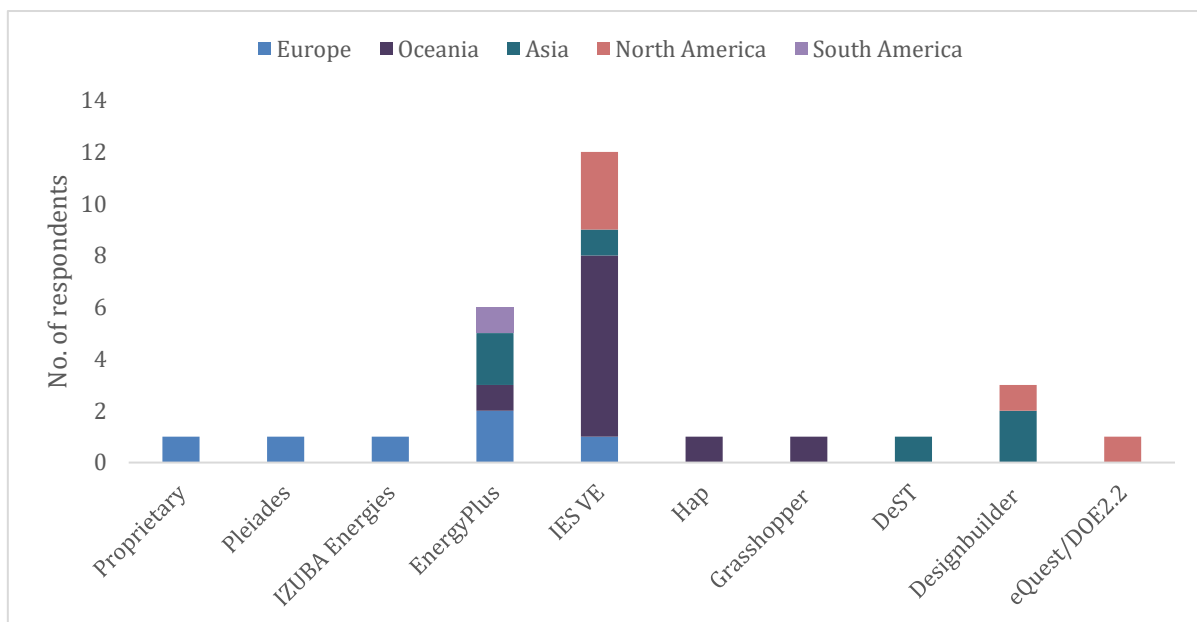
(c) Software: Survey resutls by region

(d) Software: Survey resutls by profession

Figure 5.19 Method used for identifying the energy consumption patterns of a building

5.3.2 Suitable interval to be considered in energy consumption data

Figure 5.3.2 a and Figure 5.3.2 b shows the survey results on the energy consumption data considered in the conceptual design phase and the detail design phase. It is noticeable that annual and monthly building energy consumption data are considered for the conceptual design phase by most respondents from all regions and all professions. Hourly and daily building energy consumption data are considered for the detailed design phase by most respondents from all regions and all professional categories.

(a) Survey results by region
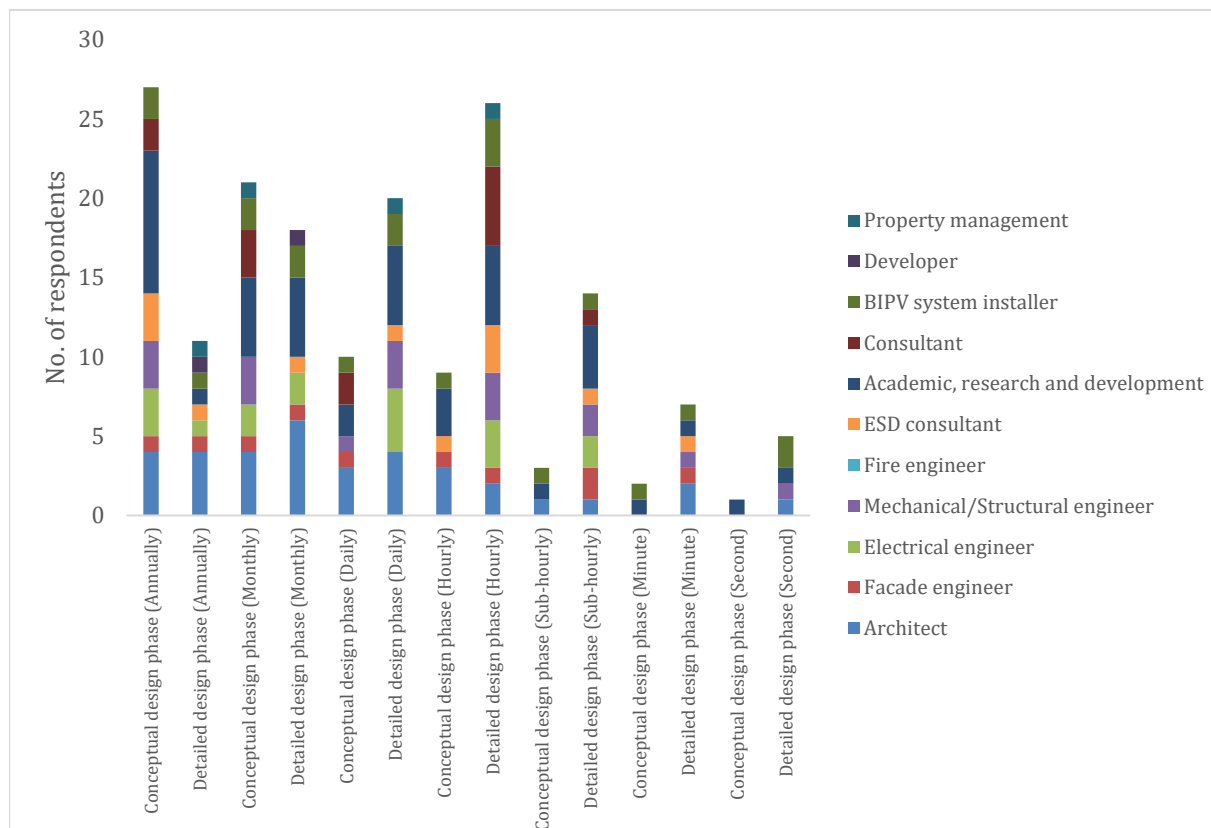
(b) Survey results by profession

Figure 5.20 Suitable interval to be considered in energy consumption data

5.3.3   Data file formats for storing building energy consumption data

As discussed in Section 4.3.3, building energy consumption data can be stored as excel files, text files or as Comma Separated Value (CSV) files. Figure 5.3.3 a and Figure 5.3.3 b shows the survey results on the file formats used for building energy consumption data. In total, a higher number of respondents across all regions and professions use MS Excel spread sheets to store building energy consumption values, followed by Comma Separated Value (CSV) files. Further, MS Excel spread sheets are more popular among both BIPV professionals and building professionals than CSV files.
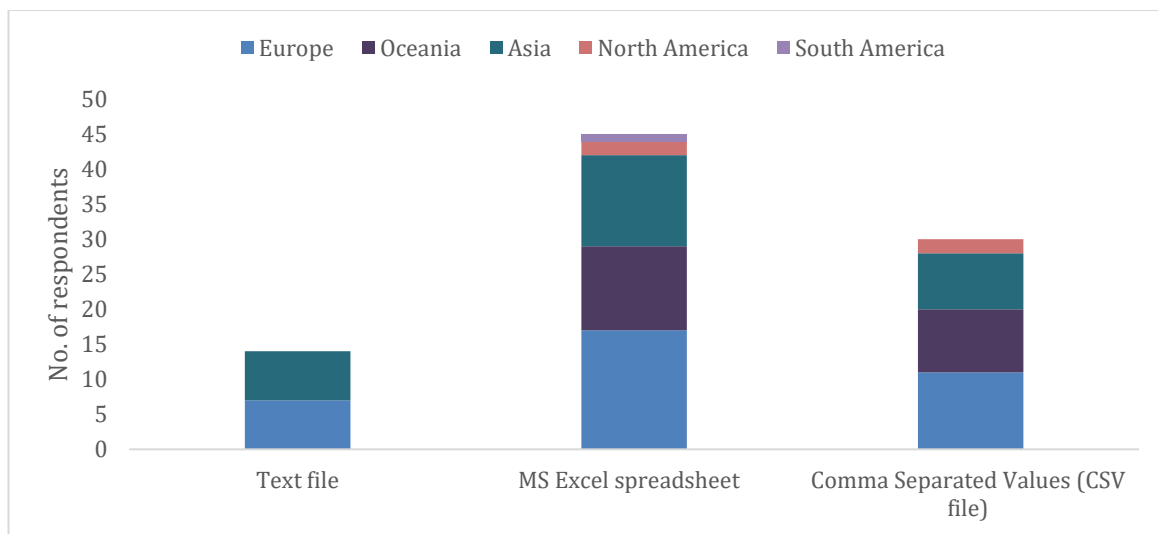
(a) Survey results by region
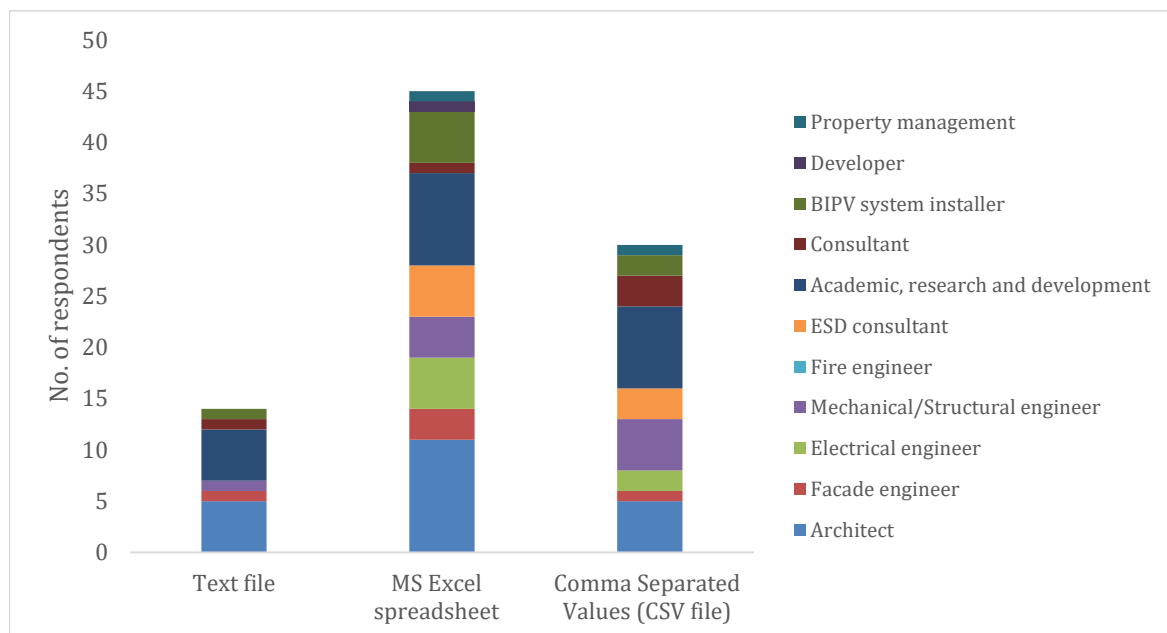
(b) Survey results by profession

Figure 5.21 Data file formats for storing building energy consumption data

5.3.4 Methods used to identify the thermal impact of BIPV designs

BIPV envelopes need to comply with the building standards relating to thermal comfort. As discussed in Section 4.3.4 there are several methods to identify the thermal impact of BIPV designs. As shown in Figure 5.3.4 a and Figure 5.3.4 b, majority of respondents use simulation software to identify thermal impact. Simulation of thermal load needs to be done while considering the whole building project. Also, it requires specific knowledge on the subject. Therefore, many respondents employ building simulation software. Compared to other methods, many respondents from Europe, Oceania and North America prefer the use of simulation software. Respondents from Asia also prefer to calculate solar heat gain manually. ESD consultants and Academics primarily use simulation software. Figure 5.3.4 c and Figure 5.3.4 d shows the software used for simulating thermal load. IES VE is mostly used for identifying the thermal impact in BIPV projects, especially in Oceania and North America. EnergyPlus is more popular in Europe. It can be noted that Architects, Engineers, ESD consultants and PV consultants' favour IES VE.
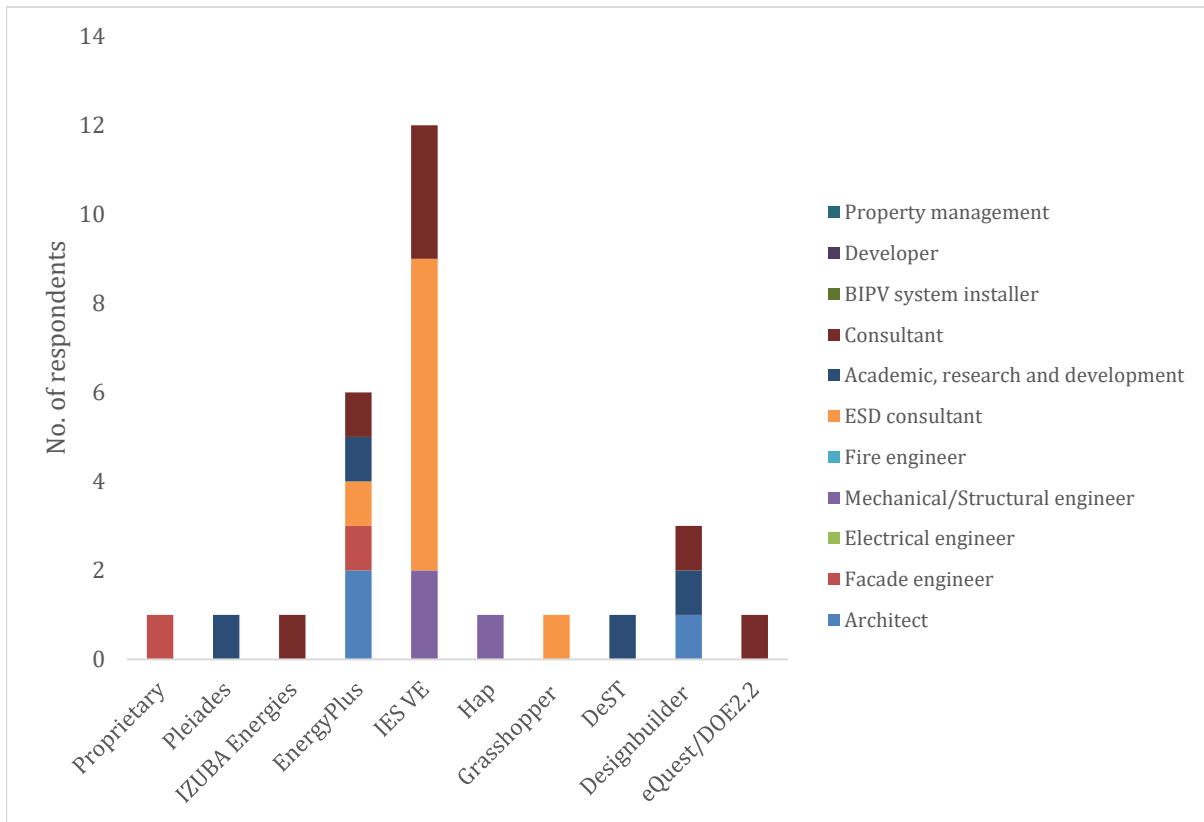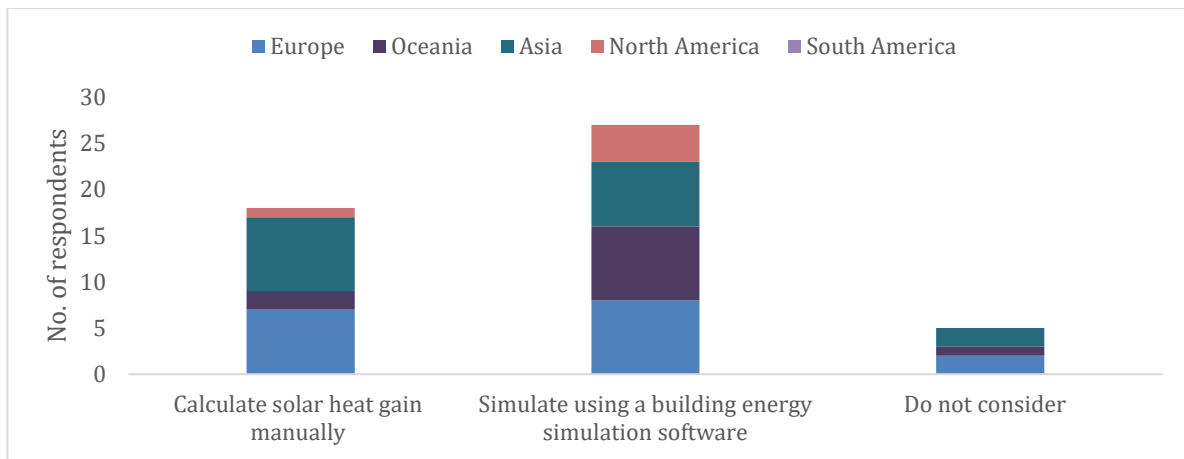

(a) Method: Survey results by region
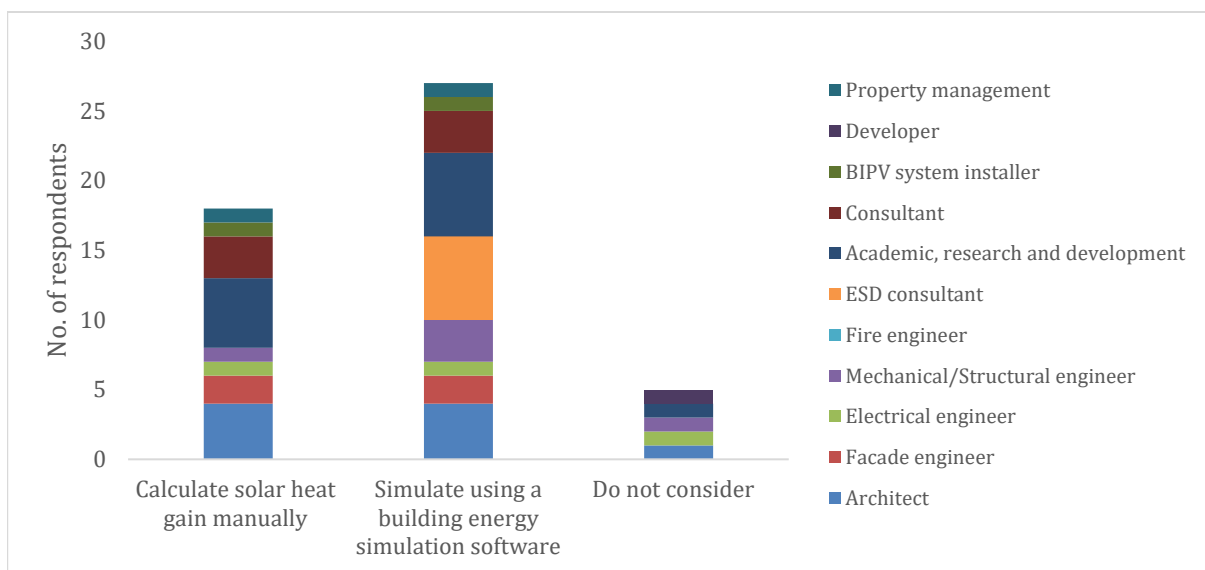
(b) Method: Survey results by profession
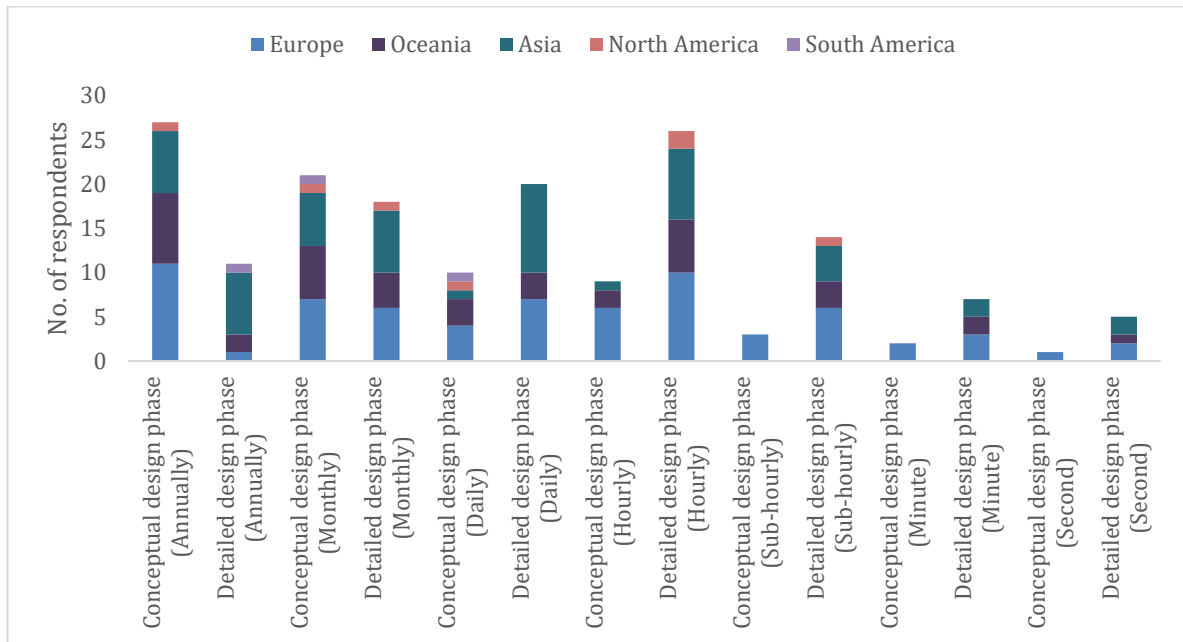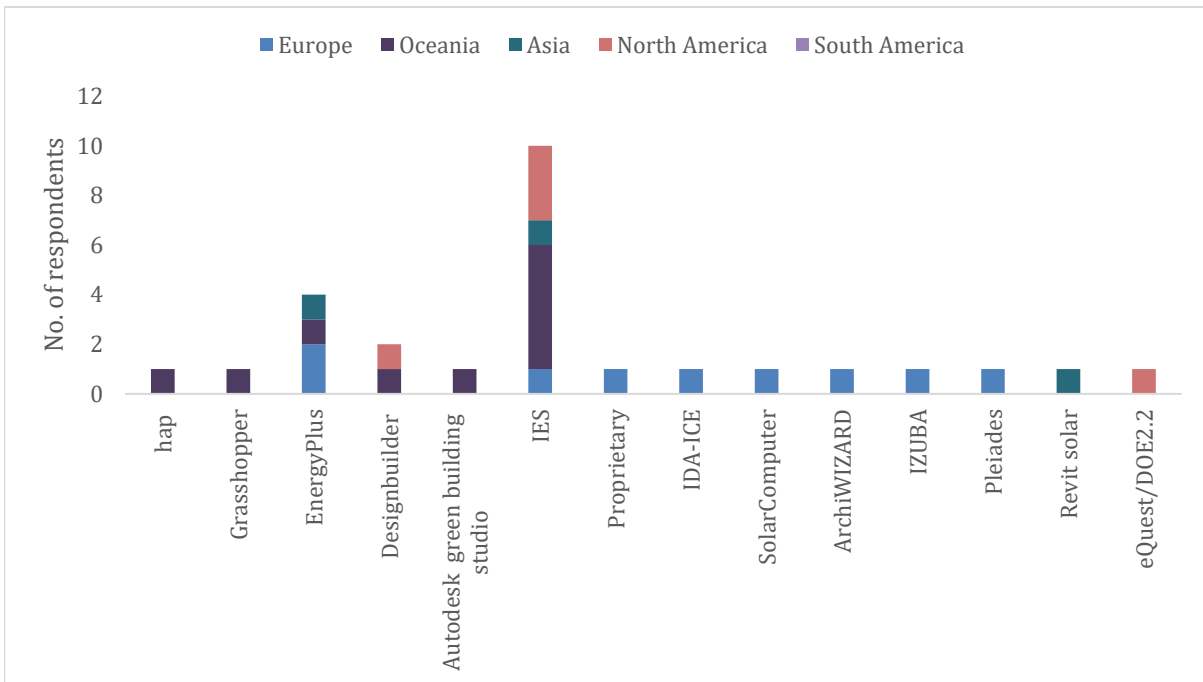
(c) Software: Survey results by region
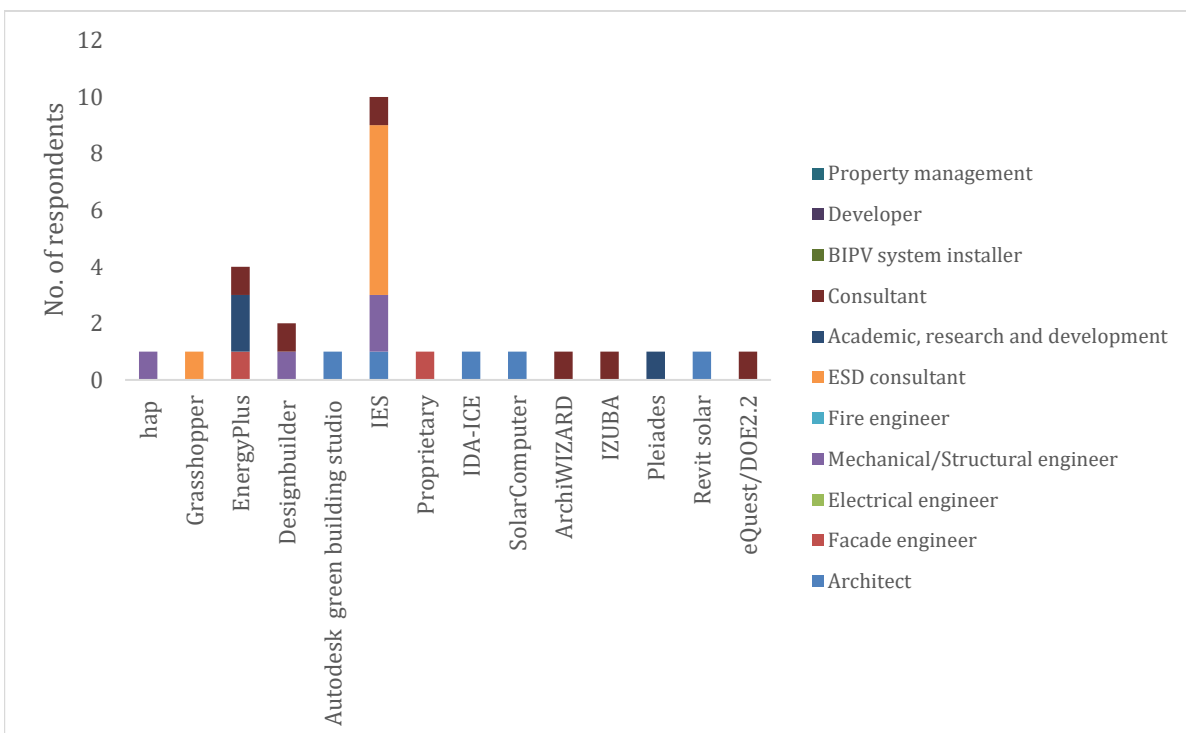

(d) Software: Survey resutls by profession

Figure 5.22 Methods used to identify the thermal impact of BIPV designs

5.3.5 Method(s)/software to simulate the heat island impact

As discussed in Section 4.3.6, there are not many methods to explore heat island effects of BIPV systems. As shown in Figure 5.3.5 a and Figure 5.3.5 b, most respondents in different regions have mentioned that they do not calculate heat island impact. However, the few respondents who have simulated the heat island impact of BIPV projects have used software such as Rhino and grasshopper (ESD consultant in Oceania), EnergyPlus (Academic in Asia) and Envi-met (Architect in Europe and Academic in Asia). Overall, the results indicate that impact of heat island effect is not commonly considered for BIPV projects.
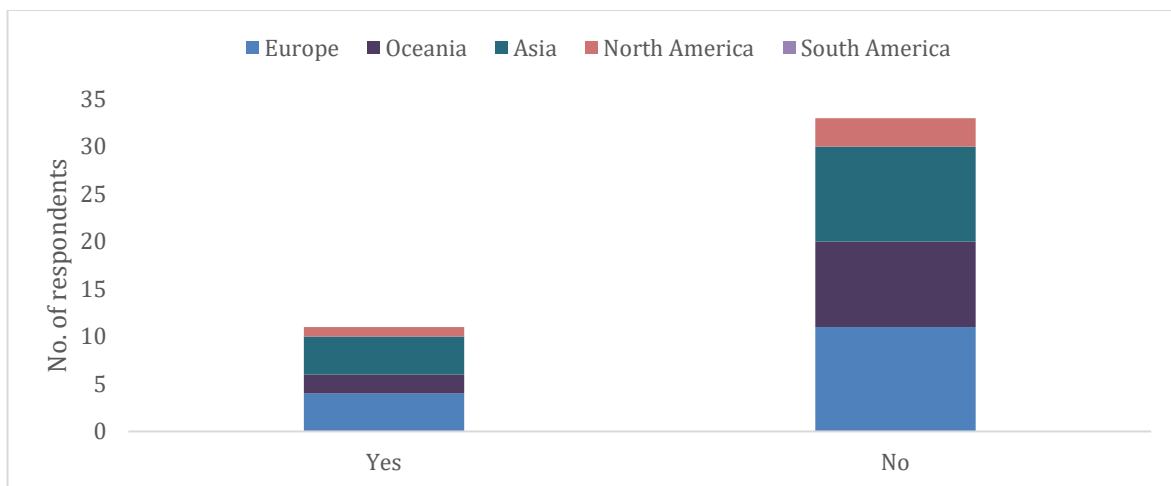
(a) Survey results by region
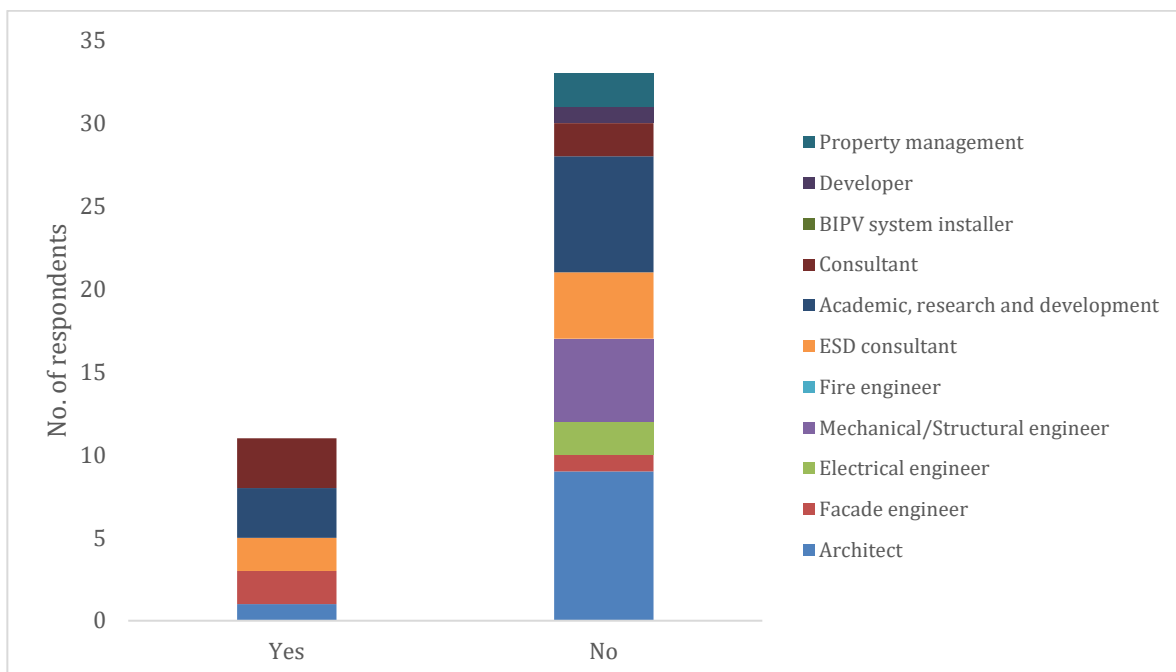
(b) Survey results by profession

Figure 5.23 Method(s)/software to simulate the heat island impact

5.3.6 Methods used to identify the impact on daylighting

As discussed in Section 4.3.6, A BIPV envelopes can impact natural lighting and visual comfort of indoor spaces of the buildings. As shown in Figure 5.3.6 a and Figure 5.3.6 b, several methods are used to identify the impact on daylighting in BIPV designs. Most survey respondents use simulation software to identify BIPV design impact on daylighting. However, it should be noted that respondents in Asia prefer calculating the daylighting manually. The entirety of building project should be considered when simulating daylighting. Therefore, many respondents employ building simulation software across all the regions. Furthermore, professionals such as Architects, ESD consultants and Academics prefer to use software for the daylighting simulation. Engineers and BIPV system installers calculate the daylighting impact manually. It can also be seen that, few BIPV installers and Developers do not consider the impact on daylighting in BIPV designs. Figure 5.3.6 c and Figure 5.3.6 d shows the software used for simulating daylighting. Radiance and IES VE are mostly used for identifying the impact of daylighting in BIPV projects, especially in Oceania. Furthermore, IES VE, Radiance and Grasshopper are the most popular choices among ESD consultants. Radiance is also favoured by Academics.
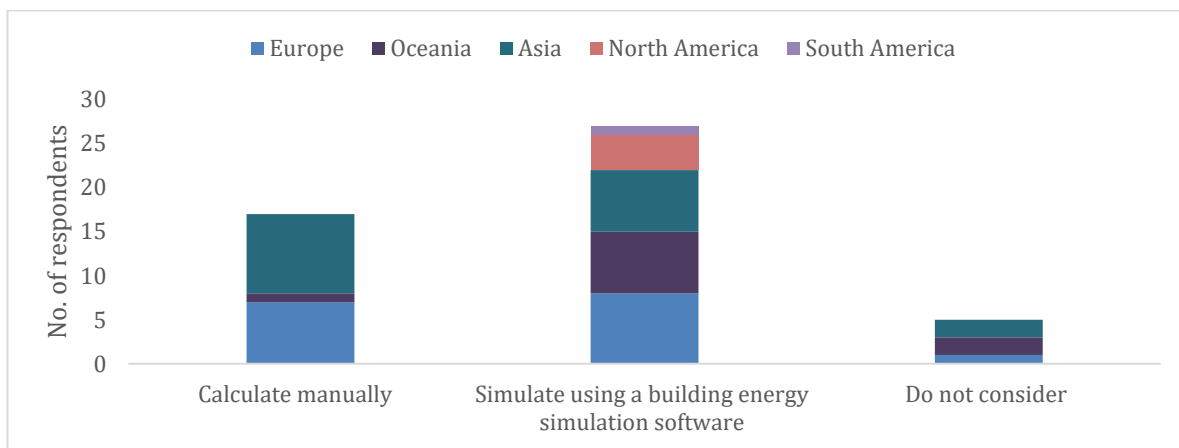
(a) Metthods: Survey resutls by region
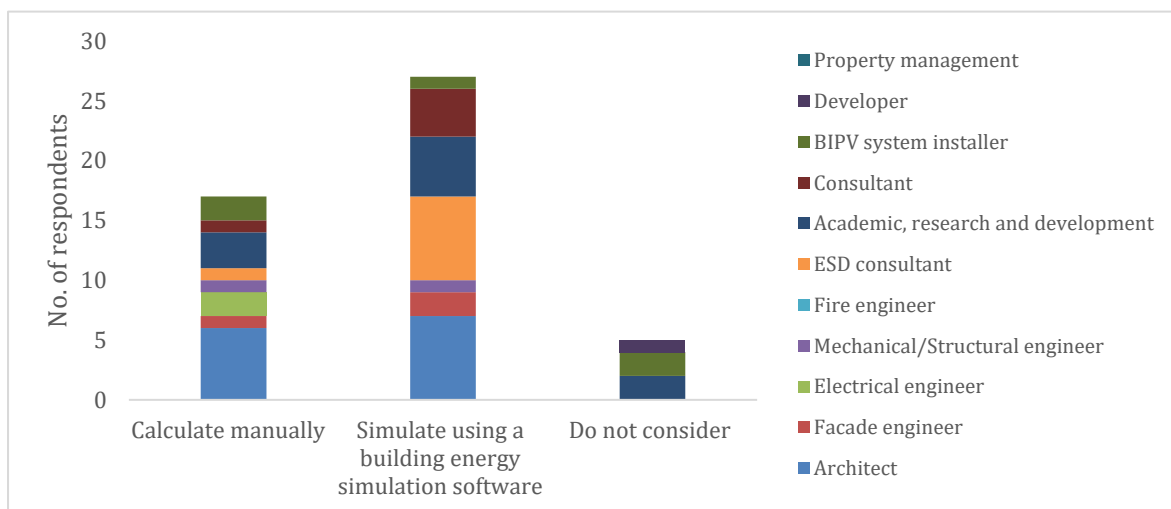
(b) Metthods: Survey resutls by profession
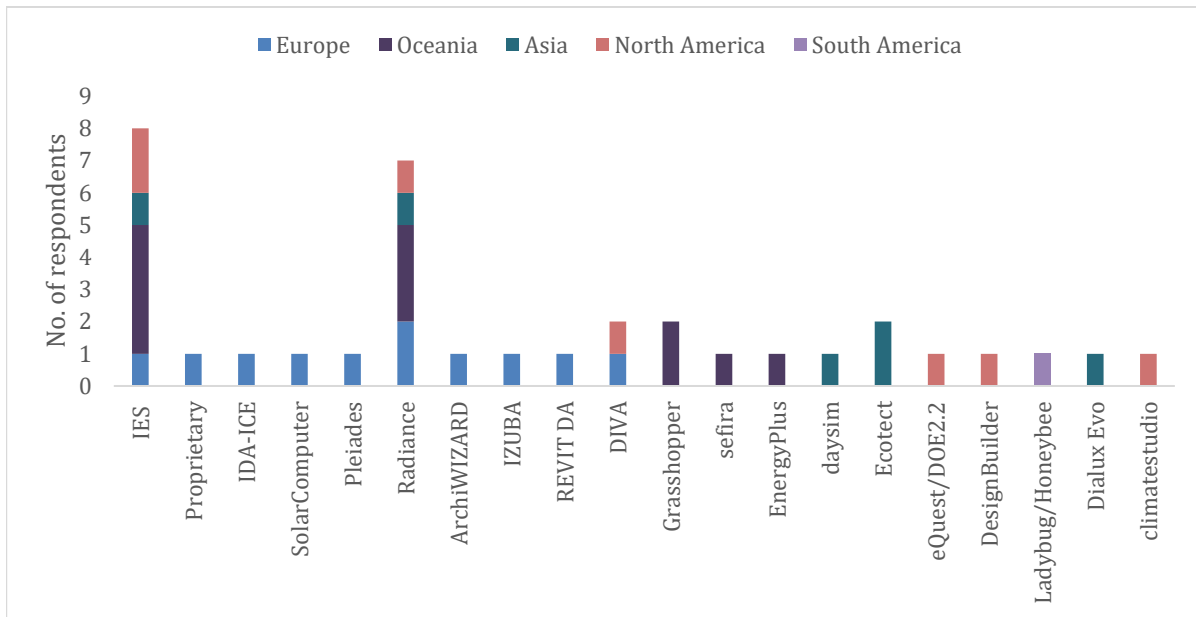
(c) Software: Survey resutls by region
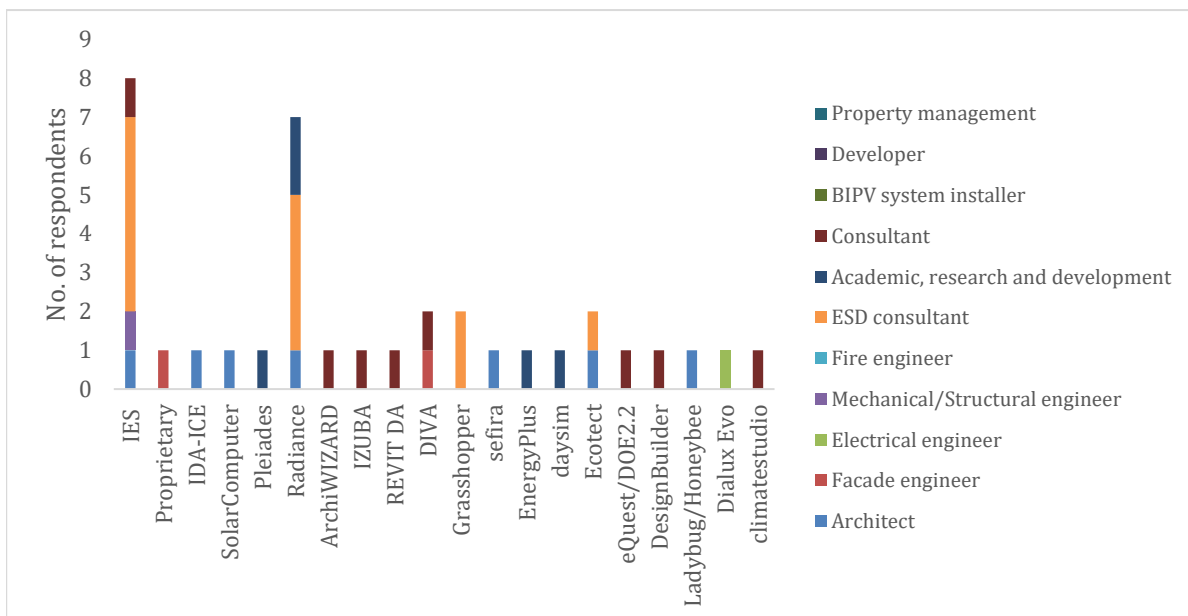
(d) Software: Survey resutls by profession

Figure 5.24 Methods used to identify the impact on daylighting

5.3.7 Structural loads considered during the planning and development of BIPV designs

Another important factor which directly impact the selection of BIPV systems engineering is the structural loads. Figure 5.3.7 a and Figure 5.3.7 b show the survey results on types of structural loads considered in BIPV designs. A higher number of the respondents from all regions agreed that dead load, wind load, snow load, live load and seismic load need to be

considered in structural analysis of BIPV designs. Structural load analysis requires specialised knowledge. The survey results show that Mechanical/Structural engineers consider dead load, wind load, snow load and live load in BIPV structural analysis. Generally, software is used to facilitate the structural load analyses as shown in Table 5.3.1. In Netherlands and China, proprietary software is used for the structural load calculation by Façade engineers and Academics. Spreadsheets are used for structural load calculation in Australia and USA. Software such as SpaceGass and RISA also being used in Australia and USA.
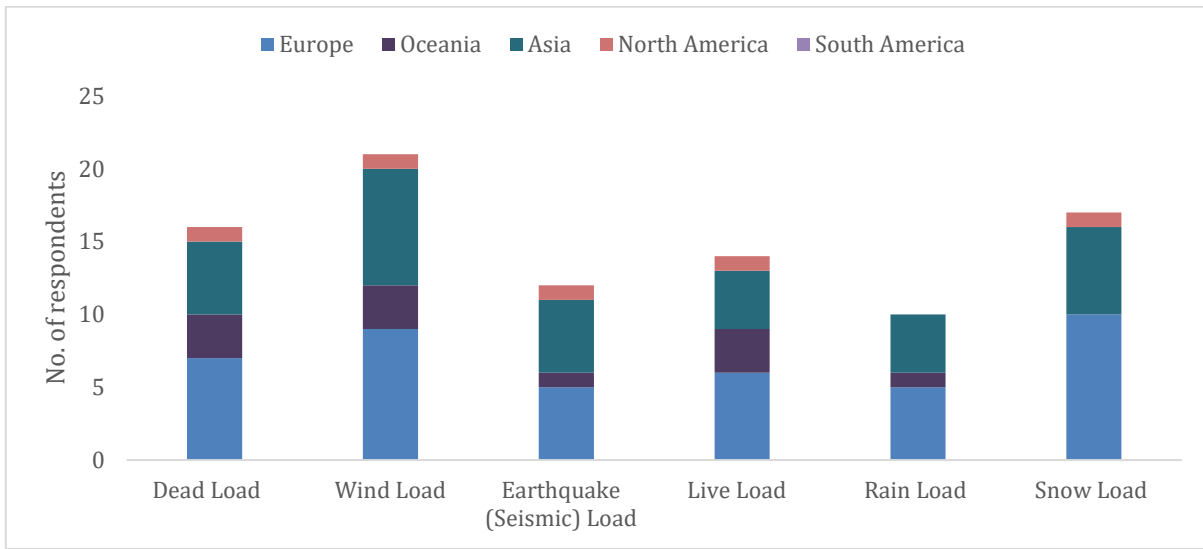
(a) Survey results by region
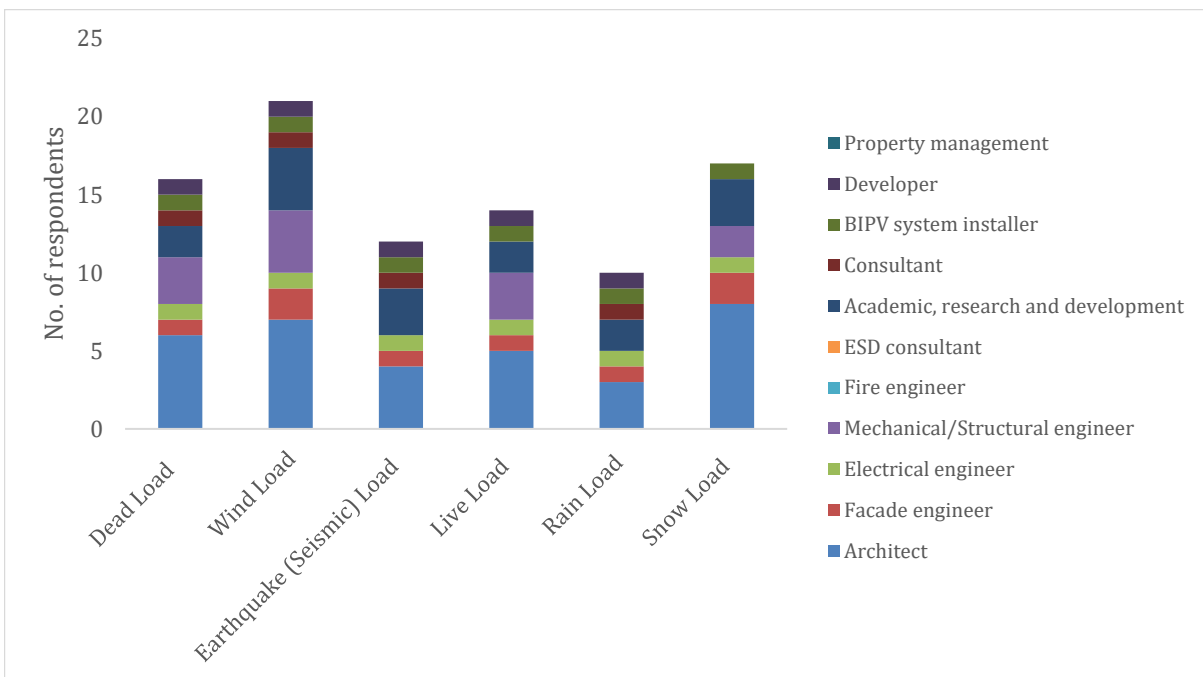
(b) Survey results by profession

Figure 5.25 Structural loads that impact BIPV designs

Table 5.3.1 Software for structural load calculation

Country	Software
Netherlands	Proprietary software
Australia	Manual calculations SpaceGass
China	Software that complies with GB50009 (National standard)
United States	Spreadsheets RISA

5.3.8 Software used to identify the fire related impact in BIPV designs

As discussed in Section 4.3.9, fire safety is a very important consideration in the application of BIPV as a building envelope element. Generally, fire safety related to BIPV designs require testing and confirmation of BIPV products. This section was designed specific for respondents with fire-related knowledge. In total, there are five responses from four Fire engineers and one Façade engineer. According to them, specialised software or method are used for identifying the fire related impact as shown in Table 5.3.2. The software Fire Dynamics Simulator (FDS) is mentioned by the respondents from Europe, Oceania and Asia.

Table 5.3.2 Software used to identify the fire related impact in BIPV designs

Country	Software/method
Netherlands	Proprietary software
Sweden	Fire Dynamics Simulator (FDS)
Australia	Thermal Radiation Analysis (TRA) Fire Dynamics Simulator (FDS)
China	Fire Dynamics Simulator (FDS)

5.4 Workflows and methods used in financial and design outcome

As discussed in Section 4.4, the financial and design outcome is important for decision making in BIPV project adoption. The clients or property developers are required to evaluate which BIPV design matches their requirements to ensure that the right investment decisions can be made. The following sections presents the survey findings on the factors considered in estimating the financial feasibility of BIPV projects and methods used for identifying the best BIPV project solution.

5.4.1 Indicators considered for identifying the economic feasibility

Section 4.4.1 identified six economic indicators for identifying the economic feasibility of BIPV projects. Figure 5.4.1-a and Figure 5.4.1-b shows the survey results on indicators used for evaluating the economic feasibility of BIPV projects. Overall, the NPV and ROI are the most popular choice, followed by PB. NPV, ROI and PB are the popular choices for BIPV economic analysis in Europe, Asia and Oceania. Further, most of the building design and BIPV design

related professionals use NPV, ROI and simple payback period for the evaluation of economic feasibility.
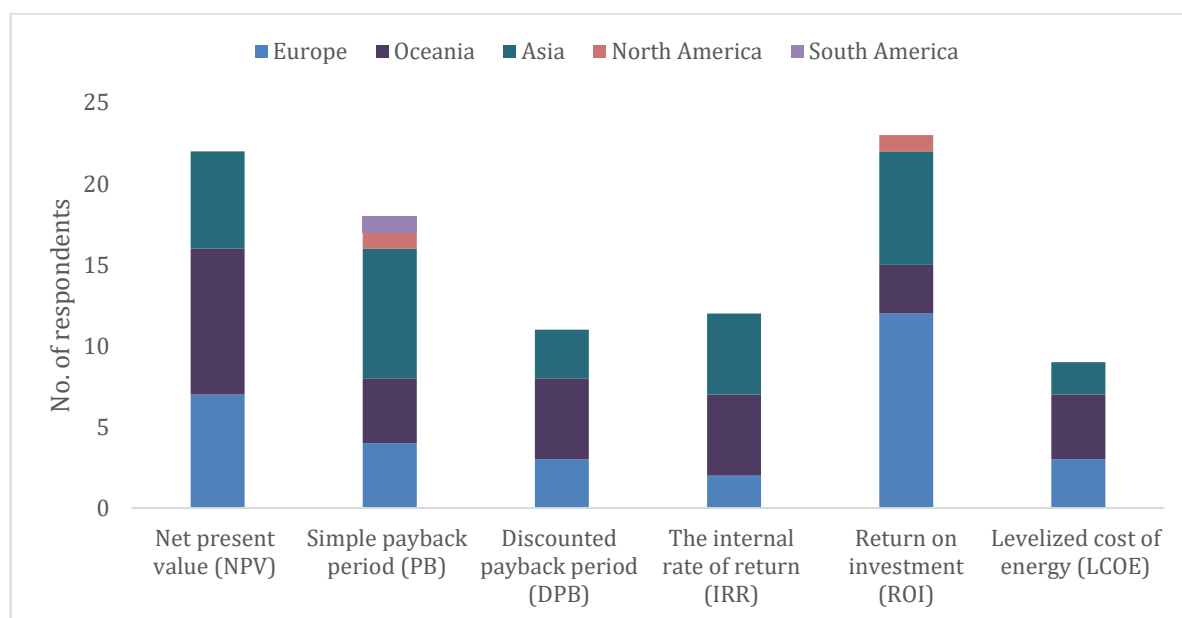
(a) Survey results by region
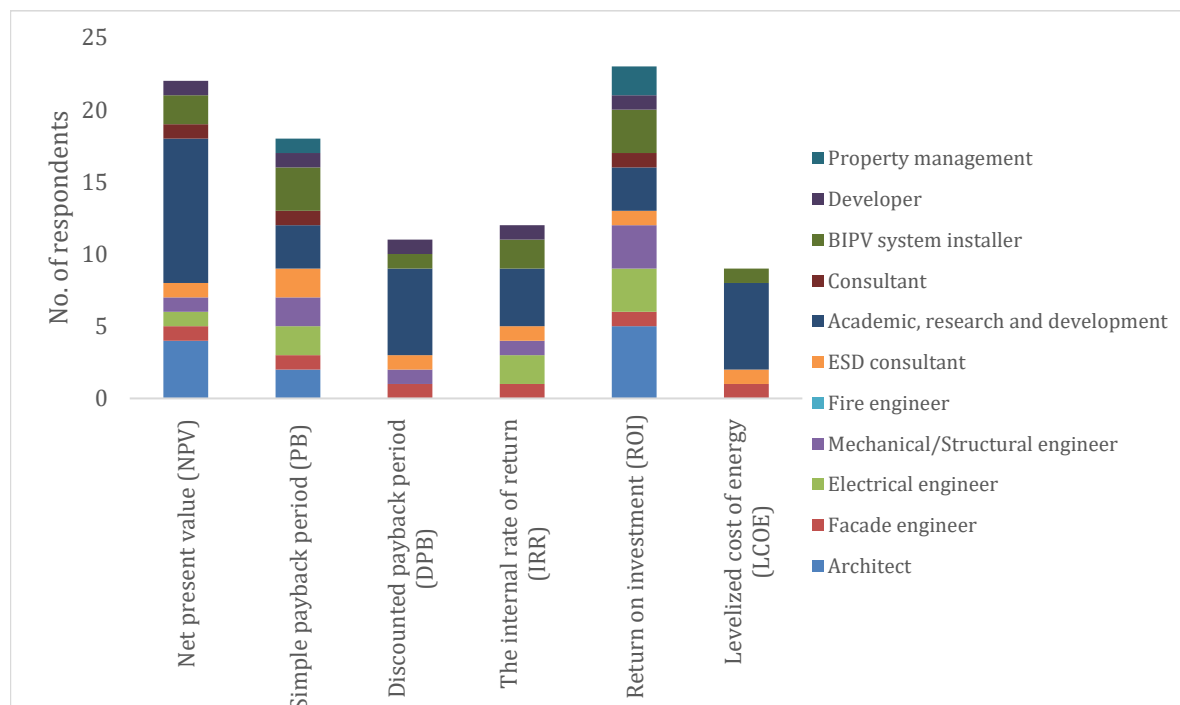
(b) Survey results by profession

Figure 5.26 Indicators considered for identifying the economic feasibility

5.4.2 Capital cost (initial costs) of BIPV

Section 4.4.2 identified the elements considered under the capital cost of BIPV projects. Figure 5.4.2 a and Figure 5.4.2 b shows the survey results on the capital cost or initial costs of BIPV projects. Overall, BIPV module costs, mounting structure cost, installation cost, costs of electrical devices (BOS) and installation costs have been confirmed by the survey respondents from all regions and by all professions. However, compared to other capital costs, contingency values are not taken into consideration by many respondents. The contingency value is always put as a percentage during the cost estimation process. The percentage value is decided by the quantity surveyor. The AEC and BIPV industry professions don't have the cost estimation experience would not consider contingency under BIPV project cost. Therefore, future research should be conducted on the important financial aspects required to financially evaluate BIPV projects.
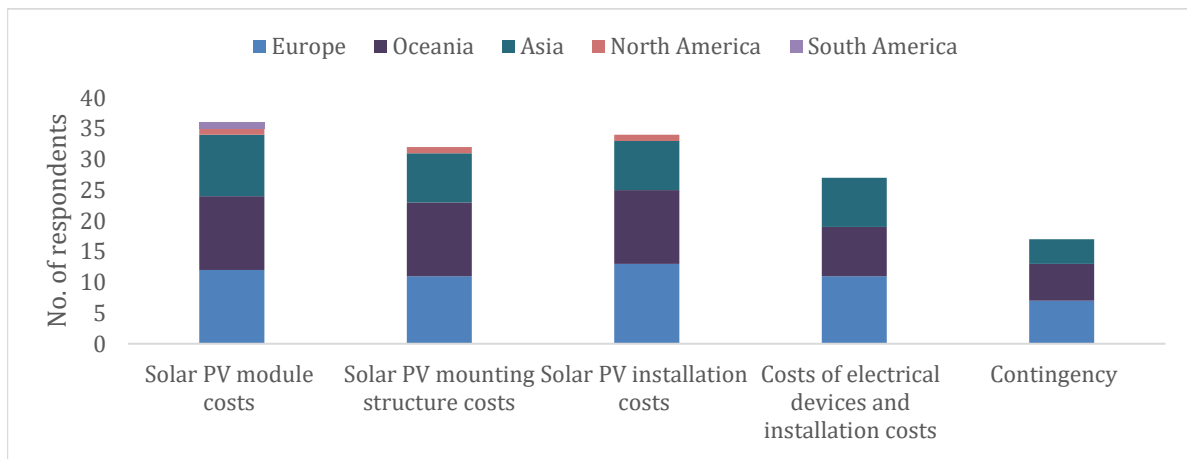
(a) Survey results by region
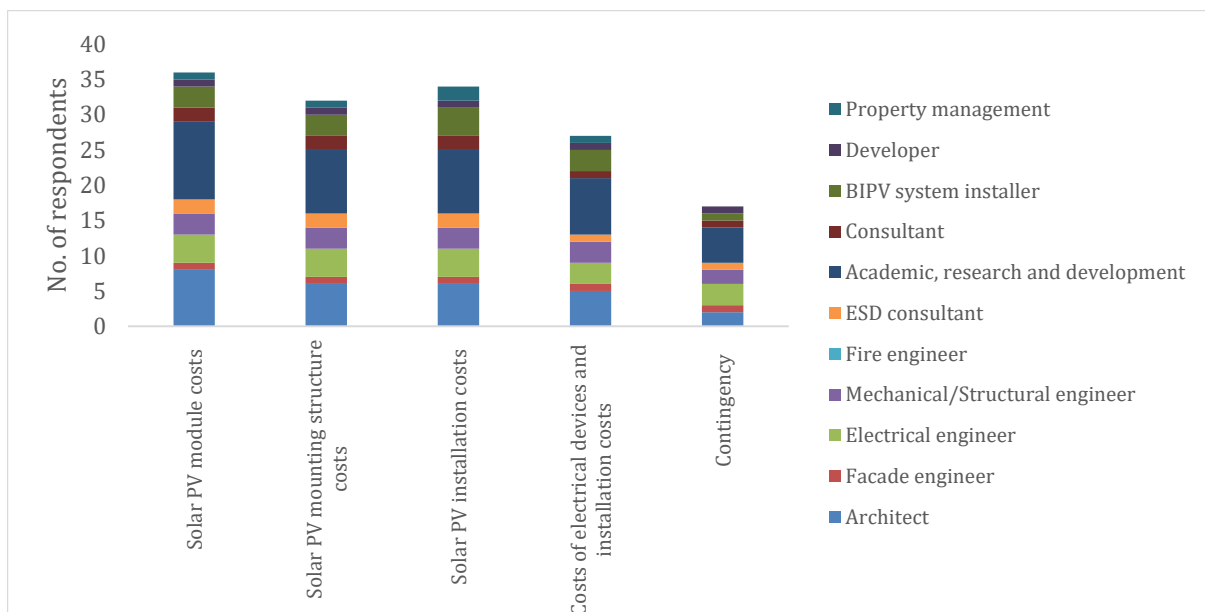
(b) Survey results by profession

Figure 5.27 Capital cost (initial costs) of BIPV

5.4.3 Operations and maintenance costs of BIPV

As discussed in Section 4.4.3, there are nine different operations and maintenance (O&M) costs considered in the life cycle of BIPV projects. As shown in Figure 5.4.3 a and Figure 5.4.3 b, the survey results have confirmed, repair of BIPV modules, Balance of System (BOS) and mounting system, replacement of BIPV modules, replacement of BOS, replacement of the mounting system, insurance, and depreciation under O&M costs of BIPV projects. It is noted that a higher number of respondents consider cleaning costs, repair of solar PV modules, replacement of solar PV modules and depreciation under O&M costs. However, not many uses replacement expense of mounting system under the O&M costs.
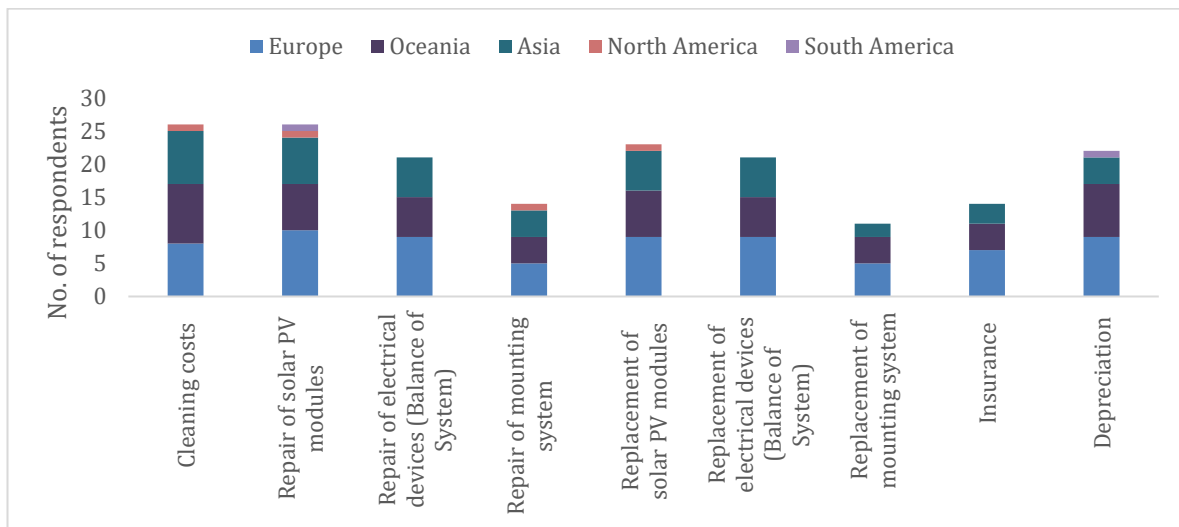
(a) Survey results by region
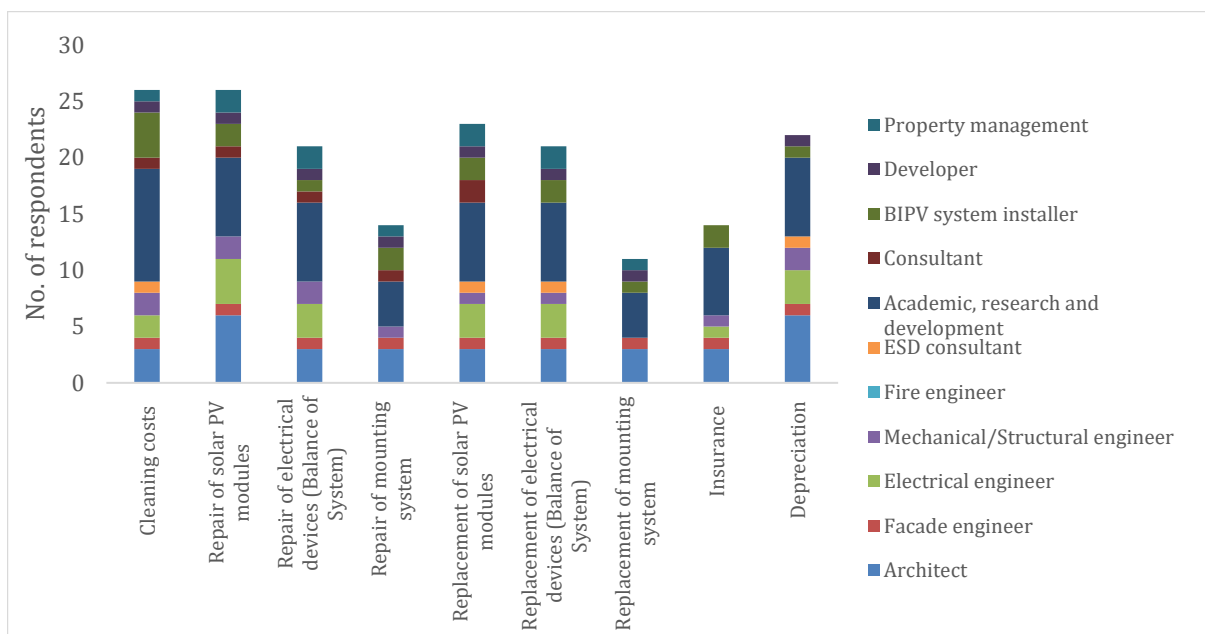
(b) Survey results by profession

Figure 5.28 Operations and maintenance costs of BIPV

5.4.4 Life cycle income of BIPV

As discussed in Section 4.4.4, in general, the most common life cycle income of a BIPV project is the saving from energy self-consumption and the income from feed in tariffs. However, salvage value and savings from reducing building thermal loads can also be considered. Figure 5.4.4-a and Figure 5.4.4-b shows the survey results on life cycle income of BIPV projects. Overall, the respondents have confirmed the above life cycle income elements. Most professions in all the regions consider the saving from energy self-consumption, the income from feed-in tariffs and salvage value to estimate the life cycle income. However, the savings from reducing building thermal loads are considered only in Europe, Oceania and Asia most by Architects, Academics and BIPV system installers.
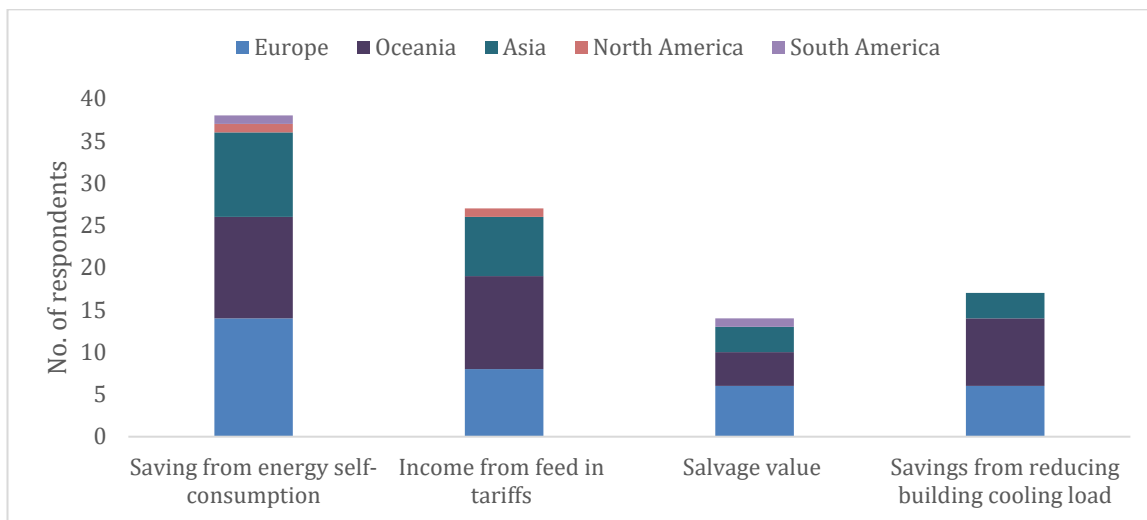
(a) Survey results by region
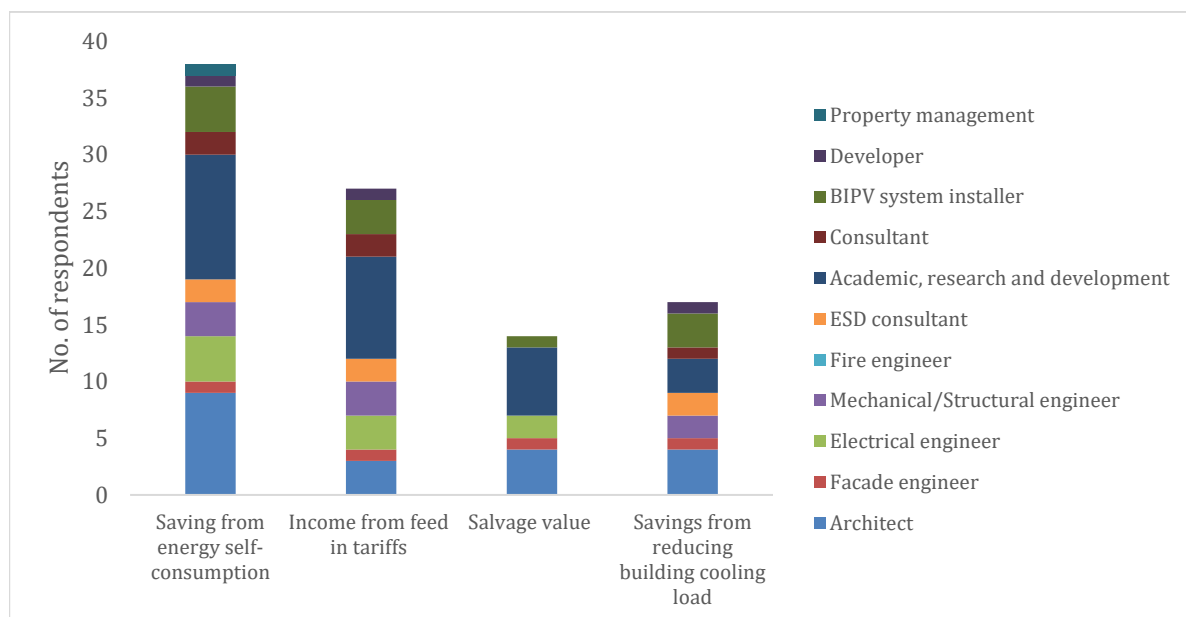
(b) Survey results by profession

Figure 5.29 Life cycle income of BIPV

5.4.5 Material cost offset as a benefit in the building envelope design evaluation

As discussed in Section 4.4.5, BIPV modules completely replace traditional building envelope materials. Figure 5.4.5 a and Figure 5.4.5 b shows the survey results on the use of material cost offset as a benefit in the building envelope design evaluation process. Overall, 79% respondents take material cost offset as a benefit in the economic evaluation. The survey results show that the material cost offset of BIPV is considered by most professions in Europe, Oceania, Asia, North and South America.
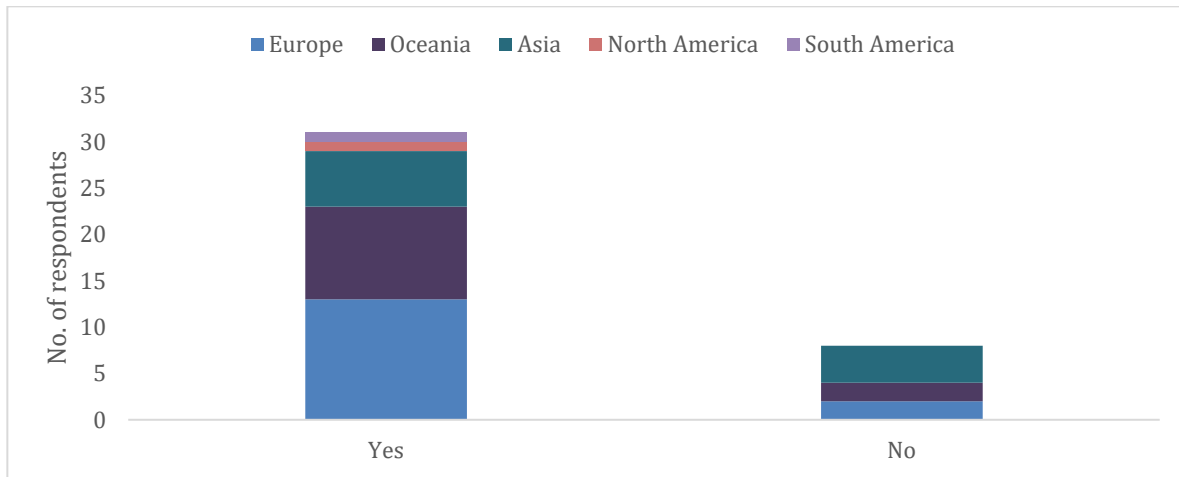
(a) Survey results by region
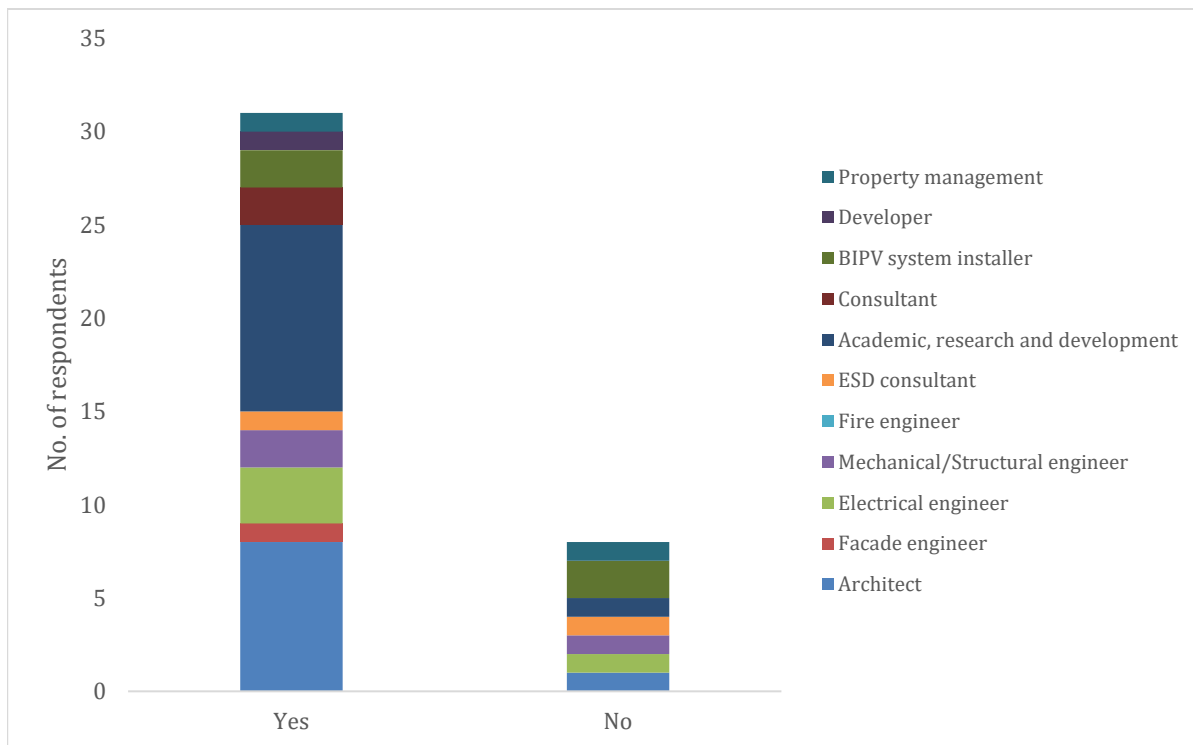
(b) Survey results by profession

Figure 5.30 Consideration on material cost offset

5.4.6 CO$_2$ emissions associated with BIPV

BIPV as a renewable energy source helps reduce the CO$_2$ emissions from energy generated from fossil fuel. Estimating the CO$_2$ emissions associated with the BIPV helps to implement an emission reduction strategy to the overall building, improve building energy efficiency and reduce its environmental impact. CO$_2$ emissions associated with BIPV systems is an important factor that should be considered in BIPV designs. As mentioned in Section 4.4.6, there are two ways of calculating CO$_2$ emissions: 1. Calculating the emissions avoided; 2. Calculating the embodied emissions of the BIPV system caused during the manufacturing, construction, and decommissioning phase. Figure 5.4.6 a and Figure 5.4.6 b shows the survey results on CO$_2$ emissions associated with BIPV systems. Over 40 of the respondents confirmed that the most suitable method is to calculate the emissions.

The region wise results are demonstrating that the calculation of emission avoided is more common in Europe, Asia, Oceania and North America by most professional categories. However, in terms of profession, several Architects, ESD consultants, Academics and BIPV installers consider calculating the embodied emissions in BIPV projects. Overall, not many respondents do not estimate embodied emissions of BIPV projects. Both emissions avoided, and embodied emission need to be considered to identify the environmental impact of BIPV projects. However, estimating the embodied emission during the design phase is difficult due to lack of information. Therefore, developing a method to estimate embodied emissions associated with BIPV projects in the design phase could be a potential research area.
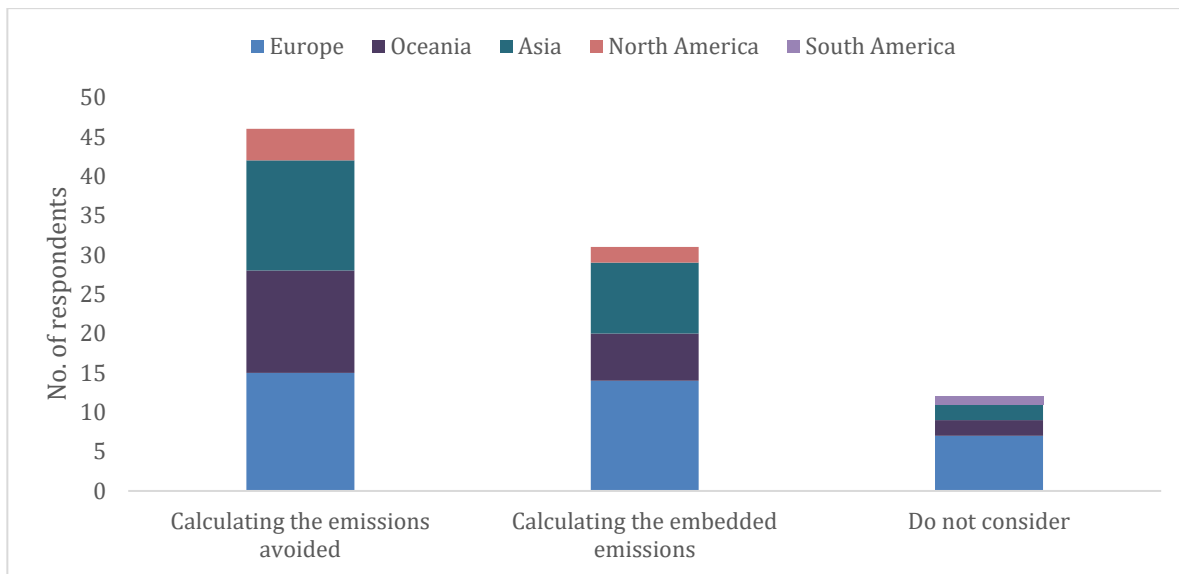
(a) Survey results by region
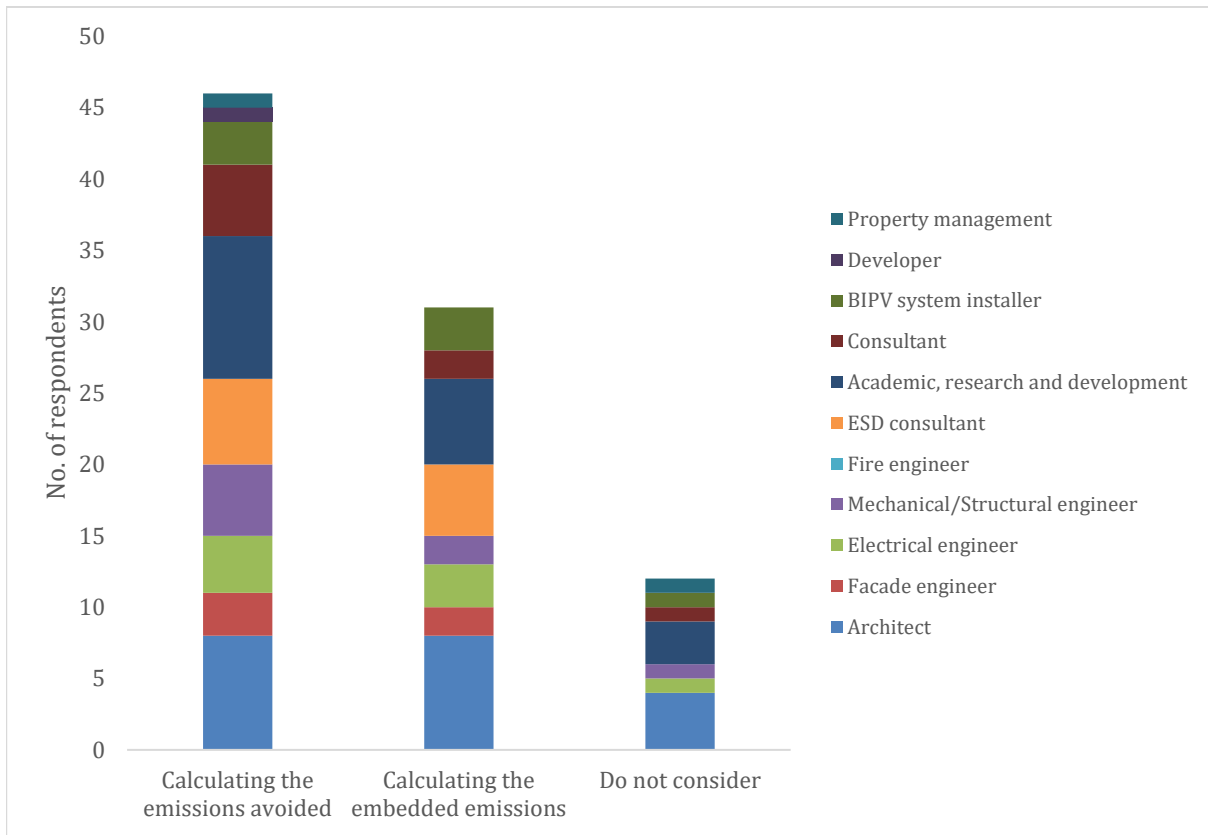
(b) Survey results by profession

Figure 5.31 CO$_2$ emissions associated with BIPV

5.4.7 Optioneering/decision making methods

As discussed in Section 4.4.6, traditional workflows, parametric workflows, and integrated optimization can be used as optioneering or decision-making methods. Figure 5.4.7 a and Figure 5.4.7 b presents the survey results on the above methods. The most popular method used in all regions is multiple solution comparisons using parametric workflows. Parametric workflows are highly used by Architects, Academics and Constants. However, traditional workflows are preferred by Architects and Mechanical/Structural engineers. The survey results show that except for Academics not many uses integrated optimization methods. However, compared to other methods integrated optimization methods have the potential to improve the decision making of BIPV designs with use of advance AI algorithms.
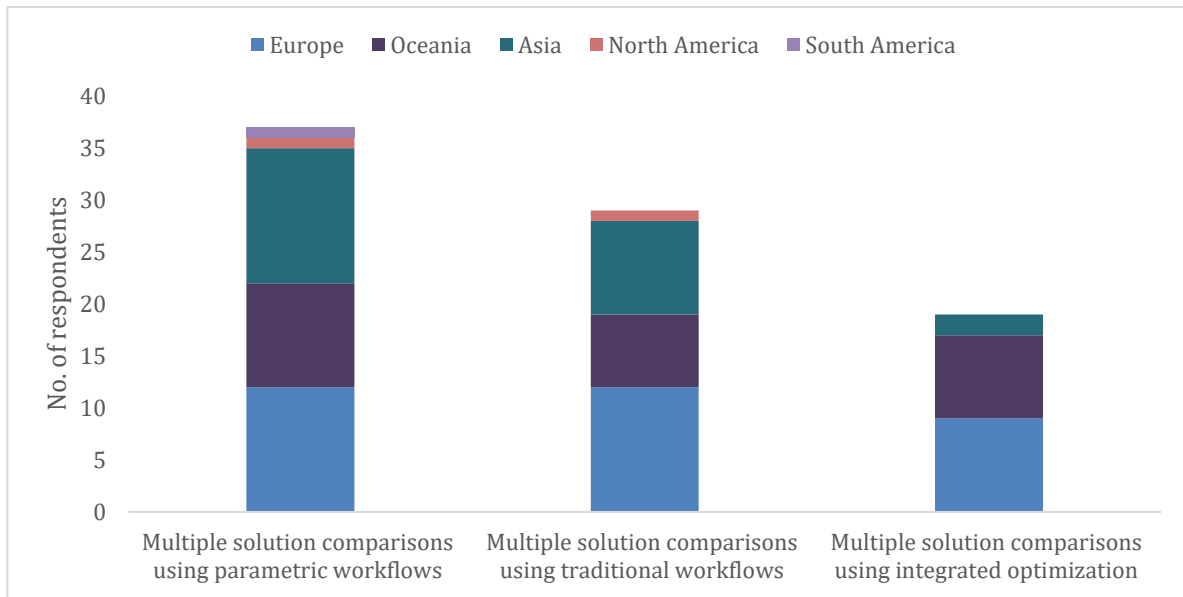
(a) Survey results by region
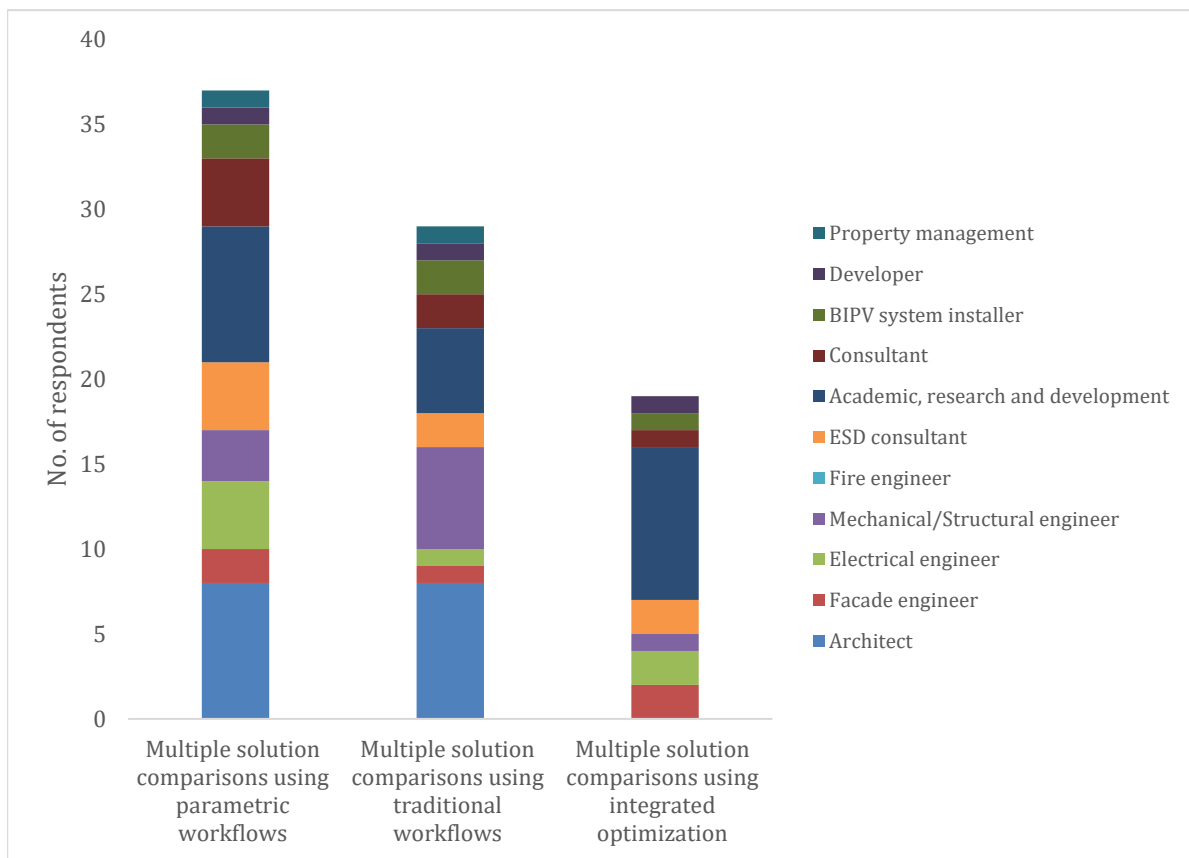
(b) Survey results by profession

Figure 5.32 Optioneering/decision making methods

5.4.8 Factor(s) that impact the optimum design of BIPV

Various factors can impact the decision for selecting BIPV designs such as cost, energy generation and reduction of CO_2 emissions and thermal impact. Figure 5.4.8 a and Figure 5.4.8 b present the survey results on the factors that impact the optimum design of BIPV. The results show that cost and energy generation are the two most common factors considered. Other factors such as aesthetics is mentioned by several respondents from Europe and Oceania. In terms of professions, most of the professional categories consider cost, energy generation and reduction of CO_2 emissions. Other factors such as aesthetics, construability, maintenance requirements and impacts on building are considered by Architects and ESD consultants. In Asia structural, fire, electrical thermal safety is also considered in the BIPV design evaluation. Overall, the survey results show that BIPV designs can be evaluated in different perspectives based on the regional and professional requirements.

(a) Survey results by region

(b) Survey results by profession

Figure 5.33 Factors that impact the optimum design of BIPV

Based on above findings, the process of BIPV design and analysis can be illustrated under 4 steps as shown below:

BIPV design and analysis

Step 1

Solar irradiation

Stakeholders: Façade engineers, Architects, Electrical engineers, BIPV system installers, PV consultants, ESD consultants, Academics

Developing building model

Identifying project location

- Google maps
- IP addresses
- Manually selected from a list

Creating building geometry and surrounding environment

2D
- CAD software

3D
- CAD or BIM software
- GIS modelling
- CAD or BIM software with LiDAR assisted point cloud data

Photorealistic visualisation
- Autodesk Revit
- Sketchup
- Rhino
- Autodesk Maya
- 3D studio max
- Lumion,
- SU Podium rendering plugin for SketchUp
- MicroStation a
- KeyShot

Data exchange formats
- Autodesk Revit.rvt
- Open BIM (ISO).ifc
- SketchUp.skp

Models for higher spatial resolutions
- Custom made tools

Solar irradiation analysis

Weather parameters
- Irradiance
  - Beam/direct normal irradiance
  - Diffuse horizontal irradiance
  - Global horizontal irradiance
- Temperature
- Wind speed

Model for POA estimation
- POA (Beam only)
- POA with shading and ground reflected (Albedo)
- POA sky diffused
- Ray tracing with radiosity Ray tracing with rasterization

Methods for shading approximations
- Ray tracing
- Shading percentage
- Far field shading horizon map
- Near field shading factor
- Sky view factor
- Reduction of incident irradiation
- Shading index

Type of weather data
- Long-term averaged data
- Ground mounted meteorological data
- Satellite based meteorological data
- Measured at site
- Hybrid

POA sky diffuse model
- Isotropic Sky Diffuse Model
- Simple Sandia Sky Diffuse Model
- Hay and Davies Sky Diffuse Model
- Reindl Sky Diffuse Model
- Perez Sky Diffuse Model

Weather data step values
- Conceptual design – Annual
- Detailed design – Hourly

Weather file formats
- EPW files from the EnergyPlus
- Typical Meteorological Year

Software for estimating POA irradiation
BIMSolar, IES VE, PVsyst, TAS, Revit Solar, PV Watt, Pleiades, Helioscope, PV GIS, Radiance and SAM

Step 2

Power output analysis

Stakeholders: Electrical engineers, Architects, Façade engineers, PV consultants, and Property managers

Importing properties of technical components of BIPV
- BIPV component database in software
- Online platform
- Add manually

Models for calculating DC output of BIPV
- PV cell temperature model
- Power model by Heydenreich et al. (2008)
- Sandia PV Array Performance Model (SAPM)
- Loss factors model (LFM)
- Single diode model
- Two-diode model

Software for calculating DC output of BIPV
- BIMsolar
- PVsyst
- PV*Sol
- SAM
- Retscreen

Step 3

Building performance

Stakeholders: Architects, Electrical engineers, Mechanical/Structural Engineers, Fire engineers, Façade engineers, PV consultants, ESD consultants, Property managers and Academics

Building energy consumption

Models for identifying the energy consumption patterns
- Calculating the watt hour data
- Use historical information electricity bills
- Simulation software to identify building energy demand (e.g. IES VE, EnergyPlus)
- Measure building energy consumption
- Percentage of monthly energy consumption based on the usage

Suitable interval for energy consumption data
- The conceptual design phase – Annual and monthly
- Detailed design phase – hourly and daily

Data file formats for building energy consumption
- Text file
- MS Excel Spreadsheet
- Comma Separated Values (CSV)

BIPV impact on building factors

Structural loads considered for BIPV designs

dead load, wind load, snow load, live load and seismic load, live load, rain load

- Calculate manually
- Use software for structural load calculation (e.g. proprietary software, SpaceGass, RISA)

Methods/software for daylight impact
- Calculate manually
- Use building simulation software (e.g. IES VE,Radiance, DiVA, Grasshopper)

Methods for thermal impact of BIPV designs
- Calculate manually
- Use building simulation software (e.g. IES VE, EnergyPlus, DesignBuilder)

Software for fire related impact
- Fire Dynamics Simulator (FDS)
- Thermal Radiation Analysis (TRA)
- Proprietary software

Methods/software for heat island impact
- Rhino and Grasshopper
- EnergyPlus
- Envi-met

Figure 5.34 Workflow of BIPV design and analysis

Step 4

Financial and design outcome

Stakeholders: Developers, ESD consultants, PV consultants, Academics and Property managers

Assessing economic and environmental feasibility

Economic	Lifecycle cost of BIPV	O&M costs of BIPV	Lifecycle income of BIPV
• NPV • ROI • PB • IRR • DPB • LCOE	• Capital cost of BIPV • Module cost • Mounting structure cost • Installation cost • Cost of electrical devices and installation • Contingency **Material cost offset**	• Cleaning • Repair of BIPV modules • Repair of BOS • Repair mounting system • Replacement of BIPV modules • Replacement of BOS • Replacement of the mounting system • Insurance • Depreciation	• Saving from energy self-consumption • Income from feed in tariffs • Salvage value • Savings from reducing building thermal loads

Environmental

- Emissions avoided
- Embodied emissions

Decision making

Optioneering /decision making methods

- Multiple solution comparisons using parametric workflows
- Multiple solution comparisons using traditional workflows
- Multiple solution comparisons using integrated optimization

Factors for optimum design of BIPV

- Cost
- Energy generation
- Reduction of CO_2 emissions
- Thermal impact
- Aesthetics
- Constructability
- Maintenance requirements
- Building value
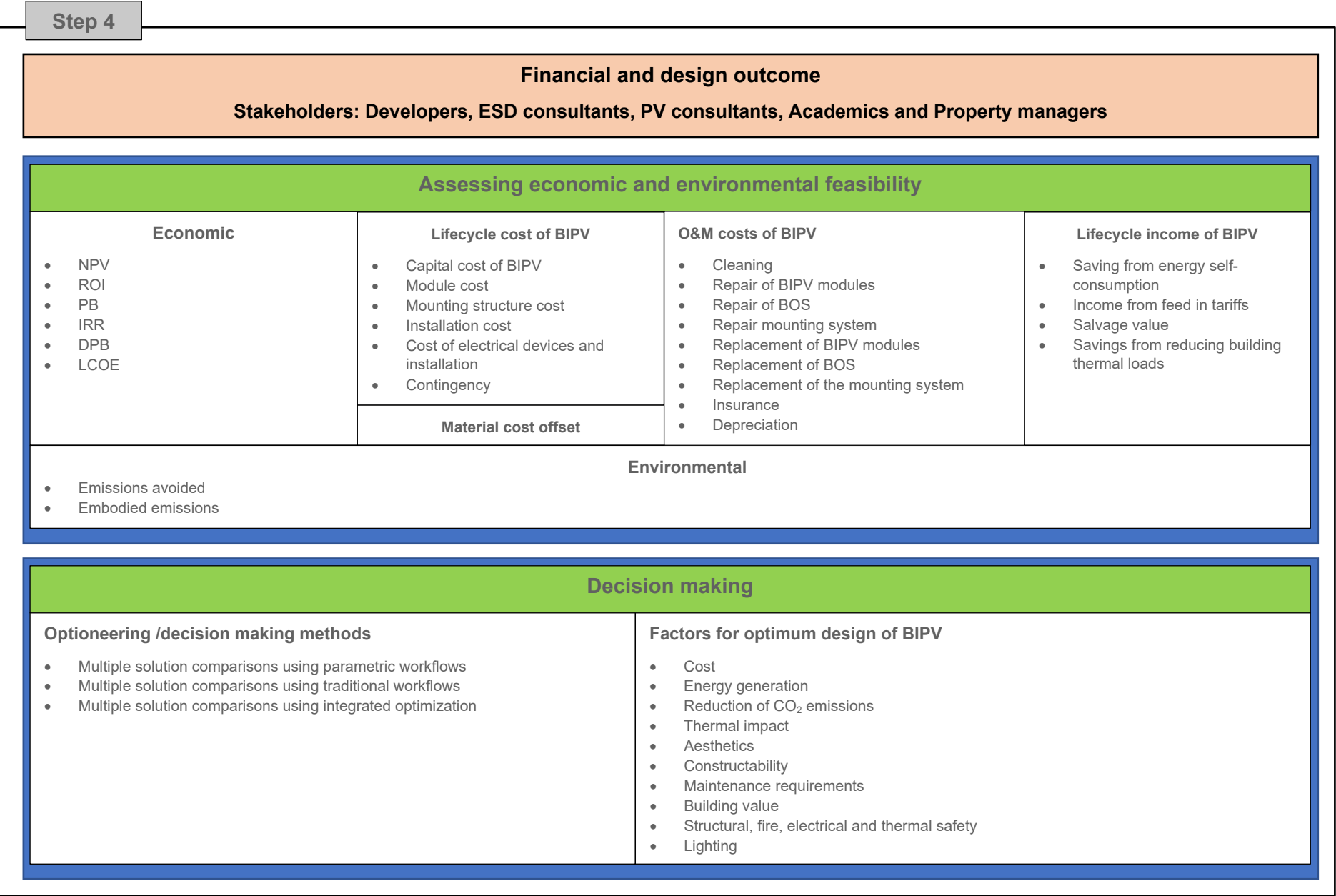- Structural, fire, electrical and thermal safety
- Lighting

Figure 5.35 Workflow of BIPV design and analysis (contd.)

6 CONCLUSIONS

This study identified approaches, methods, and workflows in BIPV digital design and analysis process used globally by building, construction and BIPV industry professionals under 4 categories: 1. solar irradiation 2. BIPV power output 3. building performance and 4. financial and design outcome. The findings from the questionnaire survey show that various methods and tools are used for solar irradiation modelling and simulation, BIPV power output modelling or simulation, building performance modelling or simulation and financial and design outcome. Further, the results show that application of the identified methods vary based on the country and professional requirements.

Furthermore, the survey results indicate that further research is required on the methods that are more suitable for BIPV design and analysis. Especially more research on the methods and models used to estimate POA, power output, embodied emissions, heat island impact, thermal, daylighting, structural and fire requirements of BIPV projects are required. Following components should be considered in future BIPV specific software/design processes:

- **BIPV product database**: The survey findings show that users of the BIPV simulation software prefer databases available BIPV products which can be used in the BIPV design and planning and/or construction process. The product database based on types of BIPV applications and manufacture/supplier specifications could facilitate the development of design and design documentation.

- **System design documentation**: BIPV system design documentation such as CAD drawings, wiring diagrams and project plans are important in the design and analysis process of a BIPV project.

- **Shading**: Unlike conventional PV, BIPV design process need to consider the micro, mezzo or macro shading levels (Stamenic and Erban, 2021) and further research in this area is very essential.

- **Embodied Energy in BIPV**: IEA PVPS Task 12 have developed a guideline on life cycle assessment of photovoltaic electricity (Fthenakis et al., 2011) that can be a useful tool for determining the embodied energy in BIPV projects. However, the problem lies with the difficulty of obtaining the data needed for the LCA analysis or the data cannot be validated. Another issue which needs attention is the misconception that estimating the CO_2 footprint or emissions could increase the cost of BIPV products. Therefore, there can be conflicting interests between new producers of BIPV, existing producers and project developers where the latter might fear that PV and BIPV would become more costly if the CO_2 footprint or emissions are known and perhaps even incorporated in the cost prices. Therefore, estimation of embodied energy associated with BIPV projects need to be considered in a future software development process, which allows life cycle emission assessment to be performed.

- **Customer requirements**: BIPV projects are designed to a high degree according to customers or the project's needs. Therefore, there should be more research into the BIPV design and analysis in relation to the aesthetical, cost and energy output of BIPV designs to understand how building owners, designers, policy makers should adopt BIPV applications.

- **Decision support models**: Currently, there are no decision support models the installers, end users, projects developers could use to identify feasible BIPV design

solutions. Even for BAPV there are few integrated calculations that match the energy profiles with the total amount of recommended PV installed, usually just the ROI is calculated and the maximum PV system size.

- **BIPV in urban context**: There should be an examination of the relationship between the type and intensity of land use, ground positions and energy generation of BIPV and the heat Island effect to identify the impact of BIPV in the urban environment in different part of the world. The identification of the impact of BIPV on the urban environment could provide designers and end users a comprehensive knowledge on the feasibility of BIPV applications in a metropolitan setting. Identification of the impact of BIPV on the urban environment could provide designers and end users a comprehensive knowledge on the feasibility of BIPV applications in a metropolitan setting.

Due to the cross-functional nature of BIPV as a building material and an electro-technical device, there's a need to improve the knowledge and awareness of both the AEC industry and BIPV industry professionals on the BIPV design and analysis methods and workflow. Therefore, there's a need for a streamlined process or workflow for BIPV digital design and analysis. Furthermore, a simplified design process can improve the application of efficient and cost-effective BIPV in construction projects. Thereby aiding to reduce the carbon emissions associated with fossil fuels generated electricity.

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APPENDIX A: QUESTIONNAIRE SURVEY

Design workflows for building envelopes/ building envelopes with solar panels

Operative Approaches, Methods and Workflows in Simulations Related to Building Envelopes

INTRODUCTION

We are conducting the research on "Design workflows for building envelopes/ building envelopes with solar panels" aiming to investigate the operative methods and workflows relevant to building envelope design and digital process and formalize a framework for design and management of Building Integrated Photovoltaics (BIPV projects). We conduct a web-based questionnaire survey to collect data for the aforementioned study and you are kindly invited to take part in this survey. The International Energy Agency (IEA) PVPS Task 15 is distributing this online survey to their contacts who are eligible for this study. This will be done to assure the confidentiality of your contact information. The target respondents are building designers, engineers, BIM expert, and academics.

It will take approximately 10 minutes to complete, and you can fill the questionnaire at anytime and anywhere you prefer, before 31 October 2020. Participation in this research project is voluntary. If you do not wish to take part, you do not have to. Please note that submitting your completed questionnaire is an indication of your consent to participate in the study and no other written consent will be requested. If you decide to withdraw at some stage, you simply have to leave the web page without saving your responses or submitting them. The server will automatically save your responses but only send your responses to us if you've completed the survey. However, please note that once you submit your data, it is not possible to identify which data was provided by you therefore, your responses cannot be removed from the system after submission.

We are more than happy to clarify any issues you have. If you are willing to participate and have difficulties with how to proceed, please contact the research team through the Australian representative of IEA PVPS Task 15 Dr. Rebecca Yang at rebecca.yang@rmit.edu.au. Also, if you are interested in the outcome of this study, please contact the research team through the same email address. To answer this survey, BIPV design experience is NOT essential. We kindly request you to fill this questionnaire to the best of your ability and submit at your earliest convenience. We ensure you that your personal information will not be revealed in the study and no action of any sort will be carried out without your consent. We appreciate your participation in this study.

Professional Details
This section will ask about your professional details and experience. Please select the best suited answers related to your professional background to receive the relevant sets of questions.

_____

1. **Based on your involvement in building/architecture/engineering/construction industry, select the most suitable group for you?**

☐　　Architect (1)

☐　　Facade engineer (2)

☐　　Electrical engineer (3)

☐　　Mechanical/Structural engineer (6)

☐　　Fire engineer (7)

☐　　ESD consultant (4)

☐　　Academic, research and development (8)

☐　　Consultant (9)

☐　　Infrastructure suppliers/ retailers (10)

☐　　BIPV system installation (11)

☐　　BIM specialist (12)

☐　　Other (Please specify below) (5)

_____

_____

What is your current occupation and position?

_____

---

2. **How long have you involved in building/construction industry?**

    ○ 0-2 years (1)

    ○ 2-5 years (2)

    ○ 5-10 years (3)

    ○ 10+ years (4)

---

3. **Which country are you from?**

    _____

---

4. **Do you have experiences in building envelope (façade & roof) simulation and analysis?**

    ○ Yes (1)

    ○ No (2)

---

5. **Do you have experience related to simulation and analysis of "Building Integrated Photovoltaic (BIPV)" designs?**

    ○ Yes (1)

    ○ No (2)

---

6. **This survey consist two set of questions. Please select the set of questions relevant for your expertise.**

○ Approaches, methods and workflows used in building envelope/building envelope with solar panel design (For building design experts) (1)

○ Approaches, methods and workflows specifically relevant to building information modelling enabled building envelope with solar panels (For BIM experts) (2)

○ Both (4)

---

7. **Approaches, methods and workflows used in building envelope/building envelope with solar panel design**

The next section will ask about approaches, methods and workflows used in building envelope/building envelope with solar panel design. Please select the topics you are comfortable to answer. You can select multiple topics.

7.1 **Solar irradiation modelling or simulation**

☐ Based on location (2)

☐ Solar irradiation for a specific building envelope (3)

☐ Both (4)

7.2 **Solar power output modelling or simulation**

☐ Power output of building envelope with solar panels (1)

7.3 **Building performance modelling or simulation**

☐ Building energy consumption (1)

☐ Structural loads (2)

☐ Thermal loads (3)

☐ Daylighting (4)

☐ Fire (5)

☐ All (6)

7.4 **Financial and design outcome**

☐   Building envelope financial analyisis (1)

☐   Decision making in design (2)

☐   Both (3)

End of Block: Default Question Block

Start of Block: Block 2

Display This Question:

If Solar irradiation modelling or simulation = Based on location

Or Solar irradiation modelling or simulation = Both

Based on Location

This section will ask about approaches, methods and workflows used in modelling or simulating the location of the building envelopes (façade & roof)

Display This Question:

If Solar irradiation modelling or simulation = Based on location

Or Solar irradiation modelling or simulation = Both

8. **Which tool (or tools) do you use for modeling building envelopes/ building envelopes with solar panels?**

☐   Sketch-up (1)

☐   Rhinoceros (4)

☐   AutoCAD (5)

☐   ArchiCAD (6)

☐   Revit (7)

☐   Other (Please specify below) (8)

_____

- -

Display This Question:

    If Solar irradiation modelling or simulation = Based on location

    Or Solar irradiation modelling or simulation = Both

9. **Which tool (or tools) do you use for simulating a building envelope with solar panels ?**

☐   PVGIS (1)

☐   DIVA for Rhino/Grasshopper (4)

☐   Ladybug/Honeybee (5)

☐   Revit Solar Analysis (11)

☐   PVSYST (6)

☐   EnergyPlus (7)

☐   Modelica (8)

☐   Homer Pro (9)

☐   PV*SOL (12)

☐   Solar Advisory Model (SAM) (13)

☐   Other (Please specify below) (10)

_____

Display This Question:

    If Solar irradiation modelling or simulation = Based on location

    Or Solar irradiation modelling or simulation = Both

10. **What methods have you used for identifying the location (i.e. longitude and latitude) of the building envelope/ building envelopes with solar panels in simulation tools?**

☐ Google maps (1)

☐ IP addresses   (2)

☐ Manually selected from a list (3)

☐ Other (Please specify below) (4)

_____

Display This Question:

    If Solar irradiation modelling or simulation = Based on location

    Or Solar irradiation modelling or simulation = Both

11. **What methodology do you find suitable for modelling the geometry of the building and surrounding environment of a project which has solar panels on its envelope?**

☐ 2D CAD   (1)

☐ 3D CAD   (2)

☐ GIS based modelling (4)

☐ Point-cloud data using LIDAR-assisted modelling   (5)

☐ Do not model the building and surrounding environment (6)

☐ Other methodology (Please specify below) (7)

_____

----

12. Are you using any software for (photorealistic) visualization of building envelope with solar panels?

   ○ Yes (Please specify the software below) (1)

   _____

   ○ No (2)

- -

13. What is the commonly used 3D format for data exchange between collaborators or data import?

☐   Open BIM (ISO) .ifc (1)

☐   GreenBuilding XML(gbXML) .xml (2)

☐   EnergyPlusTM format .idf (3)

☐   Trimble® SketchUp®.skp (4)

☐   AutoDesk® REVIT®.rvt (5)

☐   AutoDesk® REVIT®family.rfa (8)

☐   Other (Please specify below) (6)

   _____

☐   Have not imported 3D formats (7)

14. What weather parameters do you consider for identifying solar potential (Plane of array irradiation) for building envelopes/ building envelopes with solar panels?

☐ Global Horizontal Irradiance (GHI) (1)

☐ Direct Normal Irradiance (DNI) (2)

☐ Diffuse Horizontal Irradiance (DHI) (3)

☐ Other (Please specify below) (5)

_____

☐ Not sure (6)

End of Block: Block 2

Start of Block: Block 3

Solar Irradiation for a Specific Building Envelope

This section will ask about approaches, methods and workflows used is solar irradiation simulation.

15. **Which type of weather data for designing building envelopes with solar panels are you using?**

☐   Ground mounted meteorological stations (1)

☐   Satellite based meteorological data (2)

☐   Measured at site (3)

☐   Hybrid (4)

☐   Long-term averaged data (6)

☐   Other (Please specify below) (5)

_____

Display This Question:

If Solar irradiation modelling or simulation = Solar irradiation for a specific building envelope

Or Solar irradiation modelling or simulation = Both

16. **Which type of weather file formats do you use?**

☐   EPW files from the EnergyPlus website (1)

☐   Typical Meteorological Year (TMY) (2)

☐   Other (Please specify below) (5)

_____

☐   Not sure (6)

----

17. **What software do you use to estimate Plane of array irradiation (POA) for building envelopes with solar panels?**

_____

_____

_____

_____

_____

18. **Which models does your software use to estimate Plane of array irradiation (POA) for building envelopes with solar panels?**

☐   POA (Beam only) (1)

☐   POA with shading and ground reflected (Albedo) (3)

☐   Ray tracing with radiosity (5)

☐   Ray tracing with rasterization (6)

☐   Other (Please specify below) (8)

_____

☐   Not Sure (9)

19. **Which POA sky diffuse model have the above software used to estimate POA irradiance for building envelope with solar panels?**

☐ Isotropic Sky Diffuse Model (1)

☐ Simple Sandia Sky Diffuse Model (2)

☐ Hay and Davies Sky Diffuse Model (3)

☐ Reindl Sky Diffuse Model (4)

☐ Perez Sky Diffuse Model (5)

☐ Other (Please specify below) (6)

_____

☐ Not Sure (7)

----

20. **Which types of shading approximations does your software use for building envelopes with solar panels?**

☐   Far-field shading horizon map (1)

☐   Far-field (Horizon) shading factor (2)

☐   Near-field shading factor (3)

☐   Shading percentage (SP) (4)

☐   Reduction of Incident Irradiation (RII) (5)

☐   Shading Index (SI) (6)

☐   Sky View Factor (7)

☐   Ray tracing approach (8)

☐   Other (Please specify below) (10)

_____

☐   Not Sure (11)

Display This Question:

   If Solar irradiation modelling or simulation = Solar irradiation for a specific building envelope

   Or Solar irradiation modelling or simulation = Both

21. **What weather data step values do you use for solar irradiation data ?**

	Conceptual design phase (1)	Detailed design phase (2)
Minute (1)	○	○
Hourly (2)	○	○
Daily (3)	○	○
Monthly (4)	○	○
Annually (5)	○	○
Other (Please specify below) (6)	○	○

Display This Question:

If Solar irradiation modelling or simulation = Solar irradiation for a specific building envelope

Or Solar irradiation modelling or simulation = Both

22. **Have you used or are aware of any models suitable for simulating building envelopes with solar panels performance with higher spatial resolutions (PV cell level or higher) which can be used for complex building envelope installations?**

_____

End of Block: Block 3

Start of Block: Block 4

Display This Question:

If Solar power output modelling or simulation = Power output of building envelope with solar panels

Power Output of Building Envelope with Solar Panels

This section will ask about approaches, methods and workflows used in modelling or simulation the PV power output of building envelopes with solar panels.

---

23. **How do you import properties of the technical components of a building envelopes with solar panels into your simulation?**

○ In my software, I can access a database of components (e.g. PV modules, inverters) and can automatically load them. (1)

○ I am using online platforms to import product data (Please specify) (2)

_____

○ I am using a specific exchange format to import products (Please specify) (3)

_____

○ I am adding properties manually (4)

○ Other (Pleas specify) (5)

_____

---

24. **Have you used any software for calculating the Electric DC output of building envelopes with solar panels?**

○ Yes (Please specify the name of the software below) (1)

_____

○ No (2)

---

25. **Which methods are used in the above software for calculating the Electric DC output of building envelopes with solar panels?**

☐ Forecasting power output using PV cell temperature model (1)

☐ Power model by Heydenreich et al. (2008) (2)

☐ The Sandia PV Array Performance Model (SAPM) (3)

☐ Loss factors model (LFM) (4)

☐ Single diode model (5)

☐ Single diode Rs-model/4-parameter model (6)

☐ De Soto "Five-Parameter" Module Model (7)

☐ The two-diode model (8)

☐ Other (Please specify below) (9)

_____

☐ Not sure   (10)

End of Block: Block 4

Start of Block: Block 5

Building Energy Consumption

This section will ask about approaches, methods and workflows used in modelling/simulation of building energy consumption.

---

26. **What method do you use for identifying the energy consumption patterns of a building?**

☐　　　Calculate total Watt-hours per day for each appliance used in the building/project (1)

☐　　　Percentage of monthly energy consumption based on habitual use and use during weekends and holidays (3)

☐　　　Use historical information from electricity bills (4)

☐　　　Measure building energy consumption real time (5)

☐　　　Simulate using a building energy simulation software (Please specify the software below) (6) _____

---

27. **What's the suitable interval to be considered in energy consumption data?**

	Conceptual design phase (1)	Detailed design phase (2)
Annually (1)	○	○
Monthly (2)	○	○
Daily (3)	○	○
Hourly (4)	○	○
Sub-Hourly (5)	○	○
One minute (6)	○	○
Seconds (7)	○	○
Other (Please specify below) (8)	○	○

Display This Question:

If Building performance modelling or simulation = Building energy consumption

Or Building performance modelling or simulation = All

28. **Which type of data file formats do you prefer/use for storing building energy consumption data?**

☐   Text file (1)

☐   MS Excel spreadsheet   (2)

☐   Comma Separated Values (CSV file) (3)

☐   Other (Please specify below) (4)

_____

---

29. **When considering the CO2 emissions associated with building envelopes (façade & roof) /building envelopes with solar panels, which methods would you prefer?**

☐   Calculating the emissions avoided (1)

☐   Calculating the embedded emissions of the PV system cause during the manufacturing, construction and decommissioning phase (2)

☐   Both (4)

☐   Do not consider (3)

Thermal Load

This section will ask about approaches, methods and workflows used in

modelling/simulation of heat gain and heat island effect of building envelopes (façade & roof).

---

30. **What methods do you use to identify the thermal impact (heat gain coefficient) of building envelopes (façade & roof)?**

☐   Calculate solar heat gain manually (1)

☐   Simulate using a building energy simulation software (Please specify the software below) (3) _____

☐   Other (Please specify below) (4)

_____

☐   Do not consider (5)

---

31. **Have you used any method(s)/software to simulate the heat island impact of building envelopes (façade & roof) ?**

◯ Yes (Please specify method/software) (1)

_____

◯ No (2)

Daylighting

This section will ask about approaches, methods and workflows used in modelling/simulation of daylighting through building envelopes (façade & roof).

---

32. **What methods do you use to identify the impact on daylighting in building envelopes (façade & roof)?**

☐   Calculate manually   (1)

☐   Simulate using a building energy simulation software   (Please specify the software below) (2) _____

☐   Other (Please specify below) (3)

_____

☐   Do not consider (4)

Structural   Loads

This section will ask about approaches, methods and workflows used in modelling/simulation of structural loads related to building envelopes (façade & roof) and building envelopes with solar panels.

---

33. **Which structural loads do you calculate during the planning and development of building envelopes (façade & roof) /building envelopes with solar panels?**

☐   Dead Load   (1)

☐   Wind Load (2)

☐   Earthquake (Seismic) Load (3)

☐   Live Load (4)

☐   Rain Load (5)

☐   Snow loads (6)

☐   Other   (Please specify below) (7)

_____

34. **What methods and software do you use to identify the structural impact on building envelopes (façade & roof) /building envelopes with solar panels?**

_____

_____

_____

_____

_____

Fire

This section will ask about approaches, methods and workflows used in modelling/simulation of fire related parameters in building envelopes (façade & roof) and building envelopes with solar panels.

35. **What methods and software do you use to identify the fire related impact in building envelopes (façade & roof) /building envelopes with solar panels?**

_____

_____

_____

_____

_____

End of Block: Block 5

Start of Block: Block 7

Building Envelope Financial Analysis

This section will ask about approaches, methods and workflows used for identifying the economic impact of a building envelope designs/ building envelope with solar panels.

36. **Which indicator(s) do you consider identifying the economic feasibility of building envelopes (façade & roof) /building envelopes with solar panels?**

☐   Net present value (NPV) (1)

☐   Simple Payback period (PB) (2)

☐   Discounted payback period (DPB) (3)

☐   The internal rate of return (IRR) (4)

☐   Profitability Index (PI) (5)

☐   Return on investment (ROI) (6)

☐   Levelized cost of energy LCOE) (7)

☐   Other (Please specify below) (8)

_____

----

37. **Comparing to traditional building envelopes (façade & roof), what factors do you consider under capital cost (initial costs) of building envelopes with solar panels?**

☐   Solar PV module costs (1)

☐   Solar PV mounting structure cost (2)

☐   Solar PV installation cost (3)

☐   Costs of electrical devices (Balance of System) and installation costs (5)

☐   Contingency   (6)

☐   Other (Please specify below) (7)

_____

Display This Question:

    If Financial and design outcome = Building envelope financial analyisis

    Or Financial and design outcome = Both

38. **Comparing to traditional building envelopes (façade & roof), what factors would you consider under operations and maintenance costs/life cycle costs of building envelopes with solar panels?**

☐ Cleaning costs (1)

☐ Repair of solar PV modules (2)

☐ Repair of electrical devices (Balance of System) (3)

☐ Repair of mounting system (4)

☐ Replacement of solar PV modules (5)

☐ Replacement of electrical devices (Balance of System) (6)

☐ Replacement of mounting system (7)

☐ Insurance (8)

☐ Depreciation (9)

☐ Other (Please specify below) (10)

_____

Display This Question:

If Financial and design outcome = Building envelope financial analyisis

Or Financial and design outcome = Both

39. What factors do you consider under life cycle income of a building envelope (façade & roof) /building envelopes with solar panels?

☐ Saving from energy self-consumption (1)

☐ Income from feed in tariffs   (2)

☐ Salvage value   (3)

☐ Savings from reducing building cooling load (4)

☐ Other (Please specify below) (5)

_____

Display This Question:

If Financial and design outcome = Building envelope financial analyisis

Or Financial and design outcome = Both

40. One benefit of building envelopes with solar panels is that they completely replace traditional building materials. Do you consider this cost offset as a benefit in the building envelope design evaluation?

○ Yes   (1)

○ No (2)

End of Block: Block 7

Start of Block: Block 8

Display This Question:

If Financial and design outcome = Decision making in design

Or Financial and design outcome = Both

Decision   Making   in   Design

Building envelopes (façade & roof) /building envelopes with solar panels planning process

includes identifying numerous design options. This section will ask about approaches, methods and workflows used for identifying best design out of various design options.

Display This Question:

   If Financial and design outcome = Decision making in design

   Or Financial and design outcome = Both

41. What optioneering/ decision making methods would you like to see in the design methods of building envelopes (façade & roof) /building envelopes with solar panels?

☐　　　Multiple solution comparisons using parametric workflows   (1)

☐　　　Multiple solution comparisons using traditional workflows (2)

☐　　　Integrated optimization (using machine learning techniques such as genetic algorithms, neural networks etc.) (3)

Display This Question:

   If Financial and design outcome = Decision making in design

   Or Financial and design outcome = Both

42. Which factor(s) will impact you to identify the optimum design of the building envelope (façade & roof) /building envelope with solar panels?

☐　　　Cost   (1)

☐　　　Energy generation   (2)

☐　　　CO_2 emissions (3)

☐　　　Thermal impact (4)

☐　　　Other (Please specify below) (5)

_____

Remarks

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52. **If you have any other feedback or comments for this study, please let us know below.**

_____

_____

_____

_____

_____