Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 246 (2024) 4288–4296

Procedia Computer Science

www.elsevier.com/locate/procedia

28th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems (KES 2024)

Optical and Thermal Modeling of a Transparent BIPV System for Dynamic Performance in Buildings

Roberto Garay-Martinez[a]* , Muhammad Talha Siddique[a]

[a]*Institute of Technology, Faculty of Engineering, University of Deusto, Avda. Universidades, 24, Bilbao 48007, Spain*

Abstract

In developed countries, the building sector accounts for up to 40% of the consumed energy. During the past centuries, fossil fuels have been the main energy source to heat, cool, or provide electric power to buildings, but with the increasing energy prices in the beginning of the 21st century, an increasing number of products and systems have been developed for the integration of renewable energy systems in the building sector.

One of the most commonly used technologies involves the integration of photo-voltaic (PV) systems in the building fabric. Several technical solutions are available for this integration, although most common ones are related to PV integration in roofs. However, an increasing interest has been shown in semi-transparent PV systems for integration in windows and curtain-wall systems.

Keywords: Renewable energy integration; Photo-voltaic (PV) Systems; Building Sector

1. Introduction

The utilization of Photo-Voltaic (PV) technologies has burgeoned in recent decades as a pivotal strategy for harvesting energy, offering a renewable alternative to traditional fossil fuels. This surge in adoption has led to the development and market introduction of numerous PV products, predominantly featuring flat elements. Typically, these elements have been integrated into building envelopes by mounting them over opaque areas, primarily providing shading effects with limited impact on the thermal performance of buildings.

---

* Corresponding author. Tel.: +0-349-4413-9000 -Ext 2045.
E-mail address: roberto.garay@deusto.es

10.1016/j.procs.2024.09.278

However, recent years have witnessed the emergence of innovative technologies and systems wherein PV elements are seamlessly integrated as integral parts of construction elements, including semi-transparent systems designed for glazed areas within buildings. Of particular promise is the application of semi-transparent PV technologies in building envelope systems such as Curtain-wall systems, prevalent in a significant proportion of commercial and office buildings. Notably, integrating PV elements into building facades offers a larger installed area compared to roof integration, underscoring the importance of specifically considering these systems in thermal building models.

At the design stage of a building, thermal modeling serves as an indispensable tool for assessing energy requirements and ensuring the thermal comfort of occupants. Moreover, employing such models for building-integrated PV (BIPV) systems allows for the verification of expected performance levels, a critical aspect given the financial viability of BIPV systems hinges on their performance.

This paper presents a comprehensive thermal, optical, and electrical model of a BIPV system, designed to be implemented within TRNSYS. By coupling optical and thermal modeling techniques with a detailed PV performance model, this study aims to provide a robust framework for evaluating the dynamic performance of BIPV systems within building environments.

2. Methodology

The methodology employed in this study aims to comprehensively model the optical, thermal, and electrical behavior of building integrated photovoltaic (BIPV) systems. The approach involves a systematic process for simulating the interactions between glazed elements, photovoltaic layers, and external environmental factors. By integrating optical and thermal modeling techniques, along with a detailed PV performance model, we aim to provide a robust framework for evaluating the dynamic performance of BIPV systems in building environments. The methodology is structured into several key components, each addressing specific aspects of the modelling process. These components are outlined in detail below:

2.1. Optical and Thermal Modelling Of Glazed Systems

Glazed envelope elements are composed by a number of semi-transparent layers and chambers containing air or other gases.

The aim of such elements is the introduction of natural light into the building, while at the same time maintaining a controlled indoor ambience. As these elements are identified as one of the main heat-losing systems in buildings, strong attention is paid to the thermal insulation of these assemblies.

As a result, the thermal characterization of such systems has been traditionally performed through their main functions:

- Solar radiation transmission (OPTICAL modelling)
- Thermal insulation (THERMAL modelling)

2.1.1. Optical modelling

2.1.1.1. Short wave radiation

The interaction of a glazed system with short-wave radiation is studied through optical models. Within the building energy performance assessment framework, this short-wave radiation is solar radiation.

When short-wave solar radiation reaches a glazing, this radiation can be transmitted to the other side of the glazed element, reflected back or absorbed within the glazed element. The absorbed radiation is converted into heat, which will be later integrated within the thermal model.

This phenomenon can also be observed for each of the layers in multi-layered glazed elements, included gas chambers.

2.1.1.2. Optical properties of materials

Within each layer of a glazed element, the proportion at which solar radiation is transmitted, reflected or absorbed is dependent on the surface (reflectivity) and volumetric properties (absorptivity) of the materials.

The reflectivity of a surface defines the ratio of energy which is reflected in a certain material interlayer; while the absorptivity of a material defines the ratio of energy is absorbed within 1m depth of material.

Within each layer, a multiple reflection-transmission formulation is developed which defines the transmittance, reflectance and absorptance values of the layer. These values define the ratio of solar radiation which is transmitted, reflected or absorbed within each layer.

When laminated layers are present (EVA or similar materials), these can be modelled with a specific transmission factor for this layer or with combined transmittance, reflectance and absorptance values of those laminated elements

2.1.1.3. Wavelength-dependent properties

Optical properties of materials are highly dependent upon the wavelength of the incident radiation. This variation of properties is very relevant within the wavelengths involved in the solar spectrum.

To obtain a proper optical characterization of glazed systems, the optical problem can be solved for each wavelength and then integrated according to the relative weight of each of the wavelengths in the solar spectrum.

An alternative solution is the identification of a reduced number of zones (5 to 10 vs. 1500) where homogeneous properties are observed and then proceed to a weighted sum of the solutions for each of the zones

2.1.1.4. Incidence angle

The optical properties of glazed systems are also clearly dependent upon the incidence angle of solar radiation. This dependence is caused by two parameters: reflectivity, which is angle dependant; and the absorptance, which depends on the length of the solar path within the glazed element.

The optical behaviour of glazed systems is usually defined according to international standards [1] [2] [3], which do not take into account the incidence angle of the direct radiation and assume a standard incidence angle of 0º (normal incidence), as optical properties are pseudo-constant for incidence angles in the range 0º-60º, while are modified rapidly for angles larger than 60º.

Within the development of the optical model for the BIPV module, it was found that the number of hours for incidence angles larger than 60º is not neglectable. And with this in mind, the proposed formulation performs a recalculation of optical parameters for the specific incidence angle on the glazed element.

For clear glass or laminates, a direct geometrical recalculation was prescribed, while for Low-emissive surfaces, a multiple sine law for transmittance and reflectance was selected. This model is identical to the one used in [9] for the same purpose.

Although a large share of the optical behaviour is due to direct solar incidence, some of the incident radiation has already been reflected by clouds, the ground or other surrounding obstacles, before reaching the building fabric. In this case, it is seldom known the incidence angle of this radiation due to the occurring multiple reflections. In this case, the radiation is considered as “diffuse”, having no preferential incidence angle, as opposed to “direct” radiation, which is assumed as directly incident form the sun.

The diffuse performance figures of glazed systems are obtained through a weighted averaging of performance figures under direct incident radiation at regular intervals from 0º to 90º.

2.1.2. Thermal modelling

Within the definition of “thermal models” in glazed systems, the following phenomena are modeled:

1. Long-wave (thermal) radiation
2. Conduction
3. Convection

These models are used to define the thermal field of glazed systems. The thermal field is defined by the thermal properties of the glazing, the temperature of the neighbouring ambiences and the heat input from the solar radiation absorbed in each of the panes of the system. The heat input is distributed equally to both sides of the pane where it is absorbed.

The resulting thermal model (figure 1) consists on a series of dynamic non-linear equations, which are converted into steady-state linear equations by using the following assumptions:

1. Within the temperature range air chambers in buildings, thermal radiation can be linearized [9]. In practical situations in buildings, the resulting error is bounded below 1%.
2. Thermal mass of glazed elements can be neglected, especially compared with other elements in buildings (floor slabs, massive walls,) with much larger time constants.

2.2. Derived thermal properties

The preceding chapters provide an overview of the physical modeling of glazed systems (figure 2) within the thermal performance assessment of buildings.

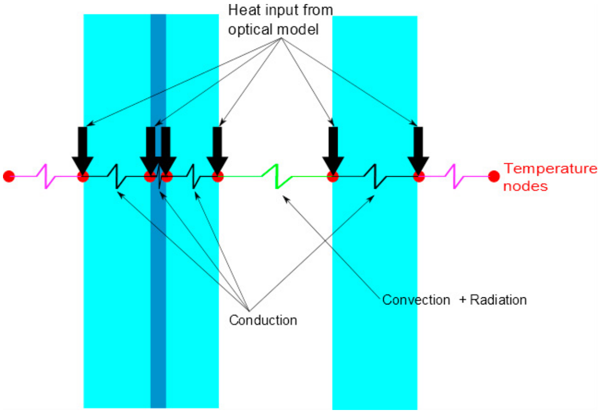

Figure 1 Schema of one dimensional thermal model

Even if models satisfying the previously expressed complexity could be integrated within thermal models of buildings, the thermal behavior of glazed devices are commonly introduced in such models through standardized performance figures. These figures being the following:

1. Thermal transmittance of glazed system (U, [W/m2K]).
2. Solar transmittance (t, [-])
3. Solar heat gain coefficient (SHGC/SHGF/g, depending on nomenclature, [-])

These performance figures are commonly provided by manufacturers and allow for comparison within systems at component level. In most countries minimum/maximum figures are set for these parameters in building codes.

Solar transmittance values are commonly expressed in normal/perpendicular and/or hemispherical values, and visible transmittance and solar/visible reflectance can also be provided.

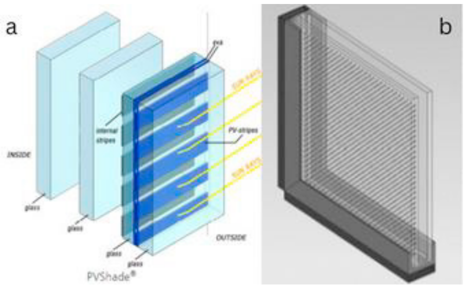

Figure 2 PVshade ® system [14] (a) and Kyotec ® system [9] [16] (b)

The difference between "solar" and "visible" performance figures lies in considered bandwidth of the radiation. "Solar" performance figures consider all the solar radiation, while "visible" refers only to a subset of it. According

to [1], the visible wavelength band is bounded between 380 and 780 nm
These performance figures are obtained through a series of highly standardized calculation and test procedures [1] [3] [4] [5] [6] [7] and commercial and non-commercial software tools and databases are available for designers to obtain these figures from standard manufacturer information [9] [10] [11] [12] [13] [14] [15].

2.3. Optical and thermal modelling of a PV layer

The PV layer in the glazed element must be modeled for its compatibility with the original glazed system model. This means that an optical and thermal model should be developed for such an environment.

Regarding the optical behavior, a model providing angle and wavelength dependent direct, and diffuse absorptance, reflectance and transmittance of the PV layer is required.

Depending on the type of PV system, these properties can be obtained by different means. In the case of semi-transparent, homogeneous PV cells [18], optical formulation similar to that presented in [3] can be applied. However, other PV systems [9] [16] , based in finite PV cells in various arrangements are not able to be modelled in such way.

The proposed BIPV model (figure 3) was developed to characterize one of these latter systems. This system consisted on a series of spherical PV cells placed in close arrangement one to the other. In this case, Ray tracing techniques were used to provide a correct optical characterization of the system

A purpose-specific ray-tracing program (figure 4) was written and a representative size of the PV cell mesh was modelled. The incidence angle of the solar radiation varied with 2 degrees of freedom: Relative azimuth and incidence angle. The solar incidence angle (figure 5) varied from normal to (nearly) tangential incidence, while the relative azimuth was varied from 0 to 180º (180º to 360º azimuth angles were obtained through a symmetry property)

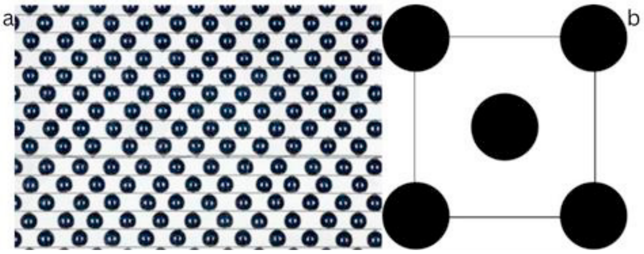

Figure 3 PV grid with Sphelar ® technology [17] (a) and its representative dimensions (b)

Regarding the thermal performance, the PV layer was considered nearly as any common glazed layer. The only modification was required due to the PV behavior of the layer. This implies that a certain amount of the absorbed radiation was converted in electricity, and the thermal input to the thermal system should be reduced due to this effect.

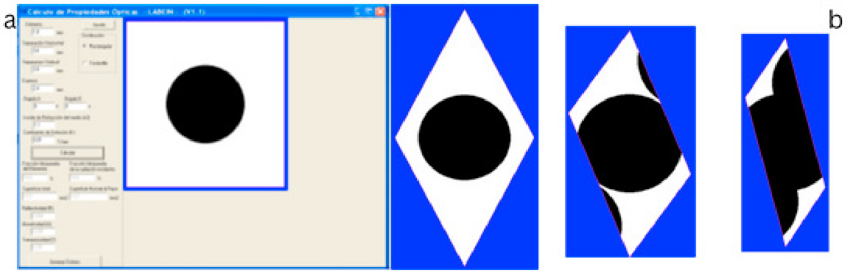

Figure 4 Ray-tracing process of one representative piece of the sphelar grid.

Ray-tracing application (a) and view of the grid for various incidence angles (b)

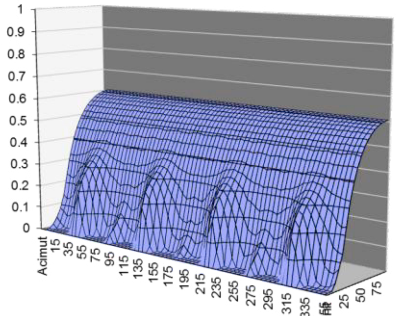

Figure 5. Results of the ray-tracing. Transmittance of the PV layer for one specific wavelength band.

2.4. PV performance model

The PV electrical model intends to provide the output electrical power of the embedded PV system. The performance of a PV system is highly dependent on the temperature of the silicon cell. This being especially critical for fenestration-embedded applications.

The modeling of PV systems is quite a complex with a variety of approaches to the modeling of PV systems. Not only the PV modules but also DC/AC inverters and other electric/electronic devices should be taken into account when defining such a system.

The PV model selected in this work is focused on the overall electrical output of such a system, which should balance accuracy vs. computational effort, as it is focused in coupled modeling at building level, which should be able to be simulated at sub-hourly time steps in full year simulations.

The PV model has been selected to allow for this use of the model. The selected model is based in four expressions:

1. Cell temperature: The temperature of the PV cell is established as a function of the surrounding temperature, the absorbed solar energy and the nominal operating temperature of the PV cell.

$$T_{cell} = T_{env} + (TONC - 20) * \frac{G_{cell}}{800} \tag{1}$$

2. Output electrical power at cell level: The output electrical power is obtained as a function of the absorbed solar energy, the cell temperature and the maximum power generation and its sensitivity upon temperature under standard test conditions.

$$P_{elec\_cell} = Pmpp(STC) * \frac{G_{cell}}{100} * ((T_{cell} - 25) * (\frac{kmpp}{100} - 1) \tag{2}$$

3. Output thermal power: This value is obtained as a function of the absorbed solar energy and the energy which is converted into electric power.

$$P_{term} = G_{cell} - P_{elec\_cell} \tag{3}$$

4. Output electrical power at module level: at this stage the performance of DC/AC inverters is considered.

$$P_{elec\_AC} = P_{elec\_cell} * \eta_{elec\_cell} \tag{4}$$

It should be taken into account that, in some cases the PV cell surface does not match the surface of the glazed element. This is clearly visible in [13, 14, 21], but it can be also be relevant in some other circumstances (figure 6). In these situations, a triple surface conversion will need to be achieved. A linear conversion is produced as a function of the areas of PV cells and the module.

1. Conversion of the solar absorption, G.

$$G_{PV} = \frac{S_{Module}}{S_{PV}} * G_{Module} \tag{5}$$

2. Conversion of the output electrical power, Pelec_AC

$$P_{elec\_AC} = \frac{S_{PV}}{S_{Module}} * P_{elec\_AC\_PV} \tag{6}$$

3. Conversion of the output thermal power, Pterm.

$$P_{term\_module} = \frac{S_{PV}}{S_{Module}} * P_{term\_PV} \tag{7}$$

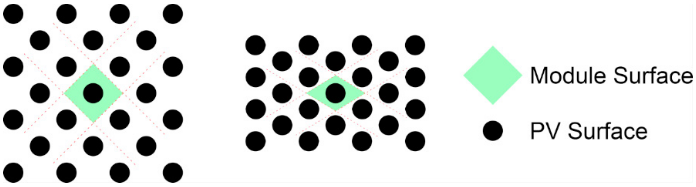

Figure 6. Graphical representation of PV/Module surface ratio under different incidence angles

2.5. Coupled modelling

The previously defined formulation and algorithms are combined into a single algorithm composed by three main blocks, each of them composed by a series of sub-elements.

1. Block 1: Optical behavior
2. Block 2: Thermal behavior
3. Block 3: PV-electrical behavior

The order of resolution is produced in the following way:

1. Resolution of the Optical behavior
2. Iterative resolution of the Thermal and PV/Electrical phenomena.

The Optical system is solved through the following process:

1. The direct incident solar radiation is split into various bands of homogeneous optic properties. The split ratio is defined according to the relative relevance of each band in the solar spectre
2. For each layer, and each wavelength band, reflectance, transmittance and absorptance are calculated as a function of the incidence angle.
   a. For the layer with PV cells, the non-specular reflection of solar radiation is considered.
   b. For the layer with PV cells, two different absorptance values are obtained:
      I. Radiation absorbed by the PV cell
      II. Radiation absorbed in the layer, but not in the PV cell
3. Steps 1 and 2 are also performed for diffuse radiation.

4. A matrix containing the multiple reflections according to the net-radiation method is produced. The matrix is written with separate terms for direct and diffuse components of the solar radiation. Independent matrixes are obtained for each wavelength band.
5. The equation systems are solved, and the results of each system are aggregated according to the weighting in step 1.
6. The following results are obtained:
    a. Transmitted solar radiation: Direct and diffuse components of the transmitted radiation are obtained as independent parameters.
    b. Absorbed radiation in each layer.

The Iterative Thermal/PV model is performed in the following way:

1. For each layer, the thermal resistance is obtained.
    a. When air gaps are present, the thermal resistance is calculated according to [8], with an initial temperature estimation from the previous time step.
2. The absorbed energy from the optical model is distributed equally at both sides of the corresponding layer.
    a. In the case of the PV layer, an initial execution of the model provides the initial Pterm_module which is included in the thermal model.
3. A matrix of the thermal system is built and temperatures and heat fluxes at all the interlayers are solved.
4. Steps 1 and 2 (initialization) are repeated with the new thermal field.
5. Steps 3 and 4 are repeated until the process converges.

3. Results

The model as defined in the previous chapters was implemented in TRNSYS 16. On this purpose, a new TRNSYS type was created which was programmed in a new dll in C++.

An external text file format was created in which all the relevant properties of each layer were defined. This approach allows for easy switching of different kinds of BIPV systems in the simulation process. In fact, the properties of the PV layer were defined as “technology independent” in which results from ray-tracing calculations were introduced as 2D angular properties. In this way, sphelar, planar, reflective PV technologies could be simulated with the same TRNSYS TYPE.

This type was programmed in TRNSYS coherent units and allowed for independent input variable linkage for radiant and ambient temperatures (figure 7)

Output variables included surface temperatures, convective heat transfer, shortwave heat transfer (solar/optical) and long wave radiant heat transfer (thermal).

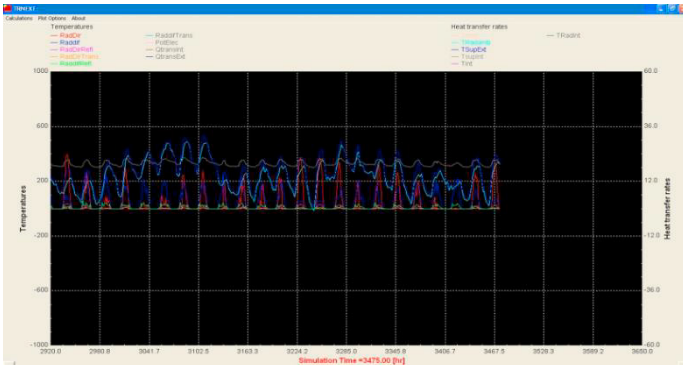

Figure 7. Coupled simulation of BIPV curtain wall system

The model was validated according to [8]. The specific issues related to the thermal performance of the PV cell were validated according to a thermal model which was created as part of [15].

4. Conclusions

A model for the dynamic assessment of the thermal and electrical performance of a BIPV system has been designed and implemented. This model relies on pre-existing calculation methods for glazed systems, and provides an alternative method for the PV layer. This method allows non-1D PV array systems, through ray tracing calculations.

An implementation of this model has been performed in TRNSYS 16, the BIPV model can be linked to building models, meteorological data, shading masks for a whole year dynamic assessment of the BIPV system or buildings containing such a system.

Acknowledgements

The authors would like to thank the Spanish Government, who partly funded this work, and Professors Alvarez, Molina and Salmerón (University of Seville), for their advice in the development models for glazed elements.

References

[1] EN 410:2011, “Glass in building - Determination of luminous and solar characteristics of glazing”, CEN, 2011

[2] EN 673:2011, “Glass in building - Determination of thermal transmittance (U value) - Calculation method”, CEN, 2011

[3] ISO 9050:2003, “Glass in building -- Determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors”, CEN, 2003

[4] ISO 9845-1:1992, “Solar energy -- Reference solar spectral irradiance at the ground at different receiving conditions -- Part 1: Direct normal and hemispherical solar irradiance for air mass 1,5”, ISO. 1992

[5] EN ISO 10077-1:2010, “Thermal performance of windows, doors and shutters - Calculation of thermal transmittance - Part 1: General (ISO 10077-1:2006)” , CEN, 2010

[6] EN ISO 10077-2:2012/AC:2012, “Thermal performance of windows, doors and shutters - Calculation of thermal transmittance - Part 2: Numerical method for frames - Technical Corrigendum 1 (ISO 10077-2:2012/Cor 1:2012)” , CEN, 2012

[7] EN 13947:2006, “Thermal performance of curtain walling - Calculation of thermal transmittance”, CEN, 2006

[8] ISO 15099:2003, “Thermal performance of windows, doors and shading devices -- Detailed calculations”, CEN, 2003

[9] Alvarez, S. “Análisis Dinámico del Comportamiento Térmico de Edificios”, Universidad de Sevilla, 1986.

[10] Energy Plus v7.0, Engineering Reference, DOE, 2012

[11] Karlsson, J., Rubin, M., & Roos, A. (2001). Evaluation of predictive models for the angle-dependent total solar energy transmittance of glazing materials. Solar Energy, 71(1): 23-31.

[12] Karlsson, J. (2001). Windows: optical performance and energy efficiency (Doctoral dissertation, Acta Universitatis Upsaliensis).

[13]Kyotec, Tecnalia & Kyosemi, http://www.energiaenedificacion.com/en/2010/01/12/kyotec-desarrollo-de-muro-cortina-que-integ ra-celulas-solares-fotovoltaicas-de-nueva-generacion/ [2013/06/11]

[14] PVShade®, Cost Effective Renewables, Final Publishable report, page 13 “Glazing unit with integrated PV”. http://www.cost-effective-renewables.eu/ [2013/06/11]

[15] Guardian Glass Configurator, Guardian, http://023app47.guardian.com/configurator.zip, 2013/05/27.

[16] Guardian Sunguard, Performance Comparison Tool, http://www.sunguardglass.es/SunguardProducts/PerformanceComparisonTool/, [2013/05/27]

[17] Optics 6, Lawrence Berkley National Laboratory, http://windows.lbl.gov/software/optics/optics.html, [2013/05/27]

[18] Schueco ProSol BIPV system for façade integration, http://www.schueco.com/web/uk/architekten/solarstrom_und_waerme/products/photovoltaics/fassadenmodul_prosol_tf, [2013/06/11]