

Modelling and simulation of Building-Integrated solar thermal systems: behaviour of the system

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ABSTRACT

Building-Integrated Solar Thermal (BIST) systems have been applied in a number of buildings and provide multiple advantages in comparison with the Building-Attached (BA) installations. The present article is a critical review about solar system modelling with emphasis on BIST configurations. The review includes also BI solar systems which produce electricity (Photovoltaic: PV) or both electrical/thermal energy (Photovoltaic/Thermal: PVT) in order to provide a more complete view of the current literature. For some cases where the system and/or the model are of great interest, BA configurations are also cited. The references are presented separated into groups, based on the type of the model (thermal, energetic simulation, etc) and based on the specific characteristics of each system (solar thermal collector, skin façade, etc). The present review is the 2nd part of an investigation about BIST modelling and it focuses on modelling studies about the solar system itself. The results reveal that most of the works about BI configurations refer to PVT, PV or skin façades while there are few studies about BIST systems. Thus, there is a need for more investigations about BIST installations, especially for active configurations which could provide thermal (or electrical/thermal) energy for building energy requirements. On the other hand, more optical simulations are also necessary. Taking into account the findings of the 1st part of the present investigation, most of the BIST modelling studies focus on the system itself; thereby, more works which examine the system in conjunction with the building are needed. Moreover, concepts such as BI concentrating solar systems could be also examined provided that the system is viable from technical/economic point of view.

Keywords: Modelling; Building-Integrated solar thermal systems; Building-Integrated Photovoltaic (PV); Building-Integrated PV/Thermal; System behaviour

1. INTRODUCTION

Solar energy technologies provide promising solutions for the reduction in the energy consumption of buildings. Several building-integrated solar systems are commercially available and have been realized in buildings (IEA SHC Task 41, 2014). BIST systems offer multiple advantages compared to Building-Attached (BA)

installations due to higher aesthetic value, replacement of the traditional building elements and utilisation of solar energy in buildings (Kalogirou, 2013).

The present study investigates the theoretical and experimental based literatures on BIST systems. Since BIST concept is new only few studies have been reported in this area. These studies are experimental based (Lai et al., 2014; Maurer et al., 2014) and/or modelling based (Maurer and Kuhn, 2012; Notton et al., 2013; Motte et al., 2013a; Motte et al., 2013b) while regard several types of integration such as in building façade (Lai et al., 2014; Maurer et al., 2014) or in building gutters (Notton et al., 2013; Motte et al., 2013a; Motte et al., 2013b). Concerning the modelling works, some studies give emphasis on the system itself (Notton et al., 2013; Motte et al., 2013a; Motte et al., 2013b) and some examine the system in conjunction with the building in a holistic approach (Maurer and Kuhn, 2012; Maurer, 2012; Maurer et al., 2013).

This study provides an extensive literature review grouped into model types such as thermal, energetic simulation and specific characteristics of the system such as solar thermal collector, Photovoltaic-Thermal (PVT), Concentrating PVT (CPVT), skin façade, etc. Although emphasis is given on the BIST systems, other types of systems (BI PV, BA solar thermal, etc) are also presented to provide a complete picture of the current literature. The present investigation is the 2nd part of a review study on BIST modelling. The 1st part of that review (ref...) focuses on works which examine building/system in a holistic approach while the 2nd part (present work) focuses on studies which examine the system itself (not in conjunction with the building). In this way, the gaps in the literature in the field of BIST modelling are identified while BI configurations for future studies are also proposed. In the literature the only review about opaque solar façades and transparent/translucent solar façades is that of Quesada et al. (2012a; 2012b); however, that work included experimental as well as theoretical studies and did not focus on modelling investigations. In the frame of the present study (as well as in the 1st part of the present work), emphasis is given on the BIST modelling studies providing details about the adopted modelling methodologies and identifying gaps in the literature in terms of model types and system types. Thus, the present investigation (in combination with its 1st part) provides useful information for the development of "future BIST systems".

2. MODELING OF BUILDING-INTEGRATED SOLAR THERMAL SYSTEMS

The literature reviews are grouped into the following categories: energetic, thermal, energetic/thermal, and optical simulations. In this case, "energetic" modelling refers to empirical models which use for instance a collector efficiency curve. On the other hand, "thermal" modelling refers to detailed physical models which use thermal nodes and resistances. Within each of these categories the review is presented based on the type of the system: solar thermal collector, skin façade, PVT, etc.

2.1. Studies of Energetic Simulation

2.1.1. BI, Solar thermal

Windholz et al. (2011) built a BIST demonstrator and fitted an empirical model to the monitoring data. They reached good agreement for times with fluid flow.

Dowson et al. (2012) presented measurement results of a polymer air collector with aerogel. Based on the measurements, the collector was modelled and the annual gain was calculated as well as a payback time. A steady state model was developed to characterise the aerogel solar collector. This type of collectors offers an opportunity to improve the efficiency of flat plate solar air collectors by replacing their conventional glass covers with lightweight polycarbonate panels filled with aerogel insulation.

Welz et al. (2013) developed a detailed model of a transparent solar thermal façade collector with vacuum tubes. With the detailed model, the efficiency was calculated not only depending on the temperature difference between the fluid and the ambient temperature and the irradiance, but also depending on the mass flow of the air inside the vacuum tubes. A procedure to calculate the best operating conditions was presented.

2.1.2. BI, Skin Façade

A multi-skin façade is one way of collecting solar energy which can be used to support the building services.

Modelling of a Double-Skin Façade (DSF) system was conducted by using the mass balance network method and CFD (Hensen et al., 2002). It was noted that the network method is more suitable for this type of “everyday” design support work but for the other important areas the network method would benefit from CFD, or vice-versa. The results revealed that both the network method and CFD have advantages and disadvantages for modelling this type of natural and hybrid ventilation systems.

An analytical method was adopted to perform a thermofluid-dynamic analysis of ventilated façades (Patania et al., 2010). The Fluent software was utilized that uses finite-difference numerical solution technique based on integration over the control system. For the simulation, the assumptions for the climatic conditions were: indoor air temperature equal to 297 K, inlet air temperature of the duct equal to the outdoor air temperature (= 301 K). A steady state calculation method, suitable for the design applications, was adopted to study the energy performances of ventilated façades during the summer period. The authors noted that the energy performance of this type of façades improves when their external layer has low values of thermal conductivity, high values of density and high values of the specific heat.

2.1.3. BI, Solar Chimney

Roof integrated solar chimneys use solar radiation to heat air and induce natural ventilation through a house. Thus, they can improve the performance of roof-integrated PVs by removing heat absorbed by the panels and enhance buoyant free cooling at night. DeBlois et al. (2013) designed and modelled a roof-integrated solar chimney. An unobtrusive, integrated solar chimney was designed for a single-detached home. ESP-r modelling tool was used for the designing and to predict the thermal dynamics in changing ambient conditions. CFD was used to calibrate key model inputs while a sensitivity analysis evaluated the model sensitivity for several inputs and assumptions. The mathematical model consisted of a heat balance for nodes at each surface and in each zone and a pressure-based airflow balance. The airflow network included buoyancy forces and losses in the channel, at the inlet and outlet, balanced over all of the nodes. The 2D CFD model was created in ANSYS Fluent and was more accurate heat transfer and fluid flow model than the heat transfer correlation and pressure-based network used in ESP-r. The model adopted a steady-state assumption and temporally constant temperature boundary conditions for the walls. For flow driven by natural convection the natural convection correlation selected for the walls of the channel worked well but not for the other flow modes. The RSC concept appeared to be promising as a way of providing free cooling in a house throughout the day and night, without requiring major changes in the form of the house.

2.1.4. BI, Trombe Wall

A 1D finite difference simulation model for solar walls was developed and applied for four different configurations: composite solar wall, Trombe wall, insulated Trombe wall, non-ventilated solar wall (Zalewski et al., 2002). The model was validated with the measured heat transfer experimental data. The model can be used to study the effect of design parameters or new materials (important for the future development of solar walls) and to compare different types of solar walls.

2.1.5. BI, PVT

Simulations of combined heat and electricity production from BI PVTs were performed for three typical applications (5°C: primary circuits of heat pumps; 15°C: cold water preheating; 25°C: pool water preheating) and two different European climates (warm: Athens; moderate: Prague) (Matuska, 2012). A mathematical model based on principle theory for energy balance of solar thermal collectors was developed for unglazed solar flat-plate hybrid PVT liquid collector (PVT-NEZ). The input parameters of the model were: thermal, optical, electrical, geometrical properties of PVT collector parts, climatic conditions, operation conditions. The output parameters of the model were: electric and thermal power output, output liquid temperature, absorber surface (PV cell) temperature. The model was used to simulate building envelope-integrated installations with added adjacent envelope insulation including heat resistance at the back side of PV or PVT collector with constant temperature at the back. External energy balance of PVT absorber (heat transfer from PVT absorber surface to ambient) and internal energy balance of PVT absorber (electric yield, heat transfer from the PVT absorber surface to liquid) was used in the PVT-NEZ model to find PVT absorber temperature (PV cell) and relevant heat transfer coefficients. The results

showed that the main factors defining the quality of PV-T thermal performance are: cooling fin quality (conductivity, thickness, length) and bond conductance between riser pipe and cooling fin. Building integration brings a large improvement especially to low-tech PVTs. The high-tech BI PVTs show negligible temperature difference between PV and liquid at nominal conditions. The roof-integrated BI PVTs provided 15% to 25% more electricity than BI PV systems in warm climate (Athens) and 8% to 15% in moderate climate (Prague) and the heat production was up to 10 times higher than the electricity production.

The performance of a multifunctional PVT hybrid solar window was investigated (Davidsson et al., 2009). The PVT solar window was constructed from PV cells laminated on solar absorbers and placed in a window behind the glazing. In order to reduce the costs of the solar electricity, reflectors were added to focus radiation onto the solar cells. A model for the electrical output and hot water production was developed to perform yearly energy simulations where different effects such as shading of the cells or effects of the glazing could be included or excluded. TRNSYS (Beckman et al., 1994) was also used. The simulation program was calibrated against measurements of a prototype solar window placed in Lund in the south of Sweden as well as against a solar window built into a single house, Solgården, in Älvkarleö in the middle of Sweden.

Delisle and Kummert (2014) adopted a new concept of equivalent useful thermal energy production combining electrical and thermal energy production to compare BI PVT air collectors with side-by-side PV modules and solar thermal collectors. A case study of 40 m² south-facing roof located in Montreal, Canada was examined. TRNSYS simulations were performed for the BI PVT/air system, and side-by-side PV modules and liquid solar thermal collectors (PV + T). The total energy production by both systems was assessed by converting electricity into heat with various conversion factors. For a factor of 2, the BI PVT produced 5–29% more equivalent useful thermal energy than the PV + T for a water temperature at the heat exchanger inlet 10°C.

An artificial neural network was used to estimate the PV conversion efficiency of a BI PVT array (Ghani et al., 2012). Previously a numerical approach was adopted to quantify the effect of flow distribution on the PV output of a BI PVT array. This approach was time consuming and computationally intensive. To address this issue, the authors proposed an Artificial Neural Network (ANN) that can be used to approximate the PV array yield of specified shape operating under parallel/reverse flow in the manifolds and also with one or two fluid channels cooling each string of cells. By approximating the yield for each scenario, the optimal configuration can then be selected. It was found that the neural network can be successfully trained for this specific case offering a fast alternative to the original numerical approach.

2.1.6. BI, PV

The electrical and thermal simulation of a roof-mounted BI PV system inclined at 45° (located in Ballymena, Northern Ireland) and facing due south was performed using TRNSYS (Mondol et al., 2005). A new TRNSYS type was developed for the modelling of inverter output and the modifications were made to standard TRNSYS types for global-diffuse correlation and PV module temperature. Statistical analysis was

performed with the measured and predicted data for three global-diffuse correlations and four tilted surface radiation models to find the best combination for estimating the beam and diffuse components of the horizontal insolation and total, beam and diffuse components of insolation at the inclined PV surface, respectively. Measured and simulated electrical PV outputs were compared on daily basis. The developed TRNSYS type for inverter was validated with measured data. The results revealed that the modification of global-diffuse correlation and module temperature prediction improved the overall accuracy of the simulation model. Over the period of simulation, the monthly average error between the measured and the predicted PV output was 6.89% while the monthly average error between the measured and predicted inverter output was found to be 4.7%.

The simulation of a BI PV system was performed to optimise its performance through parametric analysis (Yoo, 2011). The efficiency of the BI PV system as a shading device was examined at different months (weather data: Suwon area, Korea). The simulation program SOLCEL was developed to calculate the shading effect on the solar cells, PV module temperature, incident solar irradiance, BI PV output. The BI PV efficiency was significantly varied over the months and the variation of module temperature was insignificant with respect to the solar intensity.

Low-light level dependence of PV module efficiency is very important for the accurate modelling of BI PVs, especially in northern latitudes and in climates with significant cloud cover. Stamenic et al. (2004) conducted a "low-light condition" modelling for BI PVs using a single diode solar cell model. The model introduced a single lumped parameter to the ideal diode equation to characterize the non-ideal characteristics of the cell. The model was first applied to the open circuit voltage data collected for a solar module operating under low irradiance conditions. After validating the model, the model was then applied to calculate the hourly total power production. The proposed model was able to accurately predict the actual energy production of a test system. A grid-connected array of BI PVs integrated into a building in Burnaby (Canada) was used for assessing the accuracy of the model.

A performance analysis and modelling of a BI PV system in Romania was conducted by Fara et al. (2013). Forecasting tests were run by utilizing Autoregressive Integrated Moving Average (ARIMA) models. ANN techniques were also evaluated (based on meteorological variables) to enhance the forecasts of solar irradiation.

Muresan et al. (2006) performed numerical simulations for a vertical solar collector integrated in a building frame. The simulations included radiation and turbulent natural convection coupling. A vertical double-skin PV façade was considered for an elementary study. During winter, fresh air was aspired by the air supply system; during summer, thermal chimney effect cooled the PV. The collector was subjected to direct and indirect sun irradiation while the space between the wall and the collector formed a channel (at the bottom of which air was admitted and buoyancy-driven convection was developed). Damping functions were inserted in the kinetic energy of the turbulence dissipation equation to account for viscous and wall-damping effects. A finite-volume scheme with a second-order discretization method (for both advection and diffusion terms) was applied. Pressure correction method was adopted. The resolution was performed by using the SIMPLER algorithm. Coupling of radiation heat transfer with conduction in the collector cover and overall coupling with thermo-aerodynamics

phenomena in the air channel was used. The study concluded that further work is needed to include realistic variations of radiation properties, including photoelectric effects and sun irradiation, so that a complete parametric study will allow extracting the best strategy to integrate PVs into building.

A long term monitoring performance of a transparent amorphous silicon thin-film PV module for a window application was carried out in Korea (Yoon et al., 2011) in order to examine the practical application of BI PVs. The simulation of this system revealed that the output of the system can be improved up to 47% by changing the building location in terms of azimuth and shading indicating that both these factors are useful design parameters for the optimisation of the BI PV performance. ESP-r was utilized to analyze influencing parameters.

A study was conducted on façade and rooftop integrated PV installations (Dwi Atmajaa, 2013). In order to achieve a greater solar insulation on the PV modules the installation distance to module length ratio was calculated. Other calculations also performed to observe Effective Load Carrying Capacity (ELCC) against PV penetration level to perceive the optimum PV penetration level for high ELCC without resulting operational problems.

Masa-Bote and Caamaño-Martín (2014) developed a methodology to estimate BI PV electricity production under shadow. The developed methodology was validated by means of one-year experimental data obtained from two similar PV systems (Madrid, Spain). The study included several weather conditions: clear, partially overcast, fully overcast sky. The errors between measured and predicted electricity generation were less than 1% and 3% in annual and daily basis. The accuracy of the model improved by considering reduced PV performance at low irradiance. The proposed methodology is claimed to be simple, easy-to-use and accurate.

2.1.7. BI, CPV

Fernández et al. (2014) proposed a model based on ANN for the prediction of the maximum power of a low-concentration PV for building integration. The model took into account the parameters that influence the electrical output of these systems: direct irradiance, diffuse irradiance, module temperature and the transverse and longitudinal incidence angles. The ANN model provided accurate results under clear and cloudy days; however, the accuracy of the model was better for the clear days than for the cloudy days.

2.1.8. BA, Solar thermal

Karim et al. (2014) investigated a double-pass counter flow V-grove collector. In that design of the collector, the inlet air initially flowed at the top part of the collector and changed direction once it reached the end of the collector and then, flowed below the collector to the outlet. A mathematical model was developed for the collector and simulations were carried out by using MATLAB programme. The simulation results were verified using experimental data and the difference in results was below 7%. A parametric study was conducted and it was found that solar radiation, inlet air

temperature, flow rate and length had a significant influence on the efficiency of the air collector. Furthermore, the results were compared with single flow V-groove collector.

2.1.9. BA, Solar cooling

Fong et al. (2012) compared the performance of solar cooling systems with solar collectors in sub-tropical regions (such as Hong Kong) using simulation method. Two types of solar collectors and the corresponding cooling systems, namely the flat-plate collectors for absorption refrigeration and the PV panels for DC-driven vapour compression refrigeration, were used in the analysis. It was found that in both cases, the adoption of BI solar collectors resulted in a lower solar fraction. The reduction in solar fraction was more pronounced in the peak load season when the solar radiation was nearly parallel to the solar collector surfaces during the daytimes, especially for those facing the south direction. It was concluded that the use of BI solar collectors for solar cooling systems should be restricted only to situations where the availability of the roof was limited or insufficient in sub-tropical regions.

2.2. Studies of Thermal Simulation

2.2.1. BI, Solar thermal collectors

Measurements and corresponding modelling of transparent solar thermal façades was presented by Maurer et al. (2012). A detailed physical model offers predictions of the benefits, easy collector optimizations and also the possibility of quantifying the uncertainties of the simulation. The method to determine these uncertainties was presented.

The performance of a novel solar collector developed for water heating was evaluated by using numerical method (Motte et al., 2013a). The solar collector was integrated into building gutters. MATLAB was used for the numerical calculations by using a finite difference model. Good agreement between numerical and experimental results was found. At low reduced temperature, the thermal performances were close to the conventional ones. However, it was noted that the thermal insulation can be improved through optimising the collector shape. Further studies have been proposed to develop correlations between the thermal coefficients and the environmental parameters (e.g. sky temperature correlated to the clearness index).

Anderson et al. (2010) examined the colour effect on the thermal performance of BI solar collectors. 1D, steady-state thermal model based on the Hottel–Whillier–Bliss equations was utilized. The validated model was used to calculate the fraction of a typical domestic water-heating load provided by the various theoretical coloured configurations. An F-chart was constructed for the operation of the collectors in Auckland (New Zealand). It was found that the low-cost coloured mild steel collectors contributed most in terms of meeting the domestic hot water demand. The performance of coloured solar collectors can be accurately modelled using a combination of experimental and numerical techniques.

An experimental study was conducted on a novel wall (integrated façade): solar heater combining curtain wall structures, heat transfer mechanisms and natural circulation loop designs (Lai et al., 2014). Over daily use conditions, the system-wide energy harvest ratio of the test cell was between 0.45 and 0.78 and it was not significantly affected by the cooling (feed) water flow rate. The primary design considered the integration techniques into the building and installation costs. The prototype was developed based on “vertical framing and detaching” arrangements consisting of vertical frames, lintels, windows and upper/lower wall boards (Fig. 1).

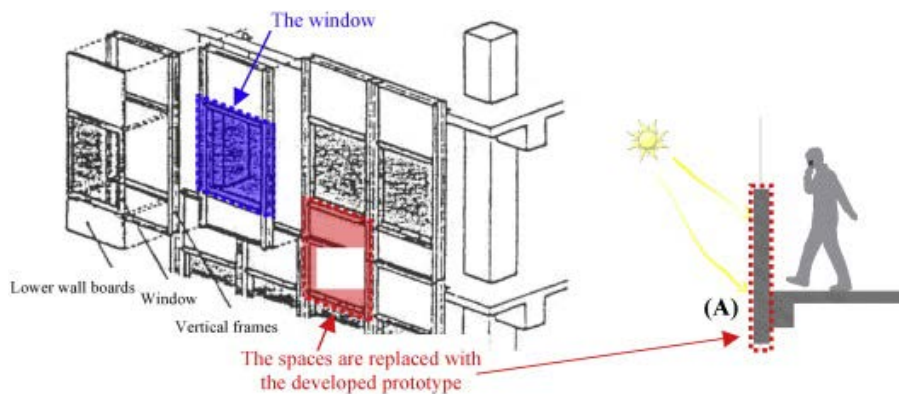


Figure 1. The development of the prototype “solar heater” wall of Lai et al. (Source: Lai et al., 2014).

Giovannetti et al. (2013) developed a insulated glass including an absorber. They developed a detailed physical model for this collector and assessed the glass deflection due to thermal expansion theoretically and experimentally.

2.2.2. BI, Skin Façades

A simulation method was developed to study temperature behaviour of double façades (von Grabe, 2002). The accuracy of the model was tested using experimental data and the accuracy of the model was improved by modifying the flow resistance for several geometries.

A lumped simulation model was calibrated for DSF systems with controlled rotating louvers and ventilation openings (Park et al., 2004). The approach of the investigation was based on a parameter estimation technique and in situ monitoring of a full-scale element mounted on the south facing façade of an existing building. The new approach was based on a postulated “minimalistic” lumped model which was calibrated on in-situ measurements. The authors noted that the model is very accurate, reliable and simple.

Balocco and Colombari (2006) proposed a non-dimensional analysis as a method to analyze mechanically ventilated double glazed façade energy performance. A comparison between Nusselt number solved by experimental data and Nusselt number calculated by the validated multivariable correlation function was reported. The authors mentioned that due to its wide validity field the proposed method can be used to analyze

thermodynamic performances of glass DSF with mechanical ventilation. Applying non-dimensional analysis to a mechanically ventilated double-glass façade, a correlation between 12 non-dimensional numbers was obtained while the model was validated using experimental data. The proposed method is useful for the study of thermal energy performances of mechanically ventilated DSFs for different climatic conditions, aspect ratio, shading device systems and also different thermo-physical characteristics of two glasses.

Coussirat et al. (2008) studied the performance and the influence of numerical sub-models on the CFD simulation of free and forced convection in double-glazed ventilated façades. The CFD Fluent software was adopted for flow and heat transfer modelling. The goal of the study was to investigate the undesirable building overheating for the case of Mediterranean climates.

Pérez-Grande et al. (2005) investigated the influence of glass properties on the performance of double-glazed façades. It was shown that an appropriate selection of the glasses forming the channel can reduce the thermal load into the building by almost an order of magnitude. It was also proved that an appropriate use of the air stream flowing between the glass surfaces can improve the global thermal balance. The thermo-fluid dynamics problem was solved by finite-volume commercial code, FLUENT, with a standard k– ϵ turbulence model.

Guardo et al. (2009) adopted a CFD approach to evaluate the influence of construction and operation parameters on the performance of Active Transparent Façades (ATF) in Mediterranean climates (in order to study overheating). The parameters that affect the reduction on solar load gain are related with the optical properties of the glass. An increase in length-to-depth ratio caused a decrease in the ATF efficiency in terms of solar load gains. It should be noted that it was assumed that the studied ATF was located in Barcelona (Spain).

Nassim Safer et al. (2005) performed a 3D simulation with a CFD tool of the airflow phenomena in single floor DSF equipped with a venetian blind (forced ventilation). In order to reduce the size of the mathematical model, 3D airflow was modelled by using a homogeneous porous media representation. A parametric study was carried out to analyze the impact of three parameters on the airflow development: slat tilt angle, blind position, air outlet position. The commercial CFD tool FLUENT 6.0.20 was utilized, based on the finite-volume method and the SIMPLE solving algorithm. The CFD approach enables accurate computations of the velocity–pressure fields inside the channel of ventilated DSFs.

Pasut and De Carli (2012) evaluated various CFD modelling strategies in predicting air flow and temperature in a naturally ventilated DSF. The validation of the results was based on experimental data from the literature. Important factors associated with the simulation have been discussed. The model can be used to predict the airflow patterns, air temperature and air velocity distributions and heat flux from gap into the room.

Modelling of a ventilated DSF system was based on the zonal approach (Jiru and Haghghat, 2008). In the zonal approach, the DSF can be divided into a number of control volumes, using 2D or 3D cells, which are usually larger than the cells normally

used in CFD. The advantage of using the zonal approach is that the resulting systems of algebraic equations are smaller and much easier to solve than the CFD. The zonal models can provide information on airflow and temperature distribution in a ventilated space faster than CFD, but with more accuracy and detail than lumped and control-volume models. In that study, the zonal airflow equation, power-law, was employed to calculate the airflow through the shading device and cavities. The zonal energy equation was adopted to evaluate the temperature distribution in the DSF system. The predicted temperature distributions were verified by using measured values. The case used for the development and the verification of the DSF models was an experimental test cell at the Dipartimento di Energetica, Politecnico di Torino, Italy. The results revealed that the zonal models can be used to assess the performance of the DSF system with venetian blinds. The zonal models provided more detailed information (which is not possible for the lumped and the control-volume models). Parametric study was also conducted in order to assess the influence of cavity height; inlet mass flow rate; and presence of venetian blinds on the outlet-inlet temperature difference. The result demonstrated that the influence of changing the values of each parameter was more apparent during the day than during the night. The DSF model developed can further be integrated into Building Simulation tool that includes HVAC (heating, ventilation, and air conditioning) plant and allows the evaluation of the use of control mechanisms in the DSF and their influence on the energy consumption of the HVAC system.

On the other hand, Stec et al. (2005) modelled thermal performance of a DSF with plants. Plants in office buildings can provide several advantages. These are mostly related with thermal, aesthetic, psychological, comfort level and sound attenuation. The validated simulation model was used to analyze the influence of plants on the performance of the DSF. The simulation model was built by SimulinkTM. The thermal model was represented by the heat exchange between the layers of the façade. The results revealed that in general, plants created more effective shading system than blinds providing advantages such as: for the same solar radiation, the temperature raise of the plants was about twice lower than that for the blinds; the temperature of the plants never exceeded the temperature of 35°C, when blinds could exceed 55°C; plants in the DSF reduced cooling capacity by almost 20%.

Guillén et al. (2014) investigated different types of façades considering their thermal performance during a 24-hours period. A numerical model was developed and compared with experimental data considering two different façades for buildings: on one side an opaque multilayer façade; on the other side, a ventilated façade. The temperature in every layer of the façades was successfully validated. This model was used to determine the thermal behaviour of two new ventilated façades in which the thermal mass had been changed. It was found that the air temperature and the thermal transmittance of the façade were affected by the movement in the air gap while the sun hitting the façade, leading to a reduction of transmittance close to 30% (along the air chamber). This effect is very crucial in warm climates and it is a key-factor for decreasing the cooling needs of the buildings during summer with no need of increasing the mass of the façade. In terms of the modelling, the computations were conducted by a finite-element analysis commercial package (COMSOL Multiphysics v 3.5).

2.2.3. BI, Pipes

Simplified, thermal resistance-based computer models were developed to simulate the performance of direct gain, indirect gain and integrated heat pipe passive solar systems (Albanese et al., 2012). A computer model was developed to investigate further the feasibility of heat pipe integrated walls in different climatic conditions and a parametric study was conducted to determine the design features that have a significant effect on the performance. A prototype heat pipe wall was constructed and tested to provide validation data. MatLab codes were created to simulate hourly performance of the heat pipe system, as well as direct gain and concrete and water wall indirect gain systems. A thermal network approach was adopted. An anisotropic model was utilized (three components: diffuse radiation – uniform, circumsolar, horizon brightening). The heat pipe system provided substantial gains in performance relative to conventional direct and indirect gain passive solar systems and thus, presents a promising alternative for reducing building energy use. Economic performance depended on the climate and the load to collector ratio, as well as a number of factors related to the costs of the system and of conventional heating. It should be noted that four cities were chosen to provide a range of insolation/temperatures: Albuquerque (New Mexico), Rock Springs (Wyoming, USA), Louisville (Kentucky, USA), Madison (Wisconsin, USA).

Hassan and Beliveau (2007) investigated integrated solar roof collectors using finite element analysis. The integrated roof solar collector consisted of a 6.35 mm single glass panel with a selective surface, followed by a 1-mm air-gap. The thermal collecting medium was a fluid (water with antifreeze) enclosed copper pipes. The pipes were laid within concrete cavities to minimize construction cost and time as well as to reduce convection losses. The copper pipes were connected together by means of a 1-mm copper plate absorber. 3D finite element models were developed to evaluate the thermal performance of the integrated roof solar collector. The models were used to predict the optimum set of variables that can be used in buildings in order to achieve adequate thermal comfort. Coupled conduction, forced convection, long wave thermal radiation modes of heat transfer were considered in the developed models. A specific location (Blacksburg, Virginia, USA) was modelled. ABAQUS software version 5.8 was used for finite element modelling of the solar roof panel. In Fig. 3a, the cross section of the integrated solar roof collector is illustrated while in Fig. 3b the temperature distribution in the fluid and in the solar collector is shown.

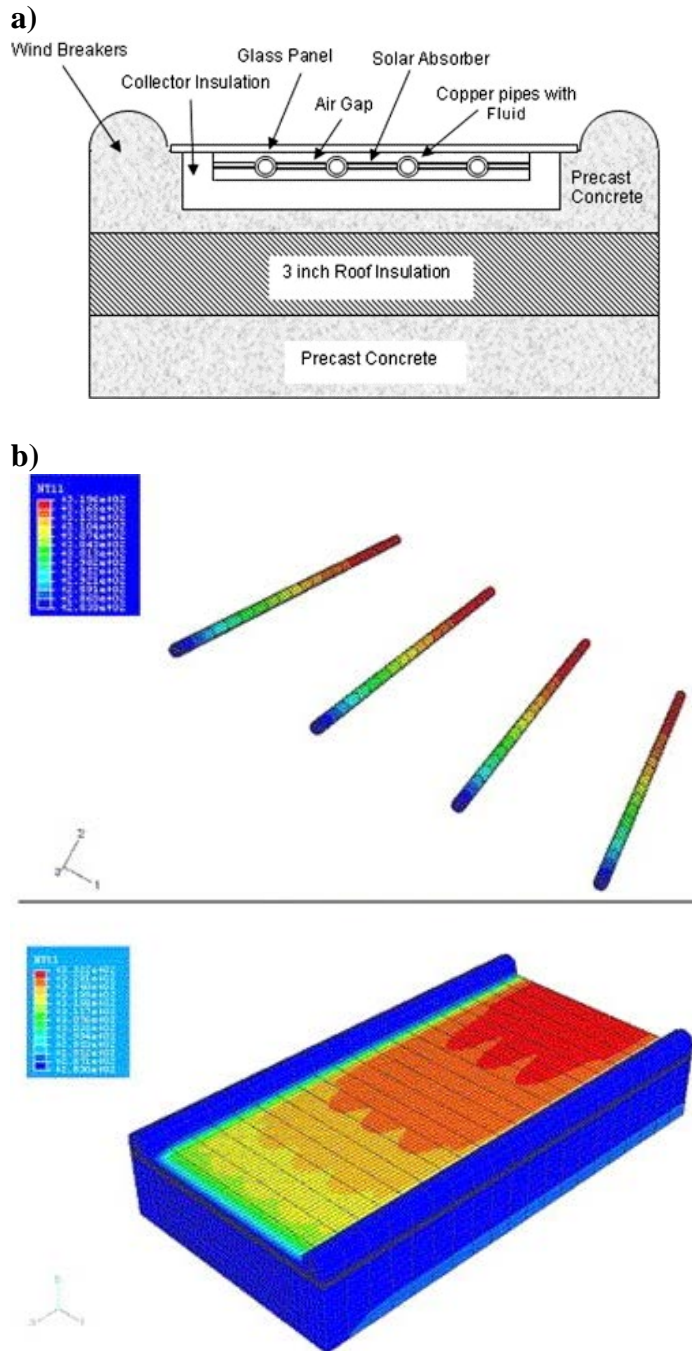


Figure 3. a) The cross section of the integrated solar roof collector, b) Temperature distribution in the fluid (above) and solar collector (below) during noon in May (600 W/m^2) (Source: Hassan and Beliveau, 2007).

A dynamic simplified thermal model for active pipe-embedded building envelopes was developed by using Genetic Algorithm (GA) (Zhu et al., 2014). An external building envelope embedded with pipes could provide advantages such as direct utilization of low-grade energy sources for reducing building cooling/heating load and improving indoor thermal comfort. The resistances and capacitances were identified in frequency domain by using GA by comparing the frequency characteristics of the

simplified model with the theoretical frequency characteristics of this structure obtained with Frequency-Domain Finite Difference (FDFD) method. Firstly, the FDFD model of this structure was established and the theoretical frequency characteristics under various disturbances were calculated for the reference of parameter identification. Then, an equivalent dynamic simplified thermal model with lump thermal network structure was developed and its frequency characteristics were also deduced and calculated. Finally, the GA estimator was adopted to identify these parameters of the simplified model for allowing the frequency responses of the simplified model to match the theoretical frequency responses by using the FDFD method. Performance prediction of this structure under realistic weather conditions, indoor air condition and circulating water temperature condition for practical applications (China) was done. The optimal simplified model provided reasonable and accurate performance prediction for the pipe-embedded light, medium and heavy weight building wall. The model accuracy may differ depending on the wall physical properties. In general, the simplified RC¹ model is a good model for predicting the heat transfer performance of this structure.

2.2.4. BI, Solar Chimney

Ong (2003) developed an analytical and physical model with thermal resistance network for a solar chimney. A wall-type solar chimney, consisted of a glass cover with other three solid walls of the chimney forming a channel through which the heated air could rise and flow by natural convection, was examined. Steady-state heat transfer equations with matrix-inversion solution procedure were utilized. The thermal performance of the solar chimney as determined from the glass, wall and air temperatures, air mass flow rate and instantaneous heat collection efficiency of the chimney were presented. Satisfactory correlation was obtained.

2.2.5. BI, Trombe Wall

A numerical model for laminar, free convection flow in Trombe wall and a modified version of the conventional Trombe wall, based on finite difference method was developed (Jubran et al., 1991). The variation of fluid velocity, temperature and the average Nusselt number were determined numerically for selected tilt angles of the glass wall for the modified version of the Trombe wall. It was found that there is a significant effect of the glass wall inclination on the average Nusselt number.

Ben Yedder et al. (1990) conducted a numerical study of laminar natural convection in composite Trombe wall systems. The natural convection problem in a composite Trombe wall solar collector with SIMPLER method (control volume) was investigated. Model for natural convection in cavities and steady, laminar, 2D flow were adopted. The results showed that the aspect ratio had a small influence on the heat transfer and other geometric parameters such as orifice position, channel size and width had important effect on the useful energy transmitted to the dwelling.

The energy modelling of a BI PV Trombe wall system was investigated by Koyunbabaa et al. (2013). A 2D simulation model of a naturally ventilated BI PV

¹ Resistance and capacitance thermal model

Trombe wall system for winter period, applied to different locations with different climatic conditions, PV types, thermal mass samples, etc was developed. The commercial CFD code Ansys CFX was adopted to model air flow and heat transfer with the Navier–Stokes equations. Ansys CFX based on finite volume technique was utilized. The validation of the model was done with experimental results of a BI PV Trombe wall built in Izmir, Turkey. The study revealed the capability of a CFD code to predict the radiation, conduction and natural convection in a BI PV Trombe wall system.

2.2.6. BI, PVT

A novel BI PVT solar collector was theoretically analyzed through a modified Hottel–Whillier model (Anderson et al., 2009). The model was validated with experimental prototype test data. 1D steady state thermal model was utilized. The electrical efficiency was calculated based on the difference between mean BI PVT temperature and Nominal Operating Cell Temperature (NOCT) (298 K). The collector base material made little difference to the thermal efficiency of the BI PVT suggested that lower cost materials, such as steel, could be utilised for these systems. The disadvantage of using steel was that the electrical efficiency would be decreased marginally. To improve the electrical and thermal efficiencies of the system it was suggested that the good thermal contact between the PV cells and the absorber is required which can be achieved by using thermally conductive adhesives. Increase in the transmittance/absorptance product resulted in the greatest increase in thermal efficiency of all the parameters assessed, without greatly reducing the electrical efficiency. The use of unglazed BI PVTs in conjunction with heat pumps could present interesting possibilities. Significant potential exists to utilise the low natural convection heat transfer in the attic at the rear of the BI PVT to act as an insulating layer rather than using additional insulation material. The use of this air layer would allow the material cost of such a system to be significantly reduced.

A heat transfer analysis of a west-facing PVT collector wall located in Hong Kong was performed using a computational thermal model (Ji et al., 2003). A simulation program HYBRIDPV-1.0 (in FORTRAN) was developed. The simulation program could determine the energy performance of a PV/hot water collector system for different PV panels, climatic region and orientations.

The effect of fluid flow and packing factor on the energy performance of a wall-mounted PV/water-heating collector system was investigated using a numerical model developed by modifying the Hottel–Whillier model (Ji et al., 2006). The combined effects of the solar cell packing factor and the water mass flow rate on the thermal and electrical efficiencies were examined. The increase of working fluid mass flow rate was found to be beneficial for PV cooling. System operation at the optimum mass flow rate improved the thermal performance of the system and met the PV cooling requirements so that a better electrical performance can also be achieved.

The design, modelling and the thermal performance of a BI PVT thermally coupled with a Ventilated Concrete Slab (VCS) in a low-energy solar house in Canada was reported (Chen et al., 2010). The system was adopted in a prefabricated, two-storey detached, low energy solar house and the performance assessment was based on

monitored data. A simplified 3D, control volume, explicit finite difference thermal model was developed to simulate the thermal performance of the constructed VCS. The model can also be used for other types of VCS. The developed model was proved to be appropriate for the design purposes and for the study of control strategies.

Aelenei and Pereira (2013) investigated innovative solutions for net zero-energy buildings. Numerical thermal analysis of two different systems for integrating on building façade: BI PVT and BI PVT-PCM (Phase Change Material) was conducted. A dynamic model was simulated by using the real climatic data of winter time measured on a building site (Lisbon, Portugal). 1D numerical dynamic simulation model inside the control volume; fully finite difference scheme; programming MATLAB/SIMULINK® with SIMSCAPE® library were utilized. The results revealed that the system with PCM decreased the temperature inside the air cavity and thus, more stable due to the storage of solar gains as latent heat in the PCM wall. The thermal efficiency of the ventilated BI PVT was higher than the ventilated BI PVT-PCM because of the airflow at elevated temperature into the room. Nevertheless, after few hours, the efficiencies of the two systems appeared to be close to each other.

A three step numerical analysis was conducted to model flow distribution, temperature variation, PV yield for a BI PVT collector for various design (manifold sizes), geometric shape (aspect ratio) and operating characteristics (Ghani et al., 2012) CFD/FEA analysis, heat transfer analysis were utilized for PV modelling. All the simulations were conducted by using Autodesk Simulation Multi-physics 2012 software. The results showed that the flow distribution within the collector had significant influence on the PV performance of a hybrid PVT collector. For uniform flow distribution PV performance was improved by over 9% in comparison to a traditional PV collector operating under the same conditions. It was found that several parameters influence flow distribution: e.g. manifold to riser pipe ratio (a ratio of 4:1 was found to be ideal and that increasing to a 6:1 ratio offered negligible improvement). It was also found that array geometry (characterised by its aspect ratio in this study) is important for both flow distribution and PV yield. That study identified that optimal mass flow rate was dependent on array shape or aspect ratio.

Liao et al. (2005) conducted a CFD study of a BI PVT system. The conjugate heat transfer in the BI PVT system cavity was studied with a 2D CFD model while the k- ϵ model was used to simulate the turbulent flow and convective heat transfer in the cavity, in addition to buoyancy effect. The longwave radiation between boundary surfaces was also modelled. Simulation results were compared with outdoor experimental data (Concordia University, Canada) and they showed good agreement. Average and local convective heat transfer coefficients were generated and PV panel average temperature and local cell temperatures were calculated and compared with the data from the experiments.

2.2.7. BI, PV

The thermal performance of semi-transparent BI PV glazings in Hong Kong was performed using a 1D transient simulation model, the Semi-transparent PV Heat Gain (SPVHG) model (Fung and Yang, 2008). The model was validated with experimental data. Annual total heat gains through the semi-transparent BI PVs under different scenarios were simulated by means of the SPVHG model. The total heat gain through the PV module was dominated by the solar heat gain. The effects of different parameters of the PV modules were also studied.

1D, finite-difference thermal model was developed to optimise the performance of double-façades with integrated PV panels and motorized blinds (Charron and Athienitis, 2006). The model used an algorithm that iteratively determined which convective heat transfer coefficient correlation to use for each surface inside the cavity using expressions that consider system characteristics and temperature distribution. The environmental conditions that were used in the model were representative of what would be experienced in Montreal, Canada. When the PVs were installed in the middle of the cavity, air flowed on both sides, increasing PV section overall (thermal-electric) efficiency by about 25%, but lowered electricity generation by 21%. Integrating 0.015-m long, 0.002-m wide fins to the PV back plate resulted to a similar increase in efficiency without compromising electricity generation. The placing of the blind in the middle of the cavity increased the vision section efficiency by 5%. By adopting that approach to optimize performance can lead to combined thermal-electric efficiencies of over 60%.

A numerical study was conducted to determine the adequate air gaps for BI PVs (Gan, 2009). FLUENT was used for 2D modelling of fluid flow and heat transfer around PV modules mounted on pitched roofs and in the vertical façade. The modelling was performed for a range of roof pitches and gap sizes. The model was validated for buoyancy-induced fluid flow and heat transfer in a tall open air cavity. The RNG k- ϵ turbulence model was utilized for modelling turbulent air flow and heat transfer. Ambient air temperature was fixed at 20°C while the incident solar radiation was first fixed at 1000 W/m² and then varied with respect to the roof inclination. A discrete transfer radiation model was adopted for modelling the radiation heat transfer from the modules to surroundings. The results revealed that the CFD technique can be used to predict the required air gap for a given type of module and method of building integration.

Friling et al. (2009) modelled the heat dynamics of BI and ventilated PV modules. The experimental data obtained from a test reference module at EC-JRC Ispra. The set-up provided the opportunity of changing physical parameters, the ventilation speed and the type of air flow. The models were first order stochastic state space models. The analysis revealed that it is necessary to use non-linear state space models to obtain a satisfactory description of the PV module temperature and to distinguish the variations in the set-up. It was found that the heat transfer increased with the increase in forced ventilation velocity but less influenced by the change in air flow type. The residual analysis demonstrated that the best description of the PV module temperature was obtained when fins, disturbing the laminar flow and making it turbulent were applied in the set-up combined with high level of air flow. The improved description by the model was mainly observed for periods with high solar radiation.

2.2.8. BI, Several systems

Sanjuan et al. (2011) compared the energy performance of an Open-Joint Ventilated Façade (OJVF) with a conventional sealed cavity façade in Madrid, Spain. The system consisted of a coating material (metallic, ceramic, stone or composite) hanging by means of a metallic-frame structure to the exterior face of the wall, creating an air cavity between wall and slab. In this way, there was a buoyancy effect and thus, an ability to reduce cooling thermal loads. The phenomena produced on a typical open joint ventilated façade and comparison of its energy performance with that of a conventional sealed air cavity façade was investigated. The thermo fluid-dynamic behaviour of both systems was analyzed with CFD using FLUENT. 3D simulations were conducted. The CFD model enabled a better understanding of the ventilation effect induced by the solar radiation in the air gap of the façade. The velocity profiles, together with temperature and heat flux distributions were compared with those obtained in a conventional sealed cavity façade. The model was also used to compare the thermal performance of both façades for the specific climatic conditions.

Chen et al. (2013) investigated the frequency domain and finite difference modelling of ventilated concrete slabs. Frequency response (FR) and Lumped-Parameter Finite Difference (LPFD) approaches for the thermal modelling of BI Thermal Energy Storage (BITES) systems were utilized. The results were compared to each other and with field-measured data from a solar demonstration house with a Ventilated Concrete Slab (VCS). The modelling techniques were applied to two kinds of VCS – one had air channel at the bottom of the mass (VCS-b) while the other had hollow cores as air channel (VCS-c). The explicit LPFD and FR models generated almost identical outcomes under periodic conditions. The accuracies of different discretization configurations and choices of time step were quantified. Time step of half an hour for FR models typically resulted in less than 3% error in the thermal performance. For LPFD models, discretization with Biot number less than 0.5 reduced error to about 5%. Larger Biot number tended to overestimate the heat flow from air to the slab over time. For practical slab thickness (0.1-0.2 m), simulation results from 2-layer VCS-b and 3-layer VCS-c models with time step of half an hour showed errors less than 9%. LPFD simulation results under non-periodic conditions were presented for VCS-b and they were compared with field-measured data from a near net-zero energy solar house.

Palmero-Marrero and Oliveira (2006) evaluated a solar thermal system using building louvre shading devices. A numerical model for the integrated solar collector was developed for different configurations such as collector with tubes; collector with larger channels; collector with smaller channels and transparent cover area. The collector efficiency was evaluated for each configuration. System thermal performance was obtained for the climatic conditions of: Lisbon (Portugal) and Tenerife (Spain). A steady state heat transfer model was assumed.

Wang et al. (2012) studied the dynamic performance of a façade-based solar Loop Heat Pipe water heating (LHP) system which was able to serve as part of the building façade or a decoration layer of the façade. The system was low cost, highly efficient and aesthetically appealing. Taking into account heat balances in different parts of the system, a dedicated computer model was developed to investigate the dynamic performance of the system. The inputs of the model were geometrical and thermal

parameters. An experimental rig was also established to examine the performance of the prototype system. The model was reasonable accurate in predicting the performance of the LHP system. Two types of glass covers (double glazed/evacuated tubes and single-glazing plate) were applied to the prototype configuration. The results showed that for both covers, the heat pipe fluid temperature rose dramatically at the start-up operation and afterwards remained a slow but steady growth while the water temperature steadily increased throughout the operational day. In overall, the double-glazed/evacuated tubes based system showed a better performance than the single-glazing based one. For the model a mathematical analysis of the thermal processes was adopted.

Manz (2003) conducted a numerical simulation of heat transfer by natural convection of air layers within vertical, rectangular cavities of façade elements. Natural convection was examined for applications in building façade elements, such as insulating glazing units, DSF, doors, etc. CFD code (commercial CFD code FLOVENT, Version 3.1; finite volume method) was utilized. An optical model was used for determining absorbed solar radiation in layers of façade elements such as glass panes, roller blinds and the CFD modelling to increase the reliability of predictions of these elements thermal transmission and total solar energy transmission.

2.2.9. BA, Several systems

Oliva et al. (1991), Plantier et al. (2003), Cadafalch (2009) and Molero Villar et al. (2009) presented detailed physical models for solar thermal collectors which in principle could be coupled to a building.

Under transient climatic conditions, solar water heaters with heat pipes are more effective in terms of capturing incident solar radiation (in comparison with other types of water heaters). Redpath et al. (2014) investigated concentrating and non-concentrating evacuated tube solar water heaters by using 2D particle imaging velocimetry. Two configurations were studied: thermosyphon fluid flow and reflective concentrators. A model manifold simulated the manifold of a heat-pipe evacuated tube solar water heater was presented. 2D-PIV (particle imaging velocimetry) revealed significant differences in flow patterns between the two manifold configurations which were confirmed by comparing Nusselt number. The results showed that the incorporation of concentrators have a small effect on the overall system efficiency but would reduce the frictional losses internally.

Sultana et al. (2011) investigated the thermal performance of a roof-integrated solar micro-concentrating collector (solar thermal system) consisting of linear Fresnel reflectors. The objective of the study was to optimize the design to maximize the overall thermal efficiency. Computational investigation of radiation and convection heat transfer to understand the heat loss mechanisms was conducted. A computational model for the prototype collector was developed by using ANSYS-CFX. The numerical results were compared with experimental measurements. The efficiency of the collector was established on the basis of ray tracing and heat loss analysis.

2.3. Studies of Energetic/Thermal Simulation

2.3.1. BI, Solar Thermal

Pflug et al. (2013) extended the standard efficiency curve of (Cooper and Dunkle, 1980) to account for losses to the building interior, too. A comparison with a validated detailed physical BIST model showed that the collector gain can be calculated well. However, the simple model had considerable errors in calculating the heat flux to the building interior.

Experimental and modelling of a novel solar thermal concept for integration into building gutter was reported (Notton et al., 2013). A numerical model was developed in Matlab by using a finite difference model and an electrical analogy. The thermal model was validated by means of experimental data under various meteorological conditions. The adequacy of that model with the experimental data was proved for various temperatures. The relative root mean square errors were around 5% for the water temperatures ranging from 4.6 % to 10% for the internal ones. The advantage of this model is that it can be modified: it is able to modify easily the characteristics and the form of the used materials.

2.3.2. BI, Skin Façades

In Mediterranean climate glazed-façade systems are responsible for the overheating of the building. In these zones, double-skin envelopes made up of two layers of glass separated by an air channel in order to collect or evacuate the solar energy absorbed by the façade are a design option that could resolve this issue. Faggembau et al. (2003) conducted a numerical analysis of the thermal behaviour of ventilated glazed façades in Mediterranean climates. The model was based on 1D-discretizations and it allowed the evaluation of the performance of the façades over a year. The numerical results of each sub-model were compared with the results of analytical models; both with reference situations and with experimental measures obtained in real-site test façade facilities (in different climatic conditions).

2.3.3. BI, PVT

Yang and Athienitis (2014) developed a prototype open loop air-based BI PVT system with a single inlet. Experiments were conducted under a solar simulator (Concordia University). A numerical control volume model was developed and validated with experimental results. Simulations were carried out to improve BI PVT system design by considering multiple inlets and other means of heat transfer enhancement. The results of the simulations demonstrated that the application of two inlets on a BI PVT collector increased the thermal efficiency by around 5% and increased the electrical efficiency marginally. An added vertical glazed solar air collector improved the thermal efficiency by 8% and for wire mesh packing in the collector the improvement was around 10%. The developed model was applied to a BI PVT roof of an existing solar house and the thermal efficiency showed an improvement of 7%. Fig. 4 shows the results obtained from this study.

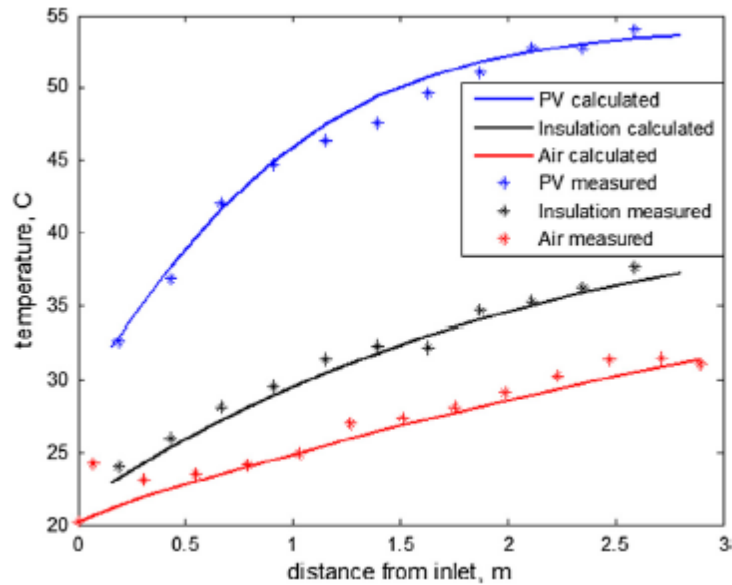


Figure 4. The numerical simulations vs. the experimentally measured data from the simulator (operating conditions: 1080 W/m^2 of solar radiation, 1.6 m/s of average wind speed and 1.5 m/s of air speed in the BI PVT cavity) (Source: Yang and Athienitis, 2014).

Buker et al. (2014) investigated the integration of unique polyethylene heat exchanger loop underneath PV modules acting as a roof element having a heat resource for solar-assisted heating and cooling technologies. A detailed thermal model was adapted in order to investigate the thermal performance of the roof. Numerical computations were performed by using Engineering Equation Solver (EES) for UK climatic conditions. The design parameters of the BI PVT roof collector were used in the model. The experimental values showed that the water temperature difference and overall thermal efficiency could reach up to 16°C and 20.25% , respectively. The energy and exergy analysis was conducted to observe the increase in energy and exergy efficiencies due to the implementation of concealed heat extraction component. Techno-economic analysis was also performed by applying the life cycle cost method. The estimated annual energy savings were found to be 10.3 MWh/year .

Agrawal and Tiwari (2010) optimized the energy and the exergy of BI PVT systems under cold Indian climatic conditions using MATLAB. 1D transient model was developed by using basic heat transfer equations. The performance analysis of a BI PVT system was evaluated for four different parallel and series combinations². It was concluded that for a constant air mass flow rate, the series combination was more suitable for the buildings fitted with BI PVTs as rooftop.

Corbin and Zhai (2010) conducted an experimental and numerical investigation on thermal and electrical performance of a BI PVT collector. An experimentally validated CFD model of a new BI PVT collector was used to examine the effect of active heat recovery on the cell efficiency and to determine the effectiveness of that

² Case 1: all six rows of the BI PVTs were connected in parallel; Case 2: three rows of the BI PVTs were connected in parallel each having two rows in series; Case 3: two rows of BI PVTs were connected in parallel each having three rows in series; Case 4: all the rows of the BI PVTs were connected in series

device as a solar hot water heater. A parametric analysis indicated that cell efficiency can be raised by 5.3% and the temperature of the hot water is suitable for the domestic usage. Thermal and combined thermal plus electrical efficiencies were found to be 19% and 34.9%, respectively. A new correlation was developed relating electrical efficiency to collector inlet water temperature, ambient air temperature and insolation to calculate the cell efficiency. The collector had 41 PV panels suspended above an array of tube-fin absorbers. Two models were developed to evaluate the performance of the BI PVT collector under different operating conditions: a collector cooled by natural convection was the base case for cell temperature comparison and a collector with a liquid-cooled tube-fin absorber into the cavity. A CFD package was utilized for the simulations. The electrical efficiency of the proposed BI PVT collector increased by 5.3% over a naturally ventilated BI PV roof and reduced the negative effects of integration into building façade. This collector provided hot water for domestic use or hydronic space heating with no additional roof space requirements. The total efficiency of the collector was predicted to be 34.9%. A new correlation was developed relating PV cell efficiency to collector water inlet temperature, ambient air temperature and insolation to predict the cell efficiency. Standard methods for characterizing solar hot water collectors were also applied to determine the collector properties. The numerical model was validated and showed good agreement with the experimental data.

Yin et al. (2013) studied the design and the performance of a novel BI PVT system for energy efficiency of buildings. A BI multifunctional roofing system was designed to harvest solar energy through PVs and heat utilization while minimizing PV efficiency loss and eliminating the material and labour redundancies of conventional PV systems. Finite element simulations were conducted. The cost and performance analysis indicated that the proposed solar roofing system provided significant advantages over the traditional asphalt shingle roof and PV systems without cooling and it has the potential for significant benefits with a small additional investment. The energy payback time and investment return period depended on several factors.

A computer simulation model was developed for a BI PV/water-heating system (Hong Kong) to study the annual performance under warm climatic conditions (Chow et al., 2009). The results showed that the PV/water-heating system had much economical advantages over the conventional PV installation. The system thermal performance under natural water circulation was found to be better than the pump-circulation mode.

Liao et al. (2007) conducted a CFD study and experimental study of heat transfer in a BI PVT system. The heat transfer in the BI PVT cavity was studied with a 2D CFD model. The realizable k - ϵ model was adopted to simulate turbulent flow and convective heat transfer in the cavity, including buoyancy effect and long-wave radiation between boundary surfaces. A PIV system was employed to examine fluid flow in BI PVT cavity and provided partial validation for the CFD model. Average and local convective heat transfer coefficients were generated with the CFD model by using measured temperature profile as boundary condition. Cavity temperature profiles were calculated and compared to the experimental data for different conditions. A good agreement was observed. Correlations of convective heat transfer coefficients were generated for the cavity surfaces. Local heat transfer coefficients, such as those presented, are necessary for the prediction of temperature distributions in BI PVs.

Li et al. (2014) developed an energy model for PVT systems with corrugated unglazed transpired solar collectors. Two systems were considered: Unglazed Transpired solar Collector (UTC) only and UTC with PVs. CFD simulations were performed. The energy models were validated with measured data (test building: Purdue University, USA) and a good agreement was found. Further study was conducted to investigate the impact of various factors that affect the thermal performance of PVTs integrated with UTCs (Li and Karava, 2014). The findings of that study revealed that the 'vertical' installation of the plate greatly enhanced exterior and interior convective heat transfer due to the combined effects of the corrugation, wind speed, suction velocity and buoyancy, for the configuration of UTC only. Increasing the turbulence intensity increased the exterior Nu. Optimizing the geometry can greatly improve the energy performance of UTC systems whereas it was less effective for UTCs with PV panels.

A dynamic model was developed to study a BI PV/water heating system (Chow et al., 2008). The numerical model was based on the finite difference control volume approach while the integrated use of energy balance and fluid flow analysis allowed the prediction of system dynamic behaviour under external excitations such as changes in weather, water consumption and make-up conditions. The predicted data was verified with experimental operating temperature and system daily efficiencies data (experimental set-up: City University of Hong Kong). The use of multi-nodal scheme was found to be most useful in apprehending the underlying physical processes. The integrated use of energy balance and fluid flow analysis allows the prediction of the system behaviour in a comprehensive manner.

Shan et al. (2014) investigated the dynamic characteristics modelling of a PVT solar collector with active cooling in buildings in China. In this paper, a brief review on PVT using various working fluids was presented. The simulation results demonstrated the influence of the meteorological parameters and the evaporating temperature on the PV and thermal performance of the PVT. Matlab software was utilized for the calculations.

2.3.4. BI, PV

Kane and Verma (2013) investigated the performance enhancement of a BI PV module by using thermoelectric cooling. Thermoelectric module was attached at the back of PV module (cooling mode). Mathematical modelling of individual systems was performed and then, the dynamic model of the BI PV/Thermoelectric system by considering the temperature of the PV panel was developed. The results of the simulations revealed that the proposed cooling method improved PV efficiency with minimal power loss.

Mei et al. (2002) estimated the thermal parameters which describe the performance of ventilated PV façades integrated into buildings. A direct numerical approach was developed for this analysis. The method allowed the heat transfer coefficients to be obtained (directly) from data measured on an operational ventilated PV façade. The results were compared with values which were taken from conventional practice.

2.3.5. BI, PCM for passive solar walls

Darkwa and O'Callaghan (2006) simulated phase change drywalls integrated with PCM materials in a passive solar building. Thermal simulations were performed by using finite difference model based on the fixed mesh method. It was found that the laminated PCM sample with a narrow phase change zone increased the minimum room temperature by about 17% more than the randomly-mixed type. The laminated system was proved to be thermally more effective in terms of evolution and utilization of latent heat.

2.3.6. BI, Double-pane window

Xamán et al. (2014) conducted a numerical study for a Double Pane Window (DPW) with Solar Control Film (SCF) in warm and cold climates. The DPW consisted of two vertical semitransparent walls (glazing-1 facing the room; glazing-2 facing the external environment and exposed to solar radiation). There was a SCF attached to glazing-1 for cold climate or glazing-2 for the case of warm climate. The effect of varying the separation distance between the glasses, room temperature and the incident solar radiation was examined. In order to perform the thermal analysis of the DPW, three cases were investigated: Case for the DPW with SCF (Case 1); Case for the DPW only (Case 2) and single glazing window (Case 3). To reduce and increase heat gains toward the inside environment, the optimal distance between the glasses was greater than 6.0 cm for both climates. In warm climate the use of a SCF was highly recommended, since 52% reduction in energy gained was achieved for Case 1 than Case 2 and 10% in the cold climate. The coupling between the momentum and continuity equations was conducted by the SIMPLEC algorithm.

2.3.7. BA, Solar thermal

Luo et al. (2014) developed a simulation model for a nanofluid solar collector based on "direct absorption collection" concept. The model was developed by solving the radiative transfer equations of particulate media and combining conduction and convection heat transfer equations. The system efficiency/temperature distributions were analyzed by considering absorption/scattering of nanoparticles and the absorption of the matrix. The simulation results agreed well with experimental data. The nanofluids improved outlet temperature and the efficiency by 30–100 K and by 2–25%, respectively than the base fluid. The study demonstrated that nanofluids, even of low-content, have good absorption of solar radiation and they can improve the outlet temperature and system efficiency. For that study, a 2D model was built to analyze the radiation and conduction in the collector. The nanofluid layer was assumed to be a particulate suspension colloid (filled with single spherical particles).

2.3.8. BA, PVT

Tonui and Tripanagnostopoulos (2008) developed an analytical model using Fortran90 to evaluate induced airflow rate and PVT system temperature for natural airflow operation. Three configurations were studied: reference; with thin metal sheet in

the middle of the air channel (TMS); with fins in the middle of the air channel (FIN). The model estimated the outlet air temperature within $\pm 2^{\circ}\text{C}$ for all the configurations. The air mass flow rate was also calculated by this model. The model results revealed that the modified systems had better thermal efficiency for all parameters, with the FIN system giving better performance than the TMS system but both systems enhanced the heat extraction from PV module for better electrical and thermal energy production.

TRNSYS simulations were performed for hybrid PVT solar systems for domestic hot water applications (Kalogirou and Tripanagnostopoulos, 2007). Prototype model was manufactured using polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) combined with a water heat extraction unit. Simulations were performed by using Typical Meteorological Year (TMY) data from Nicosia (35°), Athens (38°) and Madison (43°). TRNSYS model calculated the energy and cost of hybrid PVT system with thermosyphon and forced water flow. The results revealed that pc-Si solar cells produced more electrical energy than a-Si solar cells but the thermal energy was slightly lower.

Dupeyrat (2011) presented a simulation model for PVT collectors as well as an assessment of the PVT system performance. This PhD thesis also investigates the benefits of laminating the PV cells directly on a metallic absorber.

A steady-state simulation was performed to study the performance of PVT air heating collectors (Garg and Adhikari, 1997). The results were presented to show the effect of various design and operational parameters on the performance of the systems. The authors concluded that these results would be useful for the designing of such systems more scientifically; however, final selection of design and operational variables must be based on system cost-effectiveness. The system efficiency increased with increase in collector length, mass flow rate, cell density and decreased with increase in duct depth for both configurations.

Brideau and Collins (2014) developed a model for a PVT collector utilizing impinging jets. The impinging jet PVT flat-plate collector had five different layers: a glass cover, PV, a layer on which the PV was glued, a perforated plate and back insulation. The developed model was validated with the experimental data and found to be accurate. For 8-days testing, the worst total daily energy model predictions were within 10% and 11% of the experimental value for the thermal and electrical outputs, respectively. The influence of time step and thermal mass on the accuracy of the model were also examined. The simulation program TRNSYS was adopted for the study. The model was based on an energy balance performed at each of the collector layers.

A PVT solar collector integrating a PV panel with a serpentine-shaped copper tube (water heating component) and a single pass air channel (air heating component) was developed (Abu Bakar et al., 2014). In addition to electricity generation the collector also produced hot air and water and thus, increased the overall efficiency compared to a conventional PVT solar collector. The use of both fluids (bi-fluid) also allowed a greater range of thermal applications and it provided options in which hot and/or cold air and/or water could be utilized (depending on the energy needs and applications). 2D steady state energy balance equations for the bi-fluid configuration were developed, validated and used to predict the performance of the collector for a range of mass flow rates of air and water. The simulations demonstrated that the overall

thermal and electrical performance of the solar collector was satisfactory when both fluids were operated independently but was better when they operated simultaneously.

2.3.9. BA, CPVT

Renno (2014) optimized a CPVT system for a domestic application. To develop a high-concentration system the reflective optics with parabolic mirror concentrators of point focus type and the triple-junction cells (InGaP/InGaAs/Ge) assembled with a dual axis tracker were adopted, along with an active cooling system. The model analyzed the CPVT in terms of: direct normal irradiance, cell efficiency, module electric and thermal efficiency, thermal and electric energy provided by cell and module, cell and cooling fluid temperatures. Moreover, for each working condition the optimisation of the factors associated with the concentration decreased the CPVT system size and provided a fluid outlet temperature which satisfied the thermal and cooling demands.

2.4. Studies of Optical Simulation

2.4.1. BI, Several systems

A numerical and experimental study of solar and visible optical properties of glazing systems with venetian blinds was conducted by Glória Gomes et al. (2014). Both direct and diffuse fluxes of transmitted, reflected and absorbed solar and visible radiation within a multilayer glazing/shading system were presented. Net radiation method for solving the radiant energy exchange within a multilayer system was utilized. The numerical, the analytical and the experimental results were compared. The developed model can be used for different sun profile angles and venetian blind geometries, suitable for comparing different glazing/venetian blind solutions and devising blind control strategies. Design charts were developed to help designers and users in enhancing the thermal and daylighting indoor conditions by adjusting the slat orientation of venetian blinds. The knowledge of the solar and visible optical properties of different glazing/shading systems is crucial in identifying the most effective sustainable strategies to improve the fenestration system performance, regarding building energy consumption and indoor comfort issues.

Maurer (2012) calculated the absorptance of each collector layer and the transmittance of the collector with the “four-flux model” depending on the azimuth and altitude angle of the irradiance. The results were combined with the Perez sky model and the Tregenza (Perez et al., 1993; Tregenza, 1987) sky patches to calculate the solar absorption of each layer and the solar transmission of the whole collector for each time step.

An inorganic thin film Luminescent Solar Concentrator (LSC) was characterized experimentally (Wiegman and van der Kolk, 2013). The application was for windows in buildings (BI LSCs configurations). A light transport modelling of thin film BI LSCs was adopted to calculate the LSC light transport efficiency as a function of window size.

Di Lauro et al. (2013) presented an analysis of potential glare by using vacuum tubes in a semi-transparent façade. Different elements to reduce glare were analysed and compared. These elements can also increase the solar thermal gain. OptiCAD was adopted for the simulations.

Baldinelli (2009) investigated the performance of a glass DSF equipped with integrated movable shading devices in warm climate regions. Three different modelling levels: optics of materials, fluid dynamics of the DSF and building energy balance were adopted. The aim of that study was to optimize the system energy performance both in winter and summer. A 3D CFD model made of two opaque walls with an inlet (bottom) and outlet (top) opening in the external wall and buoyancy driven flow regime was utilized. The climatic data were for the case of central Italy. The simulation results showed the instauration of a buoyancy-induced flow inside the gap, producing the doubly beneficial effect of diminishing the heat dispersion through external walls and preheating the air for ventilation purposes.

Kerrouche et al. (2014) examined LSCs. Experimental validation of 3D ray-tracing simulations to coloured stained-glass windows for BI PV was conducted (Kerrouche et al., 2014). Ray-trace modelling in terms of design, performance evaluation, optimization of LSC was performed. The study included 70 samples – both square and circular LSCs, containing five different fluorescent organic dyes. The 3D ray-trace results showed good agreement with the experimental measurements.

Sellami and Mallick (2012) designed a non-imaging static solar concentrator for window integrated PVs. The concentrator was optically optimised. The best combination of the optical efficiency and the acceptance angle, 4x concentrator built from dielectric material, with total internal reflection was optimised. It was found to have a constant optical efficiency of 40% for an acceptance angle equal to 120° (-60° , $+60^\circ$) and an Optical Concentration Ratio (OCR) equal to 1.6x. This enables capture of the sun rays all day long (direct as well as diffuse light). Higher OCR's were achieved for different dimensions of the solar concentrator; nevertheless, the acceptance angles were relatively low. The accuracy of the optical model was approximately 95%.

Ulavi et al. (2014) investigated a semitransparent façade collector with compound parabolic concentrators in the infrared spectrum. A Monte Carlo Ray-Tracing model was used to calculate the annual gains as well as the solar heat gain coefficient.

Sprenger (2013) presented a method of calculating the absorbed radiation in complex BIPV modules depending on the weather conditions. He used the backward-ray-tracer RADIANCE and the method could be used for BIST, too.

2.4.2. BA, Low-concentration evacuated-tube solar collector

Li et al. (2014) conducted an experimental and optical analysis of a static low-concentration evacuated-tube solar collector for medium-temperature applications. The LIGHTTOOL software was used for ray tracing to evaluate the optical performance at different incident angles. The results showed that the overall average optical efficiency could reach 76.9% between 0 and 60° incident angles perfect for medium temperature applications.

2.5. Summary of the studies available in the literature

Table 1 summarises the types of simulations, types of systems and models/methods used for the simulation studies of BIST, BI skin façade, BI PV, BI PVT and other BI solar systems.

Table 1. Summary of results/references for Building-Integrated (BI) solar systems.

Simulation type	System type	Methods/Models	References
Energetic simulation	BI solar thermal	Simplified model	Pflug et al. (2013)
		Steady-state model	Dowson et al. (2012)
		Detailed physical model	Welz et al. (2013)
	BI Skin façade	Mass balance network method and CFD	Hensen et al. (2002)
		Fluent software, finite difference method	Patania et al. (2010)
	BI solar chimney	ANSYS Fluent, CFD, ESP-r	DeBlois et al. (2013)
	BI Trombe wall	1D finite difference simulation model	Zalewski et al. (2002)
	BI PVT	Mathematical model, energy balance	Matuska (2012)
Model for electrical output/hot water production and TRNSYS		Davidsson et al. (2009)	
TRNSYS Artificial Neural Network (ANN)		Delisle and Kummert (2014) Ghani et al., 2012	
BI PV	TRNSYS	Mondol et al. (2005)	
	Simulation program SOLCEL	Yoo (2011)	
	Single lumped parameter model	Stamenic et al. (2004)	
	Autoregressive Integrated Moving Average (ARIMA) models and ANN	Fara et al. (2013)	
	Finite volume, SIMPLER algorithm	Muresan et al. (2006)	
	ESP-r	Yoon et al. (2011)	
	Solar irradiation → PV performance Electricity produced by BI PVs → incorporates a model for shading losses	Dwi Atmajaa (2013) Masa-Bote and Caamaño-Martín (2014)	
BI CPV	ANN	Fernández et al. (2014)	
Thermal simulation	BI solar thermal	Finite difference, MATLAB	Motte et al. (2013a)
		1D, steady-state thermal model	Anderson et al. (2010)
		Detailed physical model	Maurer et al. (2012)
	BI skin façades	Simulation algorithm for temperature behaviour/flow characteristics of double façades	von Grabe, 2002
		Lumped simulation model	Park et al. (2004)
		Non-dimensional analysis	Balocco and Colombari (2006)
		CFD, Fluent	Coussirat et al. (2008)
		Fluent, finite volume	Pérez-Grande et al. (2005)
		CFD	Guardo et al. (2009)
		CFD, Fluent, finite volume, SIMPLE algorithm	Nassim Safer et al. (2005)
CFD	Pasut and De Carli (2012)		
CFD	Jiru and Haghghat (2008)		
Simulink™	Stec et al. (2005)		
Finite element, COMSOL Multiphysics	Guillén et al. (2014)		
BI pipes	MATLAB	Albanese et al. (2012)	
	Finite element, ABACUS	Hassan and Beliveau (2007)	
	Genetic Algorithm	Zhu et al. (2014)	
BI solar chimney	Analytical and physical model	Ong (2003)	
BI Trombe wall	Finite difference	Jubran et al. (1991)	

		Control volume CFD code, Ansys CFX	Ben Yedder et al. (1990) Koyunbabaa et al. (2013)
	BI PVT	1D steady state thermal model Simulation program HYBRIDPV-1.0 (in FORTRAN) Numerical model by modifying Hottel– Whillier model Simplified 3D, control volume, explicit finite difference thermal model MATLAB/SIMULINK® with SIMSCAPE® library CFD CFD	Anderson et al. (2009) Ji et al. (2003) Ji et al. (2006) Chen et al. (2010) Aelenei and Pereira (2013) Ghani et al. (2012) Liao et al. (2005)
	BI PV	PV heat gain model 1D, finite-difference thermal model Fluent, CFD First order stochastic state space models	Fung and Yang (2008) Charron and Athienitis (2006) Gan (2009) Friling et al. (2009)
	BA several systems	Fluent, CFD Frequency response and lumped- parameter finite difference Numerical, steady-state heat transfer model Mathematical analysis Commercial CFD code FLOVENT, finite volume detailed physical models	Sanjuan et al. (2011) Chen et al. (2013) Palmero-Marrero and Oliveira (2006) Wang et al. (2012) Manz (2003) Oliva et al. (1991), Plantier et al. (2003), Cadafalch (2009) and Molero Villar et al. (2009)
Energetic/Thermal simulation	BI, Solar thermal	MATLAB, finite difference	Notton et al. (2013)
	BI, Skin façades BI PVT	Numerical, 1D-discretizations Numerical, control volume Computations by Engineering Equation Solver (EES) 1D, transient model, MATLAB CFD Finite element Dynamic models CFD CFD Numerical model, finite difference control volume approach MATLAB	Faggembauu et al. (2003) Yang and Athienitis (2014) Buker et al. (2014) Agrawal and Tiwari (2010) Corbin and Zhai (2010) Yin et al. (2013) Chow et al. (2009) Liao et al. (2007) Li et al. (2014) Chow et al. (2008) Shan et al. (2014)
	BI PV	Mathematical modelling Direct numerical approach	Kane and Verma (2013) Mei et al. (2002)
	BI several systems	Finite difference SIMPLEC algorithm Simulation model based on “direct absorption collection” concept	Darkwa and O’Callaghan (2006) Xamán et al. (2014) Luo et al. (2014)
	Optical simulation	BI several systems	Model based on the net radiation method “Four-flux model” Light transport modelling OptiCAD 3D, CFD 3D, ray-tracing simulations Optical model RADIANCE

3. CONCLUSIONS

An extensive literature review focusing on modelling of BIST systems has been conducted. In addition PV and PVT systems are also considered in the review. The review includes systems which produce thermal, electrical (PV) or both electrical/thermal (PVT) energy.

In the field of energetic simulations about BI solar systems, most of the investigations regard BIPV while there are few studies about BI configurations of solar thermal, skin façade, solar chimneys, Trombe wall, PVT and CPV. Thus, it can be seen that there is a need for energetic simulations of BIST configurations, especially of active solar thermal systems which could provide hot air and/or water for building energy needs. Also it would be interesting the development of models about BI CPVT (Concentrating PVT) or BI CT (Concentrating Thermal) systems provided that low-cost and simple configurations will be selected. Taking into account the conclusions of the 1st part of the present review study (ref...), it can be seen that most of the energetic simulations give emphasis to the system itself; thereby, there is a need for more studies which give emphasis to the building.

In the area of thermal simulations of BI solar systems, most of the works are about BI skin façades and BI PVT while there are few studies about BI configurations of solar thermal collector, solar chimney, Trombe wall and pipes (integrated into the building). Thus, there is a need for more thermal simulations about BIST e.g. about BI solar thermal collectors since there are very few studies in this type of installations. As it was previously mentioned, the development of models about BI CPVT or BI CT systems could also be examined as well as systems which include heat storage solutions or shading devices. Also in the field of thermal simulations (and based on the results of the 1st part of the present work: ref...) the greatest part of the investigations gives emphasis to the system and consequently, there is need for more studies which give emphasis to the building.

Moreover, there are some studies which combine energetic and thermal simulation. In that field, there is also the same tendency: the greatest part of the works is about BI PVT (some of these systems include transpired collectors) while there are only few studies about BIST configurations (solar collector, skin façade, etc). Consequently, in a future prospect, energetic/thermal modelling studies about BIST (for example about active systems for hot water or hot air production, with/without concentration, with/without PCM, new concepts with nanofluids, etc) could provide useful information. In the same way with the two previous categories (and based on the observations of the 1st part of the present investigation: ref...), there is a need for studies which give emphasis on the building.

Concerning optical simulations, there is a small number of studies. These studies regard multiple configurations such as thin-film luminescent solar concentrators, non-imaging static concentrators, etc. Thus, it can be seen that there is a gap in the literature in the field of optical models and further developments are needed since optical simulations could provide useful information for the behaviour of the BIST systems.

In terms of the adopted methods/models, it can be seen that the most commonly used tool is CFD while the most commonly adopted methods are those of finite volume and finite difference.

Conclusively, the results of the present study, in combination with the findings of the 1st part of that investigation, could provide useful information about modelling of “future” BIST systems.

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