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NOVEL, PRACTICAL AND RELIABLE ANALYTICAL MODELS TO ESTIMATE ELECTRICAL EFFICIENCY OF BUILDING-INTEGRATED PHOTOVOLTAIC/THERMAL (BIPVT) COLLECTORS AND SYSTEMS

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Abstract: Building-integrated photovoltaic/thermal (BIPVT) collectors are multifunctional products that replace conventional building materials in parts of the building envelopes, such as the facades and roofs. BIPVT collectors serve as novel building envelope material that can generate thermal and electrical energy simultaneously to be utilised in buildings. Despite the remarkable potential of BIPVT collectors and systems in mitigating energy consumed in building sector, until recently, they have received only limited attention since there has been no comprehensive attempt to date to optimise BIPVT collectors in terms of design, operation and climate oriented performance parameters. Electrical efficiency is a key performance parameter for BIPVT collectors. In this respect, easy, fast and reliable determination of electrical efficiency of BIPVT collectors is of vital importance for preliminary performance assessment of this technology under various design, operational and environmental conditions. Therefore in this research, novel, practical and reliable analytical expressions are developed to estimate electrical efficiency of air type BIPVT collectors as a function of design and climatic parameters. The most common configuration of BIPVT collectors (glass to glass BIPVT collector) is considered within the scope of this study, and analytical expressions are developed for this design. The accuracy of the analytical expressions is verified through previous experimental works in literature conducted under different climatic conditions. The results indicate that the electrical efficiency of glass to glass BIPVT collector is in good accordance with previous literature.

Keywords: BIPVT collectors, electrical efficiency, analytical model, solar intensity, ambient temperature

Bina Entegreli Fotovoltaik Termal (BIPVT) Kollektör ve Sistemlerin Elektriksel Verimlerinin Tahmini İçin Yeni, Pratik ve Güvenilir Analitik Modeller

Öz: Bina entegreli fotovoltaik termal (BIPVT) kollektörler, cephe ve çatılar gibi bina kabuğunun farklı yerlerinde konvansiyonel bina elemanlarıyla yer değiştirilebilen çok fonksiyonlu ürünlerdir. BIPVT kollektörler binalarda kullanılmak üzere eş zamanlı olarak termal ve elektriksel enerji üretebilen yenilikçi bina kabuk elemanı olarak kullanılırlar. BIPVT kollektörler ve sistemlerin bina sektöründe kullanılan enerjinin azaltılmasındaki kayda değer potansiyeline rağmen, BIPVT kollektörlerin tasarım, işletme ve iklim odaklı performans parametreleri açısından optimize edilmesine yönelik günümüze dek kapsamlı bir teşebbüs olmadığından ötürü, bu sistemler yakın geçmişe kadar sınırlı ölçüde dikkat çekmiştir. Elektriksel verim BIPVT kollektörler için anahtar bir performans parametresidir. Bu bağlamda, farklı tasarım, işletme ve çevresel koşullar altında bu sistemlerin öncül performans değerlendirmesinin yapılmasında BIPVT kollektörlerin elektriksel veriminin kolay, hızlı ve güvenilir bir şekilde belirlenmesi son derece önemlidir. Bu yüzden bu araştırmada, tasarım ve iklimsel parametrelerin bir fonksiyonu olarak BIPVT kollektörlerin elektriksel veriminin tahmini için yenilikçi, pratik ve güvenilir analitik ifadeler geliştirilmektedir. Bu çalışma kapsamında en yaygın BIPVT konfigürasyonu (camdan cama BIPVT kollektör) göz önüne alınmakta ve bu dizayn için analitik ifadeler geliştirilmektedir. Analitik ifadelerin

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doğruluğu daha önceki literatürde farklı iklimsel koşullar altında gerçekleştirilen deneysel çalışmalar ile doğrulanmaktadır. Sonuçlar, camdan cama BIPVT kollektörlerin elektriksel veriminin önceki literatürle iyi bir uyum içerisinde olduğunu göstermektedir.

Anahtar kelimeler: BIPVT kollektörler, elektriksel verim, analitik model, ışınım akısı

1. INTRODUCTION

Buildings play an important role in greenhouse gas emissions since they constitute a large proportion of the global energy demand (Cuce, 2017). This dramatic scenario is usually a consequence of poor thermal insulation characteristics of building fabric (Cuce et al., 2016a). About 40% of global energy use in 2014 is attributed to buildings. It is also stated that building-related carbon emissions are more than 30% of total emissions in most developed countries. There is a strong stimulation into renewable energy technologies to mitigate energy consumption and carbon emission levels of buildings as a consequence of the latest building codes toward low/zero carbon buildings (Cuce, 2016a), however these attempts get only limited attention in developing countries since the retrofitting costs are still high and social awareness is not enough for such drastic changes from conventional to novel technologies (Cuce et al., 2016b). Additional measures such as utilising waste heat recovery systems (Cuce et al., 2016c., Cuce and Riffat, 2015a), developing novel building envelope materials for energy-efficient and eco-friendly retrofitting of existing buildings (Cuce and Cuce, 2016a., Cuce and Cuce, 2016b., Cuce, 2017., Cuce et al., 2015a., Cuce and Riffat, 2015b., Cuce et al., 2015b., Cuce and Riffat, 2015c), enhancing the current performance figures of heating, ventilation and air-conditioning (HVAC) systems (Cuce and Riffat, 2016), are also in progress for urgent and decisive mitigation of building-oriented energy consumptions. However, according to the latest reports of International Energy Agency, buildings are still responsible for a significant proportion of total world energy use.

Solar energy applications are of prime interest to mitigate energy consumption of buildings and to reduce building-related carbon emissions, and building-integrated photovoltaic/thermal (BIPVT) collectors are of significant relevance. BIPVT collectors have dual functionality which replace conventional building elements in parts of the building envelopes and generate energy. Owing to their multifunctional benefits, BIPVT collectors are considered as novel building envelope materials which can generate thermal and electrical energy in a single unit to be utilised in buildings (ElSayed 2016). BIPVT collectors and systems have a significant potential in reducing building-oriented energy consumptions and carbon emissions (Norton et al., 2011). However, they have received only limited attention until recently since there has been no comprehensive attempt so far to optimise BIPVT collectors in terms of design, operation and climate related performance parameters (Agrawal and Tiwari, 2010). Electrical efficiency is a key performance parameter for BIPVT collectors. In this respect, easy, fast, reliable and realistic estimation of electrical efficiency of BIPVT collectors is of vital significance for preliminary performance evaluation of this technology as a function of design, operational and environmental parameters (Dubey et al., 2009).

The starting point of BIPVT collectors is to develop a multifunctional unit for buildings which is capable of generating electricity and thermal energy simultaneously (Kim and Kim, 2016). Despite the dual functionality, the main priority in the applications of BIPVT collectors is the efficient production of electricity. In this respect, it is primarily required to operate BIPVT collectors at low photovoltaic (PV) cell temperature (Cuce et al., 2013). The intensive attempts in literature to improve overall performance parameters of BIPVT collectors are seen in late 1990s. However, the first efforts on the scope go back to late 1970s (Kern and Russel, 1978., Hendrie, 1979., Florschuetz, 1979). Waste heat recovery in BIPVT collectors is mostly carried out by either air or water and pioneer works are based on theoretical and numerical modelling of different designs of air and water type BIPVT collectors 1970s (Kern and Russel, 1978., Hendrie, 1979., Florschuetz, 1979., Raghuraman, 1981). Lalovic (1981) develops a hybrid amorphous silicon photovoltaic/thermal (PVT) collector for potential utilisation in buildings. Garg and Adhikari (1997) present a steady-state simulation model to investigate the impacts of various design and operational parameters on the performance of an air type PVT collector. Hegazy (2000) numerically examines four different designs of air type PVT collectors, and evaluates the effects of air flow rate and the selectivity of the absorber plate and PV cells on the thermal and electrical performance of each configuration. A similar attempt is done by Sopian et al., (2000). They examine the performance of a double pass PVT collector, and they determine the temperature rise to be 18 ^{o}C at a mass flow rate of 0.036 kg/s and global solar radiation level of 800 W/m^2. Kalogirou (2001) develops a numerical and simulation model to estimate the performance parameters of a water type PVT collector for the climatic conditions of Cyprus. He observes that the hybrid system increases the average annual efficiency of the PV module from 2.8 to 7.7% with a thermal efficiency of 49%. As it is well-documented in literature, electrical efficiency of a BIPVT collector can be enhanced by increasing the packing factor (PC), and reducing PV cell temperature through waste heat recovery (Zondag et al., 2003., Chow, 2003., Cuce and Cuce, 2014a). PF is known as the ratio of total area of PV cells to the entire area of PVT collector (Riffat and Cuce, 2011). There are several attempts of passive and active cooling methods to reduce PV cell temperature for greater electrical efficiency of BIPVT collectors (Cuce et al., 2011., Cuce and Bali, 2010). Electrical efficiency of BIPVT collectors can also be improved via solar tracking systems. Al-Mohamad (2004) shows that the tracking system can provide more than 20% enhancement compared to fixed collector. Zhou et al., (2007) develop a novel model based on current-voltage characteristics to estimate the PV module performance. Their results indicate that the electrical efficiency of a PV module mainly depends on solar intensity level and PV cell temperature.

Tiwari et al., (2006) theoretically and experimentally investigate the performance of an air type PVT collector for different climatic conditions of India. They notify that the overall thermal efficiency of a PVT collector can notably be enhanced through waste heat recovery from the back side of PV module. A similar attempt is done by Tripanagnostopoulos (2007). He presents a new type of PV/T collector with dual heat extraction operation in which air or water is utilised for waste heat recovery. He et al., (2006) investigate a similar PVT collector designed for natural circulation of water. They observe that the daily thermal efficiency can reach about 40% when the initial water temperature inside the system is the same as the daily mean ambient temperature.

The approach for the analytical assessment of the reliability of PV systems is presented by Hamdy et al., (1989). The technique is based on the logic of the fault-tree technique. The reliabilities of the different components of a PV system are used to estimate the reliability of the overall system. Zondag (2008) proposes a detailed review of PVT collectors and systems. The review covers both qualitative and quantitative performance assessment of various designs of PVT collectors. Tiwari and Sodha (2006) develop a thermal model for a water type PVT collector. Numerical computations are carried out for climatic data and design parameters. The simulations estimate a daily thermal efficiency of about 58%, which is in good accordance with previous works. Tiwari and Sodha (2007) present a parametric study to predict the overall performance of an air type PVT collector for different design options. Analytical expressions for the PV cell temperature, back surface of the PV module, outlet air and the rate of waste heat recovery from hybrid PVT air collector are derived.

Ruparathna et al., (2016) present a review on the potential methods of improving energy efficiency of existing buildings. They emphasize that BIPVT collectors and systems provide desirable features for urban buildings such as generating electricity and hot water, which is also promising for energy-efficient retrofits. Ibrahim et al., (2014) report that building energy efficiency can be enhanced from 73 to 81% by utilising BIPVT collectors. Parida et al., (2011) present a comprehensive review on PV technology covering BIPVT collectors and systems, its power generation feature, available light absorbing materials, environmental aspects and applications. Numerical models for performance and reliability evaluation, sizing and control, grid connection and distribution are also evaluated. Tripathy et al., (2016) evaluate BIPVT collectors with real time applications. Recent developments in building envelope products and their properties along with international standards and test conditions are discussed. Commercial BIPVT products for roofs, facades and skylights are given in detail. A similar extensive review on BIPVT collectors and systems is conducted by Yang and Athienitis (2016). Latest developments of various BIPVT systems, experimental and numerical works, and the influence of BIPVT systems on building performance are investigated through a systematic approach. Chow (2010) presents governing equations for thermodynamic performance assessment of PVT collectors and systems including energy and exergy efficiency. Analysis of thermal and electrical performance of semi-transparent PVT collectors is done by Park et al., (2010). The effects of the PV module's thermal characteristics on its electricity generation performance are evaluated through an experimental research. The results reveal that the output power decreases about 0.52% per the 1 ^{o}C increase of the PV cell temperature for the solar intensity of 500 W/m^2. Chemisana (2011) evaluates the advantages of building-integrated concentrating collectors (BICPV) with Fresnel lens applications. In another work, Chemisana et al., (2009) compare the performance of various Fresnel lens concentrators for BIPVT collectors. Gan (2009) examines the impact of air gap on the performance of BIPV collectors. He notifies that a minimum air gap of 0.12–0.15 m for multiple module installation and 0.14–0.16 m for single module installation is required depending on roof pitches in order to reduce possible overheating of PV modules and hot spots near the top of modules. Vats and Tiwari (2012) conduct an energy and exergy analysis for a BIPVT collector. Cucchiella and D'Adamo (2012) develop estimation strategies of performance and environmental aspects of roof mounted BIPVT collectors. Skoplaki and Palyvos (2009) present a comprehensive review on the temperature dependence of electrical performance of PV systems. Efficiency and power output correlations are illustrated as a function of PV cell temperature.

BIPVT collectors and systems are considered as the promising building envelope materials for the buildings of future (Baljit et al., 2016). However, commercialisation is still a challenge for this technology due to lack of social awareness at global scale. To be able to facilitate and speed up the commercialisation process of BIPVT collectors, theoretical and numerical models are of vital importance to justify the feasibility, practicality and reliability of this technology under different design, operational and climatic conditions. Electrical efficiency is a key performance parameter for BIPVT collectors in feasibility studies. Therefore, easy, fast and reliable estimation of electrical efficiency of BIPVT collectors is significant for preliminary performance evaluation of this technology under various design, operational and environmental conditions. Within the scope of this research; novel, practical and reliable analytical expressions are developed to predict electrical efficiency of BIPVT collectors in terms of design and climatic parameters. The most common configuration of BIPVT collectors (glass to glass BIPVT collector) is analysed in this work, and analytical expressions are derived for each case.

2. MATHEMATICAL MODEL

This paper aims at developing, novel, practical and reliable analytical expressions to estimate electrical efficiency of BIPVT collectors as a function of design and climatic parameters. The most common configuration of BIPVT collectors shown in Figure 1 (glass to glass BIPVT collector) is investigated within the scope of this research, and analytical expressions of electrical efficiency are proposed for each design. Before presenting the governing equations for each configuration, it would be useful to give information about the assumptions made in the research. One dimensional heat transfer is assumed to be a good approximation for the study. The glass cover is considered to be at uniform temperature. The system is in quasi-steady state. The ohmic losses in PV cells are assumed to be insignificant. The governing equations for the energy transport in BIPVT collectors are analysed for glass to glass BIPVT collector.

2.1. Glass to Glass BIPVT Collector

In this section, first law of thermodynamics will be applied to different parts of the glass to glass BIPVT collector in which energy transport occurs. In other words, energy balance equations will be written for PV modules, absorber plate and working fluid in order to develop an analytical expression of electrical efficiency for glass to glass BIPVT collectors.

The energy balance equation for PV modules of BIPVT collector can be written as follows:

$$\begin{aligned} G\alpha_{pv}\tau_g\zeta_{col}wdL &= \left[U_{pv,a}\left(T_{pv}-T_a\right)+U_{pv,s}\left(T_{pv}-T_s\right)+U_{pv,f}\left(T_{pv}-T_f\right)\right. \\ &\quad \left. +\,\eta G\alpha_{pv}\tau_g\zeta_{col}\right]wdL \end{aligned} \tag{1}$$

In other words, the amount of solar energy available on PV modules equals to sum of energy losses from PV modules to ambient and surrounding through convection and radiation, respectively; energy transport from PV modules to working air, and the amount of electrical energy produced by PV modules. The cell temperature of PV modules can be extracted from equation (1) as

$$T_{pv}=\frac{G\alpha_{pv}\tau_g\zeta_{col}(1-\eta)+U_{pv,a}T_a+U_{pv,s}T_s+U_{pv,f}T_f}{U_{pv,a}+U_{pv,s}+U_{pv,f}} \tag{2}$$

Electrical efficiency of a PV module as a function of cell temperature can be given by

$$\eta=\eta_{ref}\left[1-\delta_{ref}\left(T_{pv}-T_a\right)\right]\frac{G}{G_{ref}} \tag{3}$$

The energy balance equation for the absorber plate of BIPVT collector can be given by the following equation, which basically proves that the amount of solar energy available on absorber plate equals to sum of energy transport from absorber plate to working fluid, and the amount of heat loss from absorber plate to ambient:

$$G\alpha_{ap}\tau_g^2(1-\zeta_{col})wdL=\left[U_{ap,f}\left(T_{ap}-T_f\right)+U_{ap,a}\left(T_{ap}-T_a\right)\right]wdL \tag{4}$$

The absorber plate temperature of BIPVT collector can be extracted from equation (4) as follows:

$$T_{ap}=\frac{G\alpha_{ap}\tau_g^2(1-\zeta_{col})+U_{ap,f}T_f+U_{ap,a}T_a}{U_{ap,f}+U_{ap,a}} \tag{5}$$

The energy balance equation for the flowing air inside the BIPVT collector can be given by

$$\dot{m}_a c_a\frac{dT_f}{dL}dL=\left[U_{ap,f}\left(T_{ap}-T_f\right)+U_{pv,f}\left(T_{pv}-T_f\right)\right]wdL \tag{6}$$

Equation (6) can be explained as the thermal energy content of flowing air equals to the sum of heat transfer rates from absorber plate and PV module to working fluid. The two initial conditions which are required to solve this differential equation can be defined as follows:

$$T_f\big|_{L=0}=T_{f,i} \tag{7}$$

$$T_f\Big|_{L=\psi} = T_{f,o} \tag{8}$$

Under the said initial conditions, the analytical solution of equation (6) can be obtained by

$$T_{f,o} = \left[T_a + \frac{\frac{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{pv,a}}\right]^{-1}+\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}\alpha_{pv}\tau_g\zeta_{col}(1-\eta)+\frac{U_{ap,f}}{U_{ap,a}+U_{ap,f}}\alpha_{ap}\tau_g^2(1-\zeta_{col})}{\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}}\frac{G}{G_{ref}}\right]\left[1 - exp\left(-\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}\right)\right] + T_{f,i}exp\left(-\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}\right) \tag{9}$$

The average temperature of flowing air inside the BIPVT collector can be calculated by

$$\bar{T}_f = \frac{1}{\psi}\int_0^{\psi} T_f\, dL \tag{10}$$

Through equation (9), $\bar{T}_f$ is found to be

$$\bar{T}_f = \left[T_a + \frac{\frac{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{pv,a}}\right]^{-1}+\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}\alpha_{pv}\tau_g\zeta_{col}(1-\eta)+\frac{U_{ap,f}}{U_{ap,a}+U_{ap,f}}\alpha_{ap}\tau_g^2(1-\zeta_{col})}{\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}}\frac{G}{G_{ref}}\right]\left[1 - \frac{1-exp\left(-\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}\right)}{\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}}\right] + T_{f,i}\frac{1-exp\left(-\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}\right)}{\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}} \tag{11}$$

If $T_{f,o}$ is assumed to be T_a and $\bar{T}_f$ equals to T_f, analytical electrical efficiency of BIPVT collector for fixed tilt angle yields to

$$\eta = \frac{\eta_{ref}\left[1-\frac{\tau_g\delta_{ref}}{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{pv,a}}\right]^{-1}+\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}\left[\alpha_{pv}\zeta_{col}+\frac{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}{\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}\left(\frac{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{pv,a}}\right]^{-1}+\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}\alpha_{pv}\zeta_{col}+\frac{U_{ap,f}}{U_{ap,a}+U_{ap,f}}\alpha_{ap}\tau_g(1-\zeta_{col})\right)\left(1-\frac{1-exp\left(-\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}\right)}{\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}}\right)G\right]\right]}{1-\left(\frac{\eta_{ref}\tau_g\delta_{ref}\alpha_{pv}\zeta_{col}G}{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{pv,a}}\right]^{-1}+\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}\right)\left(1+\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}\frac{\frac{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}{\left[\frac{\delta_g}{k_g}+\frac{1}{U_{pv,a}}\right]^{-1}+\left[\frac{\delta_g}{k_g}+\frac{1}{U_{ap,f}}\right]^{-1}}}{\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}\left(1-\frac{1-exp\left(-\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}\right)}{\frac{w\psi\left(\frac{U_{pv,f}U_{pv,a}}{U_{pv,f}+U_{pv,a}}+\frac{U_{ap,a}U_{ap,f}}{U_{ap,a}+U_{ap,f}}\right)}{\dot{m}_a c_a}}\right)\right)} \tag{12}$$

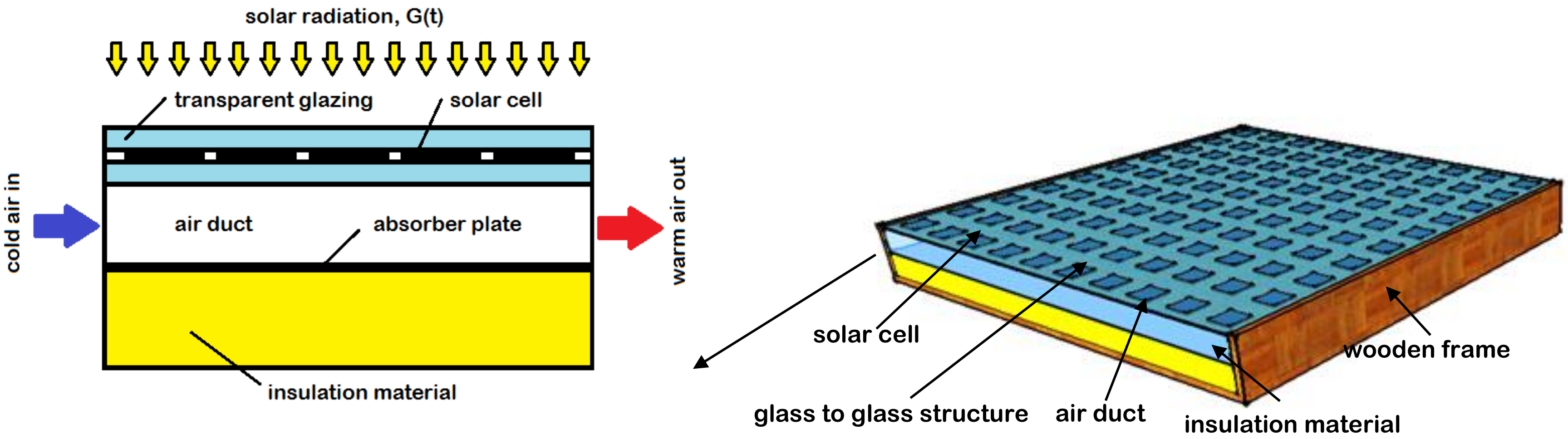

Figure 1.
Structural details of glass to glass building-integrated photovoltaic module.

2.2. Enhanced Electrical Efficiency Expression

Tilt angle is also an important parameter on the overall electrical and thermal performance of BIPVT collectors, therefore its value needs to be optimised. Cuce and Cuce (2014b) present a tilt angle optimisation research for BIPVT collectors as illustrated in Figure 2, and according to their verified results, optimum value of tilt angle (θ) is 15° which provides 2% enhancement in power output at standard test conditions (STCs). In addition, electrical efficiency is logarithmically dependent on solar intensity as previously reported by Cuce (2009).

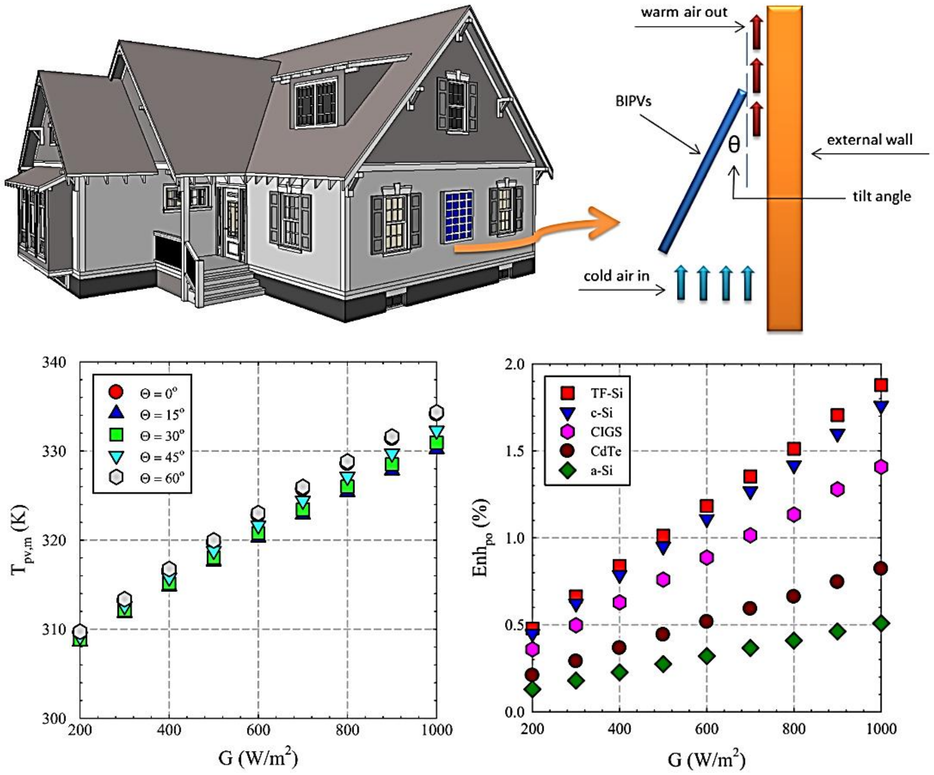

Figure 2.
Tilt angle optimisation of BIPVT collectors (Cuce and Cuce, 2014b)

Through the experimental data illustrated in Figure 3, improved expression of electrical efficiency for the optimum tilt angle can be given as follows:

$$\eta^{*} = 1.02 \times (-19.15 + 5.111 lnG) \tag{13}$$

It needs to be reported that the improved expression of electrical efficiency is meaningful for the solar intensity values between 200 and 1000 W/m^2.

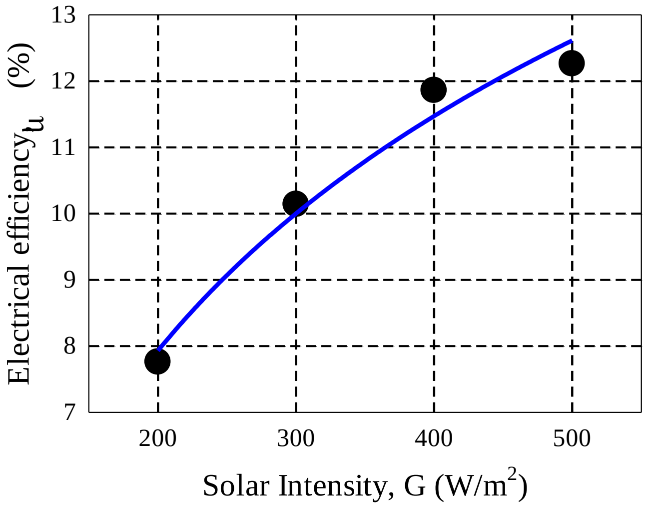

Figure 3.
Solar intensity dependency of electrical efficiency of BIPVT collectors (Cuce, 2009)

3. RESULTS AND DISCUSSION

For the accuracy verification of the theoretical electrical efficiency expression developed for BIPVT collectors, experimental data from a recent research conducted by Dubey et al., (2009) is utilised, which is shown in Figure 4. In addition, for the dimensional and operational parameters, which are required for the quantitative assessment, the same research is considered, and the relevant data is listed in Table 1. The results from the enhanced analytical electrical efficiency expression are illustrated in Figure 5. It can be easily concluded from the findings that there is a very good accordance between the analytical and estimated data. As it is previously reported in Table 1 that the estimated electrical efficiency is given to be 0.16 for STCs. Maximum value of solar intensity for the reference test day is given to be 838 W/m^2. For such a level of solar radiation, estimated electrical efficiency needs to be close to the STCs data, which is 16%. According to the analytical efficiency expression, this value is calculated to be 15.6% as shown in Figure 5, which is in good accordance with the estimated data. In this respect, it can be easily asserted that the developed analytical efficiency expression for glass to glass BIPVT collectors is a successful attempt, and thus it can be very useful for feasibility works on BIPVT systems by enabling a reliable and accurate electrical efficiency prediction.

After achieving the satisfactory accordance between theoretical and predicted electrical efficiency values, the model is utilised to evaluate the solar intensity dependency of electrical efficiency for BIPVT collectors and systems. In this respect, the solar intensity is varied from 200 to 1000 W/m^2 as shown in Figure 6, and the electrical efficiency values are determined. The results reveal that η takes value in the range of 7.93-16.15%. For 200, 400, 600, 800 and 1000 W/m^2 of incoming solar radiation, η is found to be 7.93, 11.47, 13.54, 15.01 and 16.15%, respectively. In other words, it is concluded that the electrical efficiency of a BIPVT collector logarithmically increases with the solar intensity level. It is also observed from the electrical efficiency equation developed within the scope of this research that η is independent of the ambient temperature. For the case of optimum tilt angle orientation, η values for the said solar intensity range is calculated to be 8.09, 11.70, 13.81, 15.31 and 16.47% respectively.

For readers' interest, it needs to be noted that thermal efficiency is also of vital importance for techno-economic evaluation of BIPVT collectors and systems. Although it is not in the scope of this research, a thermal analysis is carried out for the thermal efficiency of a BIPVT collector having the same constructional and operational parameters with the sample considered in this research. The results reveal that the thermal efficiency of BIPVT collector is found to be in the range of 42.5-56.3%. In this respect, total effectiveness of the BIPVT collector is determined to be in the range of 50.43-72.45% for the solar intensity range of 200-1000 W/m^2. The results are observed to be in good accordance with a recent research conducted by Ibrahim et al., (2014).

Through the literature survey, it is easy to say that there is an insignificant number of mathematical models developed for BIPVT collectors and systems. The models are usually produced for PV and PV/T systems which are using water or air as working fluid. In this respect, the model presented within the scope of this research can be considered as a source model for preliminary performance estimation of BIPVT collectors in terms of electrical efficiency.

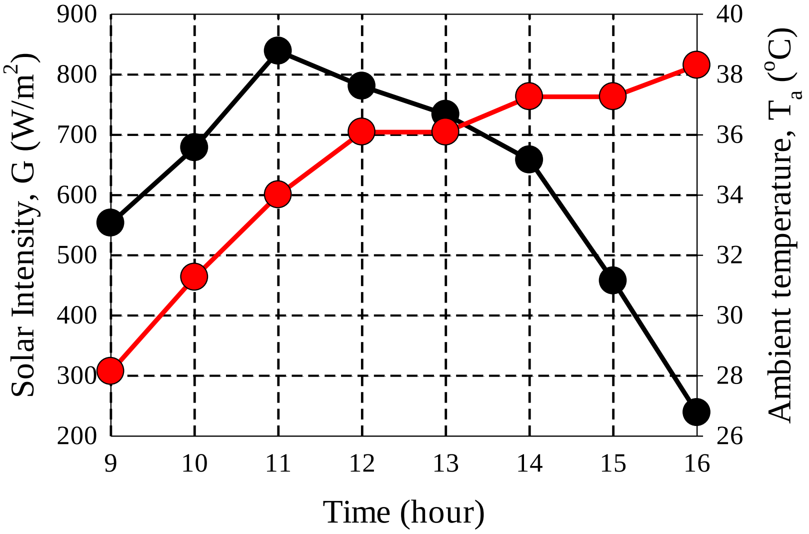

Figure 4.
Climatic data utilised for accuracy verification (Dubey et al., 2009)

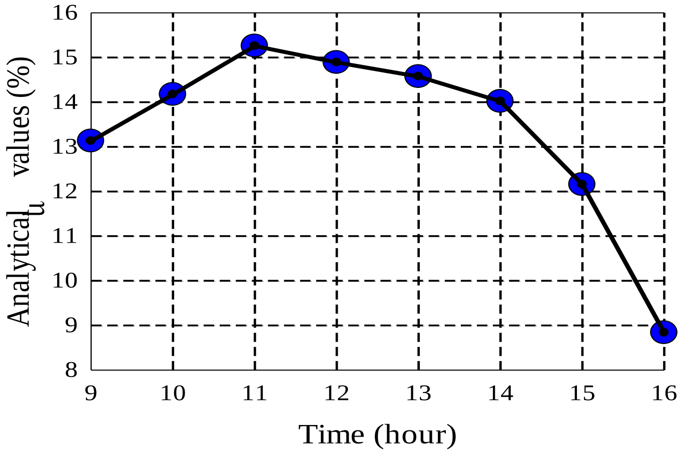

Figure 5.
Analytical electrical efficiency values for the reference test data.

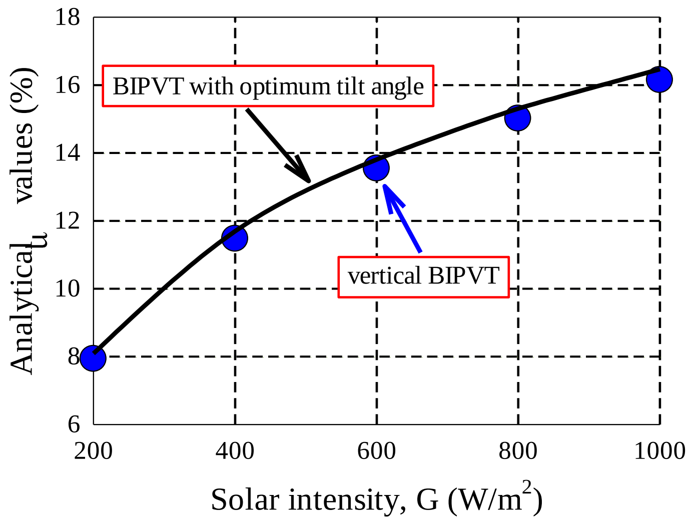

Figure 6.
Analytical electrical efficiency for different solar intensity values.

Table 1. Dimensional and operational parameters utilized in the accuracy verification

Parameter/Value
w: 0.605 m
L: 1.000 m
h: 7.60 W/m^2K
$\dot{m}_a$: 0.0058 kg/s
c_a: 1.005 kJ/kgK
$U_{pv,a}$: 7.44 W/m^2K
α_{pv}: 0.90
α_{ap}: 0.80
δ_{ref}: 0.0045
ζ_{col}: 0.83
η_{ref}: 0.16
τ_g: 0.95
δ_g: 0.003 m
k_g: 1.1 W/mK
$U_{pv,f}$: 8.59 W/m^2K
$U_{ap,a}$: 0.62 W/m^2K

4. CONCLUSIONS

Within the scope of this research, a novel enhanced electrical efficiency expression is developed for BIPVT collectors and systems. For a reference test data, the efficiency values are compared with those of estimated values, and a good accordance is achieved. The developed efficiency expression shows a good performance for glass to glass BIPVT collectors, so it can be easily utilised for the feasibility works in the scope. Following the accuracy justification of the model, electrical efficiency of BIPVT collectors is evaluated for vertical and optimum tilt angle orientations as a function of solar intensity level. The results reveal that electrical efficiency of BIPVT collector with vertical orientation is 16.15% for the standard test conditions whereas it is 16.47% for the optimum tilt angle orientation. Thermal efficiency of BIPVT collector is also considered in the research. For a solar intensity range of 200-1000 W/m^2, thermal efficiency range of BIPVT collector is determined to be 42.5-56.3%, which is in good accordance with the previous literature.

Nomenclature

G : Incident solar intensity (W/m^2)
G_{ref} : Solar intensity at reference condition(W/m^2)
L : Length of PV module (m)
η : Temperature dependent efficiency (dimensionless)
η_{ref} : Efficiency at reference point (dimensionless)
w : Width of PV module (m)
$\dot{m}$: Rate of flow air (kg/s)
U : Overall heat transfer coefficient (W/m^2°C)
T : Temperature (°C)
δ_{ref} : Temperature coefficient of PV cell
δ_g : Thickness of PV module (m)
k_g : Thermal conductivity (W/mK)

Subscription

g	glass
pv	PV solar cell
f	fluid
s	surface
col	collector
ap	absorber plate

Greek Symbols

α	absorptivity
ζ	packing factor
τ	transmissivity

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