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Assessment of energy production from photovoltaic modules integrated in typical shading devices

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ABSTRACT

This paper presents the results of three methods that measure energy produced by photovoltaic (PV) modules integrated in various external opaque shadings of typical office buildings in Greece.

These methods are related to the comparison of energy production results by three different models: a simple energy computer simulation model that uses the theoretical average PV efficiency of 12%, a more complete computer simulation model using detailed equations (using either theoretical or real PV Market products), and real PV installations.

The paper addresses the problem of designing efficient shading devices for buildings. Each examined method refers to a different design stage according to the level of information that is available to the designer. The results showed that the simple simulation and the more elaborated models have similar performance for most of the shading devices, apart from those with a complicated geometry. Moreover, the complete model that uses parameters of PV modules already available on the market can provide results of energy production even for complicated geometries. It is also concluded that the real PV installations produce results very close to the theoretical average PV efficiency of 12%.

1. Introduction

Installations of photovoltaic (PV) systems have significantly increased in the last decade in Greece (Tsoutsos, Karapanagiotis, Mavrogiannis, Tselepis, & Agoris, 2004). Additionally Greece ranks 5th worldwide with regard to per capita installed PV capacity (Hellenic Association of Photovoltaic Companies, 2013).

This paper focuses on shading systems with integrated PV, installed on office buildings' facades. PVs produce electricity only during the day. In order to reduce the energy demand of a building from the grid and maximize energy usage produced by the PV, high energy loads should be limited during day time. The working hours of office buildings is generally suitable for the function of the PVs, due to the fact that office buildings are mostly operational during daytime when energy production from the PVs is high. Additionally, shading systems with integrated PV can operate efficient during day time; because they reduce thermal gains during cooling period and at the same time they produce electricity for supporting the energy operational needs.

Over the last century the proportion of the office buildings' envelope that is transparent has increased significantly (Bizzarri, Gillott, & Belpoliti, 2011). Due to low thermal insulation property of glass in comparison to mass opaque building materials the larger the transparent fraction of the building's envelope the more important is the control of solar energy inflow, in order to keep thermal and visual conditions indoors in acceptable levels. Transparent facades need an additional control system, one that helps avoid solar radiation during the overheated period, allows enough thermal loads during the underheated period and ensures comfortable visual conditions during operating hours. Due to the fact that passive design is most of the times not totally efficient for the control of solar and thermal gains, additional active systems are used to balance the interior thermal and visual comfort conditions. As a result, today's buildings are dominated by technical systems for heating, cooling, ventilation and artificial lighting often resulting in high conventional energy consumption (Karkanias, Boemi, Papadopoulos, Tsoutsos, & Karagiannidis, 2010) and high CO_2 emissions (Meggers et al., 2012). PV shading devices can help limit the overall energy consumption in two ways: by reducing direct solar gains during the overheated period and by producing electricity to be utilized for the function of cooling, heating and lighting systems.

Integration of PVs in shading devices is an intermediate solution falling between the BIPV (Building Integrated Photovoltaic Panels) and BAPV (Building Attached Photovoltaic Panels) systems as were described by Peng, Huang, and Wu (2011). This integration of PVs

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has the advantages of the BIPV, is architecturally “clean” and attractive and offsets the cost of the shading material and the advantage of BAPV: in case they are damaged the buildings' internal function is not affected.

The main objective of this paper is concentrated in the evaluation of three well known available tools used to estimate the energy production of the PV panels integrated in shading systems. The tools available were divided into simple simulating tools, to more complete simulating tools and to measurements of real PV installations. Each tool demands special knowledge. Simple tools can be used by unspecialized designers, the complete models need special knowledge and real measurements require special instruments that are only available from specific laboratories and are involved more with research work and less with the design process. The accuracy of each design tool is determinant for the designer because is connected to the design stage that he is elaborating and the required structural detailing.

Three processes have been followed in order to reach the aforementioned objective:

- Comparison of the integrated PVs' energy production results calculated by simple simulation models with simulated results of real market products.
- Comparison of the energy production results of the simulation of real market products with measured energy production of real PVs installations.
- Investigation of the sensitivity of the simulation software used to measure the air flow near the PV panels and its affect on the electricity production.

2. State-of the art in BIPV systems

Various researchers tested PV systems integrated in Building (BIPV) in many applications. Especially the Integration of PV in shading devices has been researched in different latitudes and geometrical, architectural relations (Hwang, Kang, & Kim, 2012; Kang, Hwang, & Kim, 2012).

More specifically, PV modules applied as shading devices have been designed and used in many buildings all over the world. Since 1996, in Albany University PV modules have been used as sunshades providing 15 kW_p of energy simultaneously reducing cooling loads (Eiffert & Kiss, 2000). The combination of produced electricity with the improvements in the indoor quality conditions makes the use of BIPV on shading systems a very promising application of building technology (Bloem, 2008).

The energy efficiency of BIPV systems integrated in shading devices is a major research issue: upon it depends the promotion of their application in the building industry. More specifically, for Brazil, and since most shading devices are non vertical surfaces, Cronemberger, Caamano-Martın, and Vega Sanchez (2012) argued that “for non-vertical facades ($40° \leq \beta \leq 90°$S) the solar potential represents between 60% and 90% of the maximum global solar irradiation, even when facing south, indicating that the use of sloped building envelope surfaces, such as atriums and shading elements on facades and windows should be promoted”.

Various geometrical configurations of PV shading systems have been tested by researchers according to their efficiency and applicability possibilities. BIPV can be installed as external fixed venetian blinds facing south with an appropriate inclination, reducing maintenance costs due to the lack of user involvement with the system. Another solution is internal PV venetian blinds requiring less supporting structure (Reijenga, 2002). Due to the fact that external shading systems have proved to be more efficient in terms of lower thermal loads penetration in the interior (Olgyay & Olgyay, 1963), we focus on the energy production of external shading systems with integrated PV.

Different geometrical configurations of fixed external Shading systems with integrated PV facing south (canopy, canopy inclined, Brise soleil systems, surrounding shade) were examined according to their energy production and the resulting indoor visual and thermal comfort conditions. Systems of “surrounding shade” and of “canopy inclined single” proved to be the least energy consuming (Mandalaki, Zervas, Tsoutsos, & Vazakas, 2012).

Another important factor when assessing different geometrical configurations of PV shading systems is the simulation tool used or the measuring method of the real installation followed. Differences in the calculated values of energy production would emerge because of two reasons: due to different algorithmic equations used for estimating the energy production and due to differences in the reference conditions (Word Energy Council, 2013).

Relevant research of PV modules used in south facade is presented by Bloem (2008). Ninety-nine PV poly-crystalline Si modules are mounted in a horizontal spandrel enclosure on the south facade of an office building and are simulated with TRNSYS. This structure works as a window shading system with power 36 W in Standard test Conditions (STC). Natural ventilation was assumed in the module enclosure via vents in the upper and lower surfaces.

Due to the fact that the technical data provided by the PV industry is based on standardized measurements under laboratory conditions described in IEC 61215 (2005),when comparing laboratory data the same STC should be kept. These are described as Standard Reference Environment (SRE) and are the following: *Tilt angle*: At normal incidence to the direct solar beam at local solar noon, *total irradiance*: 800 W/m^2, *ambient temperature*: 20°C, *wind speed*: 1 m/s, *electrical load*: 0 A (open circuit, thus no current flowing), open rack mounted PV modules with optimized inclination. The conversion from STC to outdoor open rack conditions is studied and indicates an error of about 2% for p-Si PV-modules (Anderson, Bishop, & Dunlop, 2000).

Bloem (2008) also studies the influence of the increase of the air flow rate to the electricity production of the PV vertical window using the computational fluid dynamic software FLUENT. An increase in the electricity production is observed with the increase in the air flow. We will measure this increase in the production using a software package not using computational fluid dynamics called EnergyPlus.

The positive effect of PV shading systems to visual comfort in the interior of a building has been proven: Bloem, Colli, and Strachan (2005) presented an analysis based on simulation results using Esp-r software for three European areas: Greece (Athens), Spain (Barcelona), Italy (Milan) and they proved that apart from overheating, PV applied as shading devices can also reduce the effect of glare.

A basic parameter when examining different PV systems integrated in shading devices is the technology of PVs used. In order to make the shading devices more competitive in the market the glass content of the PV louvers was minimized. Weight reduction was achieved by substituting glass components of PV modules (at least in part) by flexible membranes (ZSW, 2007). The only disadvantage was that these types of flexible PV modules have a lower efficiency factor due to the type of material of the PV used. Amorphous silicon was used to substitute glass PV components, in order to make them flexible. Due to their disadvantage of low efficiency the progress in the market penetration of these types of systems is not the one anticipated, as can be seen for example in Korea, according to Hwang et al. (2012). None of the PV panels examined are made of amorphous silicon PV cell whose efficiency is much lower than monocrystalline and multicrystalline (Kang, Hwang, & Kim, 2012). In the presented research we examine one of the most efficient PV's technology: composed of glass and Si polycrystalline technology.

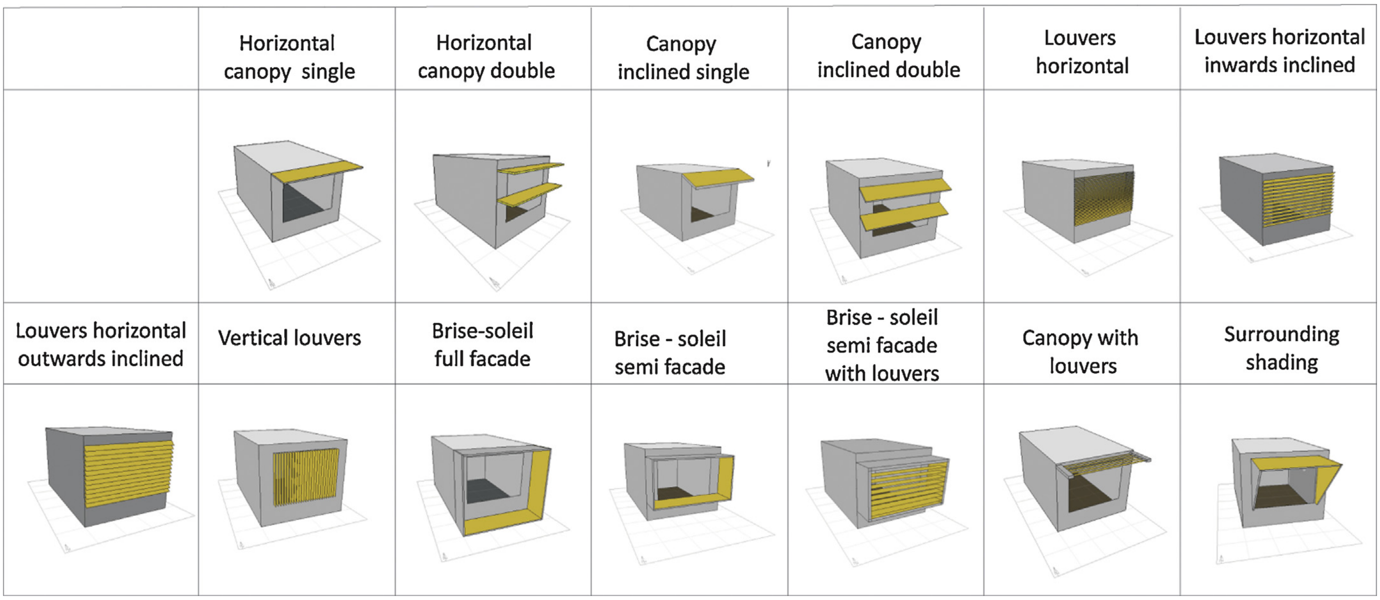

Fig. 1. Selected shading devices for PV integration (Mandalaki et al., 2012).

3. Methodology

The energy production of the aforementioned shading systems is simulated. The results were validated with measurements of energy production from actual, already installed PV panels.

The simulation of PV modules was accomplished using the software called EnergyPlus-32MP. The shading devices which were used for simulation have been published by Mandalaki et al. (2012) and can be seen in Fig. 1. Specific parts of the shading systems were used as PV surfaces. It is wise to mention at this point that the examined Shading Systems are part of malty story building and that are repeated in high and in length. This means that in Brise Soleil systems for example, PV panels that face downwards cannot be installed facing upwards, as one would expect. This is due to the fact that the Brise Soleil system of the next floor is installed on the outer side of the panel. Additionally the side panels of the same system face inwards and cannot face outwards because next to one Brise Soleil system the adjacent one is installed.

The geometry of the typical offices with the shading devices has been provided in 3D dxf format and each geometry was imported in Google Sketch Up 7 in order to work with the OpenStudio Plug-in. Moreover, models were developed using EnergyPlus software, one for each shading device. Thirteen models were developed in total to simulate the energy production from their corresponding shading devices.

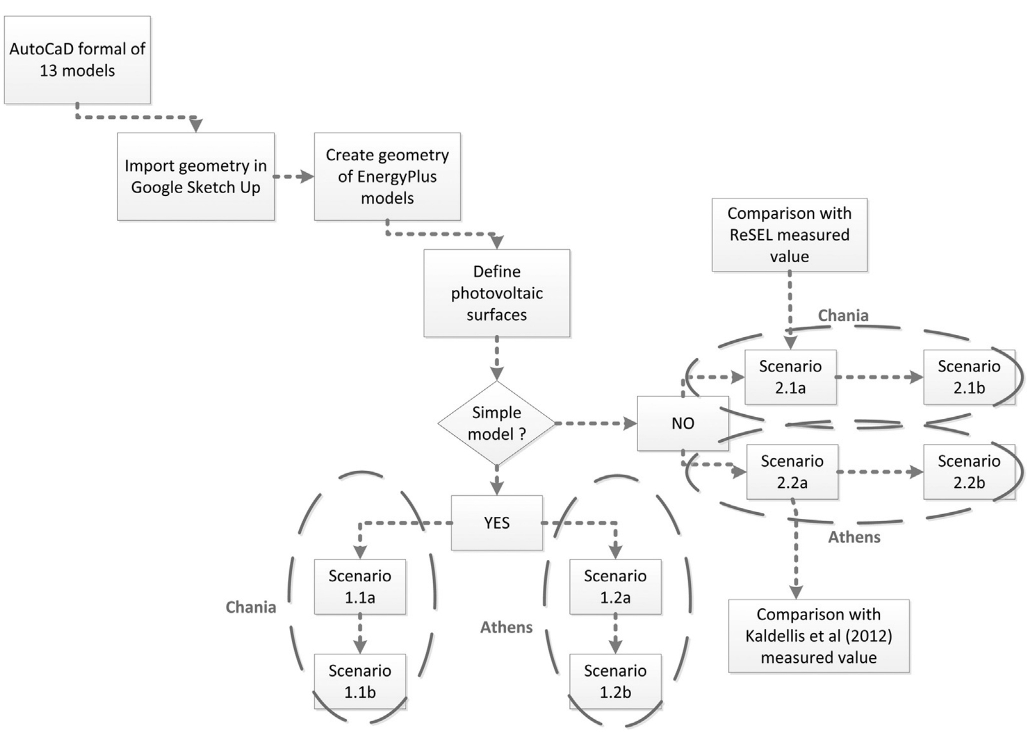

Fig. 2. Methodology followed.

The results from the aforementioned simulations were then compared with measured energy production of real PV installations in both examined latitudes. The measured results of PV's energy production were taken from Kaldellis, Kavadias, and Zafirakis (2012) for the case of Athens and from the ReSEL for the case of Chania. A difference close to 2% in the energy production results between PVs tested in STC and outdoor open rack conditions was estimated, according to Anderson et al. (2000). That divergence is mainly due to small deviations in the testing environmental conditions.

The methodology can be schematically seen in Fig. 2.

3.1. Simple PV model energy production methodology using a theoretical efficiency of 12%

In the first part of this section, a simple model is selected assuming a constant theoretical value of efficiency which is 12%. This is the usual average efficiency of the crystalline cells in Greece; although it is depending on various factors (cell specifications, the temperature and other climatic conditions, etc.) it is considered as a safe indicator to estimate the performance of crystalline PV cells.

The energy production of the PV is measured by two computer applications that use simple equations for calculating energy production: Ecotect v.5.6 and the simple model of EnergyPlus-32MP. A comparison related to the accuracy of each application is done. Even if both simple methods use a constant efficiency value to calculate the electrical output of the PV panels and do not take into account the partial shadowing effects, neither the wining and inverters losses nor the effect of temperature, their results are different (Gharakhani Siraki, 2010). We will see that these differences are mostly due to the difficulty of Ecotect to handle complicated geometrical applications.

The equation used to calculate the energy produced from the PV surface is (EnergyPlus, 2012):

$$P = A_{surf} \times f_{activ} \times G_T \times n_{cell} \times n_{invert} \quad (1)$$

where P is the electrical power produced by PV in W, A_{surf} is the net area of surface in m^2, f_{activ} is proportion of surface area with active solar cells, G_T is the total solar radiation incident on PV array in W/m^2, n_{cell} is the module conversion efficiency and n_{invert} is the direct current to alternative current conversion efficiency.

3.2. Sandia PV performance model methodology

A different, more accurate equation was used in the second part in order to simulate real PV modules available on the market. For this reason, PV models developed at Sandia National Lab, Albuquerque, New Mexico, have been created from real modules tested under various conditions. The Sandia method for the estimation of energy production of the photovoltaic modules has been used since 2004 when the methodology was published (King, Boyson, & Kratochvil, 2004). Although many more recent products can be found in the SAM (System Advisor Model) database, those selected can be fitted in the designed external shades. Moreover, the SAM database it-self is containing the methodology of the Sandia model (Blair, Mehos, Christensen, & Cameron, 2008; Cameron, Boyson, & Riley, 2008).

The adjustment of the equations in order to be used by EnergyPlus or TrNSys (Type 101) was done by Barker and Norton (2003). These equations used for the estimation of energy produced by each module are referred to the Engineering Reference of EnergyPlus software (2012): the model consists of a series of empirical relationships with coefficients that are derived from actual testing that are actually empirical coefficients (like empirical coefficient relating module temperature, empirical coefficients for polynomial function used to relate short-circuit current to the solar spectrum via air mass, empirical coefficients relating to 'Effective' solar irradiance and to Current at the maximum-power point (A), etc.). Once the coefficients for a particular module are available, it is straightforward matter to use the model equations for calculating the current–voltage curve. Additionally there are several climate and solar orientation inputs to the model including: incident solar beam, incident diffuse solar, incidence angle of beam solar, solar zenith Angle, outdoor dry bulb, wind speed, elevation, solar cells temperature.

The market PV modules were selected with an area similar to the area of each surface from the available modules stored in the Data-Set list of Energy Plus. In order to reduce overdependence of our results from just one product available on the market, three different products were selected and the average value of electrical power produced by the PV was calculated. The selected products used for the simulation are presented in Table 1.

3.3. Weather files used for simulation

Weather files are used in the simulation in order to provide Dry Bulb temperature, Humidity, Radiation, Wind Speed and Wind Direction, parameters necessary for thermal modeling. In order to have a proper comparison, between the analysis results on the energy production from PV simulated by EnergyPlus-32 MP and AutoDesk Ecotect v5.60, the weather files for both areas of Chania (35°31N, 24°01E) and Athens (37°59N, 23°43E) (Zervas, 2009) are similar to those used in the paper (Mandalaki et al., 2012). A summary of the weather data used for the simulation for the area of Chania is described in Table 2.

3.4. Description of scenarios

The simulations have been divided in 2 main scenarios and 2 main sub-scenarios as it can be seen in Table 3.

Table 1
Different photovoltaic products selected for the Shading Devices.

	Name of shading device	Different photovoltaic products available in market and selected for the simulation		
1	Horizontal canopy single	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
2	Horizontal canopy double	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
3	Canopy inclined single	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
4	Canopy inclined double	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
5	Louvers horizontal	Kyocera_KC40	Siemens_SM46	USSC_UniSolar_US-21
6	Louvers horizontal inwards incl.	First_Solar_FS-50	Photowatt_PWX750_70 W	Solarex_MSX-77
7	Louvers horizontal outwards incl.	First_Solar_FS-50	Photowatt_PWX750_70 W	Solarex_MSX-77
8	Vertical louvers	Kyocera_KC40	Siemens_SM46	USSC_UniSolar_US-21
9	Brise-Soleil full facade	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
10	Brise-Soleil semi facade	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
11	Brise-Soleil semi facade louvers	BP_Solar_BP2140S	Sanyo_HIP-HO97	Schott_SAPC_165
12	Canopy with louvers	AstroPower_AP-75	BP_Solar_BP270	Kyocera_KC80
13	Surrounding shadings	AstroPower_AP-120	BP_Solar_BP980	Sharp_NEH120E1

Table 2
Meteorological data from weather station Souda Airport [20].

Meteorological station: Chania, Crete, longitude/latitude: 24°02′/35°3′, station height: 62 m												
Month	Hours of sun (h)	Atmospheric pressure (mm Hg)	C^0			Relative humidity (%)	Av. cloudiness, 8	Rainfall (mm)	Wind direction	Total horizontal radiation	Diffuse hori. radiation	Wind speed (m/s)
			Av. air temperature	Abs. max temperature	Abs. min temperature							
1	111.7	1016.8	11.6	25.6	0.5	71.7	5.1	122.9	SW	62.1	33.1	3.2
2	128.9	1015.3	11.8	29.4	0	69.3	5	108.6	N	78.2	38.3	2.8
3	174.4	1015.1	13.2	34	0.4	68.4	4.4	71.9	SW	120.0	54.9	3
4	228.5	1013.3	16.3	35.8	5	65.4	3.5	31.9	NW	153.4	61.4	2.6
5	314.2	1014.1	20.1	38.6	8.5	62.2	2.8	13.9	NW	206.8	61.3	2.3
6	357.8	1013.3	24.5	40	13	55.8	1.3	6.6	NW	224.2	56.6	2.3
7	391.7	1012	26.5	42.5	16.6	55.3	0.6	0.5	NW	237.6	60.6	2.3
8	368.4	1012.4	26.1	41.2	12.5	57.7	0.6	2.7	NW	218.1	50.4	2.1
9	276.3	1015.3	23.3	39.6	10.5	63.9	1.6	18.2	N	163.2	43.8	2.1
10	183.8	1016.9	19.4	35.6	9.2	70.4	3.5	82.1	N	104.7	43.9	2
11	157.7	1018	16.1	35	2	72.2	4.2	70.9	N	75.1	32.7	2
12	115.4	1016.3	13.1	28.8	3.6	72.1	4.8	91.3	SW	57.4	29.7	2.6

Table 3
Presentation of the scenarios.

			1. Chania	2. Athens
1	Scenario 1: simple model	a	On the facade	On the facade
		b	Moved 0.05 m from the facade	Moved 0.05 m from the facade
2	Scenario 2: Sandia model – complete model	a	On the facade	On the facade
		b	Moved 0.05 m from the facade	Moved 0.05 m from the facade

Each scenario and sub-scenarios were analyzed as follows.

3.4.1. Scenario 1: simple model

In this scenario a simple equation was used for the calculation of energy produced from PV modules as in Eq. (1) using both Ecotect and EnergyPlus. This scenario is divided in further sub-scenarios.

In **Scenario 1.1a**, a weather file of Chania was used for all the simulations, while in **Scenario 1.1b**, the same weather file was used but typical shadings were moved 0.05 m from the south wall in order to test whether there is an increase of the efficiency of the PV modules. This hypothesis is based on the fact that the PV modules produce more energy when the wind is cooling them. In **Scenario 1.2a**, a weather file of Athens was used for the simulation process, while in **Scenario 1.2b**, the same weather file was used but typical shadings were moved 0.05 m from the south wall for the same reason as in **Scenario 1.1b**.

3.4.2. Scenario 2: Sandia model – complete model

In the second set of scenarios a more complicated set of equations was used to calculate the energy produced from the PV modules. The developed model was based on work done at Sandia National Lab, Albuquerque, NM by David King.

In **Scenario 2.1a**, a weather file of Chania was used for all the simulations, while for **Scenario 2.1b**, the same weather file was used but typical shadings are positioned 0.05 m from the south wall in order to test whether there is an increase of the efficiency of the PV modules. This hypothesis is based on the fact that the PV modules can produce more energy when the wind is cooling them. In **Scenario 2.2a**, a weather file of Athens is used for the simulation process, while for **Scenario 2.2b**, the same weather file was used but typical shadings were moved 0.05 m from the South wall for the same reason as in **Scenario 2.1b**.

4. Results and discussion

In the following chapter the data and results from previous paragraphs are analyzed. The analytical results of the aforementioned scenarios are not interesting for the reader. We will present the compared results that will contribute to the fulfillment of the main objectives of this paper.

4.1. Comparison between EnergyPlus and Autodesk Ecotect analysis simple model

As it can be seen in Fig. 3 the comparison between the two types of software indicates that the results for the area of Athens are different. The percentage of difference is increased for the louvers systems. In Fig. 4 the results for the area of Chania are presented. The percentage of difference in the results between the two types of software is much lower compared to the previous assessment. This means that the percentage accuracy in the simulated energy production is higher in areas with higher solar radiation as in the case of Chania (lower latitude), compared to areas with lower solar radiation such as Athens (higher latitude). For simple geometrical configurations of shading systems, the estimated difference is lower than 11% in the case of Chania and lower than 30% in the case of Athens. The percentage is defined by the following formula: $P = (E_a - E_b/E_a) \times 100\%$, where P is the percentage difference, E_a is the energy production of PV calculated with the model a, and E_b is the energy production of PV calculated with model b.

The percentage of difference increases for louvers, which are complicated shading devices. This is due to the fact that the EnergyPlus cannot simulate more than 30 PV panels connected in series and that the Ecotect cannot simulate overshadows between the PV louvers. When using EnergyPlus for complicated geometries of shading systems, like horizontal louvers, the large number of warnings and errors prevented the software from working properly and arriving at a rational result. EnergyPlus warns the user for possible calculation errors due to unaccounted shadow parameters which cannot be properly estimated by the software. This disability of the EnergyPlus could be overcome by designing the louvers system with less than 30 modules. Other louver systems that were examined (that have less than 30 PV panels connected in series) were simulated by EnergyPlus properly. Still though the percentage

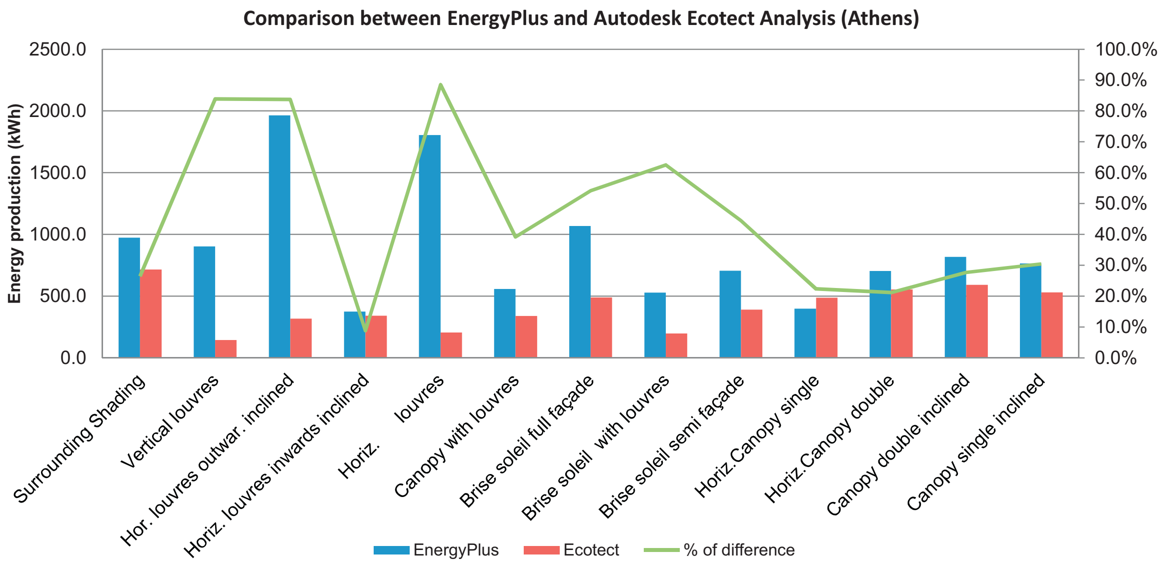

Fig. 3. Comparison of the results between Autodesk Ecotect Analysis and EnergyPlus for the Area of Athens.

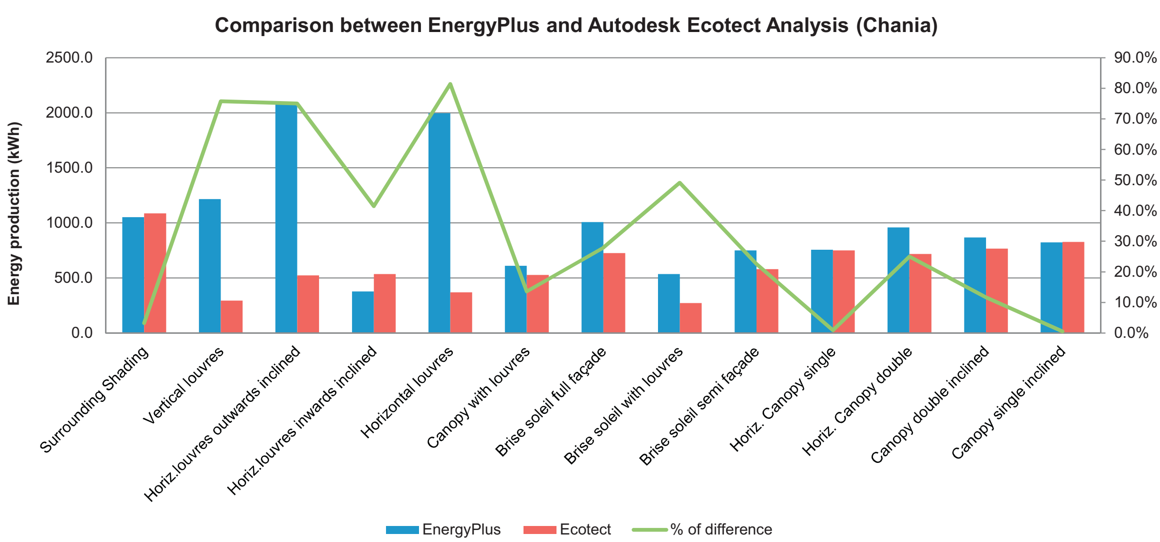

Fig. 4. Comparison between EnergyPlus and Autodesk Ecotect Analysis (for the Area of Chania).

of difference between the two models is high but this is due to the disability of the Ecotect to simulate the louvers system properly and not due to EnergyPlus. For this reason, for the next comparisons only the energy production calculated by EnergyPlus was taken into account for all louvers systems, except for the Horizontal Louvers (that are composed with more than 30 modules connected).

An additional source of errors appears for the cases of the Brise–Soleil. The difference of the results was in the range of 22–49% for Chania and 42–44% for the case of Athens. The percentage of difference is lower for the case of louvers. The source of error in these cases is due to the fact that in Brise Soleil systems one of the PV panels is facing downwards and uses only the reflected component of solar radiation. These types of panels cannot be correctly simulated by Ecotect and for this reason it was decided to use only EnergyPlus results for the next comparisons.

4.2. Comparison between simple model PV modules and real market products (simulations done in EnergyPlus)

As it can be seen in Figs. 5 and 6 the difference in energy production between real PV modules which can be found in the market and the simple model with 12% efficiency is very small, which indicates that the selection of a theoretical value of 12% efficiency approximates the overall efficiency of real PV module which can be applied on shading devices. It should be noted that the selection of real PV modules is based on the available area on the shading device and the number of modules which are in series. For example in horizontal shading devices, PV modules can only be connected in series. Only in cases of geometrical configurations of louvers the differences are higher due to complicated geometry (higher than 30% difference).

Additionally it should be mentioned that the difference of energy production per m^2 between louvers outwards inclined and canopy inclined is 44.12% (higher for the case of canopy inclined). A similar observation was made by Hwang et al. (2012). They conclude that for south facing surfaces for the case of Inchon in Korea (37°27N and 126°42E) the insolation levels on louvers inclined are 42% lower than on canopy inclined. The aforementioned latitude is very close to Athens' latitude (37°59N, 23°43E). This disadvantage of louver PV systems is probably the main reason why these types of systems have not yet entered the market dynamically. Further research needs to be done in the subject of increasing the energy production of PV louvers systems.

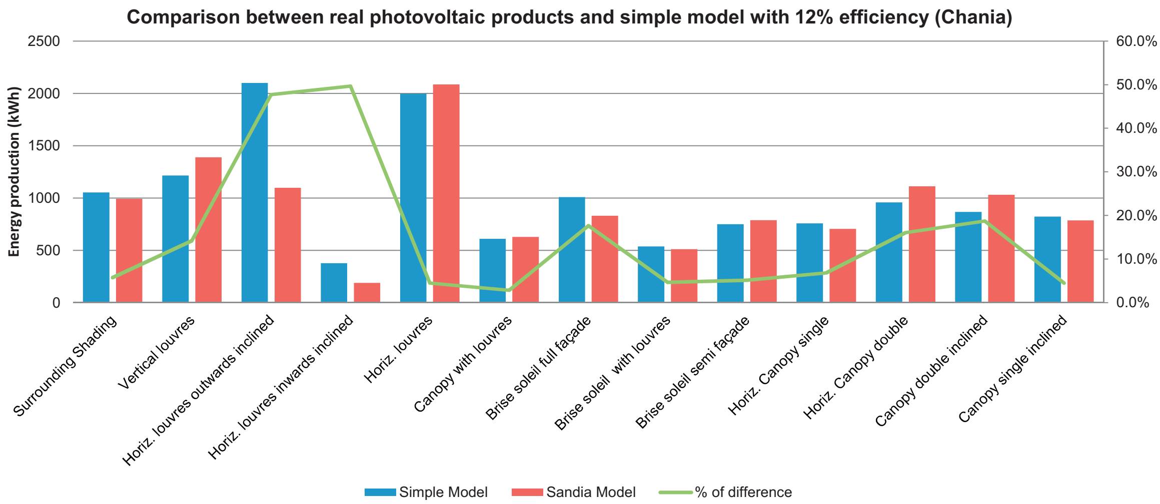

Fig. 5. Comparison between real photovoltaic products and a simple model with 12% efficiency (Chania).

4.3. Increasing the distance between exterior wall and shading (simulations done in EnergyPlus)

Figs. 7 and 8 show that there is indeed a little change in the PV module efficiency when the distance between exterior wall and shading increases. This change in the PV modules' efficiency is due to increased wind speed between the modules.

According to EnergyPlus Engineering Reference (2012) in order to calculate the energy production of the PV the full geometric model for solar radiation is used, including sky models, shading, and reflections, to determine the incident solar resource are taken into account. Additionally the strength of the DC current source is dependent on solar radiation and the *IV* characteristics of the diode are temperature-dependent. When moving the shading system away from the facade Energy Plus uses the same algorithms but the resulting shading parameter and temperature are different.

According to recent bibliography reports, an increase in the performance should be expected. The circulation of wind between the modules was expected to decrease cell temperatures therefore increase energy production (Bloem et al., 2005). The small increase in the energy production of some PV modules can be explained because in this case there is less shading in the beginning and the end of the day and because there is an increase of air circulation. For most of the cases of facade occupied systems (i.e. the louvers and canopy inclined or horizontal double) the difference in energy production is about 1% (this is acceptable for a shading device of 0.05 m distance from the facade). Similar results exist in the literature, for example the harvested energy per square meter is almost the same when changing the distance between louvers frame and outer window up to a 40 mm (Kang, Hwang, & Kim, 2012). There is no difference in temperature in systems that do not cover the glazing (i.e. canopy horizontal or inclined), as expected. We found no difference in energy production for the case of Brise Soleil full facade with louvers, probably due to the high mass of the shading system in relation to the small gap of 0.05 m.

In Fig. 9 are presented the temperature differences of the PV modules when increasing the gap between the south wall and the shading device in the case of Canopy Inclined Double, simulated

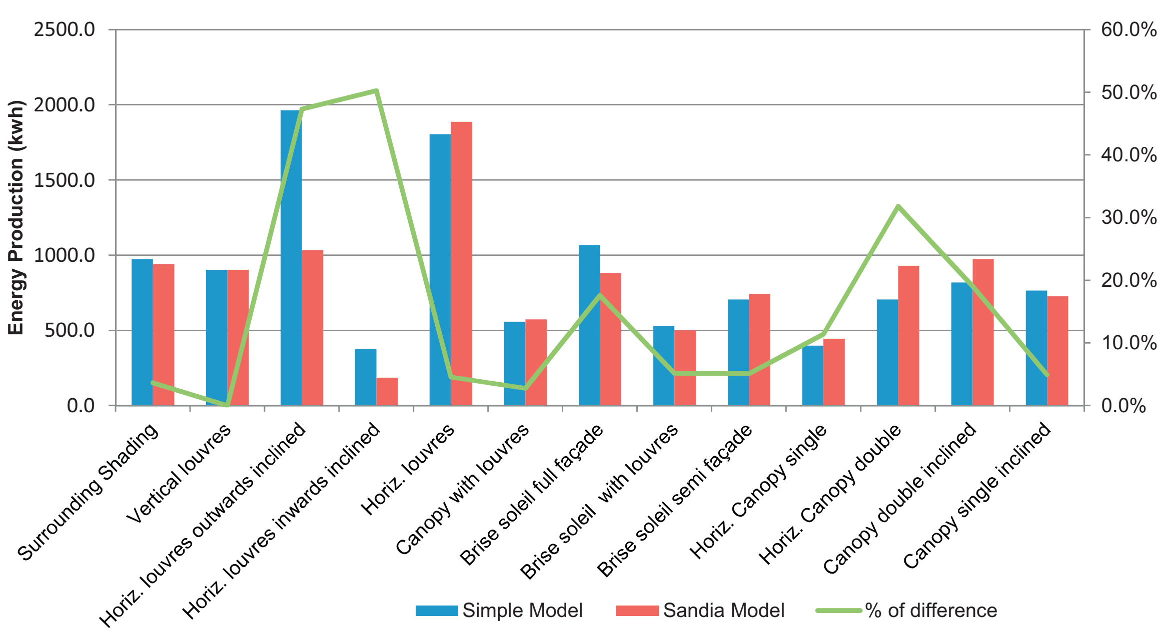

Fig. 6. Comparison between real photovoltaic products and simple model with 12% efficiency (Athens).

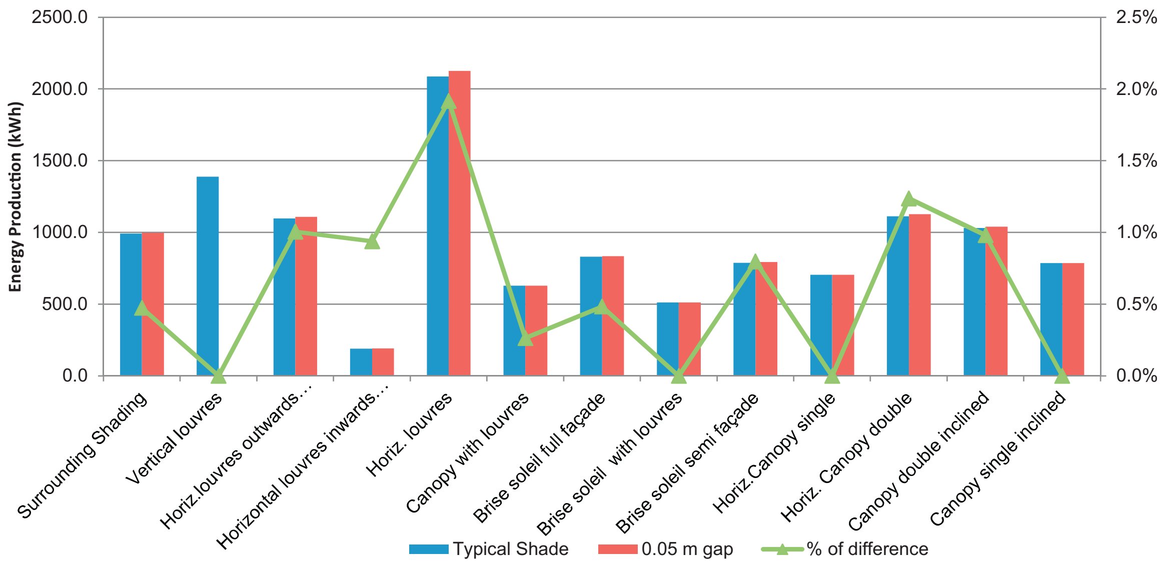

Fig. 7. Comparison between typical shadings and 0.05 m gap (Chania).

for Chania latitude. The maximum temperature difference is in the middle of the year (summer time) and is about 0.4 °C. Similar results are found for other examined shading geometries.

4.4. Comparison of measured and simulated data

The simulated results with Ecotect and EnergyPlus and the measured results for both Athens and Chania are compared for the system of canopy horizontal. In the case of Athens, measured values were taken from the paper of Kaldellis et al. (2012) and in the case of Chania measured values were taken from the Renewable and Sustainable Energy Lab (ReSEL), Environmental Engineering Department, Technical University of Crete. The environmental conditions tested are presented in Table 4 for the case of Athens and in Table 5 for the case of Chania. The results of the comparisons are available in Tables 6 and 7. Both installations (in Athens and in

Table 4
Environmental conditions of comparisons for Chania latitude.

Chania 23rd November	RaSEL Laboratory	Simulation	STC
Temperature (°C)	17.5	16.1	20
Wind speed (m/s)	2	2	1
Inclination	0°	0°	55.6°
Total irradiation (W/m^2)	419.5	400	800

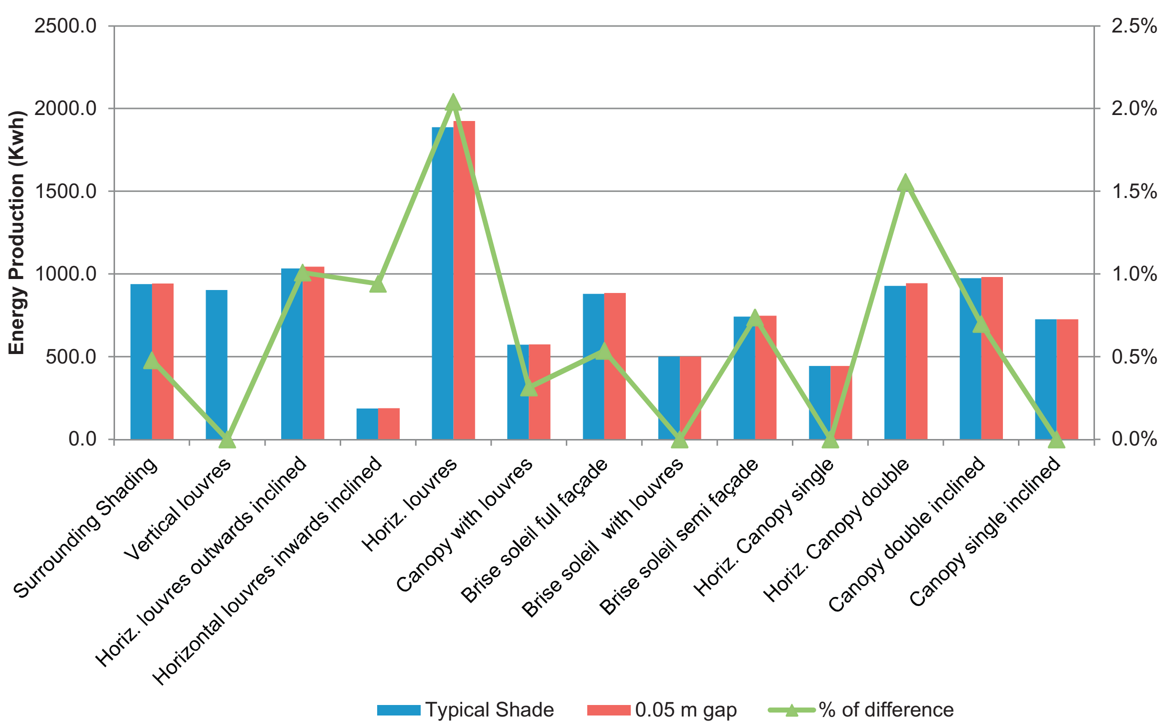

Fig. 8. Comparison between typical shadings and 0.05 m gap (Athens).

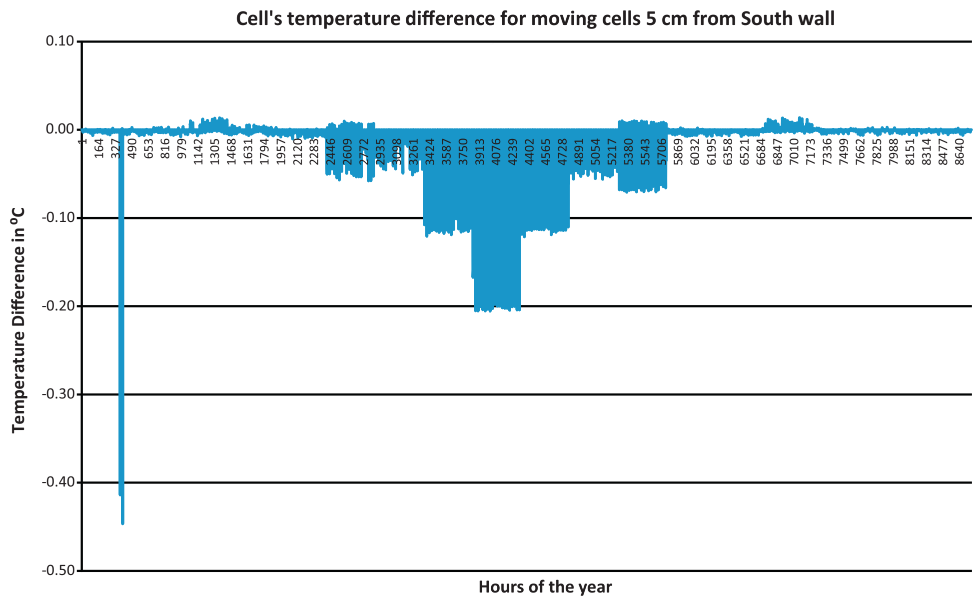

Fig. 9. Cell's temperature difference when moving cells 5 cm from south wall for Canopy Inclined Double simulated with Sandia PV models for Chania.

Chania) of PV panels are upon roofs and facing south with the inclination given in the tables. Other specific characteristics of these installations are presented in the same tables. In the absence of available in situ measurements for long periods, the comparisons presented concern only the specific days when the measurements were carried out. Small differences in tested conditions would not affect the difference of the results more than 2% (Anderson, Bishop, & Dunlop, 2000).

It is obvious that both measured and simulated results are similar. There is a 9–11% difference between the results. Possible small differences can be attributed to different PV brand type used in each case and due to the final current output.

Moreover, the type of PV modules used in all cases is similar (monocrystalline and multicrystalline ones). Additionally PV panels installed in TUC laboratory are the same brand with one type of PV simulated with EnergyPlus (Sharp).

The results of the estimated energy production by TUC and EnergyPlus are very close to each other; so we conclude that there are no big differences between various types of PV in terms of energy production. Only when a detailed study is needed the examined

Table 5
Environmental conditions of comparison for Athens latitude.

Athens 23rd November	Kaldellis et al. (2012) (DC[a]) Kyocera (LA361-K51S)	Simulation	STC
Temperature (°C)	NA	16.1	20
Wind speed (m/s)	NA	2	1
Inclination	0°	0°	55.6°
Total irradiation (W/m^2)	271	250	800

[a] DC: direct current.

Table 6
Comparison of measured and simulated results. Energy production of PV panels for Athens area on 23rd of November.

Athens 23rd November for 0° inclination	Kaldellis et al. (2012) (DC[a]) Kyocera (LA361-K51S)	Simple model of 12% efficiency simulated results for Canopy horizontal single (AC[a])	Sandia model simulated results for canopy horizontal single (AC[a]) (AstroPower_APX-90, BP_Solar_BP5130, Sharp_NEH120E1)
PV area (m^2)	2655	3500	3500
Energy production (Wh)	172.00	256.00	257.00
Energy production (Wh/m^2)	64.78	73.14	73.43

[a] AC: alternative current; DC: direct current.

Table 7
Comparison of measured and simulated results. Energy production of PV panels for Chania area on the 23rd of November.

Chania 23rd November for 0° inclination	Laboratory ReSEL at TUC measured results (AC[a]) Sharp NA-F121G5	Simple model of 12% efficiency simulated results for canopy horizontal single (AC[a])	Sandia model simulated results for canopy horizontal single) (AC[a]) (AstroPower_APX-90, BP_Solar_BP5130, Sharp_NEH120E1)
PV area (m^2)	26	3.5	3.5
Energy production (Wh)	7561.00	933.00	937.42
Energy production (Wh/m^2)	290.81	266.57	267.83

[a] AC: alternative current.

PV models should be same brand-type and the environmental conditions should identical. It is also remarkable that installations in shading devices have the same potential with roof installations to produce energy, and this emphasizes the potential of BIPV in shading systems.

5. Conclusions – suggestions for future research

The work carried out was an analysis in the subject of solar energy production by PV modules integrated in typical shadings devices and the methods of evaluation used.

It is concluded that the method of evaluation used depends on the desired accuracy of the results and the comparative or absolute research done. The accuracy of the results depends on the designer's wishes in relation to the design stage that the project has developed. The theoretical efficiency of 12% used in simple model equation is accurate enough only for simple geometrical configurations of shading devices. It is noteworthy however, that even the complete model, in relation to real market products, is accurate enough only for simple geometrical configurations. For more complicated geometries other types of research are needed. For venetian blind systems, for example, only the in situ measurements are accurate enough when exact values of energy production are needed. For systems with integrated PV that produce energy only through reflected solar radiation both simple simulation model done with a sensitive application and complete model of real market products are accurate enough.

For a comparative analysis between different geometrical configurations of shading systems with integrated PV modules (and not a value level dependent analysis) the complete model that used real market products is accurate enough. It was observed in simulations using the complete model that the difference of energy production per m^2 of venetian blind outwards inclined system and of canopy inclined system is 44.12% higher in the case of canopy inclined. This result is similar to the 42% that Hwang et al. (2012) observed for the same cases of shading systems. This fact proves the accuracy of the energy production results (comparative) of the complete model for cases of complicated geometries such as the venetian blind systems.

It was showed as well that the complete model is "sensitive" to air circulation between the facade shading system and the glazing. The model calculates the temperature differences when the gap between the shading system and the exterior wall is increased and the consequent increase in the PV energy production.

Further work could be done for shading devices of complicated geometries with high amount of connected panels and for systems that use only diffuse solar radiation, in terms of accuracy of the resulting values in relation to real PV installations.

Further work on venetian blind systems with integrated PV is suggested to be conducted in order to increase their efficiency, in levels similar to that of simple inclined systems. Additional research of in situ measurements will be required in order to cover all cases of complicated geometries of shading devices as for example for systems with more than 30 modules connected in series and for case that only diffuse radiation falls upon the PV panels. Finally it is concluded that the efficiency of simple geometry shading systems such as canopy inclined single is not lower than roof stand alone PV installations. This proves the potential of BIPV integration in shading systems to be a technically efficient solution amongst other types of PV installations.

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