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Assessment of fixed shading devices with integrated PV for efficient energy use

M. Mandalaki [a,*], K. Zervas [a], T. Tsoutsos [a], A. Vazakas [b]

[a] *Technical University of Crete, Department of Environmental Engineering, University Campus, 73100 Chania, Crete, Greece*
[b] *Technical University of Crete, Department of Architecture, El. Venizelou 127, 73100 Chania, Crete, Greece*

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Abstract

The use of external fixed shading devices to adjust solar influx radiation and to save energy is well known. However, fixed shading devices can reduce daylight availability, increase artificial light needs and block the beneficial winter solar radiation.

This paper is part of a research on the characteristics of the optimum shading device. The aim is to investigate the balance between the energy needs for heating and cooling the space that the shading device is used for and the energy that is used for lighting the same space and the energy that the shading device can produce.

In order to investigate the balance between the above mentioned parameters, thirteen types of fixed shading devices have been studied and categorized according to their energy performance, for a single occupant office room. The same office room is tested for two different Mediterranean latitudes in Athens and in Chania, Crete in Greece and for two different south facing windows' sizes.

The thermal behavior of the devices is assessed through computer simulation application and the daylight analysis is assessed with both computer simulation and physical modeling. Stable parameters were the internal loads in the office room, the south orientation of the façade and the type of glazing. Variable parameter was the type of the fixed shading device.

The study shows that all shading devices with integrated south facing PV can efficiently produce electricity which may be used for lighting. The study highlights the fact that shading devices such as Surrounding shading, Brise–Soleil full façade and Canopy inclined double work efficiently against thermal and cooling loads and may be used to produce sufficient electricity and control daylight. The study defines the geometrical parameters that will be incorporated to the overall characteristics of the optimum fixed shading device and proposes new fields of development for the BIPV technologies.

Keywords: Shading device; BIPV; Photovoltaic panel; Electricity production; Thermal comfort; Daylight availability

1. Introduction

The use of shading devices (SDs) is essential for south oriented facades, especially in Mediterranean climates. Fixed SDs can reduce increasing thermal loads during summer and at the same time control intense summer daylight, improve vision and reduce glare (Fontoyont, 1998; Mehrotra, 2005; Yoo and Manz, 2011). The choice of SD for office buildings is an issue of high importance, due to the

Abbreviations: SD, shading device; PV, photovoltaic.

* Corresponding author. Address: Technical University of Crete, St. Titos Square, 73132 Chania, Greece. Tel.: +30 6972328133; fax: +30 2821045229.

E-mail addresses: mandalaki@arch.tuc.gr (M. Mandalaki), k.zervas@dundee.ac.uk (K. Zervas), theocharis.tsoutsos@enveng.tuc.gr (T. Tsoutsos), avazakas@gmail.com (A. Vazakas).

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very specific standards of visual and thermal comfort and the need for low energy consumption (Hascher et al., 2002). The use of fixed SD reduces the incident solar radiation. This fact, poses a problem of balance between the positive reduction of cooling loads in the summer and the negative increasing of heating loads in the winter (Dubois, 1997; Tzempelikos and Athienitis, 2007).

In the first phase of this research the abovementioned facts are evaluated for south facing SD. In the second phase, the additional property of energy production through Building Integrated Photovoltaic (BIPV) panels, supplying electricity for artificial lighting, is being considered for a more thorough evaluation of the SD (Eiffert and Kiss, 2000; Harmstad, 2006; Román et al., 2006; Yoo et al., 1998).

The international research that has been done on the subject of energy assessment of shading devices does not incorporate the variety of parameters examined in this study. Either a few types of external fixed SDs are examined in terms of thermal and visual performance (Murani and Roecker, 2005) or only developed fenestration systems are examined in terms of visual comfort (Yener, 1999). In general, the assessment of various types of fixed exterior shading devices concerning total energy use, including electricity for lighting, has not arrived at firm conclusions (Dubois, 1997; Mandalaki et al., 2009). On the other hand, the state of the art on the subject of integration of PV in building's façade has been well developed in the field of energy consumption and maximum electricity production (Guiavarch and Peuportier, 2006; Hastnes, 1999; Schoen, 2001; Yoo et al., 1998; Vartiainen et al., 2000). Integration of renewable systems on SD has been developed as well, but the studies have not arrived on a specific conclusion concerning their efficiency and energy production (Hastnes, 1999; Palmero-Marrero and Oliveira, 2006).

Building integrated PV installations have already started receiving attention in EU since 1990 (Schoen, 2001). Advanced fenestration systems are currently under rapid evolution and some of them have been developed and evaluated, in order to balance the above mentioned parameters (Chow et al., 2010; Mallic et al., 2004; Roman et al., 2008; Yun et al., 2007). The use of shading devices, as an additional sun protector, can contribute positively to the overall energy balance of these systems and can offer a cost – effective and aesthetically acceptable means for integrating renewable into buildings (Palmero-Marrero and Oliveira, 2006).

Additionally it is important to emphasize the fact that despite the rapid development of the Building Integrated Photovoltaics (BIPV) technology almost none of the SDs with integrated PV examined in this paper has been in the market. Only the systems of canopy horizontal single, canopy inclined single and double have been supplied in the market. This is basically due to manufacturing and installation cost of the SDs with integrated PV. We believe though, that due to the rapid development of the BIPV technology, experienced companies will manage in the future to make the cost of these systems worthwhile.

2. Methodology

2.1. Description of the parameters

The aim of the study is the assessment of SDs with integrated photovoltaic panels (PVs) according to their energy behavior, for office buildings, in Mediterranean climate. We chose two different latitude points in the Mediterranean, one in Athens (37.58° N) and another in Chania, Crete (35.30° N). Both are coastal areas, typical examples of Mediterranean climate. This climate is characterized by mild winters with high solar radiation and long daytime and by hot summers. The extreme positions of the sun are about 77° height in the summer and about 30° height in the winter at 12 o'clock for a south facing plane. Both latitude points lie between the middle parallels of Mediterranean Sea. Demands for cooling are increasing during summer due to high temperatures and the periodical increase of population because of tourism.

The integration of PV installations in buildings is an issue of high importance that can help decrease the energy demands of the building sector taking into account aesthetic and environmental factors and promoting the idea of "act local, think Mediterranean". The specific geometrical characteristics for these two locations have been studied in relation to the sun movement for the overheated and underheated period. The overheated period for these two latitude points is considered to be between June to middle of September. In order to use these types of SDs in different latitudes, small geometrical adjustments of the devices should be done for improving their performance.

Thirteen types of south facing SDs mostly used in office buildings (Neufert et al., 2002; Olgyay, 1957) are being examined (Fig. 1). They are designed to exclude direct sunlight during the specific overheated period. A consequence of the above is that during the underheated period a specific amount of direct sunlight is entering the room in order to reduce the energy deficit of the building (Yener, 1999). The reference office building is a middle-size office building with office units aligned on two facades, separated by a central corridor, with staircase/service spaces at both ends of the building (Van Dijk, 2001). The reference building is located on a flat terrain with no shading of adjacent hills, buildings or trees.

Each SD is placed in front of a window of an office cell. This position can be repeated for each window of the building (Fig. 2). In order to simplify the results we will examine the output of a single south facing SD and not a series of them that can be placed in an office building.

The types of SDs examined are:

1. Canopy horizontal single,
2. Canopy horizontal double,
3. Canopy inclined single,
4. Canopy inclined double,
5. Louvers horizontal,
6. Louvers horizontal inwards inclined,

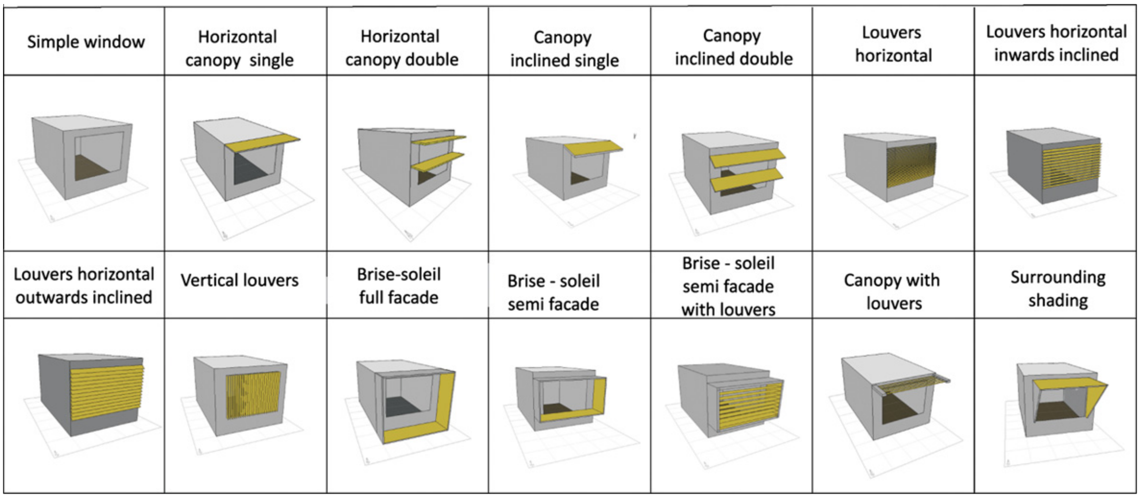

Fig. 1. Types of shading devices examined in this study.

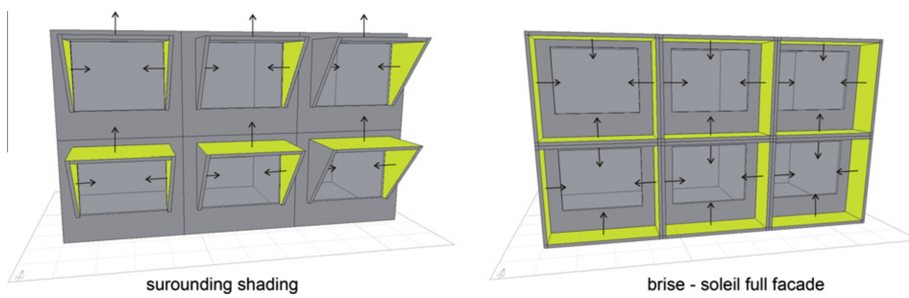

Fig. 2. Faces of integrated PV panels and configuration of repeated SD in two types of shading devices.

7. Louvers horizontal outwards inclined,
8. Louvers vertical,
9. Brise–Soleil full façade,
10. Brise–Soleil semi façade,
11. Brise–Soleil semi façade louvers,
12. Canopy louvers and
13. Surrounding shading, as shown in Fig.1.

These are compared to a single, double glazed window type without shading (Ismail and Herniquez, 2003). The characteristics of the glass used for all shading systems examined, are similar to a typical double glazed aluminum frame window with thickness $0.006 + 0.03 + 0.006 = 0.042$ m (glass, void, glass) and visible transmittance 0.898, total solar energy transmittance 0.837 and U-value 2.7 W/m^{2}k.

As shown in Fig. 3 in the methodological diagram three basic types of evaluations are used to assess the sustainability of the SD. The first one is the ability of the SDs to provide thermal comfort with small amount of energy. The second is the electricity needed for visual comfort. The third is the amount of electricity produced by the PV integrated in the SD. Additionally a fourth evaluation that corresponds to the efficiency of the PV in relation to the area it occupies, is introduced. This parameter is an additional one that can help the overall evaluation of the integration of PV to different types of SDs and introduces the economical aspect of the proposed systems. The final result is the combination of the above evaluations.

2.2. Types of simulations

The energy needs for thermal comfort in the space have been evaluated with the simulation software Energy Plus v3.1. The electricity production of the PV panels is evaluated with Autodesk Ecotect v5.60. The daylight levels that each shading device ensures in the space and the electricity production of the solar cells have been evaluated with both Desktop Radiance v1.02 and Autodesk Ecotect v5.60. All applications are common in use, available and were estimated as appropriate to validate our cases.

In order to examine the correct use of Desktop Radiance v1.02 software in daylight simulation, a physical model of 1/10 scale was constructed following the specific instructions for making daylighting models and was tested in real sky conditions as shown in Fig. 4 (Baker and Steemers, 2002; Lam, 1977). The correlation was not set to compare the values but to ascertain the relation between them. It is well known that physical models overestimate the luminance compared to “real world” conditions. This difference exists for overcast sky conditions and it increases for other types of sky conditions (Mardaljevic, 2001).

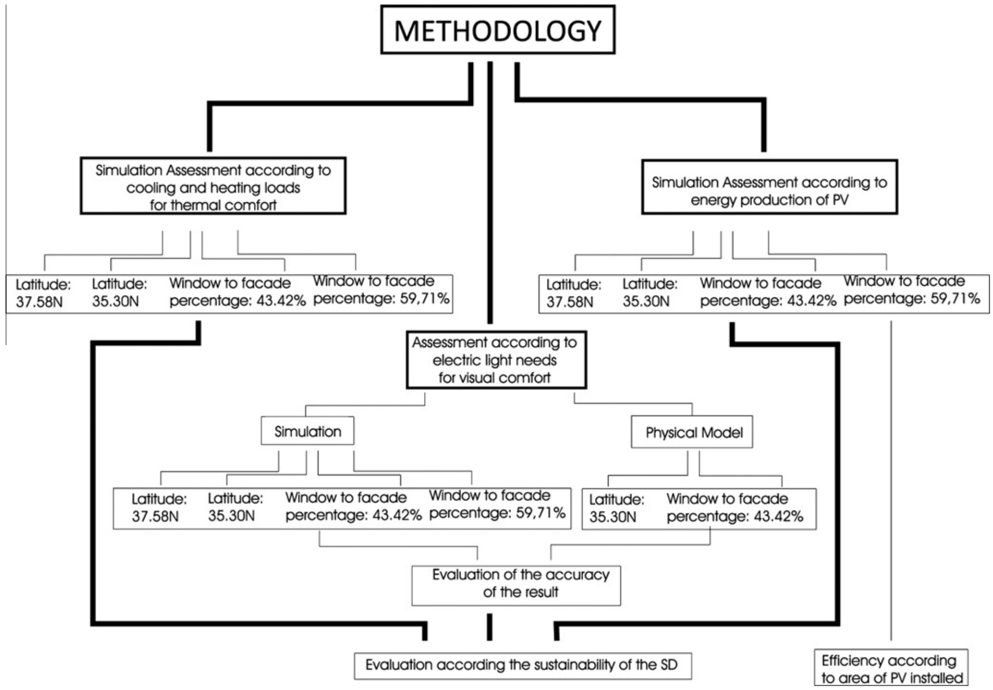

Fig. 3. Methodological diagram.

Fig. 4. Physical model in 1/10 scale for daylighting calculations of different types of SDs.

2.3. Variants and invariants

For the evaluations the only variant was the type of the shading system. Invariants were thermal loads of the office room, south orientation of facades, geometry and dimensions of the office room and window, and types of the materials used for the glazing and the interior of the room.

All assessments took place in two different latitudes and incorporated two different window sizes to reduce the possibility of a random finding. The weather data of the city of Athens were ready for incorporation to Energy Plus, Desktop Radiance and Autodesk Ecotect applications through the Energy Plus web site. The weather data for the city of Chania, Crete and their incorporation to the software is a work that has been done by the Laboratory of Sustainable and Renewable Energy, Department of Environmental Engineering of Technical University of Crete (Papantoniou and Tsoutsos, 2008; Zervas, 2009).

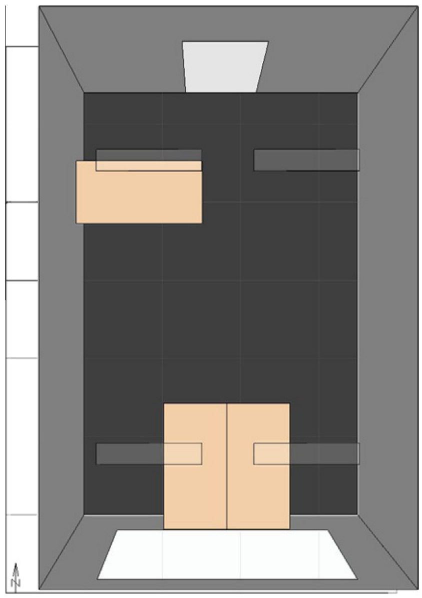

Fig. 5. Configuration and electric lights in the office reference room.

2.4. Case study description

We examine the sustainability of an office room that is used as a reference with the above SDs and its energy consumption in order to ensure temperatures between 18 °C and 26 °C and lighting levels of 500 lx and above in most of the space during the majority of office hours (09:00–17:00 for 5 days per week) (Boyce and Raynham, 2009; Grandjean, 1984;). This is 8 h per day × 5 days per week × 48 weeks = 1920 office hours; we did not take into account bank holidays. The electricity needs for electric lighting are estimated for these office hours when daylighting is under 500 lx. Relative Humidity (RH) is considered to be between 20% and 80% and the Mean Radiant Temperature (MRT) and air motion are held fixed. The MRT is assumed to be close to the air temperature, and the air motion is assumed to be modest. These combinations of air temperature and RH are plotted on a psychometric chart and they define an area known as the comfort zone (Lechner, 2001).

We assumed that all PV electricity is instantaneously used by the artificial lighting system inside the building or sold to the grid, hence no storage is needed (Vartiainen, 2001). Thus the SD is an energy production and energy reduction system, which also helps to maintain the building's energy equilibrium (Yoo and Lee, 2002).

A typical room of 3.5 m × 5.4 m × 2.9 m (width × depth × height) is used as a reference (Fig. 5). In order to achieve more concrete conclusions two types of south facing window are examined. One is 2.4 m × 1.9 m (width × high) and the other is 3.3 m × 1.9 m. This is making a space of 18.90 m^2 with a 4.56 m^2 of south window or a 6.27 m^2 of south window. The ratio of the window's surface to the floor area is either 24% (Van Dijk, 2001) or 33%. The ratio of window to façade area is 44.92% for the first case and 61.77% for the second one.

The position of the occupants as well as the position of the luminaries can be seen in the plan (Fig. 5). 4 × 50 W, High Frequency (HF) tubes, mirror-luminaries are being used to save electricity. All dimensions, provision of space and material properties are based on the project SWIFT, Switchable Facade Technology, reference office for thermal, solar and lighting calculations, terminated on 30.4.2003 (Van Dijk, 2001). For the electric light system,

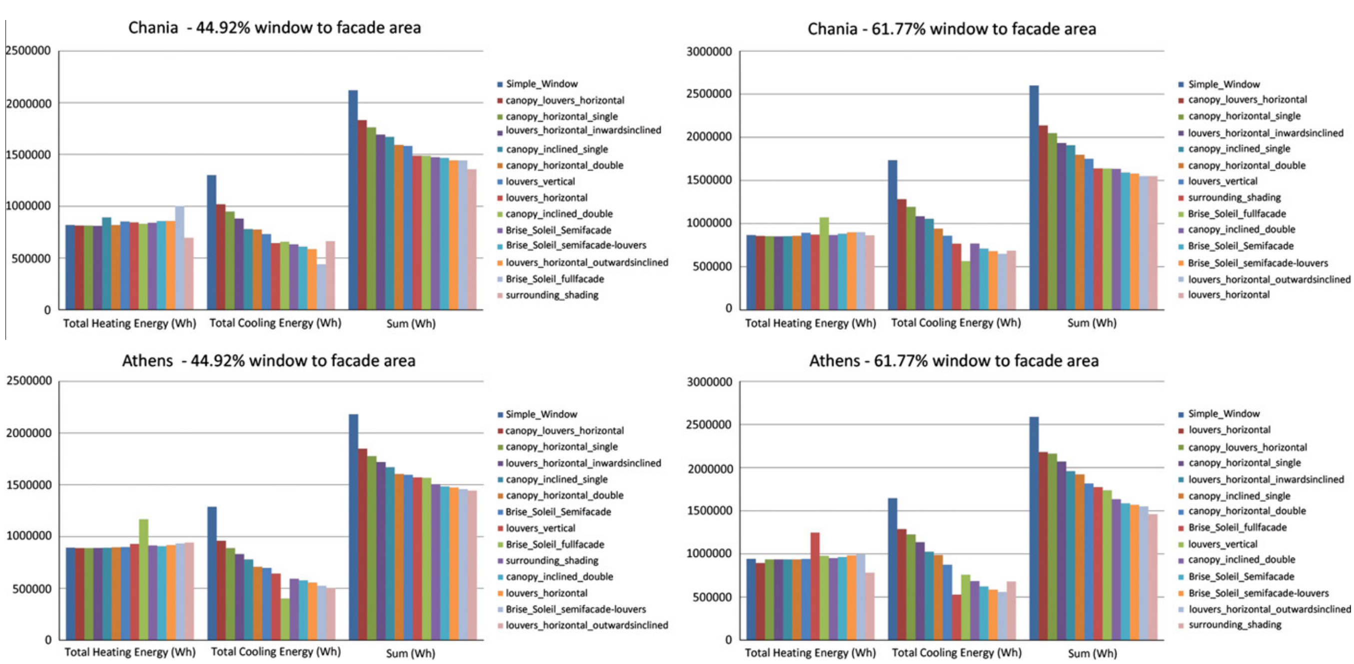

Fig. 6. Thermal and cooling loads for reference office in Chania and Athens for window 44.92% and 61.77% of façade area.

a continuous electric light dimming strategy has been assumed. Whenever the daylight luminance falls below the required level during the lighting demand period, the shortfall must be provided by electric lighting. If only an on/off control were used, the electricity needs for lighting would be much higher (Vartiainen, 1998). The demand for electricity due to artificial lighting in each reference office is directly calculated as a function of different shading devices, using the daylighting simulation formula: $E_L = P_L \cdot t_y(1 - \mathrm{DAR})$ where the P_L is the installed light power (W/m^2), t_y is the number of working hours in a year, and DAR is the daylight autonomy ratio and is defined as

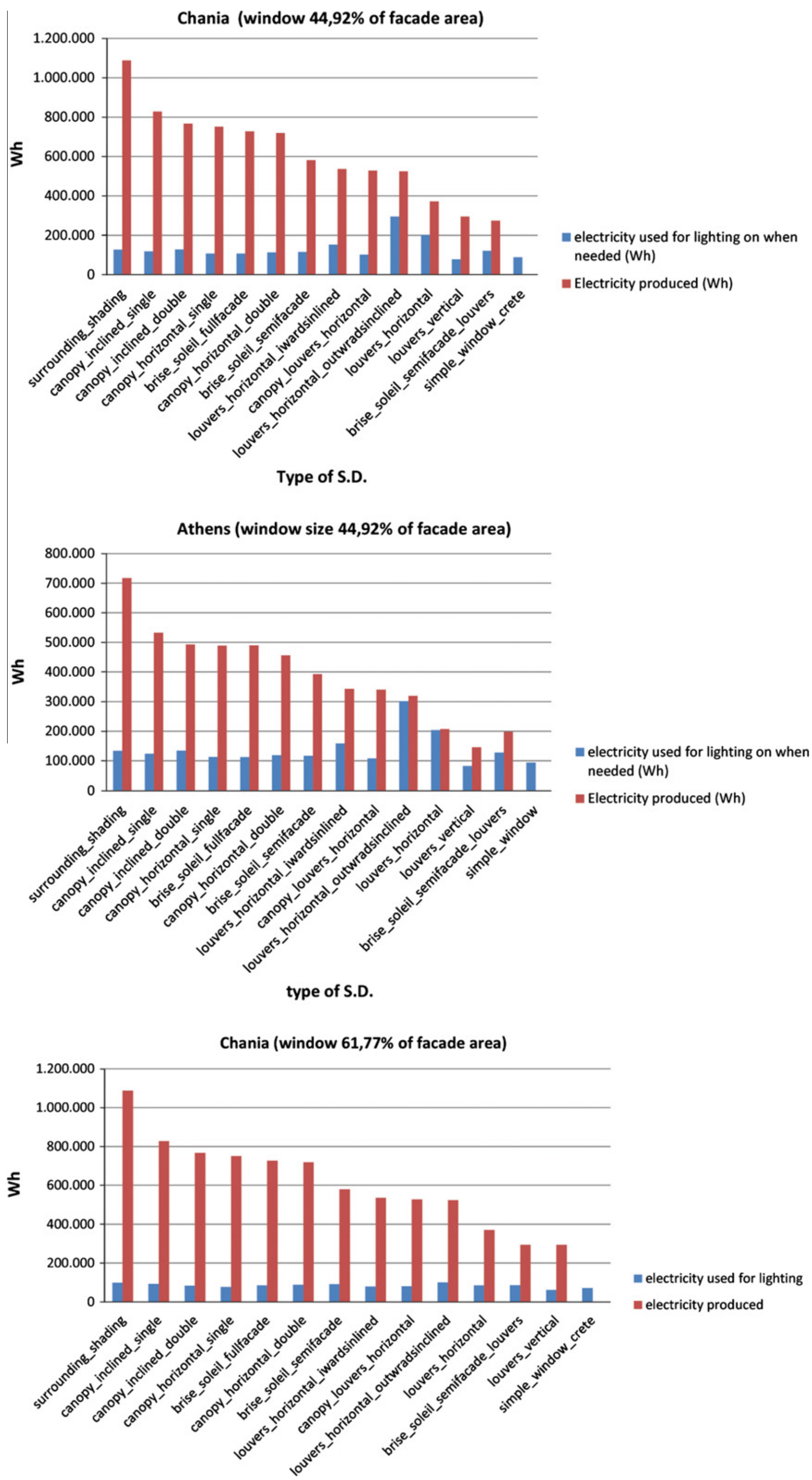

Fig. 7. Electricity production and need for lighting the reference office in Chania and Athens for window 44.92% and 61.77% of façade area.

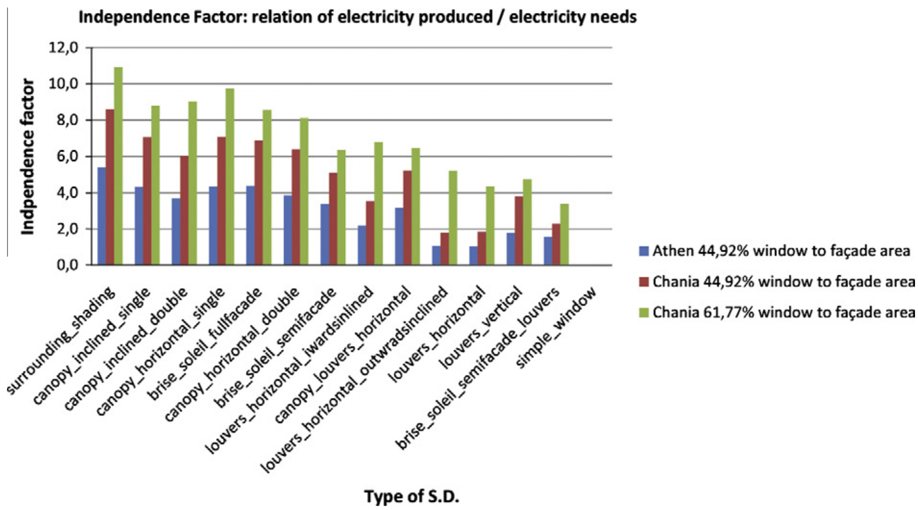

Fig. 8. Independence factor: electricity needs to electricity produced for Chania with window 44.92% and 61.77% of façade area and for Athens with window 44.92% of façade area.

the fraction of working time in a year during which sufficient daylight (more than a pre-specified set point, for example 500 lx) is available on the work plane surface (Tzempelikos and Athienitis, 2007).

2.5. Description and properties of materials used

Regarding the quality of the interior materials, all five surfaces of the reference room are considered to be adiabatic. Only the wall on the façade that incorporates the window is thermally conductive and through this wall, there is heat exchange with the outside. The materials used are the following: a concrete floor with carpet and external insulation, a suspended concrete ceiling and an interior framed plasterboard partitions considered as adiabatic, external double brick wall with insulation and *U*-value = 1.770 W/mk, density 1030.42 kg/m^3, and a double glazing as described above. The reflectance of the material used is 0.85 for the ceiling, 0.65 for the walls and 0.20 for the floor. The ground reflection for incident solar radiation is 0.20. Internal gains from lights, appliances and people have been excluded from this research.

The PV panels used are constructed from photovoltaic monocrystalline material in order to produce the most (efficiency 15% as given in Autodesk Ecotect v5.6 Software) in relation to other PV technologies (polycrystalline and thin film

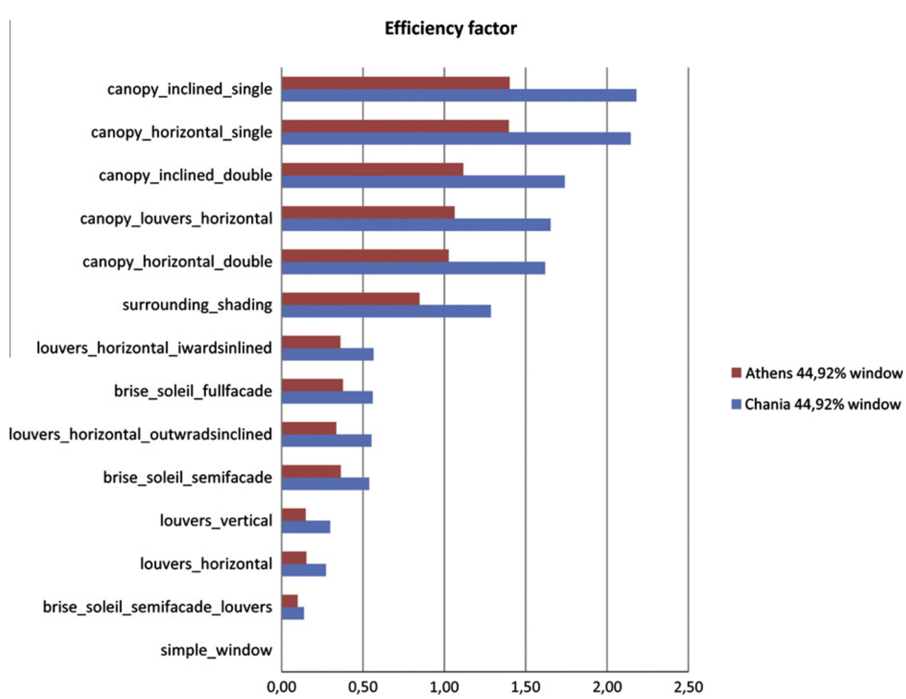

Fig. 9. Efficiency factor for Chania and Athens with window 44.92% of façade area.

technology). They are integrated to the SD following the geometry of the exterior face of each plane of it, as shown in Fig. 2.

3. Results

3.1. Thermal simulation

As expected, according to thermal simulation concerning cooling and heating loads, there are some differences between the two latitudes examined, due to different sun position. There are even some differences between the same point latitude and different window size due to new geometrical implementation that is actually needed for different window sizes than the original. These geometrical adjustments have not been made in this research because it would have confused the results.

The SDs that seem to be the most efficient for both latitudes and both window sizes are **Surrounding shading**, **Brise–Soleil full façade,Brise–Soleil semi façade and Canopy inclined double**. These are systems that are not blocking entirely the reflected sun beams and at the same time allow communion with the outside. The systems of **Louvers horizontal inclined or not and the Brise–Soleil semi façade louvers** are in a very low position in terms of energy needs, as expected. The latter, are systems that block direct and reflected sun radiation and it is obvious that they can be efficient enough in terms of cooling loads, needed most of the year. Additionally, it is important to mention that despite having SDs there is still energy needed to cool the office unit. The energy that is used for cooling is approximately the same with the energy used for heating (Fig. 6).

3.2. Daylight simulation and electricity production

The SDs are lighting control and electricity production machines. All SDs examined can efficiently provide electricity for the electric lights of the office unit. The spare energy could be used to illuminate the inner communal areas. During the peak conditions of demand of electric light, the sunlight is not available and in these periods the production of PV is low. But still, as shown in the diagrams of electricity production the production is enough to support at least the electric lighting of the reference office room (Fig. 7).

On the other hand the systems with the lowest electricity needs, meaning the highest daylight availability, are these of **Louvers vertical**, **Canopy louvers** and **Canopy horizontal single** (Fig. 7). At the same time, these systems have been positioned very high in the scale of energy consumption for heating and cooling (Fig. 6). This is due to the fact that these systems allow the exposure of the window to reflected solar radiation. With reference to reducing daylight availability, the system louvers horizontal either inclined or in front of a Brise–Soleil system permits the lowest levels daylight into space (Fig. 7). The latter perform extremely well in terms of low energy needs for heating and cooling (Fig. 6).

In order to evaluate the SDs according to their performance, the term **independence factor** is introduced. It is the ratio of electricity needs vs. produced electricity from the integrated PV. The independence factor reaches its highest value for the systems Surrounding shading. That value gradually diminishes for the **Canopy horizontal single**,

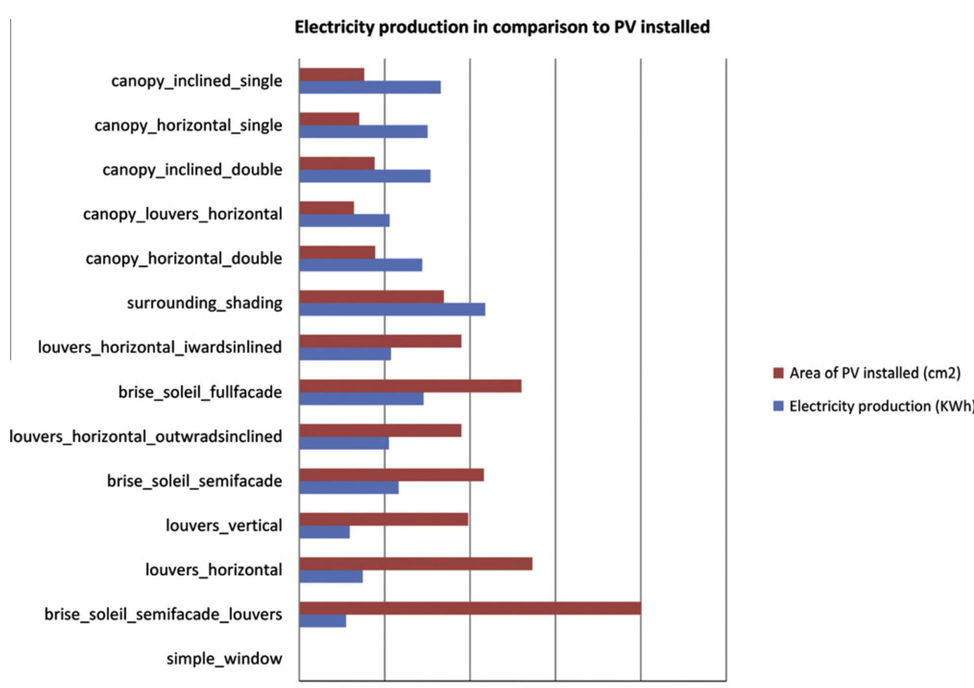

Fig. 10. Electricity production in comparison to area of PV installed for Chania with window 44.92% of façade area.

Canopy inclined single, **Brise–Soleil full façade and for Canopy inclined double,** in that order (Fig. 8).

The fourth evaluation deals with the economy of the system, in terms of the area of PV installed and the production efficiency of the system. It is obvious that the energy production of the PV is inversely proportionate to the area that it covers; the PVs' energy production rather depends on the geometrical characteristics of the SD and the overshadowing between the surfaces. An interesting point is that the system **Brise–Soleil semi façade louvers** carries the largest PV surface but at the same time it produces little electricity. On the other hand the amount of electricity the

	DATE	TYPE OF SHADING DEVICE		TYPE OF SKY	
1st Experiment					
1	25.11.2011	Canopy		Cloudy Sky	
2	27.11.2011	Brise Soleil Full Façade		Intermediate Sky	
3	28.11.2011	Canopy Louvers		Sunny sky	
4	29.11.2011	Simple Window		Sunny	
5	30.11.2011	Simple Window without Plexi		Cloudy Sky	
6	01.12.2011	Brise Soleil Semi façade		Sunny sky	
7	02.12.2011	Louvers Vertical		Sunny sky	
8	03.12.2011	Surrounding Shade		Sunny sky	
9	05.12.2011	Canopy Double		Sunny sky	
10	06.12.2011	Brise Soleil louvers		Intermediate Sky	
11	08.12.2011	Louvers horizontal		Sunny Sky	
12	29.12.2011	Canopy Inclined Double		Intermediate sky	
13	30.12.2011	Canopy Inclinde Single		Cloudy Sky	
14	14.01.2012	Louvers Horizontal Inwards Inclined		Cloudy Sky	
15	17.01.2012	Louvers Horizontal Outwards Inclined		Cloudy	
2nd Experiment					
1	04.12.2011	Canopy		Sunny sky	
2	12.12.2011	Brise Soleil louvers		Sunny sky	
3	13.12.2011	Bries Soleil Full façade		Cloudy	
4	14.12.2011	Canopy Louvers		Intermediate Sky	
5	15.12.2011	Brise Soleil Semi façade		Sunny sky	
6	18.01.2012	Canopy Inclined Double		Intermediate	
7	19.01.2012	Canopy Inclined Single		Intermediate	
8	20.01.2012	Surrounding Shade		Sunny Sky	
9	21.01.2012	Louvers Horizontal		Cloudy	
10	22.01.2012	Louvers Vertical		Clear Sky	
11	23.01.2012	Louvers Horizontal Outwards Inclined		Cloudy Sky	
12	24.01.2012	Louvers Horizontal Inwards Inclined		Intermediate	
13	25.01.2012	Canopy Double		Intermediate	
14	27.01.2012	Simple Window		Intermediate	

Fig. 11. Conditions of the experiment of daylighting levels for all SDs (time of the year and sky conditions).

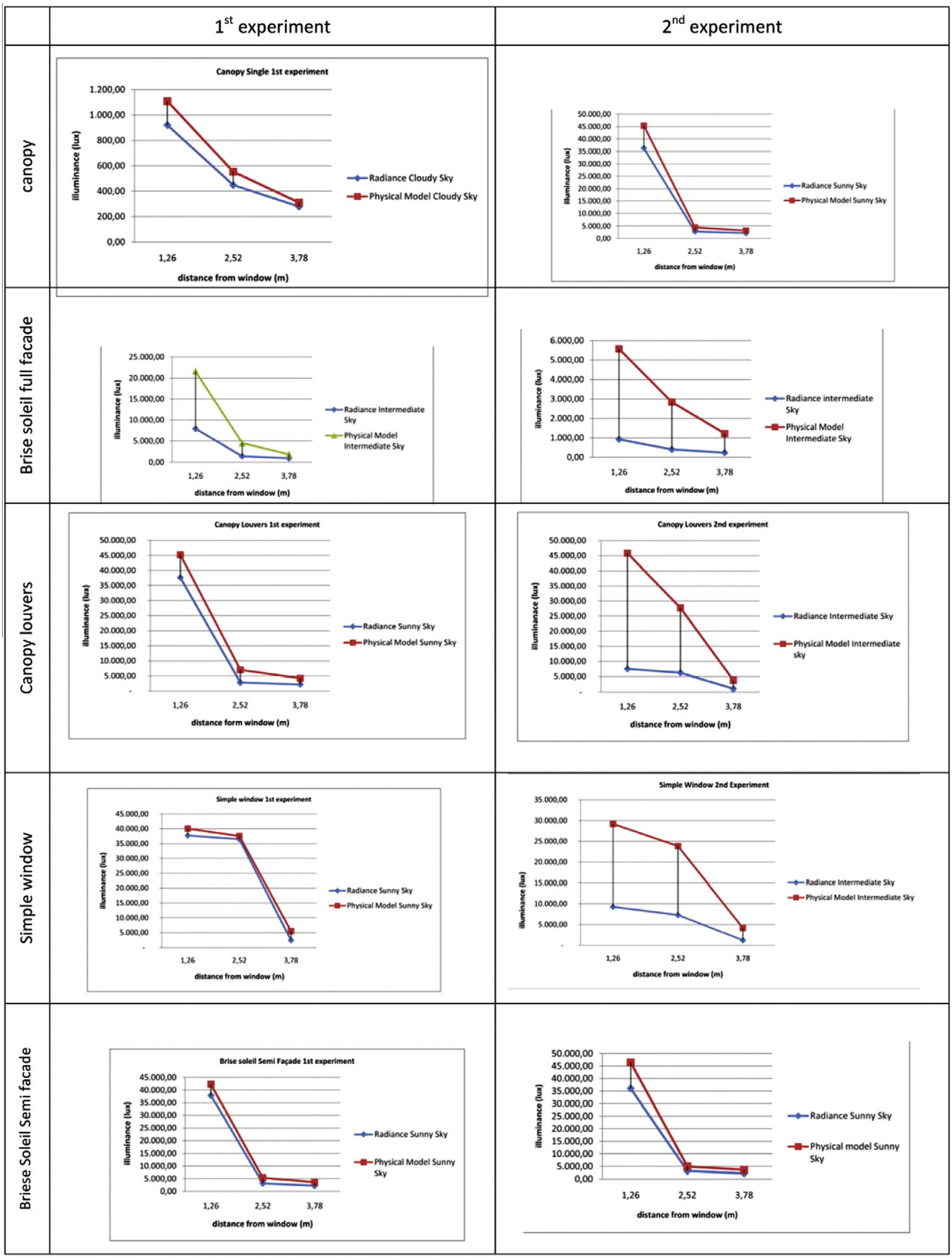

Fig. 12. Comparison of daylighting levels between simulations and physical models in various room depths.

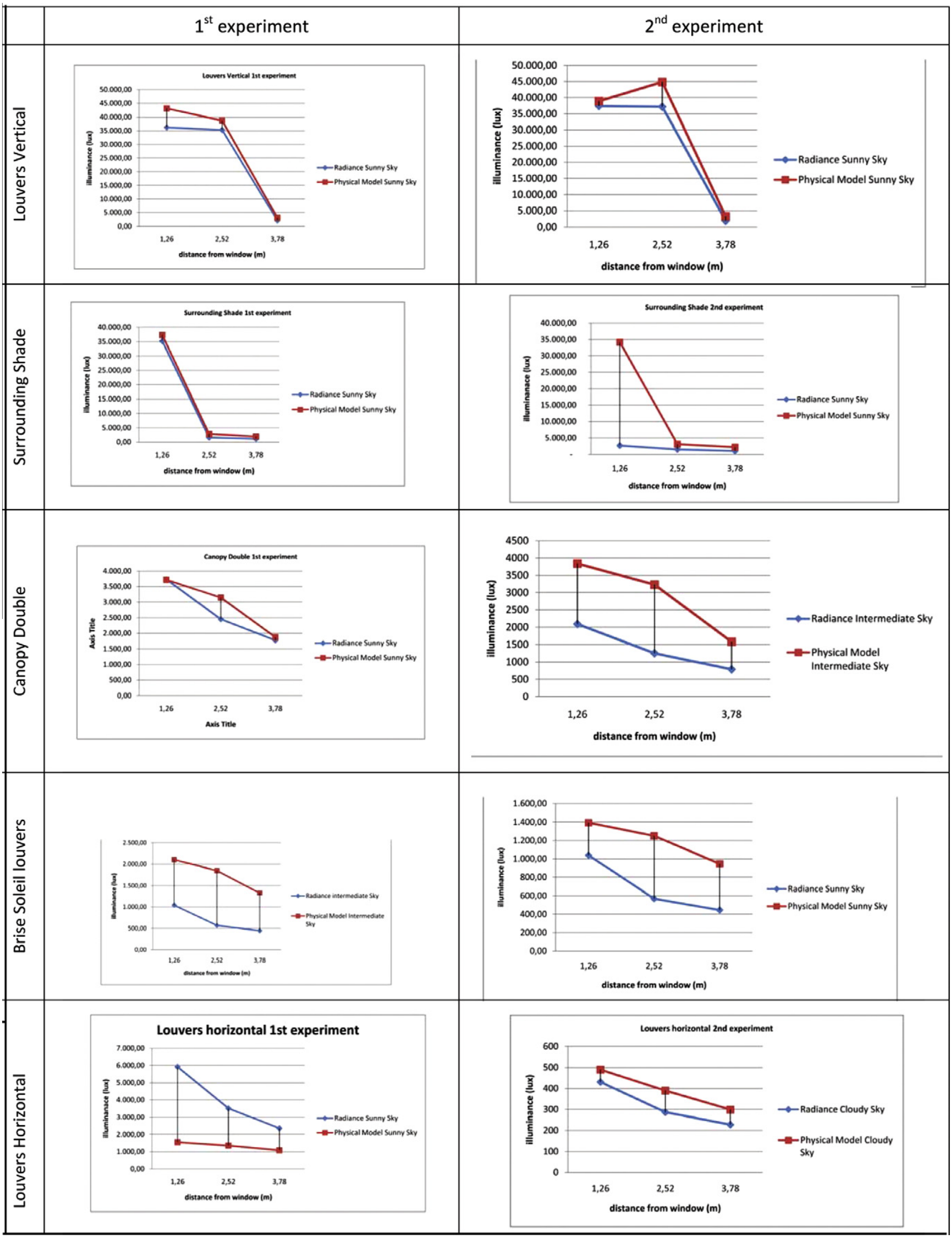

Fig 12. *(continued)*

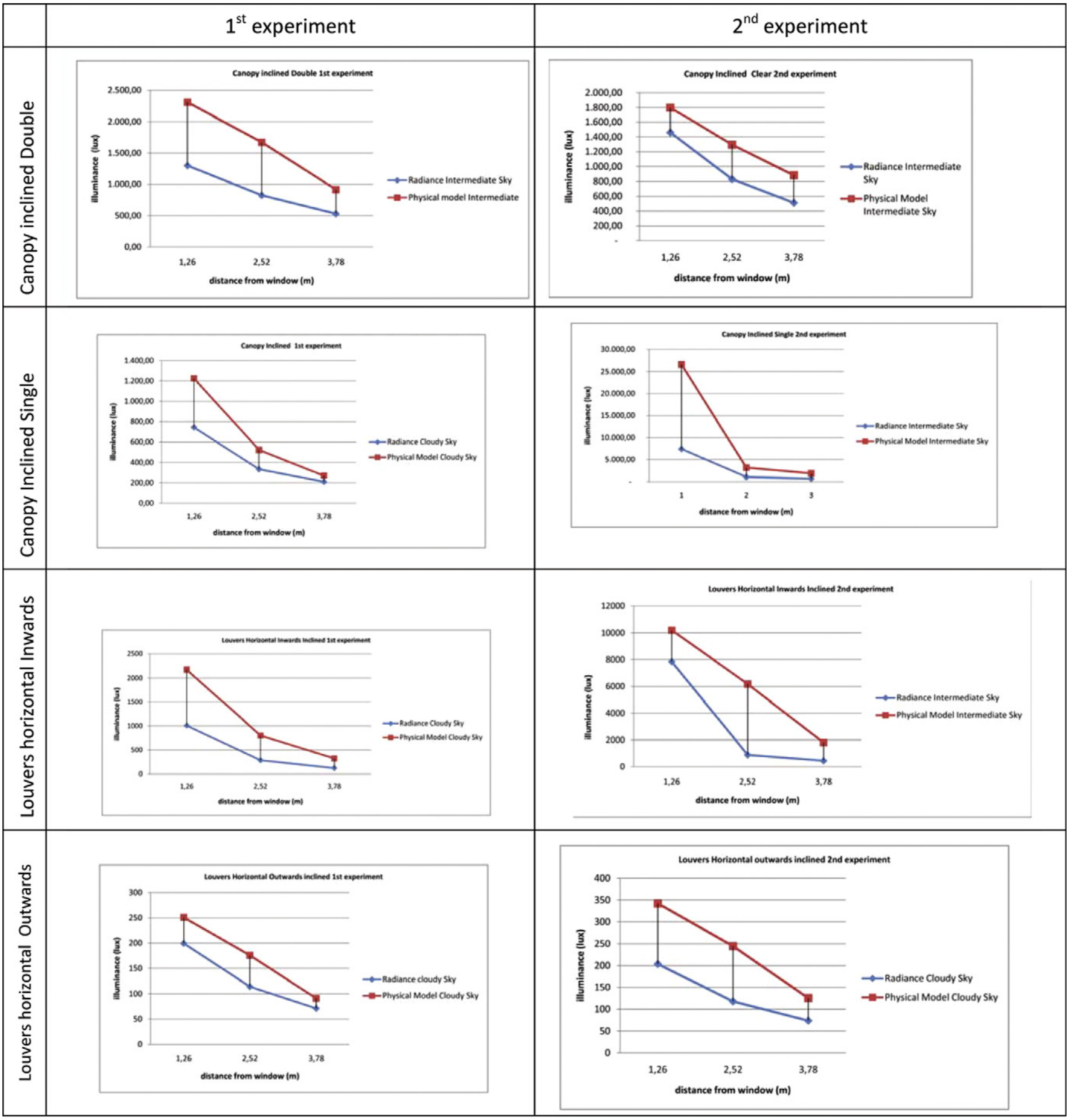

Fig 12. *(continued)*

Canopy inclined single produces is large compared to the area it covers, almost the smallest area of PV installed. For the above mentioned evaluation we are proposing a new term: the **efficiency factor.** The efficiency factor does not have anything to do with the efficiency of the PV installed. It is the ratio of area of PV installed (cm^2) vs. the electricity production through the installed PV (kW h). The high efficiency of the all **Canopy systems** (either inclined, horizontal or with louvers, single or double) can be seen in the chart (Fig. 9). It is noticeable that even thought the system of **Canopy inclined double** covers almost the double area compared to the **Canopy inclined single** as far as PV are concerned, it produces the same amount of electricity. This is probably due to overshadowing (Fig. 10).

We evaluated the **daylight simulation measurements** by doing two series of experiments for each SD in real sky conditions (Fig. 11). We constructed a physical model of the office unit in 1/10 scale and placed six light sensors inside, in order to measure the different illuminance values at the same points of the office unit for each different SD. Due to the fact that we constructed one model of the office unit and we used real sky for the experiment, we could not measure more than one SD each day of the year. Sky illuminance varies each day of the year therefore the numerical results are different when we use the same system, in the same location at the same time of the day. It is important to note that in all experiments physical models overestimate the illuminance factor as shown by Mardaljevic (2001).

These differences are diminished in sunny skies as shown in Fig. 12. A detailed analysis of the comparison between simulation and physical modeling for daylighting is strictly not the purpose of this research and it will be the subject of another paper. The comparison of the two ways of measuring can only conclude the correct use of Radiance application; therefore it allows the correct estimation of the daylight autonomy.

4. Conclusions

In order to assess the SDs for south orientation in Mediterranean climate, a necessity for a balance amongst the above mentioned parameters emerges.

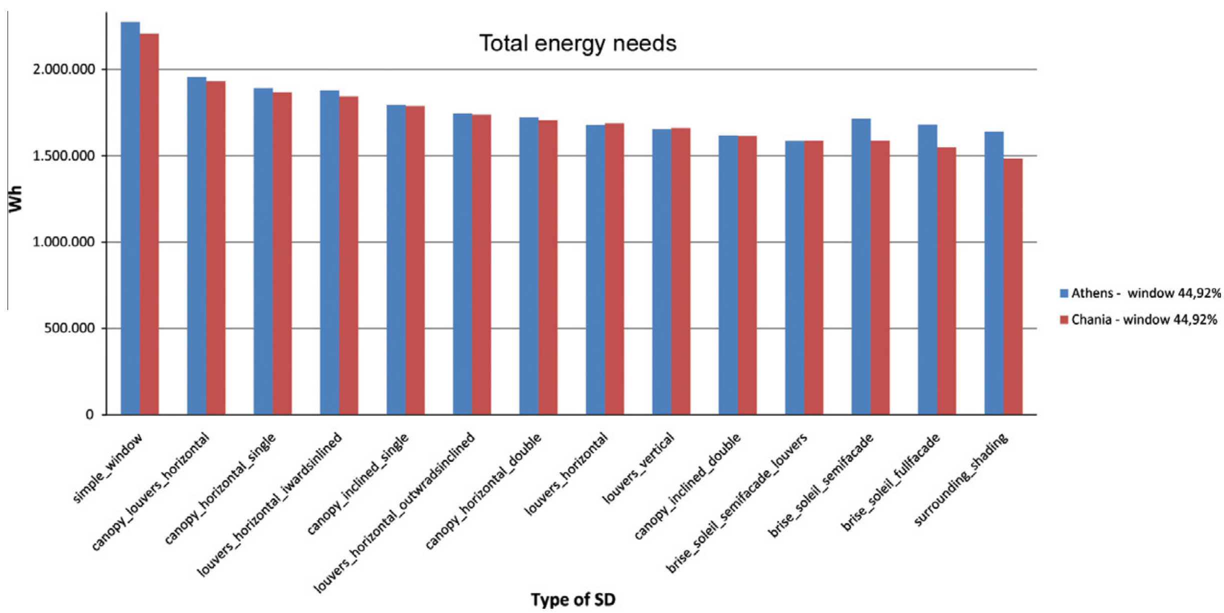

Fig. 13. Total energy needs (heating, cooling, and lighting) for the reference office in Chania and Athens – window 44.92% of façade area.

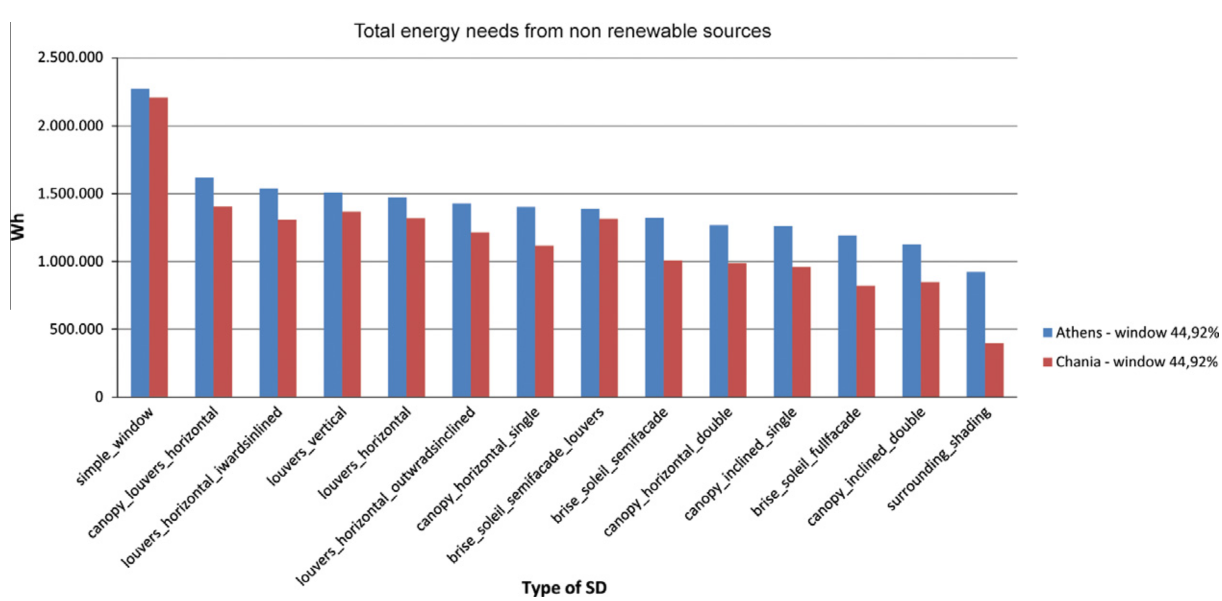

Fig. 14. Total energy needs (heating and cooling) that integrated PV cannot cover for the reference office in Chania and Athens – window 44.92% of façade area.

If we look at Fig. 13 (total energy needs), the lowest energy need for heating, cooling and lighting corresponds to **Surrounding shading, Brise–Soleil full façade, Brise–Soleil semi façade, Brise–Soleil semi facade louvers and Canopy inclined double, in that order, for Chania latitude. For Athens latitude the order is different but still the systems of Surrounding shading, Canopy Inclined double and Brise–Soleil full façade** are among the least energy consuming.

Assuming that the electricity produced from the PV can be used for heating and cooling space, the best performing system of total energy from non renewable sources, meaning the most energy efficient system, is the system of **Surrounding shading** for both latitude points (Fig. 14). The systems of **Brise–Soleil full façade, Canopy inclined double and Canopy inclined single** are considered to be energy efficient as well. Among these systems the **Canopy inclined single** is the most **efficient**, according to the way we introduced efficiency previously in this paper. Companies involved in PV industry could focus on the geometries of SD last mentioned in order to develop BIPV technologies in shading devices.

It is important to note that the most commonly used shading systems for office buildings, the horizontal louvers, outwards or inwards inclined performs badly in terms of low energy consumption from non renewable sources. These kinds of systems might be efficient in terms of energy demands for heating, cooling and lighting (they are in the middle in Fig. 13) but cannot contribute to the reduction of energy consumption. This is a factor that should be taken into account for future developments or energy renovations for these types of buildings **and introduces a path for rethinking the shading devices in office buildings.**

This research highlights the fact that **the way of conceiving SDs in buildings should be changed.** Nowadays, the needs for energy and for the reduction of conventional energy sources in the building sector are high. Shading devices can be considered as **valuable machines** of energy balance. Their geometric characteristics are a result of the avoidance of incident solar radiation in the interior, reduction of cooling, thermal and electricity loads and the maximization of energy production through the integrated PV. The way that SDs are used to be designed has to be changed. It is a new parameter that should be developed further on by buildings' industries, PVs' industries and research institutes, in order to enter the building market.

In order to arrive to a more definitive conclusion regarding the use of **SDs as valuable machines of improvement of the quality of the interior space in office buildings with less energy consumption,** further research needs to be done, that will include more quantitative measures of the SD, plus other, qualitative ones. We recommend a cost/benefit analysis of introducing SD as well as a study on the aesthetic effects of the PV installation. Additionally an assessment of glare problems, visual contact with the outside, air infiltration rate through fenestration that each SD can provide, should be done (Yener, 1999).

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