OPTIMAL DESIGN PARAMETERS OF THE BLINDS INTEGRATED PHOTOVOLTAIC MODULES BASED ON ENERGY EFFICIENCY AND VISUAL COMFORT ASSESSMENTS

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Summary

This research investigates the performance of an external shading device with integrated photovoltaic panels. The optimal design dimensions of an adjustable shading device with horizontal louvers and integrated photovoltaic panels are determined in regards to the energy efficiency of buildings and to the visual comfort of building occupants. The analyses are carried out for three different locations (25°, 35° and 45° latitude north) with three different weather conditions, and taking into consideration three different façade orientations (south east, south, and south west). The impact of the shading device design variables on the energy demand for cooling and heating, on the energy performance of the photovoltaic panels, on the use of natural light inside the building, and on the view to the outside are analyzed. The aim of this research is to offer the architects a simple tool to the design of energy efficient buildings while integrating shading devices and photovoltaic panels into building façades.

Keywords: building integrated photovoltaic, venetian blinds, energy efficiency, visual comfort, cooling load reduction.

1 Introduction

The design parameters of the photovoltaic module integrated blind (PV-blind) determine the amount of electric energy produced by the PV modules, the reduction of the building cooling loads, the use of natural light inside the building, and the building occupants visual comfort. An assessment approach, that encompasses the above mentioned energy efficiency and visual comfort issues, is indispensable in order to figure out the optimal design solution. Various reports have investigated the application of external shading devices and the building integrated photovoltaic on building facades. Kang et al. [1] investigated the harvested electric energy and the shading effect of a blind system with integrated photovoltaic modules. Sun et al. [2] assessed the combined effects of electricity generation and building cooling load reduction for various tilt angles of the shading type building integrated photovoltaic (BIPV) cladding. Hwang et al. [3] studied the maximum electric energy production of photovoltaic modules applied on a building façade.

The aim of this research paper is to identify the optimum design parameters of a PV blind system applied on a building façade taking into consideration a holistic approach for different design variables (location, orientation, weather conditions, blinds' dimensions and tilt angle). The annual total solar insolation on the panels, the reduction of the building cooling loads, and the occupants' visual comfort in terms of natural light availability and the view to the outside were assessed for each design option. The results were discussed concerning the application of amorphous silicon films and crystalline silicon cells with regards to the shading effect.

2 The assessment of the blinds installation

2.1 Blinds design variables and assessment parameters

An experimental office environment was modelled with the Ecotect [4] software. The office space consisted of a 6 x 6 m floor area, 2 levels (total height is 6 m), and a glass curtain wall. The opaque walls, the ground floor slab, and the roof slab have a high thermal resistivity coefficient. The glass curtain wall is made from a double glazing with a 2.7 w/m²k U value. The total number of building occupants is 6 (3 occupants per floor). The office space inside temperature was set to 21ºC.

The design variables that were taken into account are listed in the table below:

Tab. 1 *The blinds design variables*

Design conditions	**Design variables**		
Building location and weather conditions	25º North latitude Abu Dhabi (UAE)	35º North latitude Larnaca (Cyprus)	45º North latitude Piacenza (Italy)
Façade orientation	South	Southeast (**)	Southwest
Horizontal blinds tilt angle	0º	25º or 35º or 45º (***)	60º
Ratio R=d/L between the blinds installation distance to the module depth(*)	1	2	3

(*) the PV module depth was set to 0.5 m.
(**) only a southwest facade was considered since east / west orientations have equivalent geometric shading design solutions.
(***) depends on the building location latitude: the intermediate value (between 0º and 60º) of the blinds tilt angle was set equal to the latitude.

For a specific building location (such as 25ºN) and a specific façade orientation (such as a southern façade) the different design options that could be obtained are listed in the table below:

Tab. 2 *The design options for a specific building location (such as 25ºN) and a specific façade orientation (such as south)*

Design options	**Ratio R=d/L**	**Tilt angle**	**Design options**	**Ratio R=d/L**	**Tilt angle**
option_1_a	1	0º	option_2_c	2	60º
option_1_b	1	25º	option_3_a	3	0º
option_1_c	1	60º	option_3_b	3	25º
option_2_a	2	0º	option_3_c	3	60º
option_2_b	2	25º			

The performance of the PV blinds was assessed taking into account the parameters listed in the table below:

Tab. 3 *Assessment parameters*

Assessment parameters		Unit
1	The annual total solar insolation on the panels per square meter of panel area (*)	Wh/m²
2	The reduction of the cooling load during summer per square meter of floor area (**)	Wh/m²
3	The average daylight factor inside the office space	%
4	The geometric shading coefficient on the glass facade	%
(*) The shading effect (the amount of shadow casted on a panel) was taken into account. (**) The increase of the heating load during winter was deducted from the energy savings that occur during summer for Larnaca and Piacenza building locations. Total floor area is 36 x 2 = 72 m².		

2.2 Simulation results (*)

The energy, daylighting, and shading simulations' results are shown in the below reported figures for 25º latitude north (Abu Dhabi) and a south oriented glass facade:

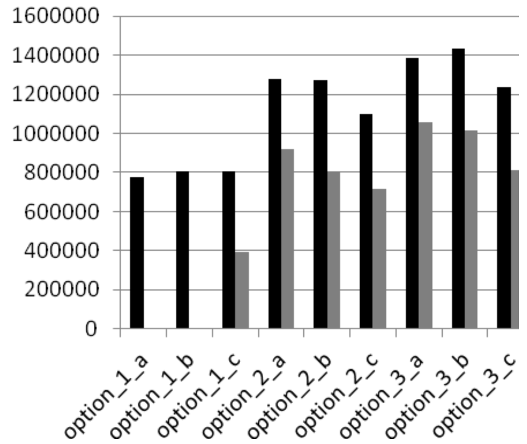

Fig. 1 *(Wh/m²) Annual total solar insolation per square meter of panel area. Black column: full year and taking into consideration the shading effect. Grey column: considering only dates and times when a panel is fully hit by solar radiation without any partial shading.*

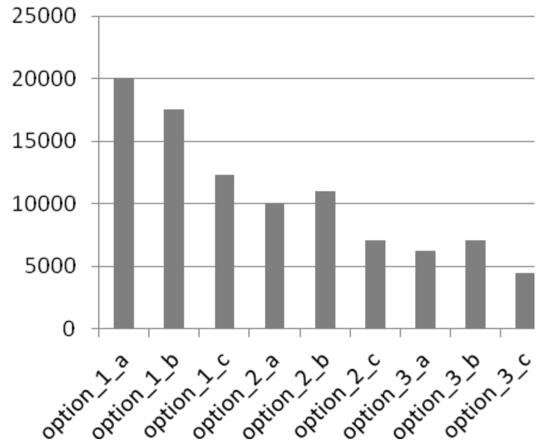

Fig. 2 *(Wh/m²) Cooling load reduction per square meter of floor area. The increase of the winter heating load is not applicable for Abu Dhabi weather conditions.*

(*) the simulation results and interpretation of other building locations and other façade orientations are reported in paragraph 4, pp. 5–10.

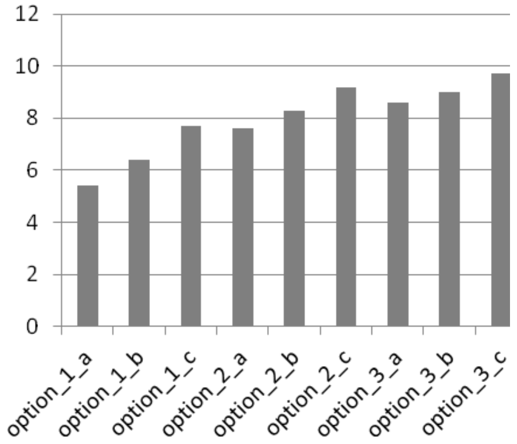

Fig. 3 *(%) Average daylight factor inside the office room*

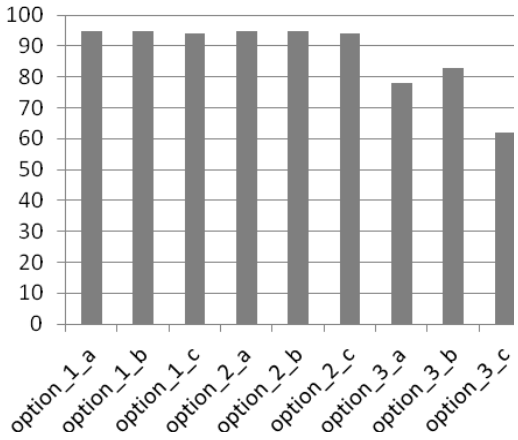

Fig. 4 *(%) Geometric shading coefficient (GSC) on March, 21 at 12:01pm (solar timing)*

2.3 Interpretation of the calculation results

Figure 4 shows that all options, ad exception of option_3_c, have a GSC above 78 % during the summer season which is considered as an efficient shading solution for a south oriented façade [5]. A Daylight Factor DF > 8 % is relative to options "2_b, 2_c, 3_a, 3_b, and 3_c" as shown in figure 3. The reduction of the DF, compared to the non-shaded glass building façade (DF = 11.6 %), is less than 30 % which is an acceptable reduction percentage regarding a shading device installation [5]. From figures 1 and 2 it could be noted that the amount of energy produced by the PV panels (considering the efficiencies of different panel technologies) is much more relevant if compared to the amount of energy saved (Fig. 2). Figure 1 shows that the maximum PV panel insolation occurs in option 3_b. By using a PV panel technology that tolerates the partial shading effect of the blinds, such as amorphous silicon thin films [6], option 3_b would be the optimal design solution. If crystalline silicon cells are used [7], in this case the partial shading of a PV module is not tolerated [6]; option 3_a represents the optimum solution.

3 Conclusions (*)

The optimal design solution, for Abu Dhabi location and a south oriented façade, is option_3_b if amorphous silicon thin films are used (since they tolerate the partial shading of a panel) and option_3_a if crystalline silicon cells are employed. *(*) See Tab.4, p. 10.*

4 Appendix I: simulation results

4.1 Simulation results: 25°N (Abu Dhabi), South-western glass facade

The energy, daylighting, and shading simulations' results are shown in the below reported figures for 25º latitude north (Abu Dhabi) and a southwest oriented glass facade:

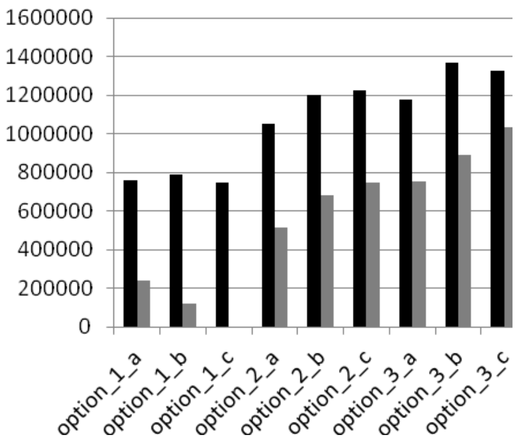

Fig. 5 *(Wh/m²) Annual total solar insolation per square meter of panel area. Black column: full year and taking into consideration the shading effect. Grey column: considering only dates and times when a panel is fully hit by solar radiation without any partial shading.*

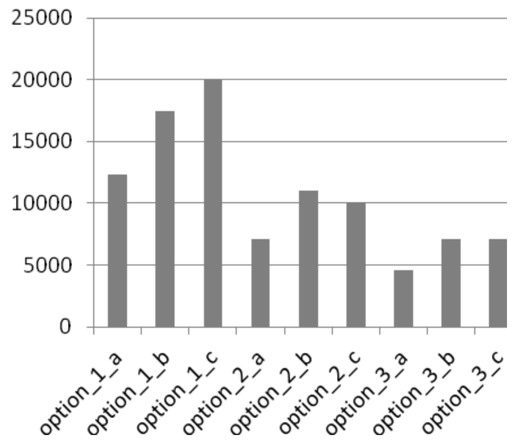

Fig. 6 *(Wh/m²) Cooling load reduction per square meter of floor area. The increase of the winter heating load is not applicable for Abu Dhabi weather conditions.*

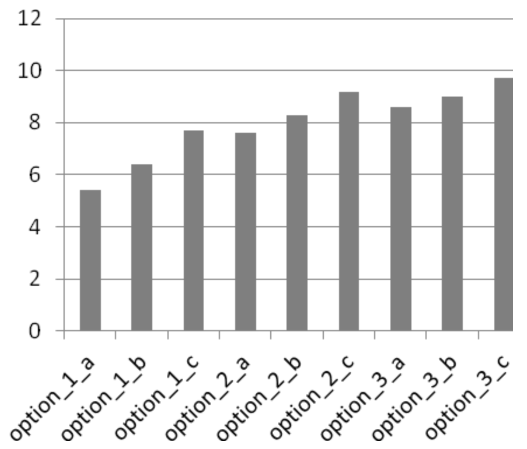

Fig. 7 *(%) Average daylight factor inside the office room*

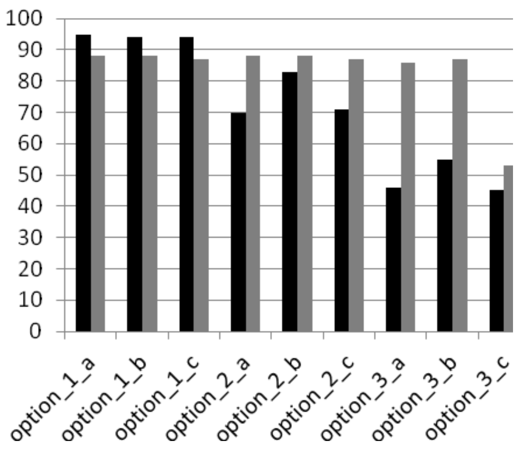

Fig. 8 *(%) Geometric shading coefficient (GSC); black: on March, 21 at 01:31pm (solar timing), grey: on April, 21 at 12:39pm (solar timing)*

4.2 Simulation results: 35°N (Larnaca), Southern glass facade

The energy, daylighting, and shading simulations' results are shown in the below reported figures for 35° latitude north (Larnaca) and a south oriented glass facade:

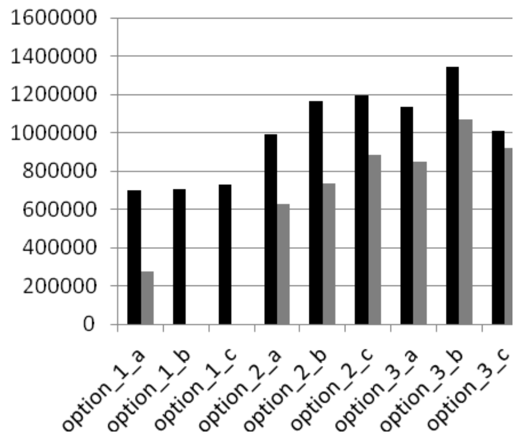

Fig. 9 *(Wh/m²) Annual total solar insolation per square meter of panel area. Black column: full year and taking into consideration the shading effect. Grey column: considering only dates and times when a panel is fully hit by solar radiation without any partial shading.*

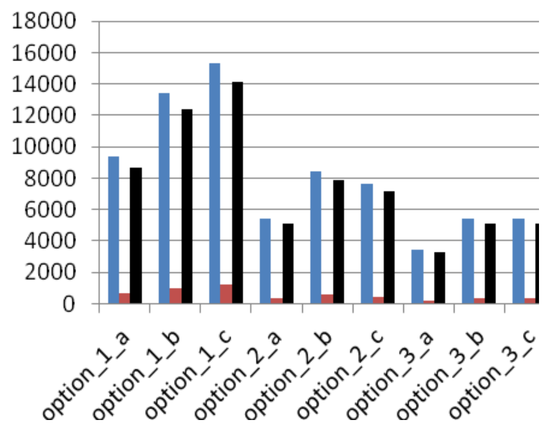

Fig. 10 *(Wh/m²) Blue column: cooling load reduction, red column: heating load increase, black column: energy savings per square meter of floor area.*

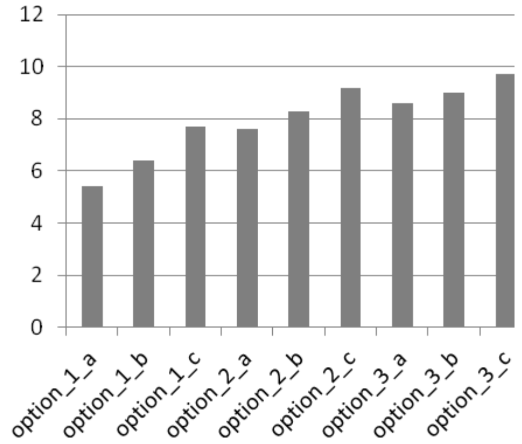

Fig. 11 *(%) Average daylight factor inside the office room*

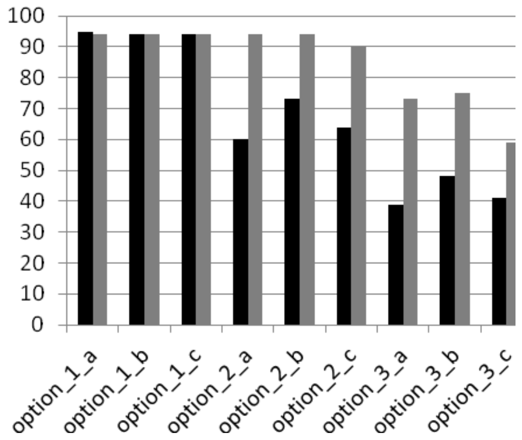

Fig. 12 *(%) Geometric shading coefficient (GSC); black: on March, 21 at 12:07pm (solar timing), grey: on April, 21 at 12:15pm (solar timing)*

4.3 Simulation results: 35°N (Larnaca), South-western glass facade

The energy, daylighting, and shading simulations' results are shown in the below reported figures for 35º latitude north (Larnaca) and a southwest oriented glass facade:

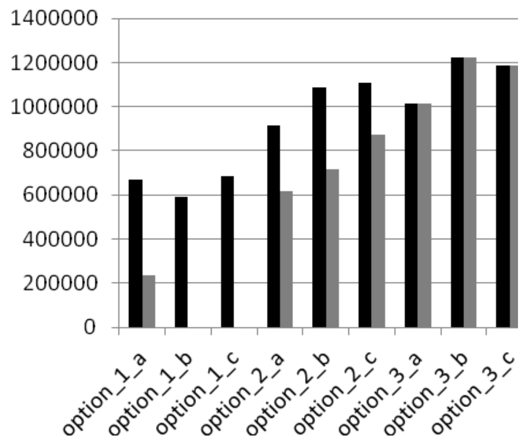

Fig. 13 *(Wh/m²) Annual total solar insolation per square meter of panel area. Black column: full year and taking into consideration the shading effect. Grey column: considering only dates and times when a panel is fully hit by solar radiation without any partial shading.*

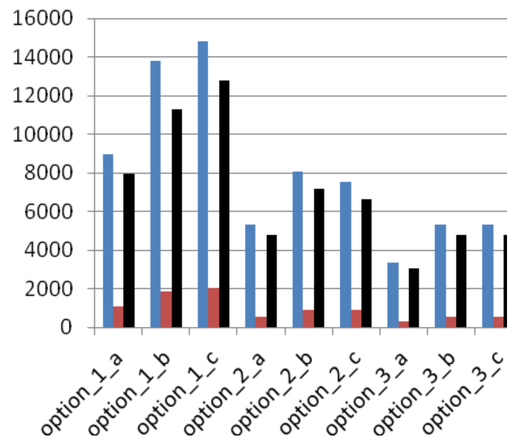

Fig. 14 *(Wh/m²) Blue column: cooling load reduction, red column: heating load increase, black column: energy savings per square meter of floor area.*

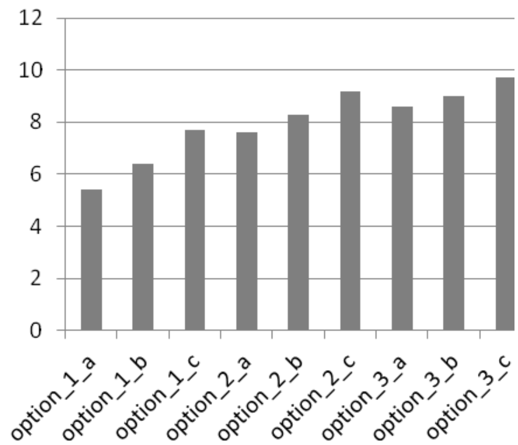

Fig. 15 *(%) Average daylight factor inside the office room*

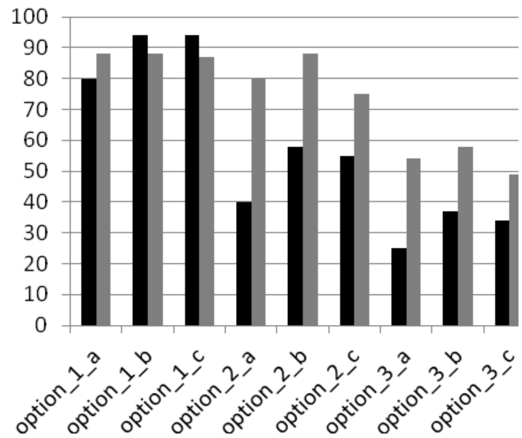

Fig. 16 *(%) Geometric shading coefficient (GSC); black: on March, 21 at 02:07pm (solar timing), grey: on April, 21 at 01:15pm (solar timing)*

4.4 Simulation results: 45°N (Piacenza), Southern glass facade

The energy, daylighting, and shading simulations' results are shown in the below reported figures for 45° latitude north (Piacenza) and a south oriented glass facade:

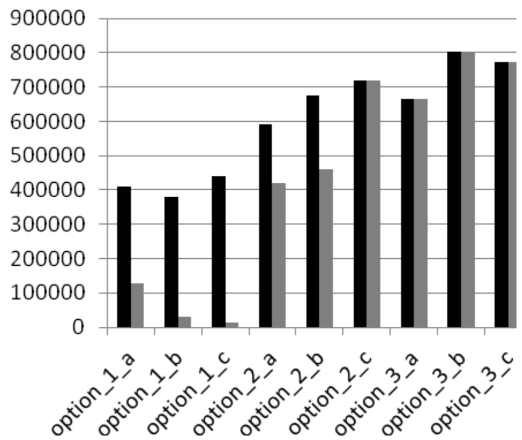

Fig. 17 *(Wh/m²) Annual total solar insolation per square meter of panel area. Black column: full year and taking into consideration the shading effect. Grey column: considering only dates and times when a panel is fully hit by solar radiation without any partial shading.*

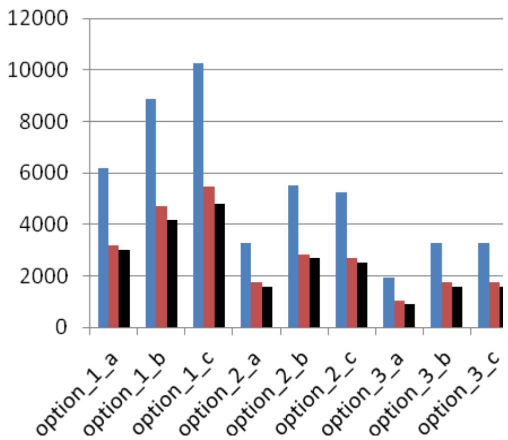

Fig. 18 *(Wh/m²) Blue column: cooling load reduction, red column: heating load increase, black column: energy savings per square meter of floor area.*

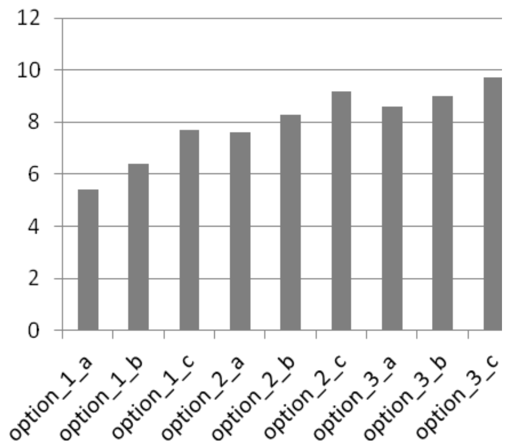

Fig. 19 *(%) Average daylight factor inside the office room*

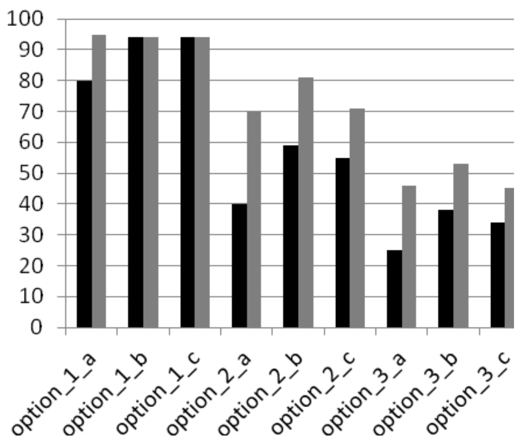

Fig. 20 *(%) Geometric shading coefficient (GSC); black: on March, 21 at 12:01pm (solar timing), grey: on April, 21 at 12:10pm (solar timing)*

4.5 Simulation results: 45°N (Piacenza), South-western glass facade

The energy, daylighting, and shading simulations' results are shown in the below reported figures for 45º latitude north (Piacenza) and a southwest oriented glass facade:

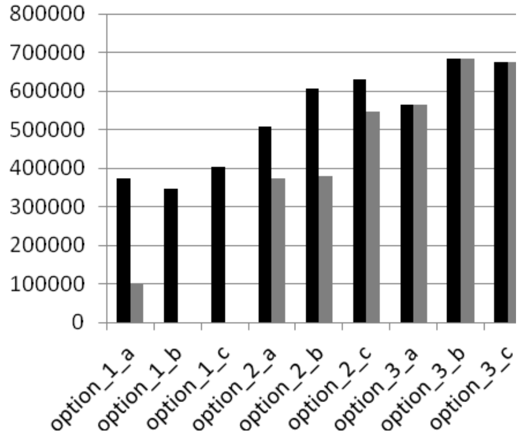

Fig. 21 *(Wh/m²) Annual total solar insolation per square meter of panel area. Black column: full year and taking into consideration the shading effect. Grey column: considering only dates and times when a panel is fully hit by solar radiation without any partial shading.*

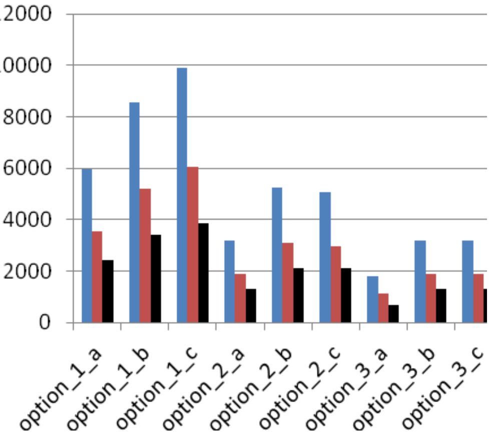

Fig. 22 *(Wh/m²) Blue column: cooling load reduction, red column: heating load increase, black column: energy savings per square meter of floor area.*

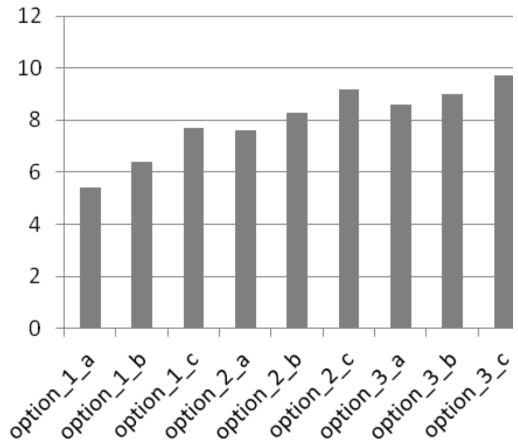

Fig. 23 *(%) Average daylight factor inside the office room*

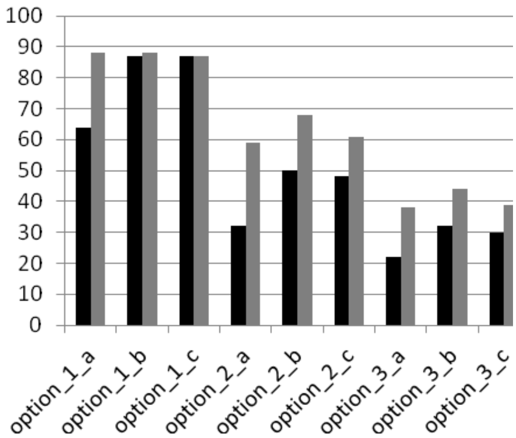

Fig. 24 *(%)Geometric shading coefficient (GSC); black: on March, 21 at 02:01pm (solar timing), grey: on April, 21 at 01:40pm (solar timing)*

4.6 Optimal design options

Tab. 4 *The optimal design options for a specific building location and for a specific façade orientation. (Left hand section is considering amorphous thin films PV panels, right hand section is considering crystalline cells PV panels).*

Amorphous thin films PV panels			**Crystalline cells PV panels**		
Building location	**Façade orientation. Amorphous**	**Optimal design option**	**Building location**	**Façade orientation. Crystalline**	**Optimal design option**
25°N Abu Dhabi	South	option_3_b	25°N Abu Dhabi	South	option_3_a
25°N Abu Dhabi	Southwest	option_3_b	25°N Abu Dhabi	Southwest	option_3_c
35°N Larnaca	South	option_3_b	35°N Larnaca	South	option_3_b
35°N Larnaca	Southwest	option_3_b	35°N Larnaca	Southwest	option_3_b
45°N Piacenza	South	option_3_b	45°N Piacenza	South	option_3_b
45°N Piacenza	Southwest	option_3_b	45°N Piacenza	Southwest	option_3_b

References

[1] KANG, S., HWANG, T. *Theoretical analysis of the blinds integrated photovoltaic modules.* Energy and Buildings 46 (2012) 86–91.

[2] SUN, L.L., YANG, H.X. *Impacts of the shading-type building-integrated photovoltaic claddings on electricity generation and cooling load component through shaded windows.* Energy and Buildings 42 (2010) 455–460.

[3] HWANG, T., KANG, S., KIM, J.T. *Optimization of the building integrated photovoltaic system in office buildings-Focus on the orientation, inclined angle and installation area*. Energy and Buildings 46 (2012) 92–104.

[4] AUTODESK. *Autodesk Ecotect Analysis – Sustainable Building Design Software –* WWW:< http://usa.autodesk.com/ecotect-analysis/>.

[5] BAHR, W. *Illuminazione naturale e schermature solari: un approcio valutativo per la scelta e il disegno delle schermature solari esterne negli edifici scolastici*. Osdotta III Seminar, Lecco 2007, Firenze University Press 2008, pp. 265–272.

[6] ENERGETHICS. *Fotovoltaico: un investimento alla luce del sole.* Energethics, 2009 [online]. WWW: <http://www.energethics.it/download/libro_sul_fotovoltaico.pdf>.

[7] SUNPOWER. *Sunpower technology powers world-class research and education center in Masdar City*. Sunpower, 2010 [online]. WWW:<http://global.sunpowercorp.com/cs/Satellite?blobcol=urldata&blobheadername1=Content-Type&blobheadername2=Content-Disposition&blobheadervalue1=application%2Fpdf&blobheadervalue2=inline%3B+filename%3D11_623_sp_masdar_uae_cs_a4_w.pdf&blobkey=id&blobtable=MungoBlobs&blobwhere=1300274723076&ssbinary=true>.