STUDY OF THE SOLAR COLLECTORS SELF-SHADING PHENOMENA FOR 18 CITIES FROM ROMANIA, BULGARIA AND FRANCE

Marian ALEXANDRU[1], Andrei DAMIAN[2]

The paper is focused on the self-shading phenomena that occur when solar collectors are placed on vertical surfaces, like building facades, in order to avoid their installation on the horizontal terraces or tilted roofs. The vertical mounting appears to be less advantageous due to a reduced view factor with the sky vault. Based on the geometric theory of the solar angles, the study outlines the influence of the climate type on the self-shading phenomena magnitude, and on the annual useful beam solar energy captured by the collectors. The analysis was performed for eighteen cities from Romania, Bulgaria and France, located at similar geographic latitudes.

Keywords: Solar Thermal Collectors, Self-shading, Building Integration, Solar Thermal Systems

Nomenclature :
α [degree] - Solar height (solar elevation)
β [degree] - Slope of the surface measured from the horizontal position
γ [degree] - Surface azimuth angle (surface orientation), the deviation of the normal to the surface with respect to the local meridian, east positive, zero south
φ [degree] - Geographic latitude, north positive
ω [degree] - Hour angle, noon zero and morning positive
θ [degree] - The angle of incidence for an arbitrarily orientated surface, the angle between normal to the surface and the sun-earth vector
A [m^2] - Total area of solar collectors
A_s [m^2] - Sunlit area of solar collectors
$I_{D\beta}$ [W/m^2] - The incident direct solar radiation on a β sloped surface
UDC [-] - Usage Degree Coefficient
SF [-] Solar Fraction : the ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application

[1] PhD student, Technical University of Civil Engineering Bucharest, Romania, e-mail:alex_mar_taco@yahoo.com
[2] Associate professor, Technical University of Civil Engineering Bucharest, Romania, e-mail:adamian7@yahoo.com

1. Introduction

Global energy consumption has steadily increased over the last decades and buildings are credited with about 40% of the total energy consumed. The construction sector presents a great opportunity to reduce greenhouse gas emissions and protect the environment. In this respect, the use of renewable energy is undoubtedly the most promising method for decreasing energy consumption in order to achieve the energy efficient building status. From all known types of renewable energy, solar energy presents the most extensive features and possibilities of direct conversion to thermal or electric energy [1].

Unlike photovoltaic systems, thermal solar technology has several advantages, such as higher economic efficiency with a shorter payback time, being a mature and reliable technology both in the domestic and large-scale applications. It is anticipated that solar thermal technologies will have an accelerated development in the coming years to increase the solar fraction in the energy balance of buildings both for the production of hot water and for their heating / cooling [2].

However, solar thermal collectors are not yet widely used to reduce conventional energy consumption in buildings, even if the price of energy is steadily increasing [3]. Architectural integration is still a major problem as per the implementation scale of thermal solar collectors. Thermal solar collectors are often viewed only as components of building installations and are installed on roofs where they are less visible and the impact on building architecture is minimal. Thus, they can be oriented and tilted so as to maximize the capture of solar energy. Because of the unevenness that characterizes the distribution of solar energy available throughout the year, there is a risk of overheating due to stagnation, especially during the summer, making it difficult to design a heat system that accurately corresponds to the energy requirement [4].

For geographic areas with middle latitudes, the location of solar panels on the optimally oriented vertical facades may be a solution to this problem. As can be seen from Fig.1, the direct solar radiation available in the capture plane is more evenly distributed over the year when the panels are in vertical position [5].

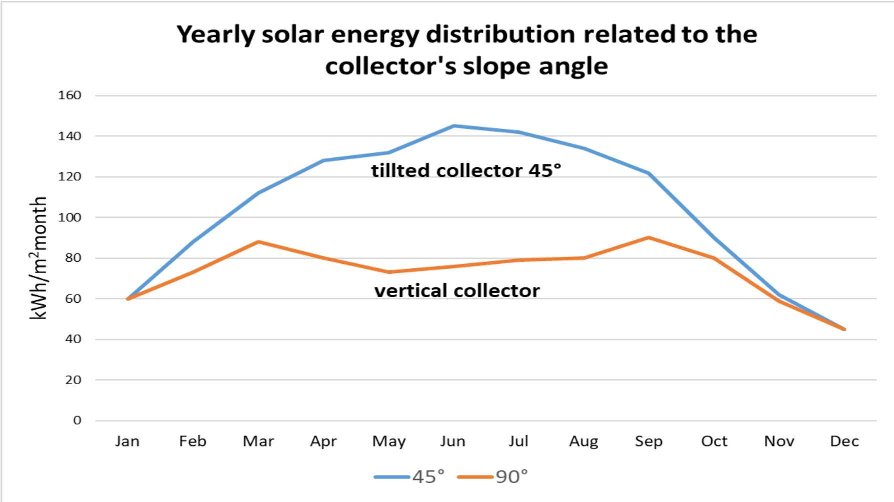


Fig.1. Yearly distribution of the solar on vertical mounted and 45° sloped panels (Graz 47°N) [5]

A. Giovanardi et al. [6] shew that the facades represent additional envelope elements for the installation of the Solar Thermal Collectors (STC) for hot water supply or buildings heating/cooling energy input. Although the incidence of solar radiation on a vertical surface is about 30% lower than for an optimally inclined surface, the STC position on the vertical facades leads to a significant reduction in the risk of stagnation and allows the system to be sized according to the actual energy requirement. In addition, STCs are less affected by their coating with dust or snow, and there is no need to periodically clean them.

T.T.Chow et al.[7] performed a study on the possibilities of predicting incidence of solar radiation on vertical surfaces. In the first part of the paper there is a review of the mathematical models for the quantitative assessment of solar radiation such as: The anisotropic sky model developed by Threlkeld [8] and used by DOE2 software, Hay and Davies model, Reindl model used by TRNSYS and Perez model used by Energy Plus. In the second part of the paper, the three mentioned software are used to predict incidence of solar radiation on an un-shaded vertical façade located in Hong Kong and having different orientations. it is highlighted that for Hong Kong (HK), due to geographic position and climatic conditions, the best orientation is South-West (SW). Also, for the other orientations, there are differences of up to 10% between the three forecasts.

A recent study by R. O'Hegarty et al. [9] analyses geometrically several types of buildings with different destinations: residential, hotel, office building, hospital, starting with a real 17-storey building with a usable area of 5200 m^2, 300 m^2 terraced area and total facade surface of 3000 m^2 corresponding to a roof/façade ratio of 0.1. Two more geometric types of buildings are considered, as shown in Figure 2, having the same usable surface of 5200 m^2, so the same requirement for hot water. In contrast, the second surface of the terrace is 520 m^2 the roof/facades ratio being 0.2 and 866 m^2 respectively for the third case with 0.4 the ratio of the surfaces. Simulations are run to determine the STC surface using the Polysun software. For the first case, a solar fraction of 0.25 can be achieved only by using the terrace and the main facade as the capture surface to meet the high water demand for the hotel and the hospital. A solar fraction of 0.5 would be difficult to achieve in this case. For buildings with a larger surfaces area ratio (0.2 or 0.4), a solar fraction of 0.25 does not involve the use of facades as capture surfaces, but becomes necessary in order to obtain a solar fraction of 0.5. In conclusion, in the case of high buildings, with a small terrace surface and a high hot water demand, the use of optimally oriented vertical facade becomes a necessity for obtaining a reasonable Solar Fraction (SF).

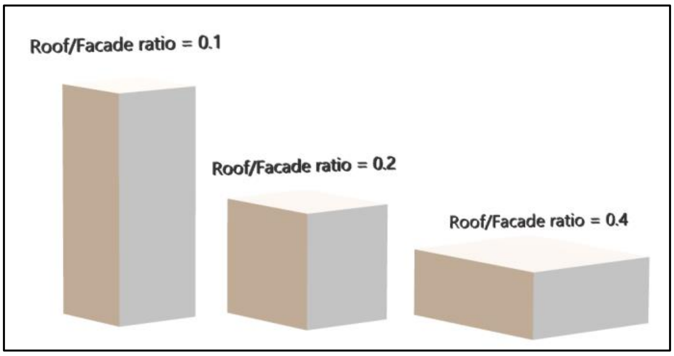


Fig. 2. The three geometric types of buildings considered. Roof/facade ratios: 0.1, 0.2, 0.4 [8]

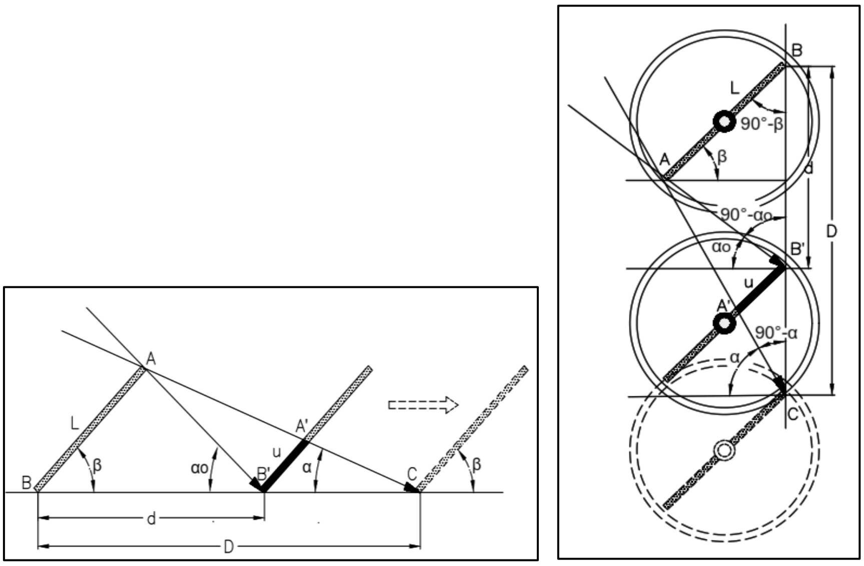
2. Study hypothesis

The study is focused on the self-shading phenomena between adjacent solar collectors placed on horizontal or vertical wall surfaces, for 12 geographical sites located in Romania, Bulgaria and France (4 sites for each country). It continues the research performed for the investigation of the self-shading phenomena for the Romania case [10]. Within this research, the complete theory of the calculation method for the self-shading areas of the collector’s rows had been extensively explained. The method relies on the solar angles calculated for every day and hour for one-year time lag, as well as on the surfaces solar azimuth.

In the paper mentioned above, the authors show that the self-shading phenomena occurs differently for the two type of panels mounting. When the panels are set on a horizontal plane, self-shading occurs for low solar height angles, therefore, at the sunset and sunrise when sunlight is reduced anyway. On the other hand, when placing the panels on vertical surfaces, the mutual shading occurs at noon, when the sun's height is the maximum, and in ideal atmospheric conditions, the solar radiation is also the maximum. This observation is confirmed by the study of I. Bergmann [5] and presented graphically in Fig. 1. Moreover, even from a geometric point of view, the self-shining phenomenon occurs differently for the two panels positioning models.

Fig. 3a schematically shows a field of solar panels located on a horizontal plane with a constant distance d between the strings of panels. The length of panels is L and the slope is β. The angle α_0 represent the angle of sun height for which a solar beam passing at the limit over the row of front panels reaches the base of the row of rear panels. For any angle α smaller than α_0, an U-length shadow strip appears on the rear panel rows. Using the trigonometric relationships between the angles and the lengths of Fig.1, it can be deduced a relationship for the dimensionless shading factor U, that characterizes the shading rate of the panels for any given α and β angles [10] :

$$U = \frac{u}{L} = \sin\beta \frac{\left(\dfrac{\tan\alpha_0 - \tan\alpha}{\tan\alpha_0 \tan\alpha}\right)}{\left(\cos\beta + \dfrac{\sin\beta}{\tan\alpha}\right)} \; [-] \qquad (1)$$



a. b.

Fig. 3. The layout of self-shading for the horizontal (a) and vertical (b) mounting. [10]

Figure 3b shows the calculation scheme for the case of placing solar panels on vertical surfaces. This is a particular case that refers to solar panels with evacuated tubes that are placed in a vertical position on the facade of a building and the tubes are rotated in their socket so that the fins form an angle β with the horizontal plane. The case is similar to that of plane panels placed with a slope β on a vertical facade, less common due to the impossibility of their integration into the building envelope.

It should be noted that in this case the distance *d* cannot be determined by calculation at the design stage of the panel grid but is constructively fixed by the panel manufacturer for reasons unrelated to the self-shading. Keeping the same notations as in the previous case and using the trigonometric relations of symmetry with the displacement with a quarter of the arch, the equation (2) is obtained for the shading factor *U* (-) :

$$U = \frac{u}{L} = \cos\beta \frac{\left(\frac{\cot\alpha_0 - \cot\alpha}{\cot\alpha_0 \cot\alpha}\right)}{\left(\sin\beta + \frac{\cos\beta}{\cot\alpha}\right)} \; [-] \quad (2)$$

Using the shading factor *U*, the sunlit surface A_s (in m^2) can be calculated:

$$A_s = A(1-U) \quad (3)$$

The direct component of global solar radiation incident on the β-tilted surface, $I_{D\beta}$ (W/m^2) was calculated using the following equation [11]:

$$I_{D\beta} = I_{DHoriz} \frac{cos\theta}{sin\alpha} \quad (4)$$

Solar height angle α (rad) was calculated according to Iqbal [12]:

$$\sin\alpha = \sin\delta\sin\varphi + \cos\delta\cos\varphi\cos\omega \quad (5)$$

The angle of incidence was calculated according to Coffari [13]:

$$\cos\theta = (\sin\varphi\cos\beta - \cos\varphi\sin\beta\cos\gamma)\sin\delta + (\cos\varphi\cos\beta + \sin\varphi\sin\beta\cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \quad (6)$$

It should be noted that the simulations had been made with 10 minutes time step and the values of direct horizontal solar radiation I_{DHoriz} were generated with the Meteonorm software for the 18 cities investigated [14]. This software is used by many building simulation tools available on the energy simulation market, providing an extended database of weather data throughout the world. This data are measured for one-hour time step by NASA weather stations and then statistically processed to become “climatic data” in order to be used for different geographical locations.

The geographical latitudes of the cities investigated spread between 41,52 °N (Sandanski – Bulgaria) and 48,82°N (Paris – France), respectively.

According to the theory mentioned in [1], we have calculated the annual beam solar energy and annual usage degree for the 18 cities, for two types of installation horizontal position of the solar collectors:

- An installation on the building terrace, with a tilt angle of 45° related to the horizontal plane, all collectors facing South, and
- An installation on a vertical South-oriented wall, with a tilt angle of 45° for the collector's plates related to the horizontal plane

In the tables 1 to 3 are presented the results obtained for the three countries investigated.

Table 1

Annual beam solar energy and usage degree for the Romania case

	Latitude angle	Theoretical available energy	Real available energy (with self-shading)		Annual usage degree	
			H	V	H	V
		[MWh]	[MWh]	[MWh]	[%]	[%]
Bucuresti	44'30" N	110.3	107.3	98.5	97.3	89.3
Iasi	47'10" N	114.0	109.9	103.5	96.4	90.7
Cluj Napoca	46'47" N	97.4	93.9	89.0	96.5	91.4
Constanta	44'13" N	116.7	112.1	103.5	96.1	88.8
Timisoara	45'46" N	93.7	91.2	84.2	97.3	89.8
Craiova	44'14" N	109.4	106.4	98.0	97.3	89.6

Table 2

Annual beam solar energy and usage degree for the France case

	Latitude angle	Theoretical available energy	Real available energy (with self-shading)		Annual usage degree	
			H	V	H	V
		[MWh]	[MWh]	[MWh]	[%]	[%]
Paris	48,82 ºN	70,4	68,2	64,4	96,8	91,5
Ajaccio	41,92 ºN	135,3	132,2	118,5	97,7	87,6
Bordeaux	44,83 ºN	89,9	86,3	81,3	96	90,4
Clermont	45,80 ºN	84,2	80,9	76,3	96	90,6
Marseille	43,43 ºN	126,2	122,7	112,2	97,2	88,9
Nancy	48,68 ºN	74,3	70,5	67,9	94,9	91,4

Table 3

Annual beam solar energy and usage degree for the Bulgaria case

	Latitude angle	Theoretical available energy	Real available energy (with self-shading)		Annual usage degree	
			H	V	H	V
		[MWh]	[MWh]	[MWh]	[%]	[%]
Sofia	42,68 °N	83,7	81,4	74,7	97,2	89,2
Chirpan	42,20 °N	91,6	88,9	82,0	97,0	89,5
Kurdjali	41,65 °N	99,2	96,2	86,5	96,9	87,2
Pleven	43,45 °N	61,2	57,9	52,7	94,6	86,1
Sandanski	41,52 °N	61,5	58,3	53,8	94,8	87,5
Varna	43,20 °N	112,5	109,4	99,8	97,2	88,7

Taking into account the great variety of the results obtained, we have chosen to split these results for future analysis into five groups, depending on the geographical latitudes of the cities investigated:

- Group 1, containing the cities: Sofia, Chirpan, Sandanski, Kurdjali and Ajaccio, for latitudes spreading from 41,52 °N to 42,68 °N ;
- Group 2, containing the cities: Pleven, Varna, Bucuresti, Craiova, Constanta and Marseille, for latitudes spreading from 43,20 °N to 44,30 °N;
- Group 3, containing the cities: Bordeaux, Timisoara and Clermont, for latitudes spreading from 44,83 °N to 45,80 °N;
- Group 4, containing the cities: Iasi and Cluj, for latitudes of 47,10 °N and 46,47 °N respectively ;
- Group 5, containing the cities: Paris and Nancy, for latitudes of 48,82 °N and 48,68 °N respectively.

3. Simulation results

In figure 4 is represented the variation of the annual usage degree coefficient (UDC) for the 18 cities and the 5 groups, according to their geographical latitudes and two types of mounting: horizontal and vertical. This non-dimensional factor could be expressed by the following relation:

$$UDC = \frac{A_s}{A} \quad [-] \tag{7}$$

In the figures 5 to 9 are represented graphically the results obtained for the 5 groups defined previously, in terms of annual useful beam solar energy radiation captured by the solar collectors, for the two possible installation cases: on vertical and on horizontal surface.

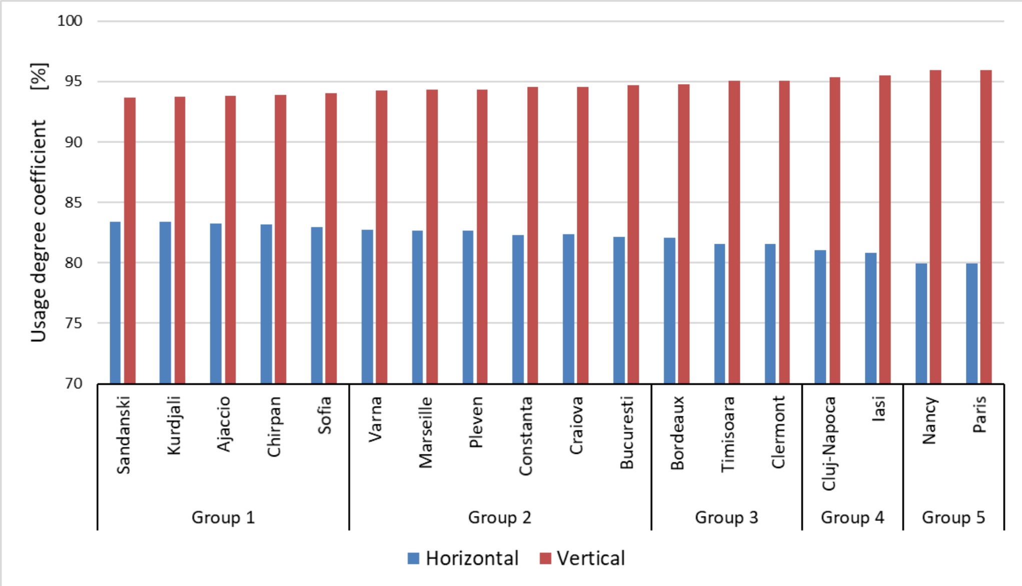


Fig. 4 : Usage degree coefficient variation depending on the cities' geographical latitudes

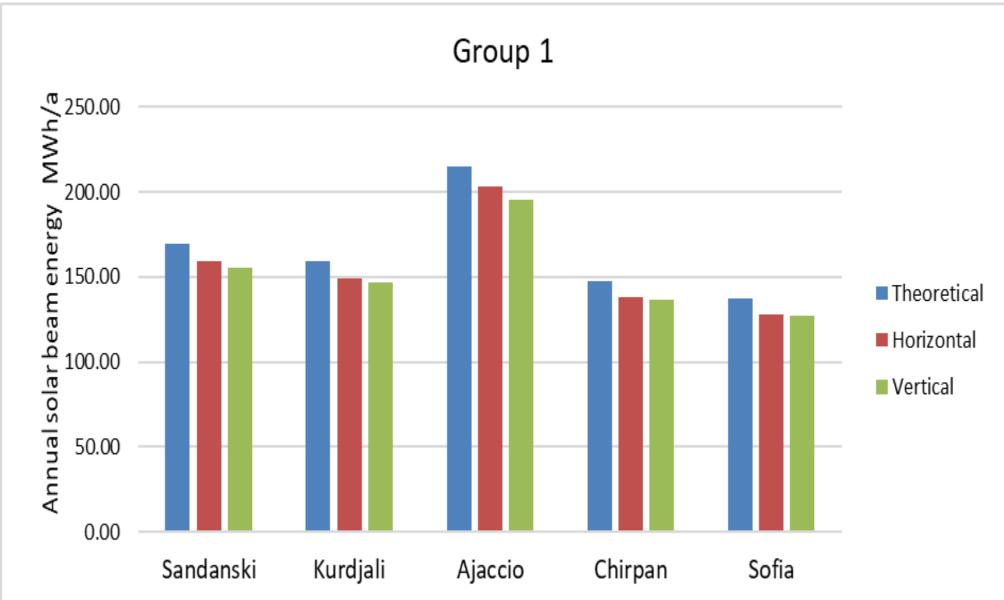


Fig. 5 : Annual solar beam energies calculated for the Group 1

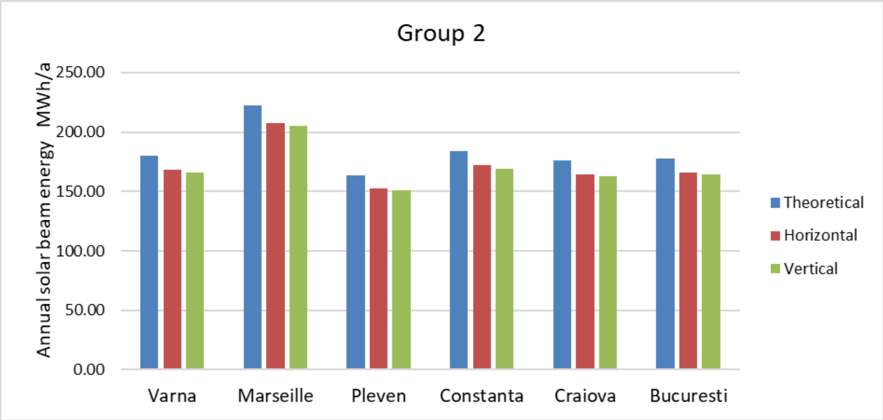


Fig. 6 : Annual solar beam energies calculated for the Group 2

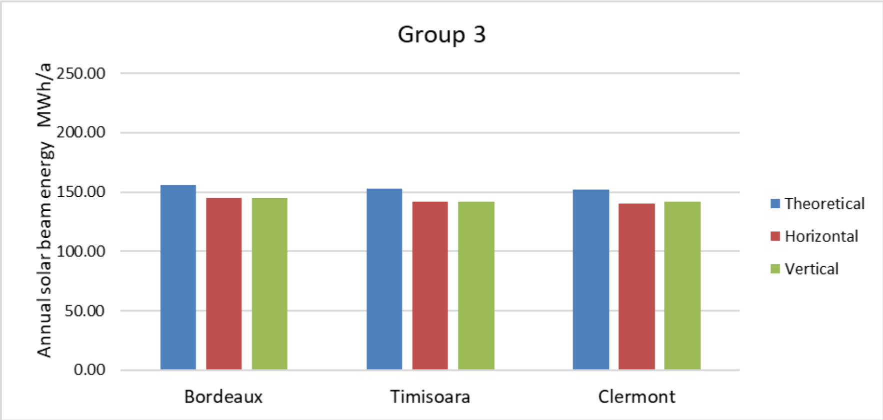


Fig. 7 : Annual solar beam energies calculated for the Group 3

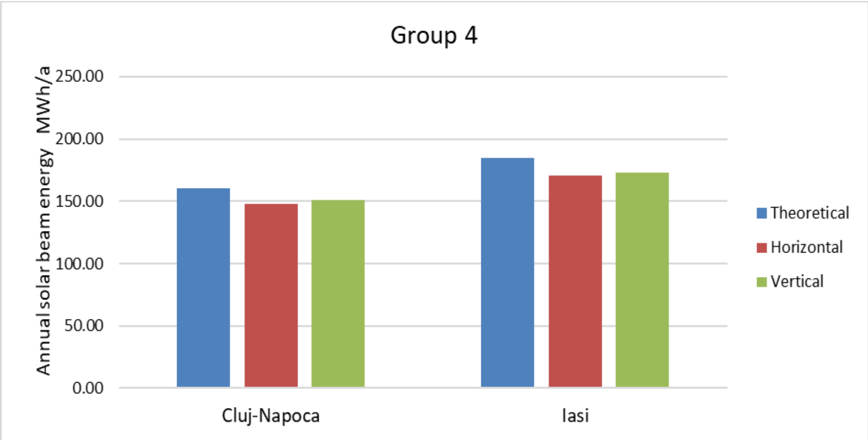


Fig. 8: Annual solar beam energies calculated for the Group 4

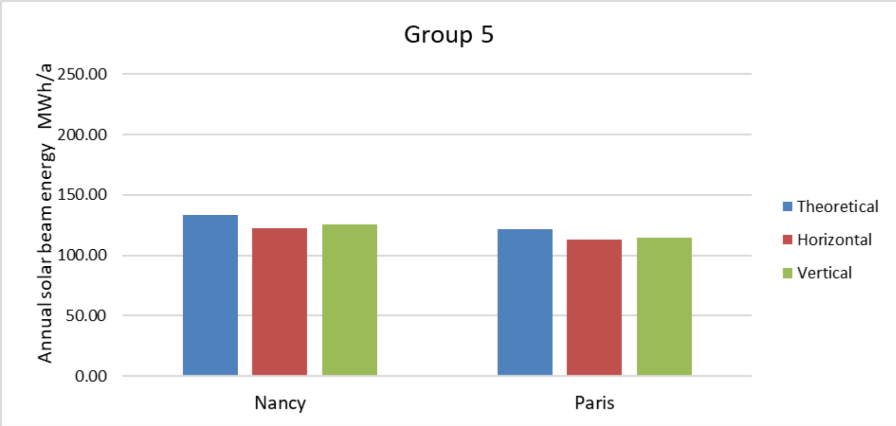


Fig.9 : Annual solar beam energies calculated for the Group 5

Three main conclusions could be highlighted from these results:

- Firstly, the self-shading magnitude appears to be more important for the horizontal mounting than for the vertical mounting in all the investigated cases;

- Secondly, the increase of the latitude angle leads to the increase of the usage degree coefficient (UDC) for the vertical mounting and to the decrease of the UDC for the horizontal mounting; this means that the self-shading phenomena magnitude are largely dependent on the geographical latitude;

- Thirdly, the annual amount of useful solar beam energy captured by the collectors depends on the local available solar energy and a comparison of the figures between the cities from each group is not relevant; however, we could observe that, as the geographical latitude increases (groups 4 and 5 in fig.8 and fig.9), the useful solar beam energy for the vertical surfaces will exceed the correspondent energy for the horizontal surfaces; this leads immediately to the idea that the vertical mounting for these cities will be more beneficial in terms of energy efficiency.

4. Conclusions

The simulation results outlined in this paper show the influence of the geographical latitude on the shading effects induced on the horizontal or vertical mounting of the solar collectors. As the latitude angle increases, the usage degree coefficient, calculated as the ratio between the sunlit area of the collectors and their total installed area, will increase from 93% to 96% for the vertical mounting and will drop from 83% to 80% for the horizontal mounting. These figures could give a good indication for the mounting schedule of the solar collectors depending on the geographical location, but they should be always combined to the local level of solar beam radiation. According to this observation, the total annual beam useful energies for the groups 1 and 2 situated at the lowest geographical latitudes appear to have similar behaviour (the useful energy for the vertical mounting is smaller than the correspondent energy for the horizontal mounting), but different magnitudes for each group taken apart, due to the local solar beam energy available on site (theoretical maximum value). Furthermore, the four cities belonging to the groups 4 and 5 show greater solar beam energy capture for the vertical mounting than for the horizontal mounting, in contrast with the behaviour observed for the groups 1 and 2. Finally, the cities belonging to Group 3, that are located at an average latitude in the assessed range, are situated in the equilibrium area where the position of the collectors does not influence the amount of solar energy harvested, except for Clermont, located the most northerly between the three cities, whose behaviour is already similar to those observed for groups 4 and 5. These observations show that the vertical mounting is more appropriate for higher geographical latitudes than the horizontal mounting.

R E F E R E N C E S

[1]. *S. Jingchun, Z.Xingxing, Y.Tong, W.Yupeng, P.Song, W.Jinshun, X.Peng*, Design Strategy of a Compact Unglazed Solar Thermal Facade (STF) for Building Integration Based on BIM Concept, in Energy Procedia, no.105, 2017, pp.1-6, The 8th International Conference on Applied Energy – ICAE2016

[2]. *G. Faninger,* The Potential of Solar Thermal Technologies in a Sustainable Energy Future. IEA Solar Heating & Cooling Programme, 2010

[3]. *M.C. Munari Probst, C. Roecker,* Towards an improved architectural quality of building integrated solar thermal systems (BIST), in Solar Energy, no.81, 2007, pp. 1104-1116

[4]. *R. Krippner, T. Herzog,* Architectural aspects of solar techniques – studies on the integration of solar energy systems, in Proceedings EUROSUN 2000, 3rd ISES-Europe Solar Congress, Copenhagen, Denmark

[5]. *I. Bergmann*, Facades integration of solar thermal collectors – a new opportunity for planners and architects, in Renewable Energy World, no.5, pp.89-97

[6]. *A. Giovanardi, A. Passera, F. Zottele, R. Lollini,* Integrated solar thermal facade system for building retrofit, in Solar Energy, no.122, 2015, pp 1100-1116

[7]. *T.T. Chow, A.L.S. Chan, K.F. Fong, Z. Lin,* Hong Kong solar radiation on building facades evaluated by numerical models, in Applied Thermal Engineering, no.25, 2005, pp.1908–1921

[8]. J.L. Threlkeld, Solar irradiation of surfaces on clear days, ASHRAE Transactions 69 (1963) pp.24–36.

[9]. *R. O'Hegarty, O. Kinnane, S. McCormack*, A case for façade located solar thermal collectors, in Energy Procedia, no.70, 2015, pp.103 – 110

[10]. *A.Damian, M.Alexandru, T.Catalina,* Numerical evaluation of the solar collectors self-shading related to their building integration, in Mathematical Modelling in Civil Engineering, no.4,2017, pp.12-26

[11]. *COST Action TU1205 BISTS* –Design and Applications Handbook,COST Office 2017, 455 p.

[12]. *M.Iqbal,* An introduction to solar radiation, 1983, Academic Press, Canada, 412 p.

[13]. *E. Coffari*, Solar Energy Engineering, in Elsevier, 1977, 526 p.

[14]. Meteonorm software – available at *www.meteonorm.com*.