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COMPARISON OF THE SOLAR INSOLATION ON THE ROOF OF CONIC DOMED HARRAN HOUSE AND THE FLAT ROOF

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Abstract: In this study, solar insolation on the conical roof and on the flat roof covering same base area of conical roofed Harran House, analyzed and compared for the purpose of which roof type is more energy efficient. For the summer season and same roof absorptivity of the surface, it was found that the conical roof absorbs 55,7 % and the flat roof absorbs 61 % of the total received radiation per unit area during the day. When the daily sum of hourly beam and diffuse radiation averages are compared, the flat roof receives ~100 % more beam radiation and ~33% more diffuse radiation than conical roof's received per unit area.
Keywords: Solar radiation, Conical roof, Flat roof.

KONİK KUBBELİ HARRAN EVLERİNİN ÇATISINA VE DÜZ ÇATIYA DÜŞEN GÜNEŞ IŞINIMININ KARŞILAŞTIRILMASI

Özet: Bu çalışmada hangi çatı tipinin daha enerji verimli olduğunu belirlemek amacıyla konik çatı yüzeyine düşen güneş ışınımı ve konik çatılı Harran eviyle aynı taban alanına sahip düz çatı yüzeyine düşen güneş ışınımı analiz edilmiş ve karşılaştırılmıştır. Yaz döneminde ve aynı çatı yüzey emiciliği için gün boyunca, konik çatının, birim alana düşen toplam güneş ışınımının %55,7'sini ve düz çatının ise %61'ini emdiği bulunmuştur. Saatlik direkt ve difüz ışınım ortalamalarının günlük toplamları karşılaştırıldığında ise, düz çatı konik çatıya göre birim alana %~100 daha fazla direkt ışınım ve %~33 daha fazla difüz ışınım almaktadır.
Anahtar Kelimeler: Güneş ışınımı, Konik çatı, Düz çatı.

NOMENCLATURE

α	The surface absorptivity at the incidence angle of θ [°]
α_n	The absorptivity at 0° incidence angle [°]
β	Slope, [°]
γ	Surface azimuth angle, [°]
δ	Declination, [°]
θ	Angle of incidence [°]
θ_z	Zenith angle [°]
ρ_g	Ground reflectance
ϕ	Latitude, [°]
ω	Hour angle, [°]
G_{sc}	Solar constant, 1367 $[W/m^2]$
I	Hourly solar radiation on a horizontal surface $[W/m^2]$
I_b	Beam solar radiation on a horizontal surface $[W/m^2]$
I_d	Diffuse solar radiation on a horizontal surface $[W/m^2]$
I_o	Extraterrestrial radiation $[W/m^2]$
I_T	Total radiation on a tilted surface $[W/m^2]$
k_T	Hourly clearness index
n	Day of the year
R_b	Geometric factor
t	Time of the day

INTRODUCTION

Harran is the town located in the southeast part of Türkiye, well-known with its conical domed houses (Fig. 1.) The use of such roof shape goes back ancient Mesopotamian civilization (Özdeniz *at al*, 1998). This type of roof can be seen especially in two regions in the world, one is in Apulia in Italy, and the other in Harran which has a hot-arid climate and average solar insolation ~7 $kW\ h/m^2 day$ for summer season. There is a common knowledge about these conical roofed buildings that they keep inside air cooler in the summer and warmer in the winter than the flat roof buildings do. Both of the high thermal capacity of the square base walls and the opening at the top of the dome that facilitates the natural ventilation has contributions in these relatively good indoor thermal conditions (Başaran, 2011). The question about the adoption of the domed roofs in the hot-arid climates, because of cultural or climatic reasons, has been investigated by many researchers.

Figure 1. A Harran conical domed house

(Pearlmutter, 1993) compared the solar exposure on the semi-cylindrical and the flat roof experimentally and found that the vaulted roof geometry has an increase in overall solar exposure ranges from %10 in summer to %30 in winter. It is emphasized on that the historical reason of the adoption of the vaulted roof construction more significative than the climatic advantage. (Faghih and Bahadori, 2009) estimated the solar radiation on several domed roofs and found that domed roofs receive more solar radiation then the flat roofs of equal base area on a recently work. (Tang *et al*, 2003) investigated the heat flux through curved (domed and vaulted) roofs into an air-conditioned building and compared with the flat roofs to compare the energy efficiency of building types regarding cooling load. The results show that the heat flux through curved roofs is always higher than through flat ones. (Tang *et al*, 2003) investigated the effect of vault angle on solar heat gains to improve curved roof building's performance in their another research and found that a domed roof with half dome angle of 90º absorbed daily about %30 more total radiation than flat roof did during the summer months. (Gomez-Munoz *et al*, 2003) also studied solar incidence over a hemispherical vault roof and then compared to a horizontal roof. They found that when sun passes near the zenith, the solar performance of a dome is better than a flat roof of equivalent base area for northern latitudes during summer. All these works show that there is no complete superiority between domed roof and flat roof. The results of comparison can change for different considerations like the size, the shape, the color, the covering materials of the roof, the season.

In this study, the solar radiation received on a typical dimensioned conical roofed Harran house and a flat roof has same base area with the conical roof, was calculated. The amount of the insolation was compared to the flat one for different conical roof surface angles. Today, despite Harran houses' relatively good indoor conditions, they are used as barn or store. The aim of this study is to investigate the adaptation of this kind of passive cooling strategies to modern buildings.

METHOD AND CALCULATIONS

To estimate solar radiation incident on the conical roof and the flat roof, the procedure given in (Duffie and Beckman, 1991) is followed. For the simplicity of the application of the procedure the conical roof form was decided as an octagonal pyramid has a base area equals to flat roof surface area. There are octagonal and also square pyramid assumptions for simplification in thermal analysis of domed roofs in literature (Faghih and Bahadori, 2011) (Fig. 2).

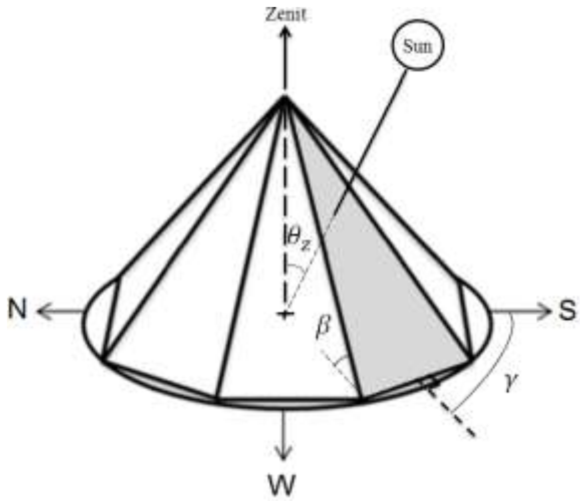

Figure 2. The simplified model of the conical roof and the essential angles for the solar geometry.

The theoretical maximum radiation received by a horizontal surface outside the atmosphere is the extraterrestrial radiation. Calculation of it on the *n*th day of the year for an hour period between hour angles ω_1 and ω_2,

$$I_o = \frac{12 \times 3600 \times G_{sc}}{\pi}\left(1 + 0.033\, cos\frac{360\, n}{365}\right) \times \begin{bmatrix} cos\phi\ cos\delta(sin\omega_2 - sin\omega_1) \\ + \frac{\pi(\omega_2-\omega_1)}{180} sin\phi\ \sin\delta \end{bmatrix} \quad (1)$$

The value of G_{sc} used in this study is 1367 W/m^2. ϕ is latitude of the location and its value is 37,1 ° N. ω is the hour angle. It is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis 15° per hour, morning negative, afternoon positive (Duffie and Beckman, 1991), which is,

$$\omega = 15(t - 12) \quad (2)$$

δ is the declination angle can be found from the expression

$$\delta = 23{,}45\ sin\left(360\frac{284+n}{365}\right) \quad (3)$$

Angle of incidence, θ, the angle between the beam radiation on a surface and the normal of that surface. The relation between the angle of the incidence and the other angles are (Fig.3),

$$Cos(\theta) = sin(\delta).sin(\phi).cos(\beta) - sin(\delta).cos(\phi).sin(\beta).cos(\gamma) + cos(\delta).cos(\phi).cos(\beta).cos(\omega) + cos(\delta).sin(\phi).sin(\beta).cos(\gamma).cos(\omega) + cos(\delta).sin(\beta).sin(\gamma).sin\,(\omega) \quad (4)$$

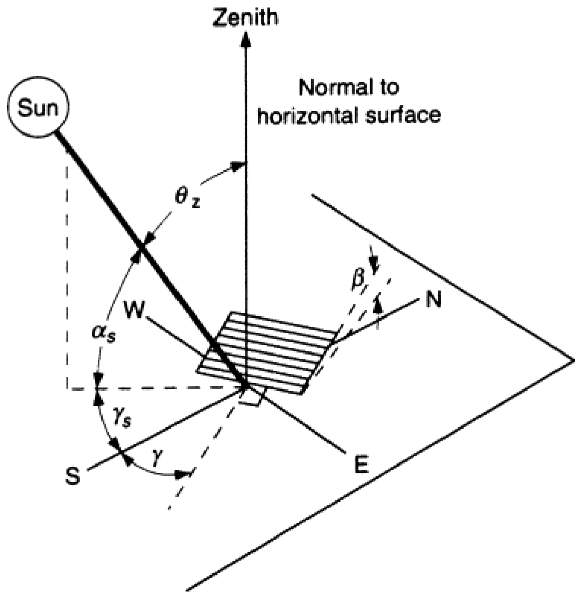

Figure 3. Zenith angle, slope, surface azimuth angle and solar azimuth angle for a tilted surface (Duffie and Beckman, 1991)

For horizontal surfaces, incidence angle is equal to zenith angle of the sun, θ_z. For this situation, the slope angle $\beta = 0$ and then the equation above becomes as,

$$Cos(\theta_z) = cos(\phi).cos(\delta).cos(\omega) + sin(\phi).sin\,(\delta) \quad (5)$$

The geometric factor R_b, the ratio of the beam radiation on the tilted surface to that on a horizontal surface at any time (Duffie and Beckman, 1991), can be calculated as indicated below,

$$R_b = \frac{Cos\,\theta}{Cos\,\theta_z} \quad (6)$$

The hourly clearness index k_T is the ratio of the hourly radiation on horizontal surface to hourly extraterrestrial radiation. In equation form,

$$k_T = \frac{I}{I_o} \quad (7)$$

In this study, the measured data obtained from Turkish State Meteorological Service records is used for the hourly total radiation on a horizontal surface. Orgill and Hollands correlation given in (Duffie and Beckman, 1991), is a function of k_T used to calculate the fraction of the hourly diffuse radiation on a horizontal plane. The correlation is given below,

$$I_d/\,I = 1.0 - 0{,}249k_T \quad for \quad k_T < 0{,}35 \quad (8)$$

$$I_d/\,I = 1{,}557 - 1{,}84k_T \quad for \;\; 0{,}35 < k_T < 0{,}75 \quad (9)$$

$$I_d/\,I = 0{,}177 \quad for \quad k_T > 0{,}75 \quad (10)$$

The isotropic diffuse model given in (Duffie and Beckman, 1991) was used to calculate total solar radiation received by the roofs. The total radiation on a tilted surface for an hour is given below,

$$I_T = I_b R_b + I_d\left(\frac{1+cos\beta}{2}\right) + I\rho_g\left(\frac{1-cos\beta}{2}\right) \quad (11)$$

Where the first, second and the third terms at the right hand side of the above equation are the beam, diffuse and ground reflected components of the total radiation on the tilted surface. I_b, I_d, R_b are total beam and diffuse radiations on a horizontal surface and the geometric factor. And also ρ_g is the ground reflectance which has a value 0,2 (Ahrens, 2006) for the summer months, and β is the tilt angle of the surfaces.

Absorbed solar radiation on the surface depends on the incidence angle of the radiation. The surface absorptivity at the incidence angle of θ is α and at 0 incidence angle the absorptivity is α_n. The polynomial relation of them given in (Duffie and Beckman, 1991) used to calculate surface absorptivity of the roofs.

$$\frac{\alpha}{\alpha_n} = 1 + 2{,}0345 \times 10^{-3}\,\theta - 1{,}99 \times 10^{-4}\,\theta^2 + 5{,}324 \times 10^{-6}\,\theta^3 - 4{,}799 \times 10^{-8}\,\theta^4 \quad (12)$$

RESULTS AND DISCUSSION

The Harran house's dome was accepted as a conical dome because its typical dimensions fit conical surface more than a circular dome. A model was defined for the both conical and flat roof has same base area which is equivalent to a circle area with 3 m diameter for the analysis and the comparison of received solar radiation. For the calculations, a spreadsheet software was used. Solar radiation on the roofs was calculated for the summer months using the measured hourly total radiation on horizontal surface at Şanlıurfa. Hourly average of the measured data used for flat roof, was shown in Fig. 4. for June, July and August. Fig. 4 also shows how the average hourly received radiation on the unit area of the conical roof changes between 6 am and 7 pm by summer months. Throughout the daylight, the most received daily total radiation by a unit area of the conical roof in June and daily total difference respect to flat roof value is 3015 w/m^2. The peak hourly received radiation difference is 389 W/m^2 for June can be seen at 1 pm in Fig. 4. When the surface areas of the roofs are considered, the total average hourly solar radiation received by these two roof types can be seen in Fig. 5. The solar radiation on a unit area of the conical roof is always less than the flat roof during the day for summer months but the surface area of the conical roof is 14,14 m^2 for $\beta = 60°$ and the base area (the flat roof

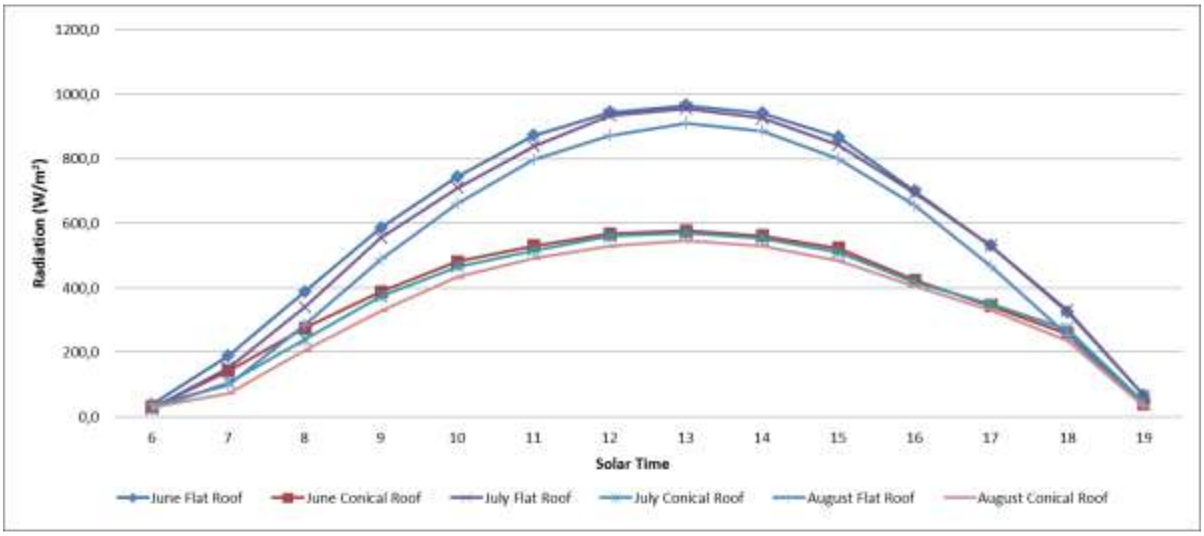

Figure 4. The average hourly solar radiation received by the unit area of the flat and conical roof for the summer months.

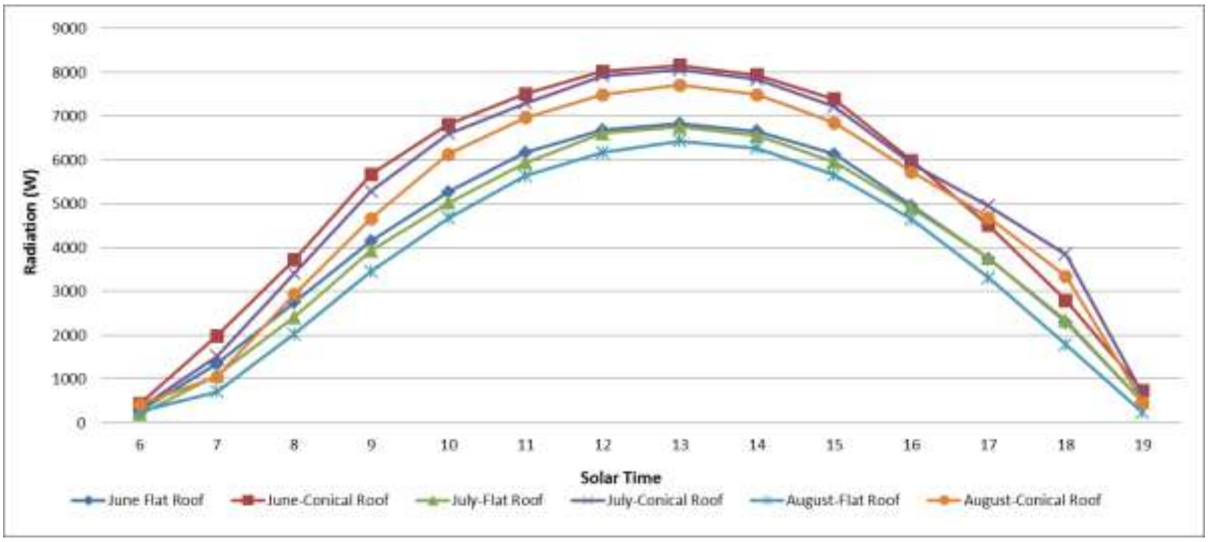

Figure 5. Hourly solar radiation on the conical roof Harran House ($\beta = 60°$) and the flat surface has equivalent base area with conical roof house for the summer months.

area) is $7{,}07\ m^2$ so because of the surface area the total received radiation on the conical roof is more than the flat roof.

In order to see how the hourly solar radiation on the conical roof changes at eight surfaces, the azimuth angles, γ which signifies that the eight directions, (Fig. 6), the conical roof surface divided into eight parts respect to central angle. For this purpose, the roof was assumed as an octagonal pyramid with a surface angle of 60° and for calculation, the average of July measured hourly radiation data was used. Fig. 6 compares the hourly solar radiation on a unit area of the conical roof surface faced to North, South , East, West, Northwest, Northeast, Southwest and Southeast. Maximum daily incident solar radiation is 5698 W/m^2 for Southwestern

and maximum of the day is 838,8 W/m^2 at 3 pm for Western surface of the conical roof.

Fig. 7. shows the ratio of the daily solar radiation on a unit area of the conical roof with changing slope angles to daily radiation on a unit area of the flat roof. This ratio is 0,99 at $\beta = 10$ ° changes to 0,42 while $\beta = 80°$. As can be seen for the conical roof type the received radiation per unit area of the roof decreases as the surface slope angle increases. But the received radiation per total roof surface area increases because of the increasing conic surface area.

Daily performance of these two roof type was compared with using the daily average data for July in Fig. 8. Also daily extraterrestrial, daily beam and diffuse radiation elements of each roof type were calculated.

During the day, a unit area of the flat roof absorbs ($4820\ W/m^2 day$) more solar radiation than a unit area of the conical roof absorbs ($2789\ W/m^2 day$). The flat roof's daily total insolation is ($7904\ W/m^2 day$) for

July and this value is 57,8 % higher than the conical roof's

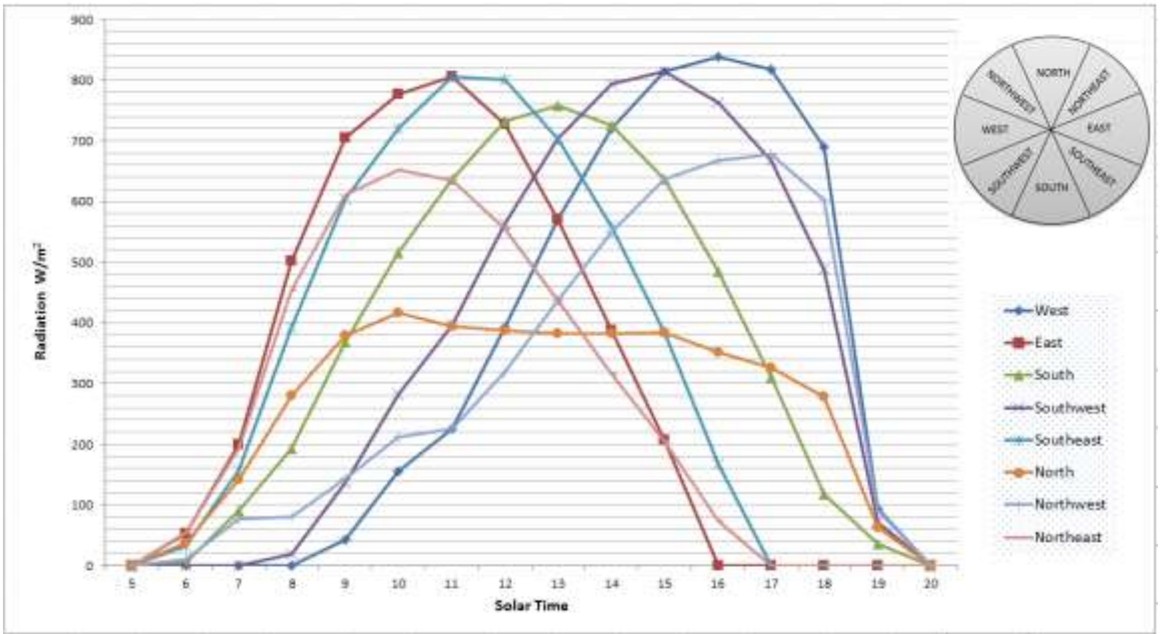

Figure 6. Variation of the solar radiation on the surface of the conical roof depending on surface azimuth angle during daylight, July, $\beta = 60°$.

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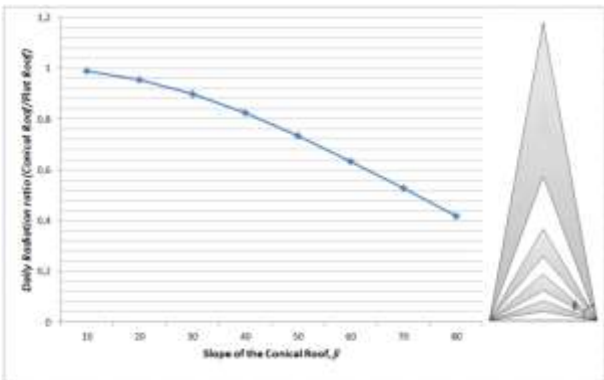

Figure 7. The ratio of the total daily radiation on a unit area of the conical roof for the different conical slope angles (β changing from $10°$ to $80°$) to the total daily radiation on the unit area of the flat roof

CONCLUSION

In order to clarify the reason of the adoption of conical roofed houses which is unique to Harran city of Türkiye, the relation of the roof shape and the insolation was analyzed.

The results given above shows that, (i) the maximum solar radiation per unit area of the flat roof is in June, this result is same with the result in (Faghih and Bahadori, 2009) which was studied throughout the year (ii) In every conical surface slope angle, the area of the conical roof surface is greater than the base area, so when the total roof area is considered for comparing of the received the radiation, the conical roof receives more radiation than the flat roof does. (iii) The solar radiation intensity throughout the flat roof surface is regular everywhere for each hour of the daylight, but it has different values and changes with the surface azimuth angle for the conical roof surface. (iv) In July for the roof absorptivity, which is practically depends on its color, $\alpha_n = 0{,}63$ (Çengel, 2011; Crosbie, 1998; Giovani, 1998), the conical roof absorbs 55,7 % and the flat roof absorbs 61 % of the total received radiation per unit area during the day. (v) When the daily sum of hourly beam and diffuse radiation averages are compared, the flat roof receives $\sim$100 % more beam radiation and $\sim$33% more diffuse radiation than conical roof's received per unit area in July.

In this study only the solar insolation was taken into account for the comparison of the performance of the conical roof and the flat roof. For a comprehensive comparison of these two roof types' thermal performance, it is needed an overall approach consists of the internal air temperature fluctuations, the heat gain through the roofs, and the surface temperatures of the roofs.

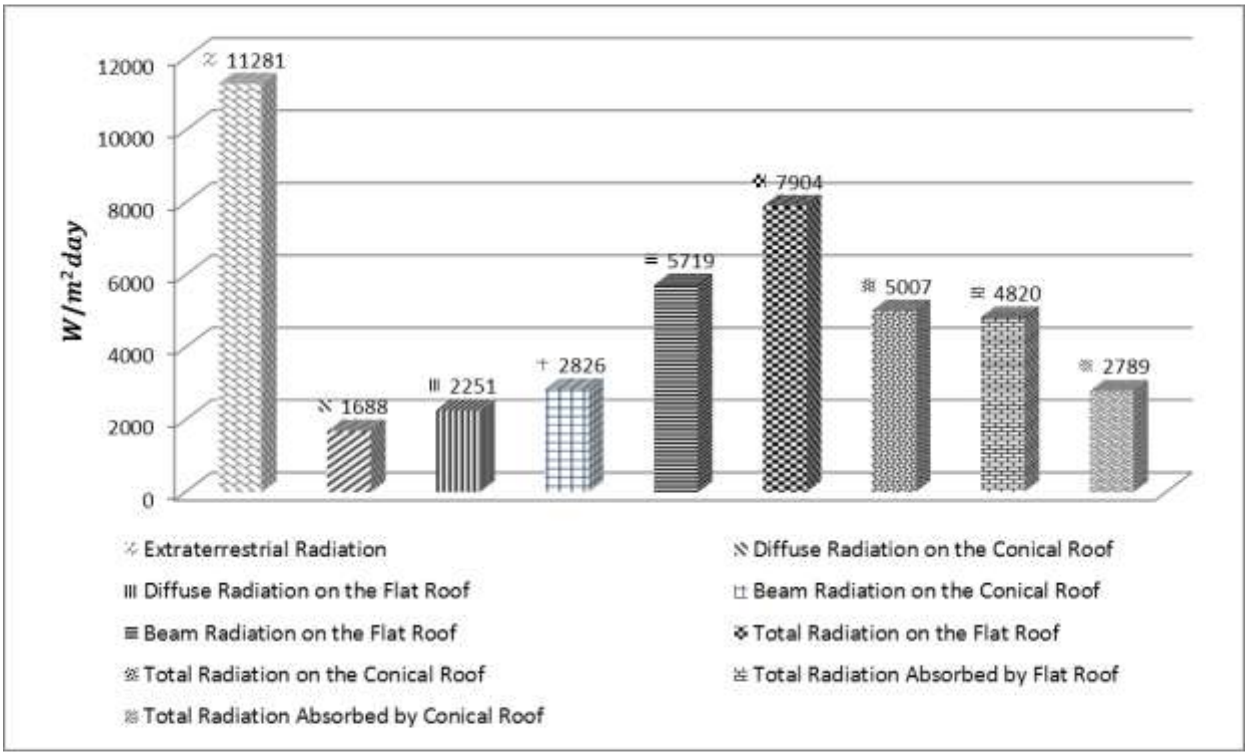

Figure 8. Comparison of the daily extraterrestrial, total, beam, diffuse radiation received by the conical($\beta = 60°$) and the flat roof.

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