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THEORETICAL INVESTIGATIONS OF THE SOLAR RADIATION AT LOCATION OF THE PASSIVE HOUSE "POLITEHNICA" FROM BUCHAREST

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The design of HVAC and solar energy systems requires an accurate assessment of the solar radiation. HVAC systems needs to adjust their output to the heat gain and solar energy systems including solar collectors and photovoltaic panels needs an preliminary evaluation of the energy that could be received at different tilt angles followed by algorithms of optimization. This study have the purposes to evaluate several theoretical models involving solar declination to reflect the diversity of the approaches and the nonlinearity of the phenomenon and then to do the evaluation of the solar irradiance and solar energy that is received at the site of Passive House "POLITEHNICA" from Bucharest.

Keywords: solar radiation, solar energy, solar collector, solar panel, tilt angle, surface orientation

1. Introduction

Solar radiation is the source of energy for which it is currently devoted much research due to the diversification of applications that use it. This study is necessary for Passive House "POLITEHNICA" of the University "POLITEHNICA" from Bucharest by three aspects: solar radiation considered for assessing the energy exchange between building and environment, for the production of electricity through photovoltaic (PV) panels, and for thermal energy assessment produced by solar collectors. This paper is a continuation of a previous work [1] where was sketched some methods and obtained some partial results that opened paths for complete investigations of the solar radiation.

Passive House "POLITEHNICA" have the following geographic coordinates: 44.4388^0 N Latitude, 26.0478^0 E Longitude and Altitude of 76.6 m. The calculation of the solar radiation is done for the year 2012 with the hourly method that also is applied for the normalizations involving bigger periods like days, months, seasons. On the south facing roof of the house with the inclination of 15^0 are installed 2 solar collectors and 26 PV panels. The solar radiation data is determined exclusively analytic by using validated formula published by several

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authors. This issue gives a remarkable advantage in studies involving prediction of the solar radiation because can be set any periods for investigations. In the technical literature in most situations are used only measured data and this fact is a limitation because of the lack of parametrization of the problem. The results are intended to be used for calculation the heating/cooling of the building, evaluation of thermal energy (received by solar collectors) and of electrical energy (received by PV panels). Solar collectors and PV panels also will rise further a problem of optimization of the tilt angle in order to gain maximum energy from the sun; the optimization will depend on the period of use (if the period is entire year or only a season), the weighting factor derived from the necessary load for each period, available installation's surface, the mobility of the panels (when the panel angle is fixed or variable based on a sun tracking system that adjust at a given step time), sky quality (clear, cloudy or polluted), conversion efficiencies, etc. A specificity of PV panels is the connection to the grid such that the functioning on a tilt angle optimized for the entire year may not be able to deliver the energy required for a period of peak load period [2]; in this case the load profile of the year gives a valuable information to establish a realistic base in optimization of the tilt angle for a given range of time [2].

Because of the complexity determined by the orbit (elliptic orbit and variable speed of the earth along of it) and the effects of scattering, for several parameters of the solar radiation are issued many studies and formula such that in this study as first step are compared different models for the solar declination and further are mainly done evaluations of the solar irradiance.

2. Literature reviews and model

In order to be developed the algorithms that determine the solar radiation there are several models validated and proposed by different authors.

In Table 1 are presented several equations of the solar declination published in technical literature. Mainly they are based on Fourier expansion (Cooper, 1969; Spencer, 1971; Bourges, 1985) of a transcendental function derived from the elliptical orbit of the earth. Other parameters of the solar radiation that have various proposals of formulas with different degrees of accuracy are the equation of time (Woolf, 1968; Spencer, 1971; Carruthers et al., 1990; Yallop, 1992), air mass ratio (Rozenberg, 1966; Kasten and Young, 1989; Young, 1994; Campbell and Norman, 1998; Pickering, 2002), direct atmospheric transmissivity (Beer-Lambert-Bouger Law, 1852; Hottel, 1976; Kreith and Kreider, 1978; ASHRAE, 2009), diffuse atmospheric transmissivity (Liu and Jordan, 1960; Orgill and Hollands, 1977; Erbs et al., 1982), etc. In Tabel 1, N is the day number in the year and N_0 is a term that include the parameters like clock time in hours, minutes and seconds [7].

It is important the time averaged solar irradiance that usually it is considered for hourly, daily, monthly or seasonal averaged periods; those methods overall per year give comparable results, but smaller the average time then the more information could be obtained about the phenomenon evolution.

Table 1

Solar declination models

Declination angle [rad]	Day Angle [rad]	Author
$\delta = \frac{23.45\,\pi}{180}\sin\Gamma$	$\Gamma = \frac{2\pi(N+284)}{365}$	Cooper (1969) [3]
$\delta = 0.006918 - 0.399912\cos\Gamma + 0.070257\sin\Gamma - 0.006758\cos 2\Gamma + 0.000907\sin 2\Gamma - 0.002679\cos 3\Gamma + 0.00148\sin 3\Gamma$	$\Gamma = \frac{2\pi(N-1)}{365}$	Spencer (1971) [3]
$\delta = sin^{-1}(0.39795\cos\Gamma)$	$\Gamma = \frac{2\pi(N-173)}{365.242}$	Boes (1976) [4]
$\delta = -sin^{-1}\left[\sin\left(\frac{23.45\,\pi}{180}\right)\cos\Gamma\right]$	$\Gamma = \frac{2\pi(N+10)}{365.25}$	Kreith & Kreider (1981) [5]
$\delta = \sin\{0.3978\cdot\sin[D - 1.4 + 0.0355\sin(D - 0.0489)]\}^{-1}$		Gruter (1984) [6]
$\delta = 0.0064979 - 0.0132296\cos\Gamma + 0.405906\sin\Gamma + 0.0063809\cos 2\Gamma + 0.0020054\sin 2\Gamma - 0.002988\sin 3\Gamma + 0.0003508\cos 3\Gamma$	$\Gamma = \frac{2\pi(N+N_0)}{365.2422}$	Bourges (1985) [7]
$\delta = 0.409\cdot\sin\Gamma$	$\Gamma = \frac{2\pi N}{365} - 1.39$	Allen et al. (1998) [8]
$\delta = sin^{-1}\{0.39785\,sin[4.869 + \Gamma + 0.03345\sin(6.2238 + \Gamma)]\}$	$\Gamma = \frac{2\pi N}{365.25}$	Campbell and Norman (1998) [9]

The books of Kreith and Kreider (1978) [10], Kreider and Rubl (1995) [5] and Duffie and Beckman (2006) [3] integrate various researches, algorithms, methods involving the engineering of solar radiation. Ulgen (2006) [11] and Ertekin et al. (2008) [12] issued an analysis based on monthly averaged solar irradiance in order to optimize tilt angle of a solar collector. Slama (2009) [13] obtained the solar irradiance for a geographic point from Tunisia then issued analysis of optimum tilt angle of a solar collector for different significant periods of time of exploitation; some of his comparisons between measurements and calculations of the solar irradiance gave differences within the limit of 10%. Dragicevic (2011) [14] calculated the solar radiation of a location point in Belgrade and further determined optimum orientation of a greenhouse based on total solar radiation availability. Baracu et al. (2011; 2013) [15][16] issued simulation of a Passive House in variable thermal conditions by implementing analytical models of the outdoor temperature and solar radiation.

Fig. 1 shows the geometry of the solar radiation on a tilted surface. This sketch prepares further the entire algorithm of parametric determination of the solar radiation. At latitude λ, solar declination δ, and hour angle ω, the zenith angle θ_z (Fig. 1) is obtained from the relation:

$$\cos\theta_z = cos\,\lambda\, cos\,\delta\, cos\,\omega + sin\,\lambda\, sin\,\delta \quad (1)$$

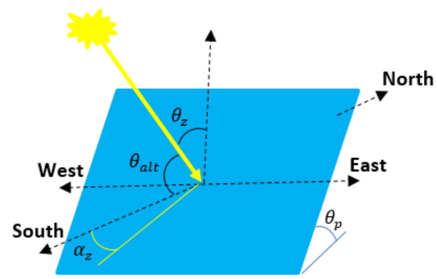

Fig. 1. Geometry of the solar radiation on a tilted surface

Further, can be obtained the azimuth of the sun

$$\sin\alpha_z = \frac{\cos\delta\sin\omega}{\sin\theta_z} \quad (2)$$

and the solar altitude

$$\theta_{alt} = \frac{\pi}{2} - \theta_z \quad (3)$$

In Fig. 1, θ_p is the tilt angle of the surface.

The equation that gives the extra-terrestrial irradiance also delivers the base of determination of all other components of the solar radiation [5]:

$$I_0 = I_{SC}\cdot\left(1 + 0.033\cos\frac{2\pi N}{365.25}\right) \quad [\mathrm{W/m^2}] \quad (4)$$

where I_{SC}=1373 W/m^2 is the solar constant.

The direct irradiance is obtained from the relation [5]:

$$I_{dir} = I_0\cdot\left[a_0 + a_1 exp\left(-\frac{k}{\cos\theta_z}\right)\right] \quad [\mathrm{W/m^2}] \quad (5)$$

where a_0, a_1, k are coefficients that describe the level of visibility from the specific location [5]. The diffuse irradiance on a horizontal surface is estimated with the relation of Liu and Jordan [5]:

$$I_{dif} = (0.271 I_0 - 0.2939\, I_{dir})\cos\theta_z \quad [\mathrm{W/m^2}] \quad (6)$$

By having both components of the solar radiation, the direct and the diffuse, can be calculated further the total irradiance:

$$I = I_{dir} \cos \theta_z + I_{dif} \qquad [\mathrm{W/m^2}] \tag{7}$$

where the term $\cos \theta_z$ derives from the air mass ratio (it measures the path length of the solar beam through atmosphere).

3. Results

It is issued a comparative analysis of several models that gives mathematical expression for solar declination. Along of the time was issued many expressions that are based on the day number of the year, N, or even taking in consideration the clock time including minutes and seconds for highest accuracy models.

Fig 2 shows the graph of the models from Table 1 and after a numerical comparison was obtained a maximum difference of 5% between their results and suggest that using simpler expressions (like the model of Cooper for example) of the solar declination still gives a reasonable accuracy.

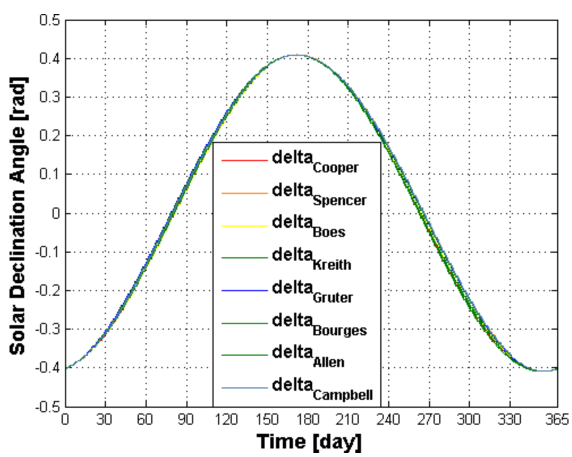

Fig. 2. Solar Declination Angle δ comparison for different theoretical models

Fig. 3 contains the graph of daily normalized horizontal solar irradiance for different latitudes to point out the influence of the location. It should be seen that the maximum of 242 W/m^2 is reached near the latitude 30^0 N ; at latitude of 45^0 N (near the studied location) the graph get closed to the max value (of the parallel of 30^0) but it is more pointed. Because of the precession of the earth's axis the graph of solar irradiance have two maximum points in the regions between 0^0

and 15^0 N latitude and then for latitudes greater than 15^0 N have only one peak value. Northern regions with latitudes between 60^0 and 90^0 N contains solar maximum of up to 209 W/m^2 (daily normalized). The results are based on the VBA and Matlab programming codes where was used Boolean logic and threshold functions capable of executing truncations of the curves of evolution of the phenomenon especially in the sunrise and sunset time points.

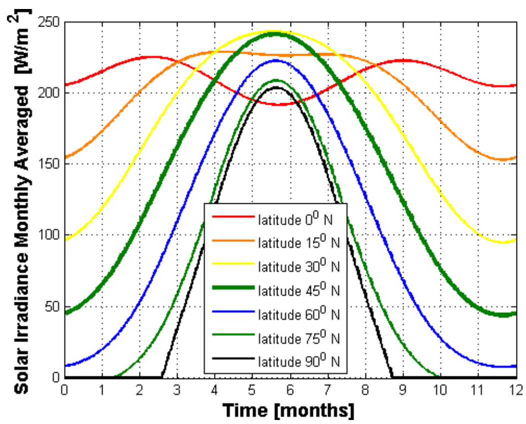

Fig. 3. Solar Irradiance daily averaged at different latitudes for the year 2012

The shading of the surroundings including neighbor buildings or trees could be taken in consideration for corrections of the solar irradiance. Regarding this fact it is issued the diagram of the solar altitude angle for the main days of the year (Fig. 4); also the information from the graphs is necessary for sun tracking systems. As it is shown the maximum solar altitude is matched in the solstice of June, 21 and the minimum in the solstice of December, 21.

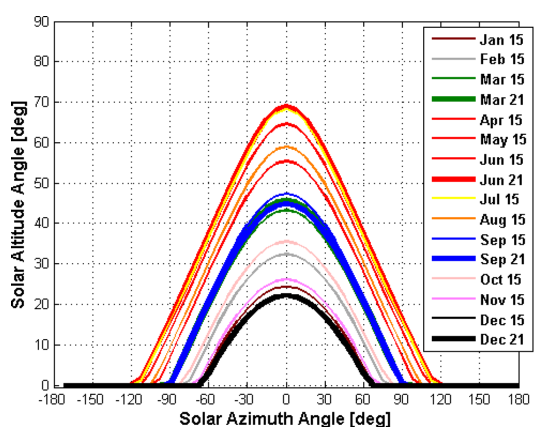

Fig. 4. Solar Altitude angle θ_{alt} of the main days of the year

Global irradiation on a tilted surface is obtained by adding the direct, diffuse and reflected components [5]:

$$I_p = I_{dir,p} + I_{dif,p} + I_{terr,p} = I_{dir}\cos\theta_p + I_{dif}\frac{1+\cos\theta_{p,H}}{2}$$
$$+\left(I_{dir}\cos\theta_s + I_{dif}\right)\rho_g\frac{1-\cos\theta_{p,H}}{2} \quad [\mathrm{W/m^2}] \quad (8)$$

where $I_{dir,p}$ is the direct irradiance on the surface, $I_{dif,p}$ is the diffuse irradiance and $I_{terr,p}$ is the irradiance from the reflection of the terrain, θ_p is the tilt angle of the surface, $\theta_{p,H}$ is the incidence angle of the solar beam on the horizontal surface and ρ_g is the reflectivity of the ground (usually with the value of 0.2).

The orientation of the surface and the tilt angle of the surface influence the magnitude of the solar irradiance and also the time when the maximum values are reached (Fig. 5).

As it can be seen in the figure, the South oriented surface with tilt angle at 300 is exposed to the maximum solar irradiance of over 700 W/m^2.

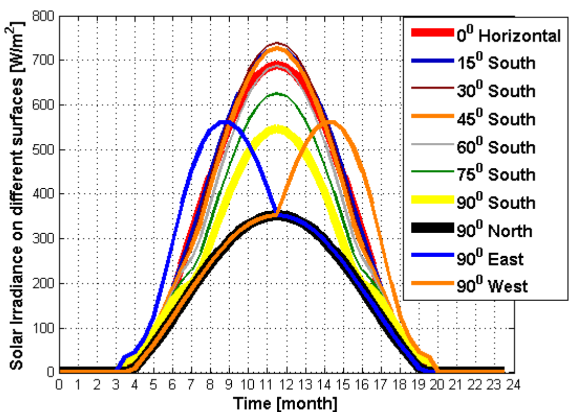

Fig. 5. Solar irradiance on different surface orientation and inclination for a particularly day (06/15/2012)

For the month of June is issued Fig. 6 in order to be described the evolution of the hourly solar irradiance from one day to another across the month of May.

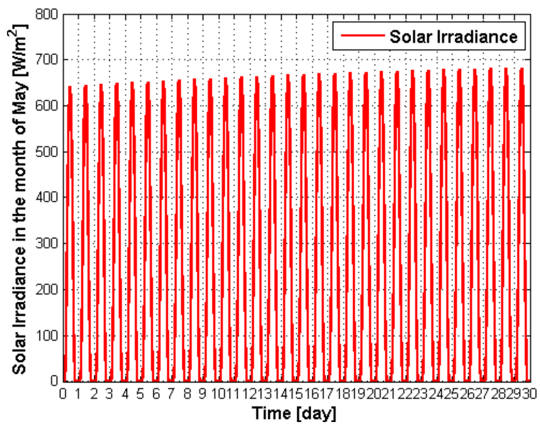

Fig. 6. Solar irradiance in the month of May

The solar global irradiance on the horizontal surface (Fig. 7) gives rich information about the evolution in time with a step of one hour pointing out the difference from one day to the next one.

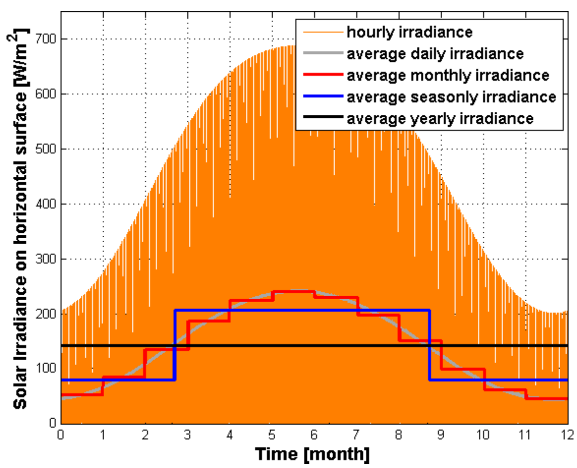

Fig. 7 Solar irradiance considered for different averaging periods

Usually the measurements are taken hourly, then normalized on the day, month, season and year and as follows the simulation takes in consideration those time periods. This generalized approach allows the interpretation of the solar radiation in multiple ways in accordance with the specific design that is chosen. The results shows a yearly average solar irradiance of 142 W/m^2 that is a basic value for the start of the design of solar equipment. Also the results involving the seasons of the year are very important if the exploitation of the solar installations have a seasonal profile; for example common off-grid installations of PV panels cannot store the overproduction of electrical energy from the summer to be used in winter such that it is necessary at least a seasonal evaluation; for the current location in the cold season the mean value of solar irradiance is 80 W/m^2 and in the warm season it is 204 W/m^2. More accurate results like monthly averaged, daily averaged or even hourly solar irradiance can be taken in consideration for smarter design. Often, the design of the solar installations will take in consideration weighting factors for the seasons based on their load profile and the resulted solar irradiance of the specific period.

Often it is necessary to evaluate the solar radiation considered for bigger periods and still keeping its pattern of evolution in time. Fig. 8 present the solar irradiance normalized for the defining day of each month.

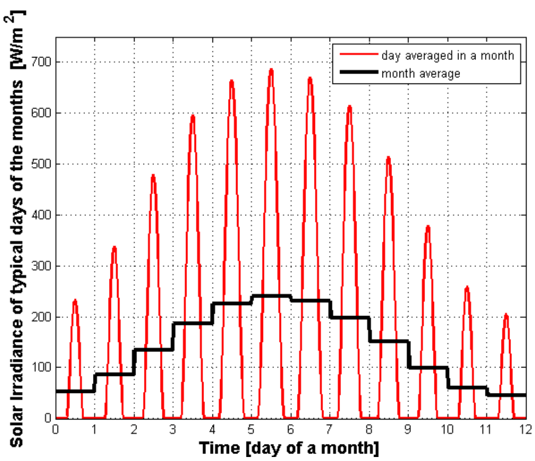

Fig. 8. Solar irradiance of averaged days which are defining for each month

Also the averaged solar irradiance on each month is available. In this way, along of the year if each month is seen as its prototype day, then it is given a relevant and compressed information about the evolution of the solar radiation.

Next stage is considering further the inclination angle of the panels/collectors (Fig. 9). It can be seen that the curve that keeps high values for almost entire year it is the one of the 30^0 inclination so the optimum tilt angle should be around this value; however, an additional study dedicated to the optimization of the tilted angle should be issued. It is obvious that the actual design of 15^0 tilt that it is already implemented can be improved further.

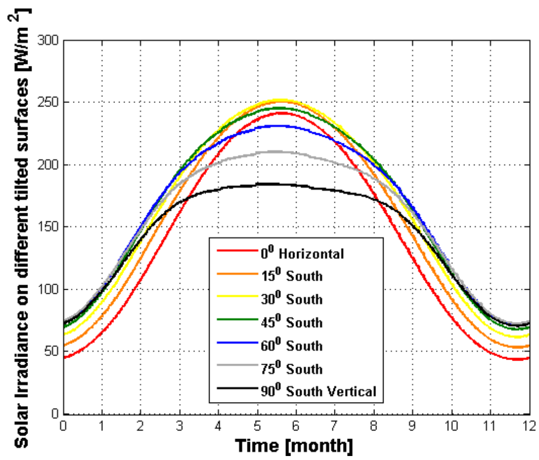

Fig. 9. Solar Irradiance daily averaged on different tilted surfaces

In Fig. 10 is obtained the cumulated energy along of the year 2012 for different azimuth angles orientations and tilt angles of the surface.

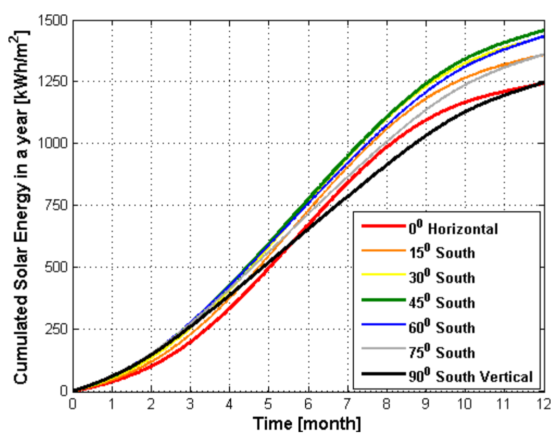

Fig. 10. Evolution of the cumulated solar energy along of a year

The result is obtained by integration of the total solar irradiance along of the year for a time step of one hour:

$$E_{cumul} = \int_{\tau=0}^{t} I(\tau)\, d\tau = E(\tau)\Big|_{\tau=0}^{t} = E(t) \quad [\text{kWh/m}^2] \qquad (9)$$

At the existing tilt angle of the panels/collectors of 15^0 is reached a cumulative energy of 1360 kWh/m^2. It can be seen also that at 300and 45^0 inclination the received energy over the year is bigger with 5% and this suggest that the actual 15^0 inclination angle of the solar panels/collectors should be increased. A rough analysis of the results indicate that the optimum inclination angle is between 30^0 and 45^0, but in order to be obtained an exact value it is necessary a dedicated analysis. It have to be pointed out that the evaluations are done only by means of solar radiation phenomenon. For the solar collectors/panels the efficiency is significant affected by temperature. For accurate energy optimizations of these equipments the results obtained from the analysis of the solar radiation have to be combined with the curve of the efficiency as function of the temperature, but this is another issue that can be analyzed separately.

6. Conclusions

In this study are obtained the results of solar radiation for the location of Passive House "POLITEHNICA" for different inclination angle of the surfaces.

A comparison of several expressions of the solar declination revealed the diversity of the approaches for solving the nonlinearity induced by the elliptic orbit of the earth and the precession of the axis and was found differences below 5%; this fact recommends in normal cases the use of simplified formula with the guarantee of acceptable accuracy.

Latitude had influenced significantly the solar irradiance at various locations distributed by 15^0 on the parallels of the earth.

It is obtained the graph of solar altitude that helps to evaluate the shading of surrounding items and also to design sun tracking systems if they will be planned to be installed.

It was demonstrated the way in which the solar irradiance is influenced by the surface orientation and the inclination angle.

For the site of the Passive House "POLITEHNICA" are issued the graphs of the solar irradiance with hourly variation and also are done normalizations that give average daily, monthly, seasonally and yearly solar irradiance. Those normalizations help to design the solar systems based on the specific periods of exploitation, load profile, etc.

The actual tilt angle of 15^0 of the solar panels/collectors can be improved for receiving more energy from the solar radiation. At 30^0 and 45^0 inclination of the surface along of the year can be received overall more solar energy with +5% or even more if dedicated optimizations are done.

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