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Numerical Evaluation of Solar Irradiation for Buildings and Solar Energy Applications

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Abstract

Determining the amount of solar energy received on a surface is important for solar energy modelling and assessment as well as for buildings energy modelling. This paper presents a comparison between analytical and experimental data for normal, diffuse, and global horizontal average hourly solar radiation per month in Beirut (33.89 N; 35.50 E). Optimal position for solar panels is also investigated in 3 configurations: constant optimal angle; monthly variable tilt angle; and solar sensors with a tracking system of the solar race. After validating the numerical model comparing it to a weather file data for normal, diffused, and global horizontal average hourly solar radiation per month, optimization was made to determine the optimal position of solar collectors according the Generalized Reduced Gradient (GRG2) Algorithm which is normally used for optimizing nonlinear problems. The results show a good accuracy between numerical model and available weather data. The optimum angle of inclination for the city of Beirut is close to 30° (27.9°). By varying this angle monthly (i.e. through an adjustable tilt chassis), a 6% increase of collected energy is obtained compared to a constant optimal angle. As for the system, it has great interest as it allows an increase of 37% of solar energy compared to a constant optimal angle.
The adopted method is of great interest since it could be replicated to any region, not just in Beirut by changing the latitude parameter and the clearness index for the site concerned.

Keywords: Solar radiation; solar data; solar modelling; clearness index; global irradiance; optimum solar panels position

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1. Introduction

The Earth daily receives a large solar energy flux. The power of this radiation is based on several criteria such as weather conditions, atmospheric diffusion (dispersion, reflection and absorption phenomena). Knowledge of solar radiation is essential to calculate various performance levels related to solar energy systems, such as solar water heaters, photovoltaic systems, concentrated solar

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power systems, and also for building sector in order to have a better adapted thermal insulation adapted to local climate and solar passive heating.

Petroleum products represent around 97% of Lebanon's primary energy needs in 2012. The country does not produce oil or coal and most of its energy needs is imported [1, 2]. The current demand for electricity in the country is around 2,500 MW and the Electricite du Liban (EDL), the public national utility who controls the electricity sector, is incessantly struggling to ensure the continuous delivery of power with its maximum in the range of 1,500 MW. The use of private generators to meet electricity demand during power rationing periods is leading to significantly higher air pollution levels and CO2 emissions. [3] Thus, changes are needed in order to promote and ensure the proper implementation of renewable energy technologies. Among a list of renewable energy sources, solar energy is an efficient and flexible energy source. Lebanon is characterized by a high potential of solar energy with a daily average of 4.8 kWh/day/m2 and a yearly average of 3,000 hours of solar radiation [1]. The importance of an accurate and precise estimation of the total amount of global solar radiation is of vital importance to assess the energy performance and manage investments of any solar energy system whether it is for electricity generation through photovoltaic systems [4, 5] or other solar thermal applications [6]. Also, solar radiation is an important parameter affecting the energy performance of buildings [7] and urban layout optimization [8, 9].

The amount of global solar radiation reaching a surface of the Earth is affected by too many meteorological, terrestrial, and geographical factors. Based on observed values, researchers have introduced a considerable number of small or large scale models for the estimation of the amount of global solar radiation [10-18]. Artificial neural networks have been successfully employed in solving complex problems in various fields and particularly for the estimation of global solar radiations on the horizontal surfaces [19-21]. Most of these models contained two submodels: the separation submodel which converts the global horizontal irradiation into direct beam irradiation and diffuse sky irradiation on the horizontal plane, and the composition submodel which transforms the horizontal direct beam and horizontal diffuse sky irradiation into the total solar irradiation on the tilted plane [22]. It is important to note that global and local climates are gradually changing under the global warming and air pollution effects; consequently, irradiation data must be regularly updated. Unfortunately, for many developing countries like Lebanon, solar radiation measurements are not easily available due to financial or technical limitations. Therefore, it is so important to elaborate solar radiation data based on high performance models for estimating the surface solar radiation.

One of the very few available resources for Lebanese solar data is the study of "Climatic Zoning for Buildings in Lebanon 2005" [23] where the solar data has been initially generated from Meteonorm software [24] that gives the direct radiation and horizontal radiation data from specific information including the location (latitude, longitude and altitude), the clearness index of the sky, the cloud cover and the type of cloud encountered. However, this study provides only daily data for each month and lacks of hourly data information. In addition, optimal positioning of solar panels is of great interest since it allows the extraction of maximum energy from the solar system and provides important insights and best practices for engineers and installers. Number of studies on the optimal positioning of solar panels around the world has been presented [25–29].

The aim of this work is to validate a theoretical model that calculates hourly solar radiation on a tilted surface throughout the year and to use it to determine solar radiation on a random tilted surface and particularly on vertical surfaces in different orientations. Then, three optimal configurations are investigated: a constant tilt angle, a monthly adjustable tilt angle, and a solar tracking system. In addition to these configurations, traditional solar collectors positioning with constant tilt angles (30°, 45°, and 60°) were evaluated.

The analytical results for the global horizontal solar radiation (GH), the normal beam solar radiation (NB), and the diffuse horizontal solar radiation (DH) were first compared to available Meteonorm TMY2 weather data file for Beirut for verification and validation. Then, the analytical model was used to determine hourly global solar radiation on horizontal, vertical West, vertical East, vertical South and vertical North planes for each month. The importance of this method is that it allows it allows the establishment of average reference data of solar radiation received by the facades of a building for the different months of the year.

In brief, the numerical method allows the determination of normal, diffused, and global horizontal average hourly solar radiation per month in Beirut. The numerical model was validated by comparing it to a weather file data; then, it was used to determine the optimal position of solar collectors according the Generalized Reduced Gradient (GRG2) Algorithm.

2. Numerical model

2.1 Theoretical model for solar radiation

The diffuse radiation is defined as the solar radiation received from the sun after its direction has been changed by scattering by the atmosphere and is given by:

The total solar radiation on a tilted surface for an hour is the sum of three components: the direct component, the diffuse component and the reflected component. A surface tilted at slope β from the horizontal has a view factor to the sky F_{c-s}= (1+cosβ)/2 and to the ground F_{c-g}= (1−cosβ)/2, therefore the equation of the total solar radiation can be written [30]:

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

An hourly clearness index k_T can also be defined:

$$k_T = \frac{I}{I_0} \quad (2)$$

where I is the particular day’s radiation received on a horizontal surface, and I_0 is the particular day’s extraterrestrial solar radiation.

$$I = I_b + I_d \quad (3)$$

The beam radiation is defined as the solar radiation received from the sun without having been scattered by the atmosphere; it is given by:

$$I_b = \frac{\tau_b}{\tau_b + \tau_d} k_t I_0 \quad (4)$$

The diffuse radiation is defined as the solar radiation received from the sun after its direction has been changed by scattering by the atmosphere and is given by:

$$I_d = \frac{\tau_d}{\tau_b + \tau_d} k_t I_0 \quad (5)$$

Where I_0 is given by:

$$I_0 = C_s(\tau_b + \tau_d).\left(1 + 0.033.\cos\left(\frac{360.n}{365}\right).\cos\theta_z\right) \quad (6)$$

The atmospheric transmittance for beam radiation τ_b is given in the form:

$$\tau_b = a_0 + a_1 \exp(-k/\cos\theta_z) \quad (7)$$

a_0, a_1, and k are constants given by:

$$\begin{aligned} a_0 &= 0.4237 - 0.00821\times(6-A)^2 \\ a_1 &= 0.5055 - 0.00595\times(6.5-A)^2 \\ k &= 0.2711 - 0.01858\times(2.5-A)^2 \end{aligned} \quad (8)$$

The ratio of diffuse radiation to the extraterrestrial (beam) radiation on the horizontal plane τ_d is given by:

$$\tau_d = 0.271 - 0.294\tau_b \quad (9)$$

The geometric factor R_b, the ratio of beam radiation on the tilted surface to that on a horizontal surface at any time, can be calculated by:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \quad (10)$$

The equation relating the angle of incidence of beam radiation on a surface, θ, to the other angles is:

$$\begin{aligned} \cos\theta = {} & \sin\delta\sin\varphi\cos\beta \\ & -\sin\delta\cos\varphi\sin\beta\cos\gamma \\ & +\cos\delta\cos\varphi\cos\beta\cos\omega \\ & +\cos\delta\sin\beta\sin\gamma\sin\omega \\ & +\cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega \end{aligned} \quad (11)$$

The declination δ can be found from:

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \quad (12)$$

2.1. Determination of the clearness index K_T

One of the sources of uncertainty of this method lies in the determination of the clearness index k_T

that significantly affects the results; so it is essential to be properly determined. The Clearness Index k_T is considered as an attenuation factor of the atmosphere and is defined as the ratio of the horizontal global irradiance to the corresponding irradiance available out of the atmosphere or extraterrestrial radiation.

Clearness index is one of the factors which can be used to evaluate the effects of cloud on extraterrestrial radiation. It is a stochastic quantity which varies with time of the day and season of the year. It can, therefore, be taken as a random variable whose future can be predicted within a specific range through a statistical analysis of its past occurrence [31].

In this work, the clearness index is estimated by correlating monthly available values through the year in Lebanon and some near cities. Fig. (1) shows the correlated clearness index values throughout the year which was based on the monthly values of Lebanon and few neighboring cities (Cairo, Athens and Beer Sheva) for a suitable interpolation [32, 33].

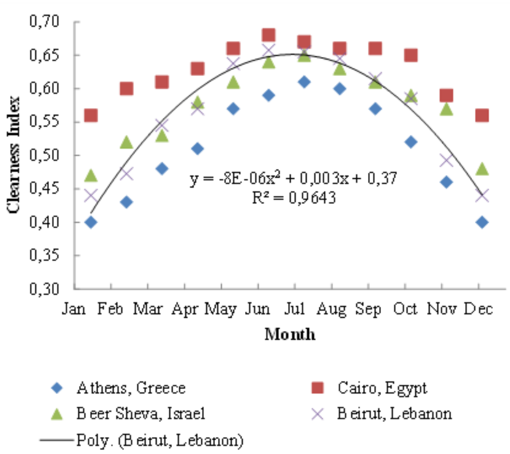


Figure 1. Interpolation of the clearness index k_T

The interpolation of kT leads to the following relation with respect to the day number in the year:

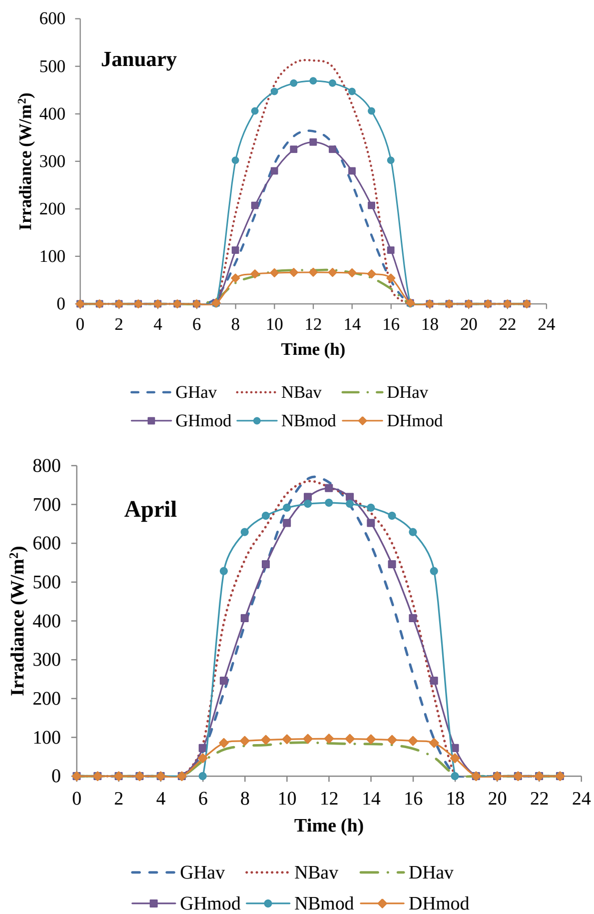
$$k_T = -8.10^{-6} n^2 + 0.003n + 0.37 \qquad (13)$$

3. Results and discussion

3.1 Validation of the method

For the validation of the numerical method, numerical results were compared to a weather file data for normal, diffuse, and global horizontal average hourly solar radiation per month. The weather file is issued from Meteonorm Software for Beirut. It is treating a typical meteorological year (TMY_2 file data). For each month, average hourly data were determined based on the weather file and compared to the data derived from the theoretical presented numerical model. The compared parameters were the global horizontal solar radiation (GH), the normal beam solar radiation (NB), and the diffuse horizontal solar radiation (DH).

Four representative months out of twelve are presented in the Fig. 2 and show a good consistency between the analytical model results and experimental results from climate file, which validates the adopted methodology. A slight difference between theoretical and experimental data is noted for the normal direct radiation; this difference is mainly due to distant shadings such as Lebanese mountains where a big amount of direct radiation is intercepted, especially in the morning and in the afternoon.



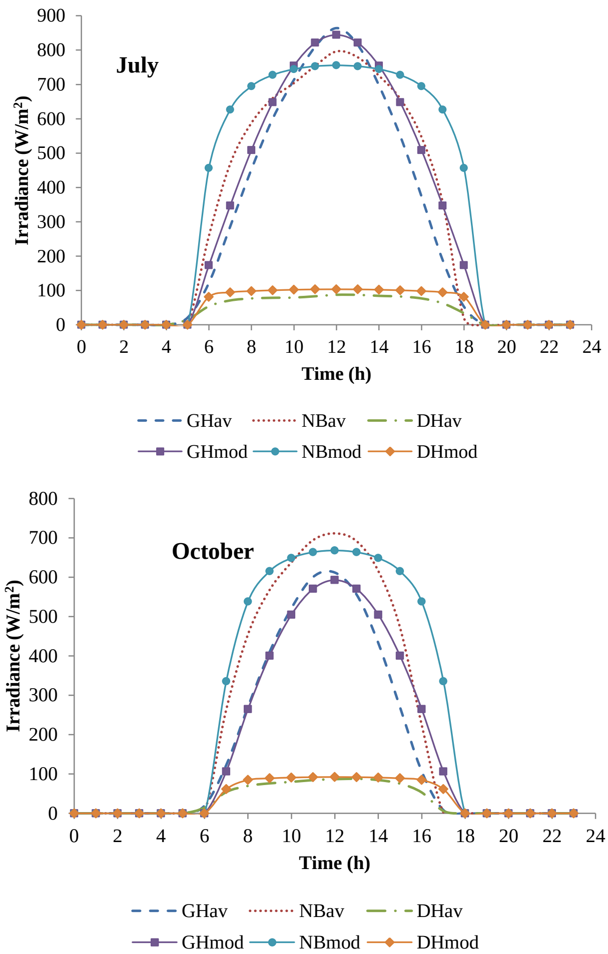


Figure 2. Average Hourly Irradiance for January, April, July, and October

In addition, the model supposes that the daily clearness index is constant; however, this parameter varies along the day with a maximum at noon which also induces some variations (overestimation in the morning and the afternoon and underestimation at noon).

Another validation of the presented model results was conducted through the study done by Sfeir [32]. Sfeir divided Lebanon geographically into two regions: (i) the coastal zone bordering the East-Mediterranean coast and where most of the population lives, and including a part of the West Mount-Lebanon mountain range (ii) and the interior Bekaa plain bounded west and east by the Mount-Lebanon and Anti-Lebanon ranges.

Fig. 3 shows a comparison between the results of Sfeir, the TMY_2 weather file values and the results of the calculation methodology for monthly average global radiation on a horizontal surface. Results show a very good accuracy for Beirut located in the coastal zone; in addition, the global radiation in the interior zone seems to be slightly higher than the coastal zone in summer and this can be mainly due to the high air humidity on the coast which decreases clearness of the sky and then the solar radiation.

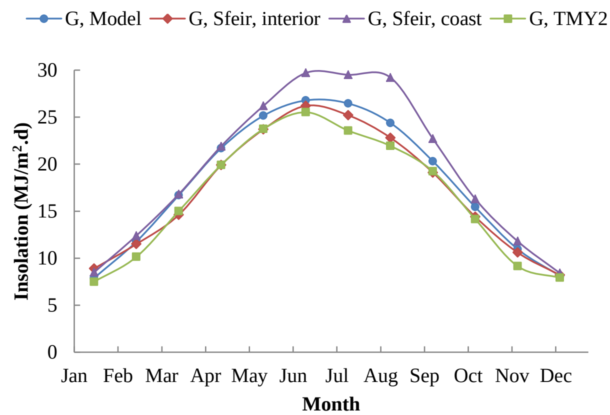


Figure 3. Monthly average global horizontal radiation in Lebanon

3.2 Global irradiance for different orientations

Global irradiance is important to be evaluated on vertical surfaces as well as horizontal surfaces, especially for the evaluation of thermal performance of buildings in summer conditions. It is also importance when PV panels are to be integrated on the building exterior walls or facades, where the new technology of BIPV (Building Integrated PV) is increasingly evolving and gaining interest as a multi-function item playing the role of building's envelope component, shading device and converting solar radiation into electricity.

Hourly Global Irradiance for typical days representing each month of the year are shown in Fig. 4 for Horizontal facades, for Vertical North and South facades in Fig. 5 and for Vertical East and West facades in Fig. 6.

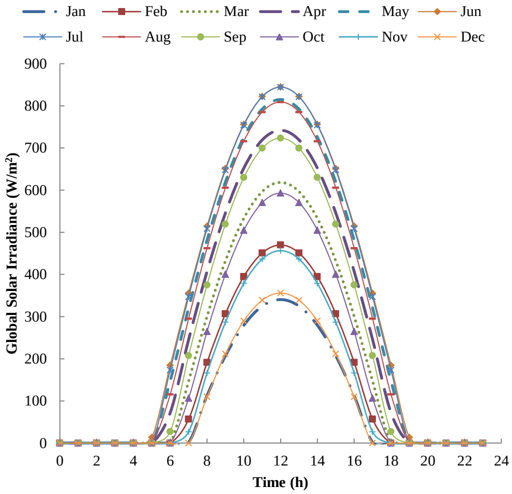
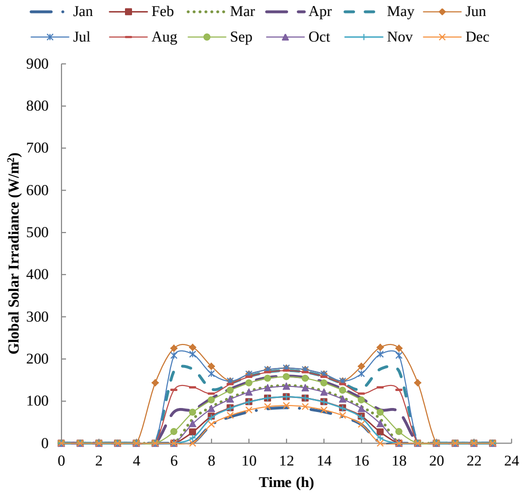
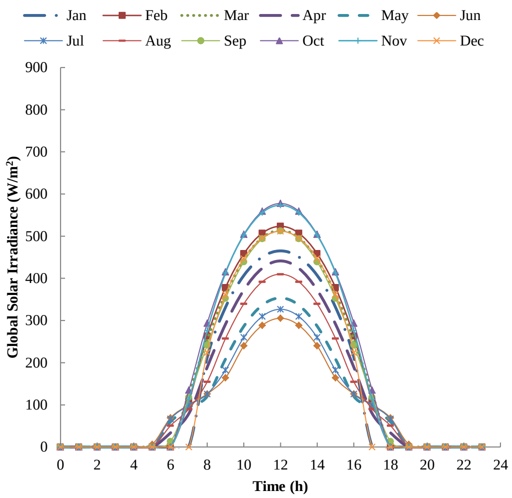


Figure 4. Hourly Global Irradiance on Horizontal Façade

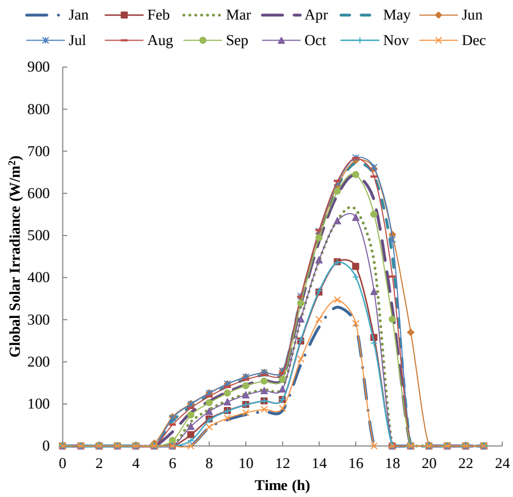


(b)

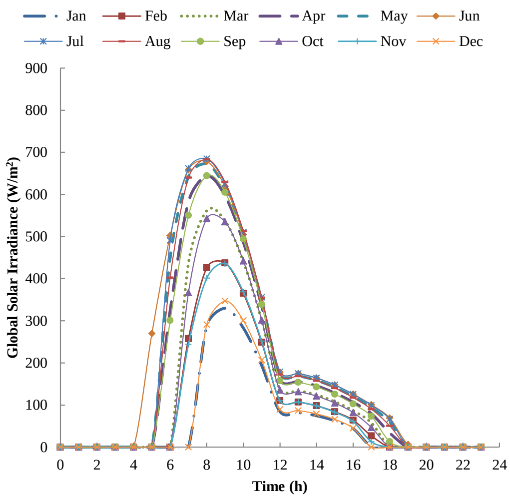
Figure 5. Hourly Global Irradiance on Vertical South (a) and North (b) Façade



(a)



(a)



(b)

Figure 6. Hourly Global Irradiance on Vertical West (a) and East (b) Façade

The results show a maximum global solar radiance in June and July for Vertical North and Horizontal planes, in May, June, July, and August for the East and West vertical planes and in October and November for South Vertical planes. The minimum global solar radiance is in January for all planes except the South where it reaches minimum values in June.

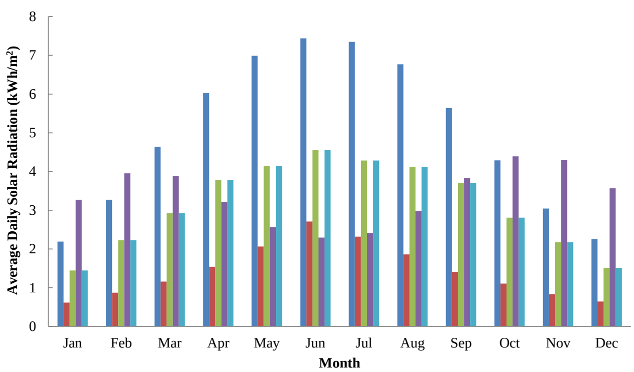


Figure 7. Total daily Global Irradiance on the different Facades

As well, Fig. 7 shows the total daily global irradiance on different oriented facades North, East, South and East in addition to the daily global irradiance on horizontal plane. Values are obtained by integrating the solar irradiance over a complete day. Results show that South oriented facades would receive their maximum solar irradiance in winter while the other facades oriented North, East and West would receive their maximum solar irradiance in summer.

3.3 Optimal solar positioning for solar collectors

This section aims to determine the optimal position of solar collectors for three configurations: a constant tilt angle, a monthly adjustable tilt angle, and a solar tracking system. In addition to these configurations, traditional solar collectors positioning with constant tilt angles (30°, 45°, and 60°) were evaluated.

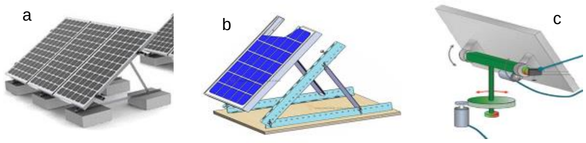


Figure 8. Case studies: constant slope angle (a), monthly variable slope angle (b), and tracking system (c)

Three relevant cases shown in Fig. 8 were studied. The first case was to find the optimal tilt angle for a maximum yearly solar radiation (a); this case assumes a fixed frame system with an optimal angle to be determined in order to have a maximum annual solar energy received on the panels.

The second case was to determine the monthly optimal slope angle for a maximum monthly solar radiation (b); this case assumes the use of a manually adjustable frame that should be adjusted every month.

Finally, the solar tracking system case was assessed. It is a device for orienting a solar panel or concentrating a solar reflector or lens towards the sun. Concentrators, especially in solar cell applications, require a high degree of accuracy to ensure that the concentrated sunlight is directed precisely to the powered device. Precise tracking of the sun is achieved through systems with dual axis tracking (c).

The optimization was made according the Generalized Reduced Gradient (GRG2) Algorithm which is normally used for optimizing nonlinear problems. It uses a robust implementation of the BFGS quasi-Newton algorithm as its default choice for determining a search direction.

a.) Optimal slope angle for a maximum yearly solar radiation

The total yearly solar radiation was optimized according to the tilt angle which was considered to be constant in this first configuration. The slope angle was considered as variable parameter and the yearly total energy received on the surface was optimized accordingly in order to find the best slope angle. It was found that the optimal angle for having the maximum solar energy on a tilted surface is 27.9° and the evolution of the average total daily global radiation for each month for this constant tilt angle is shown in Fig. 9.

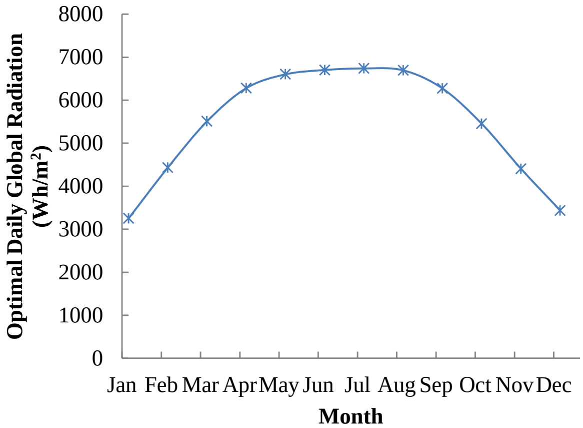
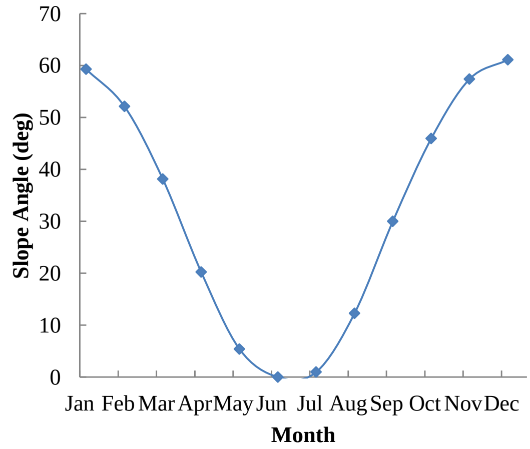


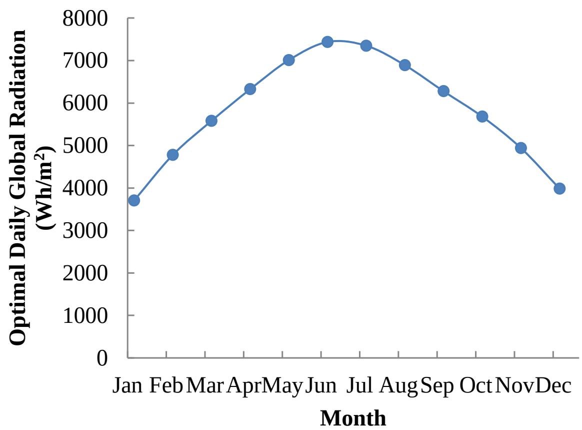
Figure 9. Average daily global radiation per month for the optimal constant tilt angle solar panel

b.) Optimal monthly slope angle profile for a maximum daily solar radiation

In this case, the total monthly solar radiation was optimized according to the tilt angle which was considered to be monthly adjustable through a manually adjustable frame that should be adjusted every month (Fig. 2b); the best calculation for case “a” was repeated for each month. The optimal angles for each month and the monthly evolution of the average total daily global radiation for the monthly adjustable tilt angle is shown in Fig. 10.



(a)



(b)

Figure 10. Optimal monthly tilt angle per month (a) and average daily global radiation per month (b) for a monthly adjustable tilt angle

c.) Tracking solar panels

A solar tracker is a device that orients a payload toward the sun to minimize the angle of incidence between the incoming sunlight and a solar panel. This increases the amount of energy produced from a fixed amount of installed power generating capacity.

The total solar radiation on a tilted surface is obtained by replacing β by θ_z in Eq. (1):

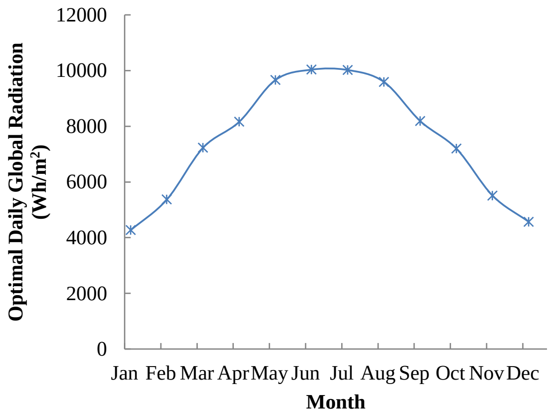


Figure 11. Average daily global radiation per month for a solar tracking system

$$I_t = \frac{I_b}{\cos\theta_z} + I_d\left(\frac{1+\cos\theta_z}{2}\right) + I\rho_g\left(\frac{1-\cos\theta_z}{2}\right) \qquad (14)$$

The evolution of the average total daily global radiation for each month for a solar tracking system is shown in Fig. 11.

d.) Comparison of the 3 optimal solutions

The comparison between the three above mentioned optimal solutions in Fig. 12 shows a slight energy gain between the optimal slope with fixed frame and the monthly optimal slope with adjustable angle frame. A noticeable energy gain can be observed when a tracking angle system is used especially during the sunny season from April to September.

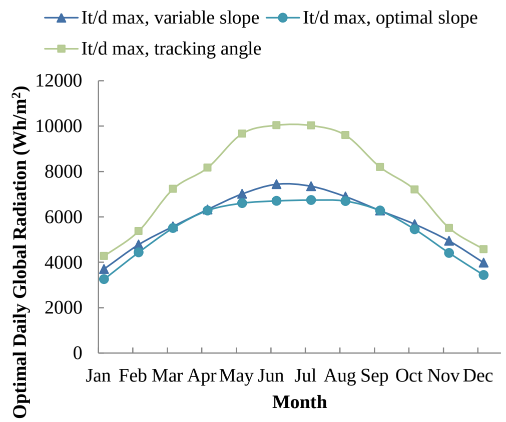


Figure 12. Comparison of the optimal average daily global radiation per month for the 3 configurations

e.) Traditional slope angles

It is interesting to evaluate the effectiveness of the traditional configurations of solar collectors with a constant slope angle and a 0° azimuth angle (South orientation). The examined angles are 30°, 45°, and 60° since they are the mostly used in practice. Results in Fig. 13 show that the best configuration is for a 30° slope angle especially in summer conditions; however, in winter, systems with 45° and 60° inclinations are slightly better. These angles are recommended for small scale solar water heating applications where high efficiency is required in winter and low efficiency is preferred in summer to avoid very high temperatures in the system [34].

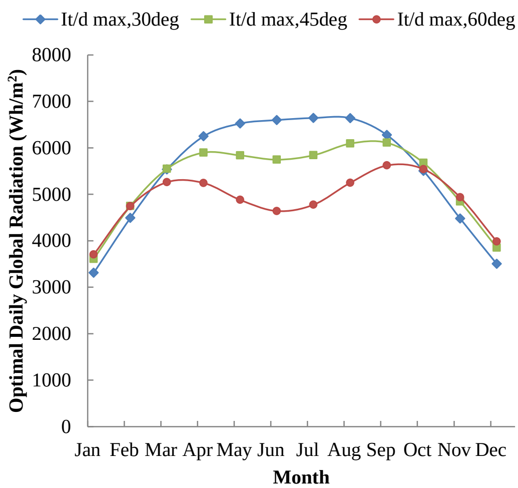


Figure 13. Optimal average daily global radiation per month for traditional tilt angles

4. Conclusion

This paper presented a theoretical analytical method for the determination of solar irradiance in Beirut for different orientations at any time of the year (day and hour). The input data were limited to the specification of tilt and azimuth angles, date, and time. The clearness index was approximated based on interpolation for 3 neighboring cities and was expressed as function of the day number in the year. The results show a good consistency between the analytical model and results from climate file, which validates the adopted methodology. A slight difference of xx % between theoretical and experimental data is noted for the normal direct radiation. Three optimal configurations were studied: a constant tilt angle, a monthly adjustable tilt angle, and a solar tracking system. The results show that the optimum angle of inclination for the city of Beirut is close to 30° (27.9°). By varying this angle monthly (i.e. through an adjustable tilt chassis), a 6% increase of collected energy is obtained compared to a constant optimal angle. As for the solar tracking system, it has great interest as it allows an increase of 37% of solar energy compared to a constant optimal angle. These optimal configurations were also compared with traditional solar collectors' positioning with constant tilt angles (30°, 45°, and 60°).

The method can be applied for any tilt and azimuth angles and not necessarily the ones used in this paper. It can also be replicated for other cities by changing the latitude angle and finding a new correlation between the clearness index and the day number in the year for the concerned location.

Nomenclature

Φ	Latitude, the angular location north or south of the equator, north positive; $-90° \le \Phi \le 90°$
δ	Declination, the angular position of the sun at solar noon; $-23.45° \le \delta \le 23.45°$
β	Slope angle, the angle between the plane of the surface in question and the horizontal; $0° \le \beta \le 180°$. ($\beta > 90°$ means that the surface has a downward-facing component.)
γ	Surface azimuth angle, the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive; $-180° \le \gamma \le 180°$
Ω	Hour angle, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive
θ	Angle of incidence, the angle between the beam radiation on a surface and the normal to that surface
k_T	Daily clearness index; it depends on the cloudiness and usually varies between 0.4 and 0.6 as shown in the various references
GH	Global Horizontal Solar Radiation
NB	Normal Beam Solar Radiation
DH	Diffuse Horizontal Solar Radiation
I	Particular day's radiation received on a horizontal surface
I0	Particular day's extraterrestrial solar radiation
Cs	1367 W/m2 (solar constant)
n	Day number in the year starting from January 1
ρ_g	Reflectance of the ground, albedo (here we take $\rho_g = 0.3$)
τ_b	Atmospheric transmittance for beam radiation
τ_d	Atmospheric transmittance for diffuse radiation
A	Altitude in km
R_b	Ratio between the direct radiation on the surface considered and that on a horizontal surface

Subscript

av	Hourly average solar data per month
mod	Values from the numerical model

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