Ångström-Prescott Models of Solar radiation over Earth surface

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Abstract. The current energy demand increases every day and the deficit of electricity generation in Colombia due to technical aspects such as the lack of generation infrastructure, cost overruns in the construction projects of new plants and environmental variability as a consequence of climate change, entail a high risk of energy rationing; for this reason some of the users, whether industrial or residential, have decided to seek multiple alternatives to reduce the costs of their billing in interconnected areas and even supply their energy needs.

Among these alternatives is found solar energy in its thermal and photovoltaic use, a resource that must be characterized in order to determine the technical and budgetary aspects involved in the implementation of profitable energy generation projects. This article seeks to provide technical tools for the design and implementation of generation projects based on solar energy, providing physical-mathematical approach based in the classical Ångström-Prescott model that allow engineers and researchers to model the global solar radiation on the Earth’s surface in order to maximize the use of this resource in a specific geographical location.

Although there are different ways to characterize the solar resource on the earth’s surface, this paper presents a review study focused on the most important global solar radiation estimation models present in the literature.

1. Introduction
The medium-term depletion of traditional energy sources (fossil fuels) and the need to develop technologies whose impact on the environment is progressively lower, is the motive of the presented article. The increase in the cost of energy resources and the problems related to global change are forcing researchers to focus their efforts on the search for alternative sources of energy to replace fossil fuels with less impact on the environment [1].

The use of the solar resource allows the generation of electricity with a substantial reduction of environmental impacts, without greenhouse gas emissions, with fewer changes in the habitat, without noise pollution, [2], with a distributed generation close to consumers. This complementary generation is very beneficial for the community, especially for the non-interconnected zones that represent 52% of the territory of Colombia, (government report [3]) and in which service delivery may be non-existent or intermittent with low levels of reliability [4].

In other fields, applying an alternative energy model favors not only the provision of household services or public lighting, but also education [5], in the improvement of hospitals and even in
public health, as solar radiation is directly related to both positive and negative effects on human beings, like sicknesses related with UV exposure or lack of vitamin D in cases of avoiding sun [6]. In agriculture, the effect of solar radiation on the quality of products, [7], or in the multiple studies carried out by agrarian associations, where linear correlations between global solar radiation and solar brightness were performed over 17 weather stations, with satisfactory results [8].

In order to take advantage of solar radiation, it is necessary to correctly characterize the energy resource, which can be done mainly through: direct measurements by means of properly calibrated radiometric instrumentation, large-scale determination by means of satellite images or the use of radiation atlases [9], and physical models. This approach provides more accurate information than that obtained by satellite and does not require the use of expensive instrumentation; it is based on the physical-mathematical connections between meteorological observations and solar irradiance at the location to be characterized.

This representation provides more accurate information than that obtained by satellite and does not require the use of expensive instrumentation; it is based on the physical-mathematical relationships between meteorological observations and solar irradiance at the site to be characterized. In addition to allowing the sizing of systems (photovoltaic and thermal) for energy use, the models for the determination of surface solar radiation are an effective tool to fill the gaps in existing historical series [10], determination of atmospheric pollutants [11], determination of protection indicators such as UV index of exposition [12] and measurements of atmospheric turbidity [11] between other applications.

2. Solar Radiation fundamental physics

The sun is the largest source of energy for planet Earth, it provides directly or indirectly all the energy that sustains life, all food and fuel ultimately comes from plants that use the sun’s energy to convert it into food through photosynthesis. Energy from the sun is generated in the solar core, in a thermonuclear fusion process in which hydrogen is transformed into helium. In this process, every second an approximate mass of 4.4 million tons is transformed into energy, which radiates \(3.96 \times 10^{26}\)

The energy coming from the Sun is the engine of the dynamics of the atmosphere, the ocean, the climate and the terrestrial biosphere. Solar energy reaches the Earth’s surface and is converted into heat due to differences in the absorption properties of the surface. This heating is not homogeneous, so that different temperatures induce movements within the atmosphere and the oceans. This energy is an essential factor in the global biogeochemical cycles, being the primary factor in the processes of water evaporation and photosynthesis in plants [13].

Solar radiation reaching the earth’s surface is attenuated in its intensity by various energetic processes that occur along its path through the earth’s atmosphere. These processes are [14]:

(i) Selective absorption by gases and by water vapor in the atmosphere. In this process, the gaseous molecules present in the atmospheric medium, due to their spectra, are capable of retaining electromagnetic radiation with energies of the order of differences between electronic, vibrational and rotational energy levels.

(ii) Molecular scattering, also due to gases and water vapor, occurs when the spherical particle (air molecule) has a size much smaller than the wavelength of the incident radiation. This solution was derived in the 19th century by Lord Rayleigh, which is particularly useful for the study of the scattering of solar radiation by air molecules and it is responsible of the blue color of the sky in noon and the red color in sunrise and the afternoon.

(iii) Dispersion and absorption by aerosols or atmospheric turbidity. When the particle size is at the order of the wavelength of the incident radiation, the solution of the wave equation
Figure 1. Solar radiation components

is extremely complex. Only at the beginning of the 20th century, Gustav Mie successfully obtained the solution, where Rayleigh’s solution is only one case of Mie’s theory.

When solar radiation enters the earth’s atmosphere, a portion of the incident energy is attenuated by scattering and absorption. The portion of incident radiation that reaches the ground directly in line from the solar disk is called Direct Radiation, the portion that reaches the ground after being affected by attenuation processes is called Diffuse Radiation [15]. A portion of the scattered radiation returns to space (Backward Scattering) and another portion reaches the surface (Forward Scattering) See Figure 1.

The radiation reaching the earth’s surface, the sum of the direct and diffuse components, is called global radiation and is measured in dimensions of power per unit area \([W/m^2]\).

The first models for the determination of global radiation were based on solar brightness, among them the most important in the literature is the Ångström-Prescott model [16], this model
after its creation has had different interpretation of several authors who have made adjustments or improvements that allow them to use it in different parts of the world for various tasks. [17, 18]

3. Ångström-Prescott Model

It is a linear model based on the relationship between the global radiation measured over the surface, and the solar brightness, the number of hours where direct radiation can be produce shade. It determines the the slope and intercept, which are obtained from an estimated regression of data from historical series of the two physical variables [19]. The relation between variables can be described by the equation:

\[
\frac{H}{H_0} = a + b \left( \frac{S}{S_0} \right)
\]  

where: \(H\) is the global solar radiation measured at the station; \(H_0\) is the global extraterrestrial solar radiation received in a horizontal plane for a given day over the desired location; \(S\) is the number of hours of solar brightness measured at the surface; \(S_0\) is the astronomical day length obtained from the movement of the Earth around the sun; \(a\) and \(b\) are the regression coefficients of a simple linear model, determined by least squares. \(H_0\) and \(S_0\) were obtained considering the geographical position of the site, the solar declination, the hour angle for sunrise and the solar constant. Since the model is based on the translational motion of the Earth, the solar astronomy equations are necessary for the determination of \(H_0\) and \(S_0\). From the angular position of the Earth moving around the Sun [9]:

\[
\alpha = \frac{2\pi(nd - 1)}{365}
\]

where: \(nd\) is the number of the day in the year. The solar declination, the angle between the apparent position of Sun and the plane of the Earth’s equator is expressed in terms of the Fourier Series:

\[
\delta = 0.006918 - 0.399912 \cos{\alpha} + 0.070257 \sin{\alpha} - 0.006758 \cos2{\alpha} + 0.000907 \sin2{\alpha} - 0.002697 \cos3{\alpha} + 0.00148 \sin3{\alpha}
\]

With the latitude \(\varphi\) and the declination the astronomical length of the day is calculated:

\[
S_0 = \left(\frac{2}{15}\right) \left[ \cos^{-1}(-\tan{\varphi}\tan{\delta}) \right]
\]

Now is posible to calculate the radiation at the upper boundary of the atmosphere:

\[
H_0 = \left(\frac{24}{\pi}\right) I_0 E_0 \left( \cos{\varphi}\cos{\delta}\sin{\omega} + \frac{2\pi{\omega}}{360}\sin{\varphi}\sin{\delta} \right)
\]

where \(I_0 = 1367\text{W/m}^2\) is the solar constant, \(E_0\) is the correction for eccentricity of the orbit:

\[
E_0 = 1.00011 + 0.034221 \cos{\alpha} + 0.00128 \sin{\alpha} + 0.000719 \cos2{\alpha} + 0.000077 \sin2{\alpha}
\]

And \(\omega\) is the hour angle for the sunrise for every day:

\[
\omega = \cos^{-1}(-\tan{\varphi}\tan{\delta})
\]
This procedure was used successfully by the author César Chacón in the 2005 Solar radiation Atlas of Colombia [9] and was again used in the 2015 interactive atlas version available at IDEAM’s website [20].

Different corrections have been developed on this model, each estimation involves different variables, such as the latitude present in the Glower and McCulloch model [21]; each of these with the possibility of delivering a model for various parts of the world as in the Page model [22], in which the variables \(a\) and \(b\) vary leaving \((S/So)\) free. Some of the models that have been obtained from the corrections to the Ångström-Prescott model are listed as follows.

3.1. Glower y McCulloch Model:
In addition to the variables already established in the Ångström-Prescott model, this new model takes into account the latitude of the site, which is symbolized as \(\varphi\) and is valid as long as it is less than 60° [21], and is represented as follows:

\[
\frac{H}{H_0} = a (\cos \varphi) + b \left( \frac{S}{So} \right) \tag{8}
\]

3.2. Page Model:
This is considered the model that can be used in any part of the world, however, it should be taken into account that it was made for a latitude of 40° [17],[22], therefore it is better to recalculate the values for the coefficients of \(a\) and \(b\), this model is represented in the following way:

\[
\frac{H}{H_0} = 0.23 + 0.48 \left( \frac{S}{So} \right) \tag{9}
\]

where the coefficients \(a\) and \(b\) have an established value.

3.3. Bahel Model:
It is a correlation based between hours of bright sunshine and data from 48 weather stations located around the world, under different geographical locations and meteorological conditions, [23] and is represented as follows:

\[
\frac{H}{H_0} = a + b \left( \frac{S}{So} \right) - c \left( \frac{S}{So} \right)^2 + d \left( \frac{S}{So} \right)^3 \tag{10}
\]

where \(a\), \(b\), \(c\) and \(d\) are the product of regressions, with a set value of 0.16, 0.87, 0.61 and 0.34 respectively.

3.4. Benson Model
Based on Ångström-Prescott, 2 different coefficients are proposed based on the similarities of the climatic conditions of the months of the year, as follows: January-March, October-December, and April-September [24], thus:

- January-March, October-December

\[
\frac{H}{H_0} = 0.18 + 0.60 \left( \frac{S}{So} \right) \tag{11}
\]

- April-September

\[
\frac{H}{H_0} = 0.24 + 0.53 \left( \frac{S}{So} \right) \tag{12}
\]
3.5. Gopinathan Model:
It takes into account the latitude, the function of the elevation called $Z$ in $km$ and the possible percentage of insolation [25], it is based on the Ångström-Prescott model, it gives three possible functions one for $a$ and one for $b$:

$$a/b = A + B * Z + C \left( \frac{S}{S_0} \right)$$ (13)

$$a = 0.265 + 0.07 * Z - 0.135 \left( \frac{S}{S_0} \right)$$ (14)

$$b = 0.401 - 0.108 * Z + 0.325 \left( \frac{S}{S_0} \right)$$ (15)

In addition, it provides two possible correlations found thanks to measured data of radiation and sunshine duration in 14 different locations, which can be used in other places with similar geographic and climatic conditions:

$$a = -0.0309 + 0.539 * (\cos \varphi) - 0.0693 * Z + 0.290 \left( \frac{S}{S_0} \right)$$ (16)

$$b = 1.527 - 1.027 * (\cos \varphi) + 0.0926 * Z - 0.359 \left( \frac{S}{S_0} \right)$$ (17)

In this form:

$$\frac{H}{H_0} = \left[ -0.0309 + 0.539 * (\cos \varphi) - 0.0693 * Z + 0.290 \left( \frac{S}{S_0} \right) \right]$$

$$+ \left[ 1.527 - 1.027 * (\cos \varphi) + 0.0926 * Z - 0.359 \left( \frac{S}{S_0} \right) \right] \left( \frac{S}{S_0} \right)$$ (18)

where $Z$ the height upper sea level and $\varphi$ the geographic latitude.

3.6. Zabara Model:
It is a monthly correlation that relates the Ångström-Prescott model as a third order function, thus providing a coefficient for $a$ and one for $b$ [26], these coefficients are obtained from the study of 7 meteorological stations in Greece which are applied to the Page model formula, which can be seen in the equation (9).

$$a = 0.395 - 1.247 \left( \frac{S}{S_0} \right) + 2.680 \left( \frac{S}{S_0} \right)^2 - 1.674 \left( \frac{S}{S_0} \right)^3$$ (19)

$$b = 0.395 + 1.384 \left( \frac{S}{S_0} \right) - 3.249 \left( \frac{S}{S_0} \right)^2 + 2.055 \left( \frac{S}{S_0} \right)^3$$ (20)

3.7. O.O. Ajayi, O.D. Ohijeagbon, C.E. Nwadialo, Olumide Olasope Model:
This is a new model created for the country of Nigeria in which 24 years of daily data from different stations were used and in which variables such as: the latitude of the place, the average daily relative humidity, the daily duration of sunlight, the maximum daily temperature and the cosine of the number of days are implemented; using this, five equations were proposed from which their coefficients were derived [27]. After doing this it was found that the model with the best performance was Model 3, which is expressed as follows:
\[ H = a \ast (\cos \varphi) + b(\cos nd) + c \ast T_{\text{max}} + d \left( \frac{S}{S_o} \right) + f \left( \frac{T_{\text{max}}}{R.H} \right) + g \left( \frac{T_{\text{max}}}{R.H} \right)^2 \]
\[ + h \left( \frac{T_{\text{max}}}{R.H} \right)^3 + i \ast (\cos \varphi) \ast (\cos nd) + j \left( \frac{T_{\text{max}}}{\cos \varphi} \right) + k(\cos^2 nd) + l \] (21)

where: \( H \) is the surface radiation, \( \varphi \) is the geographic latitude, \( S \) are the brightness hours at day, \( S_o \) astronomical day duration, \( T_{\text{max}} \) is the daily maximum temperature in degrees Celsius, \( nd \) is the number of Julian day, \( R.H \) is the daily Relativity Humidity with \( a, b, c, d, e, f, g, h, i, j, k, l \) the correlation coefficients.

3.8. Models based on Temperature

This kind of models have an advantage over the models based on sunlight in that the variable it uses, i.e. temperature, can be the only data available in the place where the modeling is required, because it is easy to obtain. These models assume that the difference between the maximum temperature (\( T_{\text{max}} \)) and the minimum temperature (\( T_{\text{min}} \)) is directly related to the extraterrestrial solar radiation received at the surface, since the temperature variable includes radiation, humidity, cloudiness, latitude and topography of the study site, see [17], like the next model the Bristow-Campbell model.

3.9. Bristow Campbell Model:

This model relates a simple equation suggesting the use of the transmissivity of the atmosphere, i.e. the fraction of incident radiation passing through a sample of material, in this case the atmosphere. [28].

\[ \frac{H}{H_o} = a[1 - \exp(-b \ast \Delta T)] \] (22)

where: \( a \) is the transmittivity of the atmosphere, \( b \) and \( c \) are constants of every place, and \( \Delta T \) is the difference between \( T_{\text{max}} \) and \( T_{\text{min}} \).

3.10. Hargreaves-Samani Model:

They propose a simple equation based on the temperature difference [29].

\[ \frac{H}{H_o} = a(T_{\text{max}} - T_{\text{min}})^{0.5} \] (23)

where: \( a \) is an adjustment factor, recommended by the author to be 0.16 for inland regions and 0.19 for coastal regions. \( T_{\text{max}} \) the maximum temperature and \( T_{\text{min}} \) the minimum temperature.

3.11. Hunt Model:

It takes the Hargreaves-Samani model and adds a coefficient \( b \), the intercept, and in addition to adding \( H_o \) as a multiplication factor [30]

\[ \frac{H}{H_o} = a(T_{\text{max}} - T_{\text{min}})^{0.5} \ast H_o + b \] (24)

where: \( a \) y \( b \) are adjustment coefficients, which relate the atmospheric conditions of the site and \( H_o \) is the solar constant in units of \([KW/m^2/day]\)
3.12. Annandale Model:
This model was derived from the Hargreaves-Samani model, to which a correction factor is applied to the \( a \) parameter to account for the effects of reduced altitude and atmospheric thickness. \[31\].

\[
\frac{H}{H_o} = a(1 + 2.7 \times 10^{-5} \times Z) \times (T_{max} - T_{min})^{0.5}
\]

where: \( a \) is an adjustment parameter, \( Z \) is the height over sea level.

3.13. Allen Model:
I take as a basis the work done by Hargreaves-Samani but suggested an improvement that includes a factor that allows self-calibration of the model, in which the atmospheric pressure of the site is included \,[32]\.

\[
\frac{H}{H_o} = Kr(T_{max} - T_{min})^{0.5}
\]

\( Kr \) depends of average atmospheric pressure in the site, PS which is measured in \([kPa]\), \( Po = 101.3 Kpa \) is the atmospheric pressure at sea level and \( kra \) is an empirical coefficient equal to 0.17 for inland regions or equal to 0.20 for coastal regions.

\[
Kr = kra \left( \frac{PS}{Po} \right)^{0.5}
\]

Thanks to the previously developed models or the so-called classical models, improvements have been made or comparisons have been made with different expressions, which has led to the creation of new models, more recent expressions that have been treated in computer programs that speed up and develop the analysis in a faster and more efficient way, as is the case of New Temperature-based Models for Predicting Global Solar Radiation presented below:

3.14. Model of Gasser E. Hassan, M. Elsayed Youssef, Zahraa E. Mohamed, Mohamed A. Ali, Ahmed A. Hanafy:
This model was obtained from the creation of new models based on temperature for ten locations around Egypt taking the data measured from New Borg El Arab, such data were the solar radiation and temperature data for 20 years from 1983 to 2004, taken from the NASA surface meteorology and solar energy website; to obtain this model 17 new models were proposed, which yielded results that were compared with models obtained from classical literature, such as the Allen models which can be seen in equation (26), Goodin et al. and Annandale which can be seen in equation (25), in addition to this it can be observed the capacity to estimate the solar radiation in any place of the world, even if there is no solar radiation measurement equipment, because the main variable of these models being the temperature is one of the most available and easy to measure variables, having said this and after finding the mean square error, the mean absolute percentage error, the mean absolute bias error and the determination coefficient (R2) it was found that the most functional model and of better performance was model 6, this supported in a program developed in the programming language C++. \[33\].

\[
\frac{H}{H_o} = a \times T^b \times Go + c
\]

where \( a, b \) and \( c \) are empirical coefficients, \( T \) is the monthly average of temperature in degrees Celsius, and \( Go \) is the extraterrestrial sola radiation in \( MJ/m^2/day \).
3.15. Models based in other meteorological parameters:
An average of data is required to establish an accurate estimate of the solar radiation value, however, these may be very scarce, so it has been decided to use meteorological parameters other than the classic ones, such as precipitation, relative humidity, dew point temperature, soil temperature, evaporation, pressure, wind speed and rainfall [17].

3.16. Sabbagh Model:
This model is proposed to be applied in dry arid or semi-arid regions such as Iran, which are located at an average sea level, i.e. approximately 300 m, and in case the area or region for which they plan to use this model has a higher altitude, it will be necessary to modify it, this model, although it could consider the effect of relative humidity, cannot take into account the effect of dust; This is how the geographic and seasonal factor called Kg [34].

\[ H = 0.06407(Kg) \exp \left[ L \left( \frac{S}{12} - \frac{RH^{0.333}}{100} - \frac{1}{T_{\text{max}}} \right) \right] \]  

(29)

where \( Kg \) is a geographical and seasonal factor, \( RH \) relativity humidity, and \( T_{\text{max}} \) it the maximum temperature

3.17. Sabziparvar Model:
This model modifies the Sabbagh model including three new considerations such as: correction factor for altitude, correction factor distance sun land and the monthly average of the total number of days with dust, in addition to this the fact of the variation of the hours of sun that would be assumed to be 12 for any place in the world, but for latitudes considered subtropical or that exceed or are equal to 30 degrees of latitude, the variation should be considered in a different way to avoid errors of overestimation or underestimation of solar energy. [34].

3.18. Maghrabi Model:
This model was created using 9 years of solar radiation data, it was established for Tabouk in Saudi Arabia (28.38-N, 36.6-E), it takes into account five meteorological parameters for its creation, which are: perceptible water vapor, temperature, relative humidity, atmospheric pressure and possible daily sunshine hours, this model has a high accuracy, to which different statistical tools were applied in its creation, such as mean percentage error (MPE), root mean square error (RMSE), mean bias error (MBE), and correlation coefficient (R); This model was compared with 29 other models available in the literature and showed an underestimation or overestimation of measured solar radiation, the model that showed a better prediction with respect to the model developed was the Abdalla model, this does not mean that the other models are not accurate, but that being created for different places in the world, they have different pre-established conditions that in this case do not make them the most suitable. This is applicable to any place that has conditions similar to those of Tabouk in Saudi Arabia. [35].

\[ H = 163.01 - 1.04 \left( \frac{S}{So} \right) + 0.12 * T - 0.21 * P - 1.06 * PWV - 0.03 * RH \]  

(30)

where: \( T \) is the temperature in degrees Celsius, \( P \) is the atmospheric pressure, \( RH \) is the relativity humidity, and \( PWV \) is the Perceptible water vapor in mm.

As technology has advanced, use has been made of computational tools such as: Matlab which allows to simulate, model and determine characteristics, with the blocks already preset in Simulink [36], or with neural networks as for example in: Estimation of Hourly Solar Radiation Using Empirical Models and Artificial Neural Networks [37] where they use as input variables solar radiation estimates obtained from a simple mathematical model and different
easily acquired climatic variables such as: temperature, pressure and humidity, where in addition a comparison was made that showed that these turn out to be adequate or you can also count on applications such as: Arduino, which allows to create prototypes that record the measurement of solar radiation [38], or Machine Learning which programs and adapts a type of algorithms according to the need that will allow the machine to make predictions or identify different patterns, as is the case of: Solar radiation forecasting model based on Machine Learning where the objective is to reduce uncertainty, grouping data that are sent to a predictor that estimates numerical data and when compared with measured data establishes a deviation that allows to know not only the uncertainty but also to estimate a long-term energy reserve. In addition to these tools, there are also statistical methods that allow calculating the error with a certain number of established data, which in turn allows making a comparison to know which would be the most optimal model depending on each situation [39].

4. Conclusions
Solar radiation is a fundamental parameter for everything, as time goes by in our attempt to reinvent and build the future in a better way, research has led us to understand that this is an even broader topic than one would think, knowledge about solar radiation is not only important for electrical engineering but it is a knowledge that can be applied to multiple fields such as agronomy, meteorology, geography, even dermatology, to mention a few examples, since it directly or indirectly affects many of the natural and artificial processes that occur on the planet. Measuring equipment is expensive so they can not be available to everyone, so you can resort to institutions in this case for Colombia to the IDEAM (Spanish Acronym of Meteorological Institute of Colombia) or agricultural associations which may have such instrumentation and can provide the corresponding data as is the case of Cenicafé (National Center for Coffee Research). Undoubtedly, one of the most used models, despite the fact that its measured data are not very easy to obtain, is the Ångström-Prescott model, the different variations have allowed it to be applied in many parts of the world, however, this is very important since, as far as possible, these variables should be adjusted locally, to reduce the margin of error and not overestimate or underestimate the data obtained. The technological advance has allowed the creation of multiple tools, which allows that nowadays the calculation of the equations is first of all easier and that if it is applied in the correct way, it does not have errors, that is why it is so important to know the theory.

Depending on the data you have, we recommend the following:

If you have a sunshine data, the Ångström Prescott model is undoubtedly the best option, if you do not have data to perform the regression that allows you to calculate $a$ and $b$, we recommend models with pre-established variables with Page, Bahel, Gopinathan, it all depends on what other data you may have. If you have a temperature data, but you do not have the value of the constant you can use the Hargreaves-Samani model or if you have the pressure you can use the Allen model, or if you have altitude you can use the Annandale model. If you have the relative humidity, temperature and latitude, which are easily accessible data, you can make use of the Sabbagh model, but if in addition to this you have the possibility of obtaining the atmospheric pressure the model you can use is Maghrabi.

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