ISBN: 978-628-95207-4-3. ISSN: 2414-6390. Digital Object Identifier: 10.18687/LACCEI2023.1.1.455

Solar radiation as a source of clean energy: Calculation by Bristow-Campbell thermal amplitude model and validation, 2020

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Abstract- The objective of this research is to validate the thermal amplitude model of Bristow - Campbell to estimate the solar resource in the development of clean energy in the city of Huancayo (Junín - Peru) during the period 2020. The results obtained from the model were compared with the values obtained with the use of the pyranometer as a meteorological instrument, using temperature data. To estimate the available radiation throughout 2020, 732 data of maximum and minimum temperatures were downloaded obtaining 2 data/day for 366 days from the conventional meteorological station of SENAMHI installed in the province of Huancayo and for the validation process, 366 global data of solar radiation data measured by the pyranometer equipment on surface were used, the same that were downloaded from the Observatory of the Geophysical Institute of Peru (IGP) of Huancayo, the results of solar radiation estimated with the model presented an annual average of 6. 14 kWh/m2/day and with the pyranometer a value of 5.76 kWh/m2/day, the regression analysis between the estimated and measured data shows a value of r equal to 0.90, with the variation of the estimated radiation of 6.15 ± 0.36 and the measured radiation of 5.76 ± 1.24 kWh/m2/day; Thus, the use of the Bristow and Campbell model to estimate the global radiation in the province of Huancayo was presented as an adequate and efficient alternative.

Keywords: solar radiation, Bristow and Campbell model, thermal amplitude.

I. INTRODUCTION

According to the World Health Organization (WHO), 91% of the people in the world are exposed to air pollution because they live in places with non-recommended air quality levels, generating a concern in the attendants to the world conference on air pollution and health, therefore, an urgent call was made to modify conventional energies (coal, gas and oil) for cleaner energies [1]. At the industrial level, the consumption behavior is the same, representing 30% worldwide of this type of energy during the last decade [2]. For this reason, governments are expected to make a cultural change and technological development towards renewable energies in order to comply with environmental commitments [3]. In Peru the energy base is hydroelectric and projects with solar and wind energy have already started to be developed, demonstrating a cultural change as equal as in countries such as China [4] or Russia [5], for the General Directorate of Energy Efficiency (DGEE) the participation of primary energies in the electricity market in 2019 was 153 937 TJ of which the contribution was 83.9 % Hydro, 3.9 % wind, 1.8 % solar and 4.4 % other, the low contribution of solar energy draws attention due to the fact that it can provide geographically inaccessible places that do not have commercial electric power, the eight solar photovoltaic plants with an installed capacity of 284.48 MWp connected to the National Interconnected Electric System is still very little for the great potential of existing solar radiation [6]. Necessary information to determine and quantify the solar irradiation on the earth's surface and thus know the potential of photovoltaic systems, can be found in the Solar Energy Atlas, with data on the spatial and temporal distribution of solar incidence, however this information is very sensitive to weather conditions and phenomena, so the alternative of mathematical models such as Bristow - Campbell are economically accessible and also affective to find the total radiation to generate the addition of direct radiation and diffuse radiation on a horizontal surface [7]. In Huancayo, due to its location at 12º from the equator, it presents a potential for the application of photovoltaic energy, so we will use the data of the National Meteorology and Hydrology Service (SENAMHI) to obtain historical and bibliographic data that show the region. Central Peru with constant solar radiation throughout the year [8], with the objective of validating the Bristow and Campbell thermal amplitude model to estimate the solar resource in the development of clean energy in Huancayo during the 2020 period; In addition to establish the difference of extreme temperatures during the day to estimate the solar resource in clean energy development and to establish the extraterrestrial solar radiation using the Bristow - Campbell model in Huancayo during the 2020 period.

Digital Object Identifier: (only for full papers, inserted by LACCEI).
ISSN, ISBN: (to be inserted by LACCEI).
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II. METHODOLOGY

The research was conducted in the city of Huancayo, Peru, located at latitude: 12° 4' 5" South, longitude: 75° 12' 38" West with a total area of 3558.10 km2 at an altitude of 3259 m.a.s.l.; in the meteorological stations near the study area, data were obtained from daily measurements of the maximum and minimum air temperature and the value of daily global solar radiation.

2.1. Estimation of daily global solar radiation

It was performed through the empirical relation that expresses the daily total atmospheric transmittance [9].

$$\frac{R_g}{R_e} = A\left[1 - e^{-B(T_{máx} - T_{mín})^C}\right] \quad (1)$$

Where:

R_g: Global radiation (kWh/m2).

R_e: Extraterrestrial solar radiation (kWh/m2).

A: Maximum atmospheric transmittance, which depends on the atmospheric pollution of the site and the altitude.

B: Region-specific constant, depends on the constant C.

C: Region-specific constant, depending on the thermal amplitude and latitude.

The most frequently reported values for these coefficients are 0.78 for A, the range of 0.004 to 0.010 for B and 2.4 for C.

We have the following equations for the B and C coefficients:

$$B = 0.107C^{-2.6485} \quad (2)$$

$$C = 2.116 - 0.072(T_{máx} - T_{mín}) + 57.574e^{\emptyset} \quad (3)$$

Where:

$\emptyset$: Geographic latitude

2.2. Clear sky atmospheric transmittance

The atmospheric transmittance for direct radiation by the empirical relationship given in the following equation.

$$A = 0.56(e^{-0.56M} + e^{-0.095M}) \quad (4)$$

Where:

A: Clear sky atmospheric transmittance.

M: Air mass ratio.

The constants account for the attenuation of radiation by the various factors discussed above. Because scattering is wavelength dependent, the coefficients represent an average scattering over all wavelengths. This ratio gives the atmospheric transmittance for clear skies to the precision of 3%.

2.3. Extraterrestrial solar radiation

It is the energy received in a plane outside the Earth's atmosphere, the plane is tangential to the planet [10], The solar radiation received at a site depends on the solar flux outside the atmosphere. The total daily extraterrestrial insolation (R_e) incident on a horizontal surface was calculated using the following equation.

$$R_e = \frac{24(60)}{\pi} E_O\, I_{CS}\, (\omega\, sen\emptyset\, sen\delta + cos\emptyset\, cos\delta\, sen\omega) \quad (5)$$

Where:

E_O: is the eccentricity error

I_{CS}: is the solar constant (1367W/m2)

Ω: is the hour angle

$\emptyset$: is the latitude of the location of interest, and

δ: is the solar declination

2.4. Calculation of available solar radiation using the Bristow-Campbell Model

$$R_g = A\, R_e\, [1 - e^{-B(T_{máx} - T_{mín})^C}] \quad (6)$$

For best model performance, RSR and RMSE should be closer to zero, but r and NSE should have values close to 1. Agreement between estimated and measured values was evaluated quantitatively using Pearson's correlation coefficients (r), the Nash-Sutcliffe equation (NSE) and root mean square error (RMSE). The evaluation was scored as 'Very good' (0.75 <NSE <1.00), 'Good' (0.65 <NSE <0.75), 'Satisfactory' (0.50 <NSE <0.65), or 'Unsatisfactory' (NSE <0.50), according to the criteria suggested by [11]. A lower RMSE, the better performance it has of the model simulation.

The r, NSE and RMSE were calculated as follows:

$$r = \frac{\sum_{i=1}^{n}(X_i - X_0)(Y_i - Y)}{\sqrt{\sum_{i=1}^{n}(X_i - X_0)^2}\sqrt{\sum_{i=1}^{n}(Y_i - Y_0)^2}} \quad (7)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(X_i - X_0)^2} \quad (8)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)^2} \quad (9)$$

Where:

Yi y Xi: i-th values estimated and measured (MJ/m2)

X_0: average measured value

n: number of observations

For best model performance, RMSE should be closer to zero, but r and NSE should have values close to 1.

2.5. Data Analysis Methods

To determine the significance level of the Bristow and Campbell model, the Student's t-test and descriptive statistics were applied, and Matlab and Excel software were used to develop the statistical indicators and data analysis.

III. RESULTS

To determine the first objective, a thermal amplitude difference was performed, which was represented by the difference in extreme temperatures during the day, which allowed estimating the energy resource (solar) part of clean energy in the city of Huancayo during the period 2020.

TABLE I
THERMAL AMPLITUDE BASED ON TEMPERATURE

Year 2020	Temperature °C		Thermal Amplitude
Month	Maximum	Minimum	
January	20.88	7.44	13.44
February	20.54	8.29	12.24
March	20.62	7.46	13.16
April	21.50	6.14	15.36
May	21.63	4.92	16.71
June	22.04	2.46	19.57
July	22.39	1.87	20.51
August	23.07	2.99	20.08
September	21.89	6.73	15.16
October	21.57	6.88	14.69
November	23.28	6.94	16.34
December	21.15	8.20	12.95

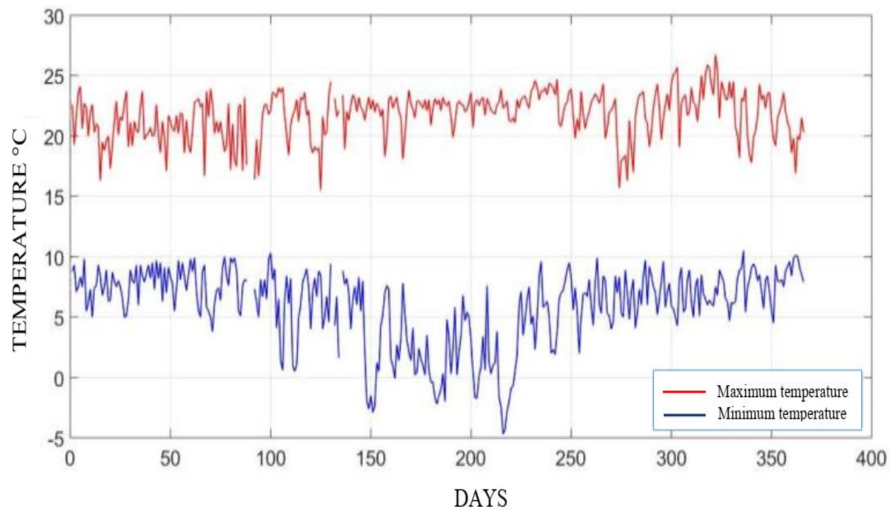

Figure 1: Daily minimum and maximum temperatures at the Huancayo observatory weather station, 2020.

Table 1 resumes the monthly averages of the maximum and minimum temperatures and thermal amplitude, showing that November had the maximum value of 23.28 °C and July had the minimum value of 1.87 °C, with the greatest temperature difference in July with a value of 20.51 °C. Figure 1 describes the maximum and minimum temperature values recorded at the meteorological station of the Huancayo observatory during the 2020 period, with a maximum value of 26.7 °C on November 17, 2020, and a minimum value of -4.7 °C on August 3, 2020. Daily data were taken for the 366 selected days corresponding to the year 2020. As for the thermal amplitude, Figure 2 shows the difference in the maximum and minimum temperature, a monthly average with a maximum value of 20.51 °C and a minimum value of 12.24 °C.

These extreme temperature data served as the main input to the Bristow and Campbell model to estimate the solar resource available in Huancayo. According to [12], it states that meteorological variables significantly influence solar radiation, obtaining a value of NSE equal to 0.77, concluding that the model is valid for estimating solar radiation according to the conditions of each location.

Regarding the second objective, the estimates of extraterrestrial solar radiation were obtained based on the monthly average of data available in 366 days (2020). The results are shown in Table 2.

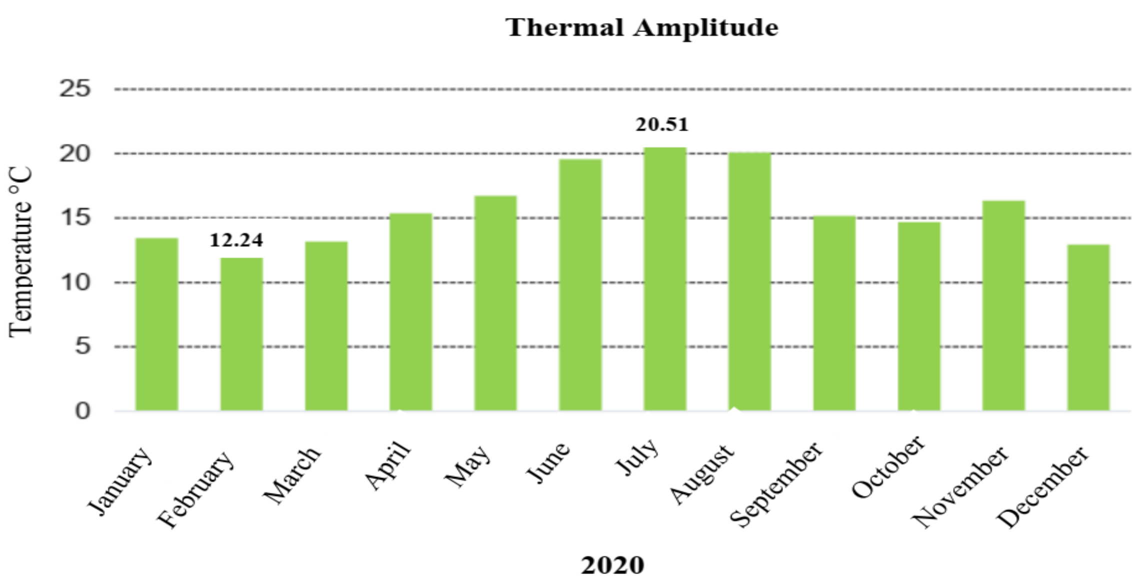

Figure 2: Difference of minimum and maximum temperatures of the meteorological station of the Huancayo observatory during the period 2020.

TABLE II
MONTHLY EXTRATERRESTRIAL RADIATION ESTIMATED WITH THE BRISTOW - CAMPBELL MODEL IN HUANCAYO. 2020

Year 2020	Extraterrestrial radiation kWh/m2/day
January	11.14
February	10.97
March	10.38
April	9.37
May	8.33
June	7.81
July	8.06
August	8.97
September	10.01
October	10.75
November	11.06
December	11.13

Table 2 shows that the maximum value is in January with a value of 11.14 KWh/m2/day and the minimum value is 7.81 KWh/m2/day in June.

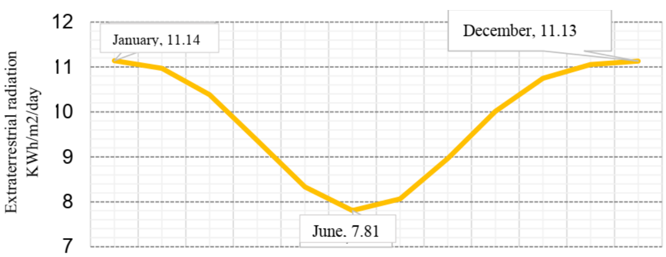

Figure 3: Difference of minimum and maximum temperatures of the meteorological station of the Huancayo observatory during the period 2020.

Figure 3 shows the monthly performance of extraterrestrial solar radiation, showing the highest values in january and february followed by a significant decrease until reaching a minimum point with a value of 7.81 kWh/m2/day in june, then it starts a new upward trend until november and december.

The Bristow-Campbell model was applied to estimate the available solar radiation in the province of Huancayo, the results are shown in Figure 4.

Figure 4 shows the monthly daily variation of global available solar radiation estimated using the Bristow-Campbell model, the sidebar of the figure shows the intensity of solar radiation with values ranging from 4 to 7.61 kWh/m2/day. This figure exemplifies the behavior of radiation in the city of Huancayo during the year 2020 and clearly shows marked values according to the seasons of the year with maximum values in summer and spring with a value of 7.61 kWh/m2/day in the month of November, while winter and autumn present the lowest values coinciding with the minimum temperature values recorded during those months. The minimum value recorded is 3.94 kWh/m2/day in May.

Figure 5 shows the monthly solar radiation estimated with the Bristow-Campbell model in the city of Huancayo during the 2020 period.

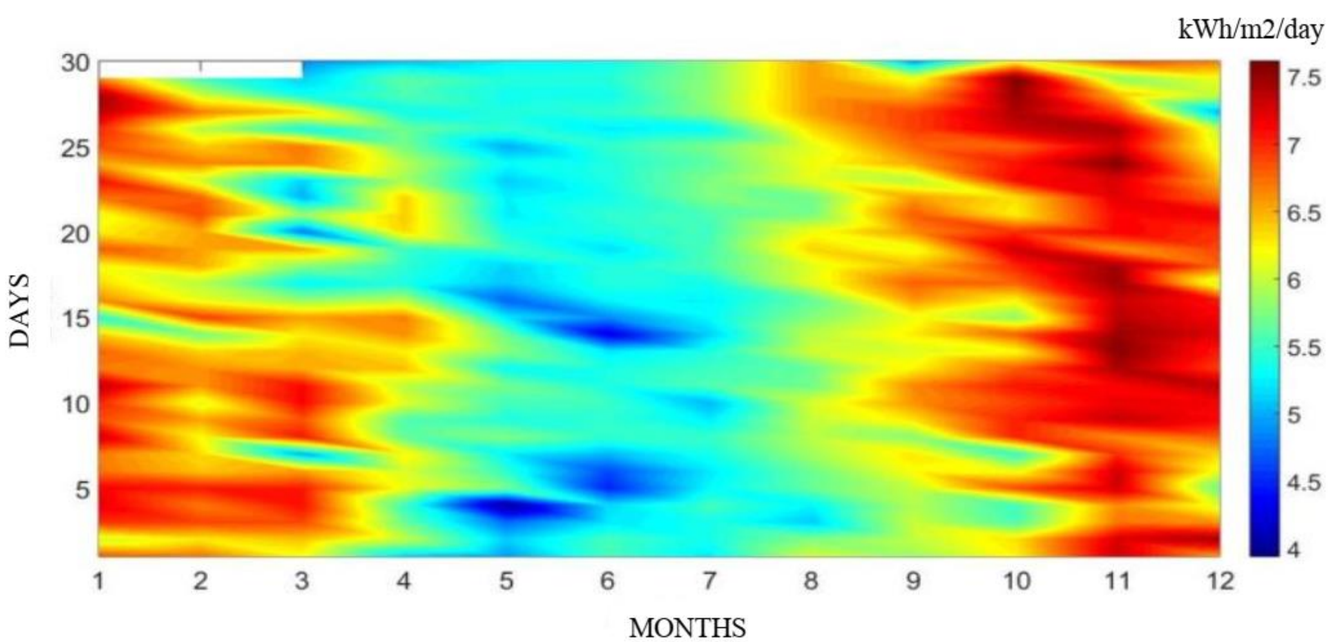

Figure 4: Daily solar radiation estimated with the Bristow and Campbell model in Huancayo. 2020

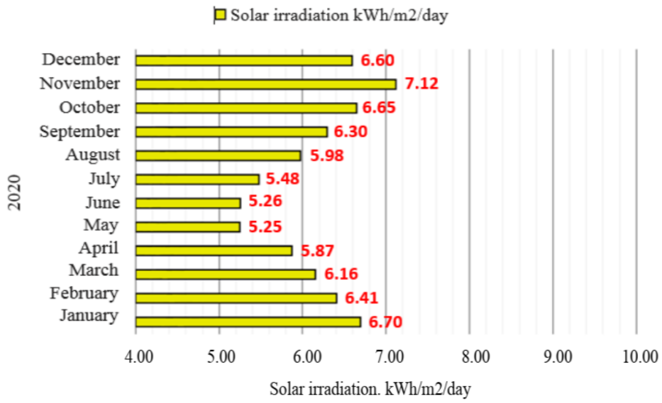

Figure 5: Monthly solar radiation measured with the pyranometer in Huancayo 2020

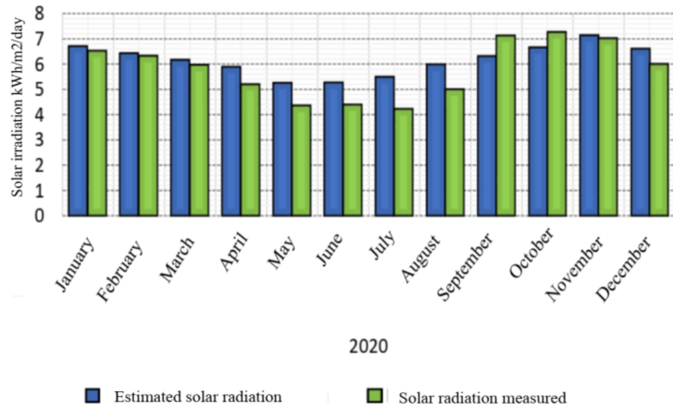

Figura 6: Comparación entre los datos de radiación solar mensual estimados y medidos en Huancayo durante el periodo 2020.

The solar radiation calculated with the Bristow and Campbell model is represented in Figure 5 with monthly averages, in which it is possible to appreciate the variation of radiation is very marked according to the seasons of the year, that in the months of May and June the minimum values of 5.25 and 5.26 kWh/m2 respectively are obtained, The tendency is to increase in the following months, reaching its maximum point in november with 7.12 kWh/m2/day, then from december onwards there is a gradual decrease in the following months, similarly in january until reaching its lowest point in may. The estimated radiation values show a variation of ± 0.36 kWh/m2/day.

The validation of the Bristow-Campbell model was carried out with the monthly average results of the measured and estimated solar radiation data shown in Table 3 and Figure 6.

TABLE III
ESTIMATED MEAN MONTHLY AVERAGE SOLAR RADIATION MEASURED IN KWH/M2/DAY IN HUANCAYO IN THE YEAR 2020

Year 2020	Estimated solar radiation kWh/m2/day	Measured solar radiation kWh/m2/day
January	6.70	6.50
February	6.41	6.30
March	6.16	5.94
April	5.87	5.18
May	5.25	4.34
June	5.26	4.38
July	5.48	4.21
August	5.98	4.98
September	6.30	7.10
October	6.65	7.23
November	7.12	6.99
December	6.60	5.98

Table 3 presents the estimated and observed solar radiation data obtained. The performance of the Bristow and Campbell model was performed by comparing a set of solar radiation data recorded at the surface with the pyranometer and data estimated with the model.

The radiation comparison was obtained in Figure 6.

Figure 6 illustrates the comparison of the radiation calculated by the Bristow and Campbell model and the monthly solar radiation measured with the pyranometer, the model can simulate the solar radiation with a very good accuracy, approaching the data recorded with the pyranometer.

IV.DISCUSIÓN

After evaluating the estimated and observed solar radiation data, it can be inferred that the performance of the Bristow-Campbell model performed through the comparison with the solar radiation data recorded at the surface with the pyranometer is accurate. The statistical results show for r a value of 0.90 indicating a high degree of linearity between the measured and simulated data, while the NSE shows a value of 0.77 indicating a good degree of model fit, the RMSE shows a value of 0.24, so the model has a good performance when performing the calculations of solar radiation; also the model used was considered by [13], as the best suited to the conditions of Junin (Peru). The results of [14] showed R2 and RMSE of 0.89 and 2.05 kWh/m2/day respectively, this similarity makes inferring that the radiation data estimated with the model produced simulations almost equal to those obtained with the pyranometer, the same happens with [15] that coincides with R2 values of 0.70 which indicates a good adjustment of the data, and it is concluded that there is a direct influence of the thermal amplitude on the solar radiation. The Student's t-test with 95% reliability and 5% significance, obtaining a Pvalue equal to 0.02, the result coincides with [16] which mentions that the data estimated by the Bristow and Campbell model are reliable at 95%.

V. CONCLUSION

The research presented monthly averages of maximum and minimum temperatures and thermal amplitude with a maximum value of 23.28 °C (november) and a minimum of 1.87 °C (july), the average annual thermal amplitude with a value of 15.85 °C, which significantly influences solar radiation. Extraterrestrial solar radiation was determined using the Bristow & Campbell model, with maximum values (january and february), followed by a significant decrease until reaching a minimum of 7.81 kWh/m2/day (june), with an upward trend to maximum values (november and december) with a maximum value of 11.14 kWh/m2/day. The annual average solar radiation estimated with the proposed model shows a value of 6.14 kWh/m2, while the annual average recorded with the pyranometer is 5.76 kWh/m2/day, with a minimum difference of 0.39 kWh/m2/day. The Bristow-Campbell model made it possible to estimate the monthly and annual mean daily global solar radiation in the Province of Huancayo with a Pearson correlation coefficient of 0.90.

ACKNOWLEDGMENT

We would like to thank the Universidad César Vallejo for the financial support for the execution of this research, within the Program de Fondos de Apoyo a la Investigation Docente-INVESTIGA UCV.

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