Modeling the Solar Radiation by Sunshine Duration in the Democratic Republic of Congo

Dieudonné Lusamba Yangindu, Mbuyu Sumbwanyambe,
Edmond Phuku Phuati, Max Seke Vangu and
Jean-Marie Tshitenge Mbuebue

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Dieudonné Lusamba Yangindu
Department of Electrical Engineering
University of South Africa
City of Tswane, South Africa
69456593@mylife.unisa.ac.za

Mbuyu Sumbwanyambe
Department of Electrical Engineering
University of South Africa
City of Tswane, South Africa
sumbwm@unisa.ac.za

Edmond Phuku Phuati
Department of Physics
University of Kinshasa
Kinshasa, Democratic Republic of Congo
edmondphuku@unikin.ac.cd

Max Seke Vangu
Department of Physics
University of Kinshasa
Kinshasa, Democratic Republic of Congo
Max.seke@unikin.ac.cd

Jean-Marie Mbuyi Mbuebue
Department of Physics
University of Kinshasa
Kinshasa, Democratic Republic of Congo

***Abstract*—The electrification rate of the Democratic Republic of Congo (DRC) is very low despite its impressive hydroelectric potential. But, it is hard to imagine that the Congolese national company of electricity could improve this rate in the next five or ten years only by building electrical infrastructure. Building electrical infrastructure requires a big capital that neither this company alone nor the Congolese Government cannot mobilize. So, solar energy seems an alternative to improve this rate. However, sizing and optimization of photovoltaic solar energy systems require knowledge of solar irradiance data related sites. The purpose of this study is to propose general models to predict solar irradiance (in kWh/m²/d) in function of sunshine duration (in h/d) for any province of Democratic Republic of Congo. Then, sunshine duration data and irradiance data related to all the provinces of the Democratic Republic of Congo have been used to establish five statistical models (linear, quadratic, cubic, logarithmic and exponential) to predict solar irradiance in any province of the Democratic Republic of Congo. The models established have been validated by the acceptable values of normalized statistical errors and the satisfaction of the Nash-Sutcliffe criteria (NS) and sufficient value of R², regression coefficient. The results show that by excluding provinces of Nord and Sud Kivu, the cubic model is the best, its value of the regression coefficient is 0.93.**

Keywords—relationship, sunshine duration, solar irradiance

III. INTRODUCTION

The overall energy need of the Democratic Republic of Congo (DRC) is covered at 95% by biomass and only 5% by electricity (19.1% in urban areas and 1¨% in rural areas) [1]. By considering that the DRC's annual population growth is around 3.2%, it is expected that its overall energy need will continuously increase. This increase is accompanied by too many constraints on the capacity of infrastructures to produce hydroelectric energy, transmit and distribute it. Therefore, photovoltaic solar energy is an alternative way to meet that demand. But, sizing and optimization of photovoltaic energy systems require knowledge of sites solar irradiance data.

So, faced with the lack of reliable meteorological data in several DRC provinces, this study proposes to provide five models to estimate the global solar irradiance on a horizontal surface based on the daily Sunshine Duration (SD) average for any DRC province. The SD data used in this study from European Centre for Medium-Range Weather Forecasts (ECMWF) collected through Climate-Data.org [2] and cover the period from 1999 to 2019 while the global solar irradiance (SI) data received on a horizontal plane from RECTscreen database collected through DRC Renewable Energy Atlas [3]. SD data was multiplied by a corrective coefficient equals 0.75 to taking into account of satellite effect in central Africa [4]. In the first step, the provinces of Nord and Sud Kivu have been taken into account and in the second step, these provinces have been excluded. The results have been validated by the acceptable values of these normalized statistical errors: Normalized Mean Absolute Error (NMAE), Normalized Mean Bias Error (NMBE), Normalized Root Square Mean Error (NRSME) and the satisfaction of the Nash-Sutcliffe criteria (NS) [5].

IV. LITERATURE REVIEW

Literature proposes several models to predict the global solar irradiance falling on a horizontal plane in function of the average of daily SD, such as the model of Angstrom [6] and improved by Prescott [7] , the model of Ögelman [8] , the cubic model of Bahel, the exponential model of El-Metwally [9]. These models are characterized by local coefficients.

The Prescott model declined as:

$$\frac{\overline{H}}{\overline{H}_0} = a + b\frac{\overline{S}}{\overline{S}_0} \tag{1}$$

Studies [10] demonstrates that the coefficient a varies between 0.06 and 0.44 while the coefficient b varies between 0.19 and 0.87.

The Ögelman model is :

$$\frac{\overline{H}}{\overline{H}_0} = a + b\frac{\bar{S}}{\bar{S}_0} + c\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 \tag{2}$$

The Bahel model has the following form:

$$\frac{\bar{H}}{\bar{H}_0} = a + b\frac{\bar{S}}{\bar{S}_0} + c\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 + d\left(\frac{\bar{S}}{\bar{S}_0}\right)^3 \quad (3)$$

The models above are the particular cases of a general model, called "polynomial model" and declined as:

$$\frac{\bar{H}}{\bar{H}_0} = a_0 + a_1\frac{\bar{S}}{\bar{S}_0} + a_2\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 + \cdots + a_n\left(\frac{\bar{S}}{\bar{S}_0}\right)^n$$

The exponential model proposed by El-Metwally can be found out either relation (3) or (4):

$$\frac{\bar{H}}{\bar{H}_0} = a + be^{\left(\frac{\bar{S}}{\bar{S}_0}\right)} \quad (4)$$

$$\frac{\bar{H}}{\bar{H}_0} = ae^{(1/\bar{S}/\bar{S}_0)} \quad (5)$$

The logarithmic model is in the following form:

$$\frac{\bar{H}}{\bar{H}_0} = a + blog\left(\frac{\bar{S}}{\bar{S}_0}\right) \quad (6)$$

In all of these relations, $\bar{H}_0$ is the daily extraterrestrial SI on a horizontal surface for a day in a month (in kWh/m²/d). $\bar{H}_0$ is given by the approximated expression in relation (7) or (8) [11] :

$$\bar{H}_0 = G_{SC} * \left(\frac{R_0}{R}\right)^2 * \frac{24 * 3600}{\pi} * \left\{1 + 0.33\cos\left(2\pi\frac{D_n}{365}\right)\right\}[\cos L \cos\delta \sin\omega + \omega \sin L \sin\delta] \quad (7)$$

In relation (7), all the angles are expressed in radian.
G_{Sc} is the solar constant; its value is 1.36kWh/m²
R_0 : Terrestrial rayon on surface (in m)
R : Terrestrial rayon at the considered altitude (in m).
L is the site latitude, ω the solar hour angle or sunset hour angle, δ the solar declination, given by the relation:

$$\delta\,(°) = 23{,}45\sin[\frac{360°}{365}(D_n + 284)] \quad (8)$$

S_0 is expressed by the following relation (in h/d):

$$\bar{S}_0 = \frac{2}{15}cos^{-1}(-tan\delta * tanL) \quad (9)$$

The contribution of this study is to determine some model to predict Solar Irradiance on a horizontal surface for any DRC province from the annual average daily Sunshine Duration by determining local coefficients of DRC province.

V. METHODOLOGY

The quantitative method has been used, by establishing the statistical relationship between the average value of Global Solar Irradiance (the explained variable) and the average of daily Sunshine Duration (the explanatory variable) for any province of DRC [12]. The research question is: What is the relationship between global solar irradiance (in kW/m²/d) falling on a horizontal surface and the annual average of the daily Sunshine Duration (in h/d) for DRC provinces?

The statistical data analysis was used to answer this question. Then, the linear, quadratic, cubic, logarithmic and exponential models have been established by using the method of least residuals [13]. The local coefficients have been calculated by identifying the relationships obtained with the corresponding models from literature.

Linear, quadratic and cubic are particular cases of the polynomial model, which has the following form:

$$\frac{\bar{H}}{\bar{H}_0} = a_0 + b\frac{\bar{S}}{\bar{S}_0} + a_1\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 + \cdots \ldots + a_n\left(\frac{\bar{S}}{\bar{S}_0}\right)^n \quad (10)$$

By analyzing data, the polynomial model is obtained in the following general form:

$$\bar{H} = a_0' + a_1'\bar{S} + a_2'(S)^2 + \cdots + a_n'(\bar{S})^n \quad (11)$$

Local coefficients $a_{n,n=1,2,3,..}$ are obtained by identifying the relation (10) to the relation (11):

$$a_n = \frac{1}{\bar{H}_0}.\frac{a_n'}{\bar{S}_0^n} \quad (12)$$

The logarithmic model obtained is:

$$\bar{H} = a' + b'log(\bar{S}) \quad (13)$$

$\bar{S}$ is positive because it representes the annual average of daily SD. By identifying the relation (13) to the relation (6), the system (14) is obtained as follows:

$$\begin{bmatrix}\bar{H}_0 & -\bar{H}_0\log(\bar{S}_0)\\ 0 & \bar{H}_0\end{bmatrix}\begin{bmatrix}a\\ b\end{bmatrix} = \begin{bmatrix}a'\\ \bar{H}_0\frac{b'}{\log(e)}\end{bmatrix} \quad (14)$$

$$a = \frac{a' + bln(\bar{S}_0)}{\bar{H}_0} \quad (15)$$

$$b = \frac{b'}{\log(e)} \quad (16)$$

The exponential model is expressed in two forms: (4) or (5). By identifying terms with (4), these values have been obtained:

$$a = a' = 0, \quad (17)$$

$$\bar{H}_0 be^{\left(\frac{\bar{S}}{\bar{S}_0}\right)} = b'e^{c\prime.\bar{S}}$$

$$b = \frac{b'}{\bar{H}_0} \quad (18)$$

$$\frac{1}{\bar{S}_0} = c' \tag{19}$$

A model is validated when its values of these statistical normalized errors: NMAE, NMBE, NRSME are acceptable and the value of statistical criteria of Nash -Sutcliffe NS is between 0.7 and 1.

Let R_i be:

$$R_i = \bar{H}_{mes,i} - \bar{H}_i \tag{20}$$

Where $\bar{H}_{mes;i}$ is the measured SI and $\bar{H}_i$ is the SI provided by the model. Then:

the Mean Absolute Error (MAE) is defined as:

$$MAE = \sum_{i=1}^{N} \frac{|R_i|}{N} \tag{21}$$

the Mean Bias Error (MBE) is defined as:

$$MBE = \sum_{i=1}^{N} \frac{R_i}{N} \tag{22}$$

the Root Mean Square Error (RSME) is defined as:

$$RSME = \sqrt{\sum \frac{R_i^2}{N}} \tag{23}$$

The criteria of Nash-Sutcliffe (NS) is defined as :

$$NS = 1 - \frac{\sum_{i=1}^{N} R_i^2}{A} \tag{24}$$

Where A is expressed in relation (25):

$$A = \sum_{i=1}^{N} (|\bar{H}_i - \bar{H}_{mean,mes}| + |\bar{H}_{mesi} - \bar{H}_{mean,mes}|)^2 \tag{25}$$

$$\bar{H}_{mean} = \frac{\sum_{i=1}^{N} \bar{H}_{meas,i}}{N} \tag{26}$$

VI. RESULTS

Two case have been distinguished. The first case was where Nord and Sud Kivu have been excluded; the second case was where they were included. Results obtained are presented in the tables and figures as follows

TABLE I MODEL COEFFICIENTS BY EXCLDING NORD AND SUD KIVU

	Linear		Quadratic			Cubic				Logarithmic		Exponential	
R^2	0.79		0.88			0.93				0.74		0.80	
NS	0.94		0.97			0.97				0.92		0.94	
NMAE	6.05%		3.92%			3.97%				5.46%		0.05%	
NMBE	4.06%		0.09%			0.84%				0.15%		-0.09%	
NRSME	7.94%		5.07%			0.26%				7.08%		6.06%	
Model Coefficients	*a*	*b*	*a*	*b*	*c*	*a*	*b*	*c*	*d*	*a*	*b*	*a*	*b*
Coef. Confindence bounds	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%
Grand Bandundu	0.12	0.63	1.34	-1.68	1.06	1.07	-3.10	4.15	-1.12	0.75	1.47	0	0.35
Grand Equateur	0.13	0.63	1.35	-1.70	1.07	1.10	-3.18	4.26	-1.15	0.76	1.48	0	0.35
Kasaï-occidental	0.12	0.63	1.34	-1.68	1.06	1.06	-3.07	4.11	-1.11	0.75	1.46	0	0.35
Kasaï-Oriental	012	0.63	1.34	-1.68	1.06	1.06	-3.06	4.10	-1.10	0.75	1.46	0	0.34
Grand Katanga	0.12	0.63	1.34	-1.67	1.06	1.04	-3.01	4.03	-1.08	0.75	1.46	0	0.34
Kinshasa	0.12	0.63	1.34	-1.68	1.06	1.07	-3.09	4.13	-1.11	0.75	1.46	0	0.35
Kongo central	0.12	0.63	1.34	-1.68	1.06	1.06	-3.07	4.11	-1.11	0.75	1.46	0	0.35
Maniema	0.12	0.63	1.34	-1.68	1.06	1.08	-3.11	4.16	-1.12	0.75	1.47	0	0.35
Province Orientale	0.13	0.63	1.35	-1.69	1.07	1.10	-3.17	4.25	-1.14	0.76	1.48	0	0.35

TABLE II. MODEL COEFFICIENTS BY INCLUDING NORD AND SUD KIVU

	Linear		Quadratic			Cubic				Logarithmic		Exponential	
R^2	0.64		0.70			0.71				0.61		0.66	
NS	0.87		0.90			0.70				0.85		0.87	
NMAE	6.30%		6.18%			12.28%				6.37%		0.14%	
NMBE	0.51%		0.46%			6.40%				0.54%		0.25%	
NRSME	7.55%		7.10%			6 .94%				7.81%		7.33%	
Model Coefficients	*a*	*b*	*a*	*b*	*c*	*a*	*b*	*c*	*d*	*a*	*b*	*a*	*b*
Coef. Confindence bounds	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%
Grand Bandundu	0.23	0.60	1.27	-1.69	1.07	-3.03	17.65	-29.27	16.60	0	0.38	0.81	1.22
Grand Equateur	0.23	0.60	1.28	-1.69	1.06	-3.11	18.10	-30.02	17.03	0	0.38	0.81	1.23
Kasaï-occidental	0.23	0.60	1.26	-1.69	1.07	-3.00	17.48	-28.98	16.44	0	0.37	0.81	1.22
Kasaï-Oriental	0.23	0.60	1.26	-1.69	1.07	-2.99	17.42	-28.88	16.38	0	0.37	0.81	1.21

Models	Linear		Quadratic			Cubic				Logarithmic		Exponential	
Model Coefficients	*a*	*b*	*a*	*b*	*c*	*a*	*b*	*c*	*d*	*a*	*b*	*a*	*b*
Grand Katanga	0.23	0.59	1.26	-1.68	1.06	-2.94	17.12	-28.38	16.10	0	0.37	0.80	1.21
Kinshasa	0.23	0.60	1.27	-1.69	1.08	-3.02	17.56	-29.12	16.52	0	0.37	0.81	1.22
Kongo central	0.23	0.60	1.26	-1.69	1.07	-3.00	17.44	-28.93	16.41	0	0.37	0.81	1.21
Maniema	0.23	0.60	1.27	-1.69	1.07	-3.04	17.69	-29.33	16.64	0	0.38	0.81	1.22
Province Orientale	0.23	0.60	1.28	-1.69	1.06	-3.10	18.04	-29.92	16.97	0	0.38	0.81	1.23
Nord Kivu	0.23	0.60	1.27	-1.69	1.06	-3.08	17.93	-29.73	16.87	0	0.38	0.81	1.22
Sud Kivu	0.23	0.60	1.27	-1.70	1.07	-3.16	18.36	-30.45	17.27	0	0.38	0.81	1.22

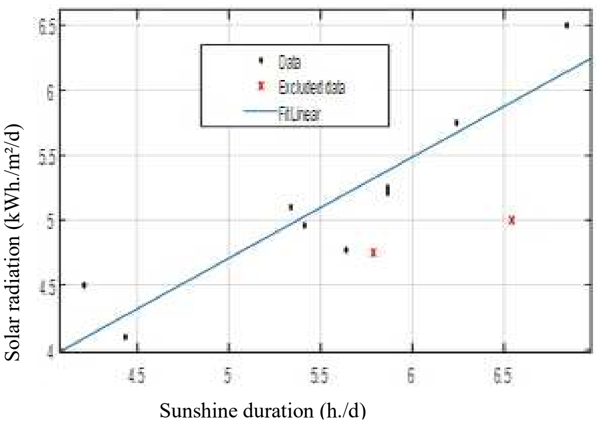

Fig. 1. Linear model (Nord and Sud Kivu excluded)

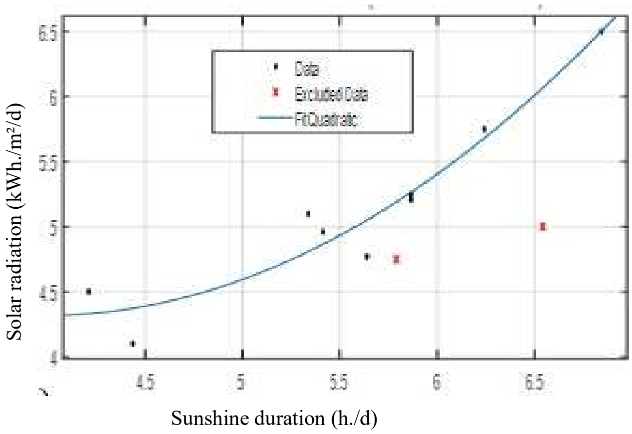

Fig. 2. Quadratic model (Nord and Sud Kivu excluded)

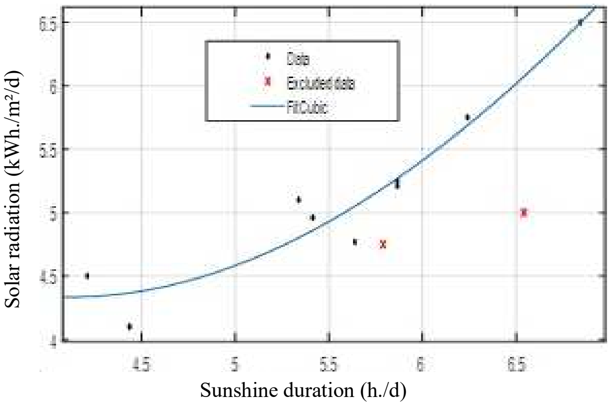

Fig. 3. Cubic model (Nord and Sud Kivu excluded)

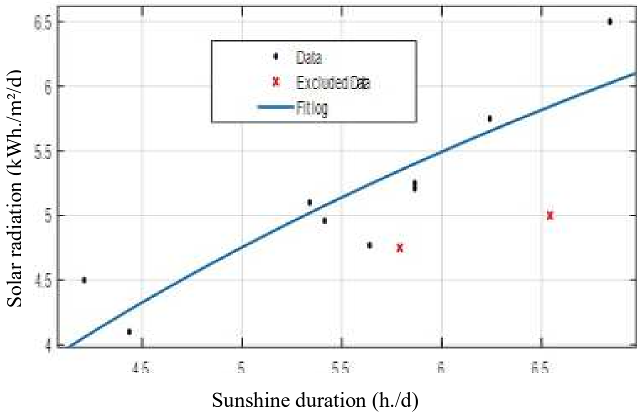

Fig. 4. Logarithmic model (Nord and Sud Kivu excluded)

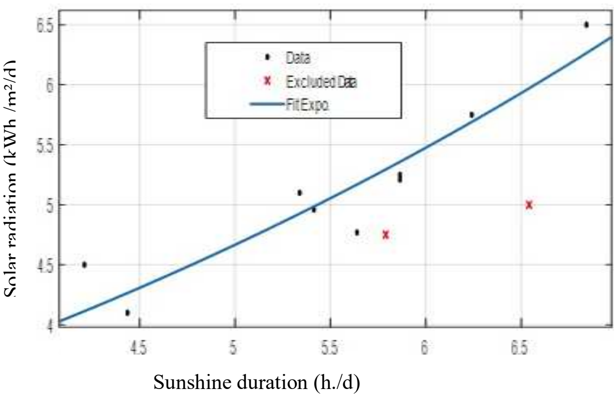

Fig. 5. Exponential model (Nord and Sud Kivu excluded)

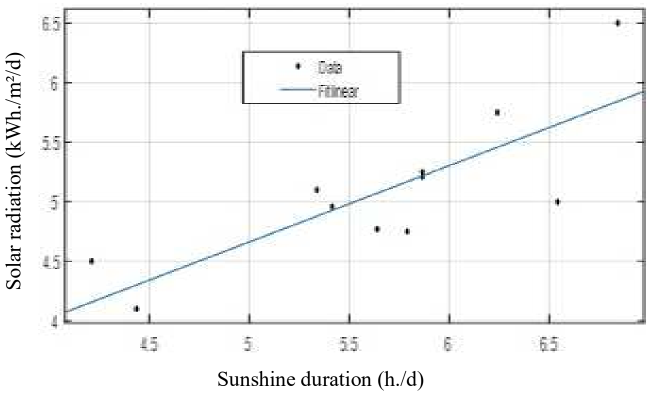

Fig. 6. Linear model (Nord and Sud Kivu included)

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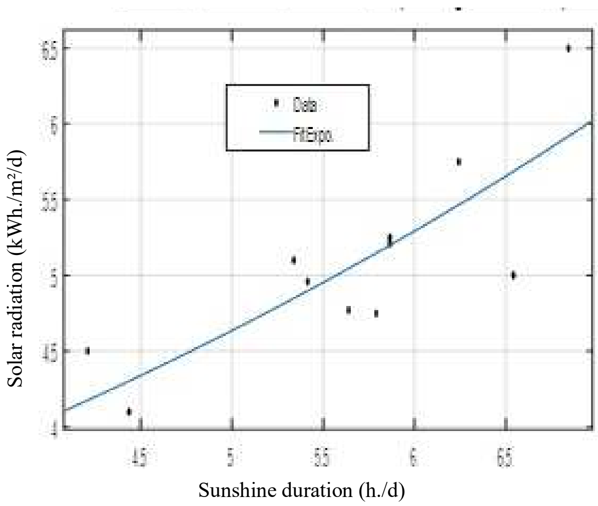

Fig. 7. Exponential model (Nord and Sud Kivu included)

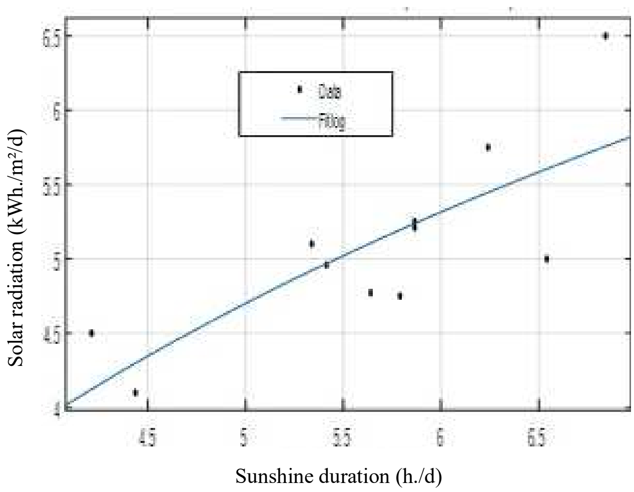

Fig. 8. Logarithmic model (Nord and Sud Kivu included)

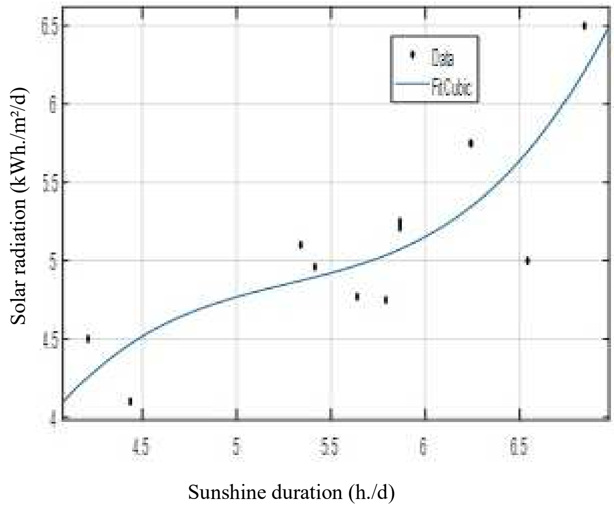

Fig. 9. Cubic model (Nord and Sud Kivu included)

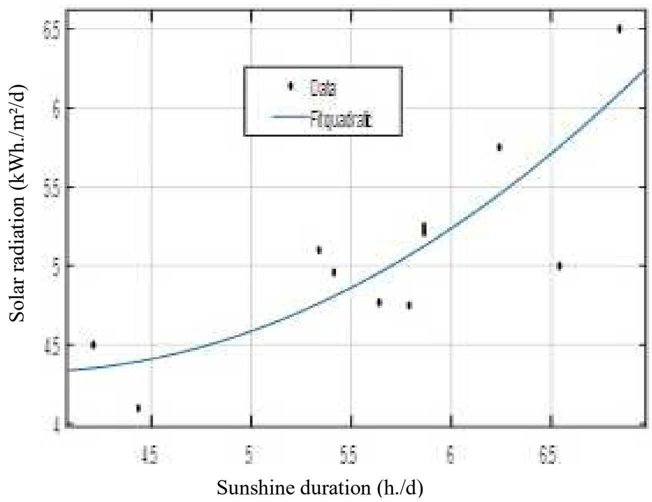

Fig. 10. Quadratic model (Nord and Sud Kivu included)

III. VALIDATION OF MODELS

According to the values obtained for the normalized errors and NS criteria in table 1 and table 2, all the four models have sufficient accuracy to predict Solar Irradiance in any of the 9 remaining provinces. But, by including the provinces of Nord and Sud Kivu, the models obtained, excepted the quadratic, have not a sufficient value of regression coefficient R^2. So, only the quadratic model has been validated for this case.

IV. DISCUSSION OF RESULTS AND CONCLUSION

Models obtained by excluding the provinces of Nord and Sud Kivu (linear, quadratic, logarithmic and exponential) have respectively regression coefficient equal to 0.88, 0.80, 0.79 and 0.74. That means these models explain more than 74% of the variance of solar irradiance and these models are acceptable. In addition, it is noticed that for this study, the quadratic model is the best one but, all of them help to predict the global solar Irradiance falling on a horizontal surface at any DRC province (excepted the two provinces mentioned above). The results provided are in accordance with the measured values. By including the provinces of Nord and Sud Kivu, it sems that the value of R^2 is less than 0.67.

That means those models can explain less than 67% of Solar Irradiance received on an horizontal surface in function of SD. The cubic model reachs 71% but, its normalized MAE is more than 10%. The study shows that, by excluding Nord and Sud Kivu, models established permit to predict the annual average value of global solar irradiance received on a horizontal surface in function of the annual average value of SD, at any DRC province. Others studies will explain why by including Nord and Sud Kivu, models established are not able to predict Solar Irradiatiance in the all provinces of DRC.

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