Estimation of Wind Turbine and Solar Photovoltaic Energy Using Variant Sampling Intervals

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***Abstract*— In this paper, we estimate renewable energy from wind and solar for different sites. Two methods are applied in case of wind energy: Weibull distribution and direct integration methodology. In additional, influence of the data sampling interval is studied. Results show that the computational method based on the integration of the power is more accurate. Also, it is shown that the hourly time resolution provides satisfactory accuracy in wind and solar resource estimation, in comparison with one minute's resolution.**

Results allow better design for hybrid systems (wind and photovoltaic energy). Moreover, Data acquisitions are minimized. A shorter time of treatment and less expensive measurement equipments are required.

***Keywords*—Wind and photovoltaic power, Energy estimation, Weibull distribution, Computational method, Data sampling interval.**

I. Introduction

Energy from renewable sources is being considered as an important generation alternative in the electrical power systems around the world due to their non contaminant nature and low environmental effects [1].Among renewable power sources, wind and solar have experienced a remarkably rapid growth in the past ten years. Additionally, they generate power close to load centres; hence reducing impacts from high voltage transmission lines through rural and urban landscapes [2]. Thus, in order to benefit the optimum from these sources, it is important to estimate their potential locally.

In this context, energy output estimation for wind turbines has been dealt by a number of researchers and references. Some authors implement simple methods evaluating a perturbation from mean wind speed and variance.For example, to calculate the available wind power, Kainkwa [3] suggests a formula,

$$Pa = \frac{1}{2}\rho[\bar{V}^3 + 3\bar{V}\sigma^2], \quad (1)$$

Where ρ is the air density, $\bar{V}$ represents mean wind speed and σ^2 the variance of wind speed. As well, Paul Gipe [4] introduced the "swept area's method". It consists of determining the wind power and then estimating the potential production of energy Ea, simply knowing the area swept by the rotor A:

$$Ea = 8760\, h/year * 1kw/1000\, W * [\frac{1}{2}\rho A\bar{V}^3 F\eta], (2)$$

With F is the Rayleigh distribution factor and η is the overall efficiency of the wind conversion system.

Although, theses methods are direct and simple, it does not take into account all critical factors that affect the amount of wind energy. Therefore, they can only partially report the regional peculiarities of the site. So, these methods can give just an approximate estimation of wind turbine energy and not a precise estimation.

Other researches focus on more "complicated" methods based on wind speed distribution models especially the two-parameter Weibull distribution. In fact, Adam Simon-Muela (et al.)[5] have described a technique to estimate the wind energy production using Weibull distribution. This technique has yielded good results. Also, they intended to provide a forecast of wind turbine energy production from several experimental measurements carefully correlated with available wind speed data. Unfortunately, results were not fully satisfactory.

In the same context, Luminita Barote and Lonela NEGREA [6] have developed an algorithm to calculate the probability of wind energy using the Weibull distribution.

Similarly, methods can be used to estimate the photovoltaic energy potential on a site.

In our paper, we have estimated the renewable (wind and solar) energy potential of three different American sites with a satisfactory accuracy. Moreover, we have analyzed the influence of wind speed and irradiation resolution on the estimation of wind turbine energy.

Subsequently, we will present some notions about wind and solar photovoltaic power, and then explicit methods and results.

II. Sources Data

Data for our study was obtained from an American Web site [7]. They correspond to three different locations:

a) National Wind Technology Center- Colorado (Latitude: 39° North, Longitude: 105° West, Elevation: 1855 meters):

Wind data were captured at approximately 10 meters above ground using a wind sensor that is measured using a Campbell Scientific SDM-INT8 interval timer, which samples the sensors at a high frequency (up to 1 microsecond) and reports the average value every 1 min to the data logger.

Total Hemispheric shortwave irradiance is measured by an Eppley Laboratory, Inc.Model PSP (Precision Spectral

Pyranometer) with calibration factor traceable to the World Radiometric Reference (WRR). The instrument is calibrated annually. Data is recorded every 1 minute.

b) *University of Nevada- Las Vegas (Latitude: 36.06^o North, Longitude: 115.08^o West, Elevation: 615 meters):*

Wind Data were measured by an RM Young 4-blade propeller and attached vane mounted on a pole at approximately 9 m (30 feet) above ground. Registration is made every 1-minute interval.

Total Hymispheric shortwave irradiance is measured by a Kipp&Zonen Model CM3 Pyranometer with calibration factor traceable to the World Radiometric Reference (WRR). They are 1-minute Data.

c) Xcel Energy Comanche Station - Pueblo, Colorado (Latitude: 38.2098^o North, Longitude: 104.5724^o West, Elevation: 1490 meters):

Wind Data were measured by an RM Young 3-cup anemometer and vane mounted 10 meters above ground level on tower. Registration is made every 1-minute interval.

Total Hymispheric shortwave irradiance is measured using a LICOR LI-200 Pyranometer mounted on an Irradiance Inc.Rotating Shadowband Radiometer (RSR). RSR mounted on the roof of a 10 foot (approx. 3 m) tall building; LI-200 sensor height is approximately 13 feet (approx. 4 m) above ground level. We dispose of 1-minute Data.

III. Wind Energy Assessement

A. Wind Power

Wind Power is given by:

$$Pw = \frac{1}{2}\rho A V^3 \quad (3)$$

With ρ: Air density (1.275 Kg/ m^3 at sea level, under dry conditions at a temperature 0°C), V: Wind speed and A: Swept area.

Only a fraction of the total theoretical power available in the wind, (3), is extractable. According to Betz' law,

$$Pex,\max = (0.593)\frac{1}{2}\rho A V^3 \quad (4)$$

The power actually available to drive a practical wind machine is much less than the theoretical maximum value defined in (4). The net effect of the various losses is incorporated into a parameter called the power coefficient Cp. With an up stream air velocity V, the extractable power can be written as:

$$Pex = Cp\ \frac{1}{2}\rho A V^3 \quad (5)$$

Where parameter Cp is a dimensionless variable but for practical wind turbines its value is usually in the range $0 \le cp \le 0.4$ [8].

The electrical output power may be written as:

$$Pe = Cp \cdot \eta gb \cdot \eta g \cdot Pw = Cp \cdot \eta gb \cdot \eta g \cdot \frac{1}{2} \cdot \rho A V^3 \quad (6)$$

With:

$Cp = \frac{Pex}{Pw}$ = turbine efficiency

$\eta gb = \frac{Pg}{Pex}$ = gearbox efficiency

$\eta g = \frac{Pe}{Pg}$ = generator efficiency

In the present article, the wind energy calculations were carried out for a wind turbine with 9 m² swept area and using an overall efficiency factor η = 25%.

B. Energy estimation by Weibull distribution

Different wind speed distribution models are used to fit the wind speed distribution over a time period, such as the Weibull, the Rayleigh and the Lognormal [9]. However, in recent years, most attention has been focused on the Weibull distribution for wind energy applications [10].

The Weibull probability density function has the following form:

$$f(V) = \frac{k}{C}\left(\frac{V}{C}\right)^{k-1} \exp\left[-\left(\frac{V}{C}\right)^k\right] \quad (7)$$

The corresponding cumulative distribution function is:

$$F(V) = 1 - \exp\left[-\left(\frac{V}{C}\right)^k\right]; (k > 0, V > 0, C > 0) \quad (8)$$

Where V is wind speed and c and k are two parameters, called the scale and shape parameters, respectively [11] [12].

In this paper and from available wind data, we have estimated the two-parameters of Weibull distribution for every site and every month by using Matlab software and by applying the regression method:

The cumulative distribution function, (8), can be linearized as follows [12]:

$$\ln[-\ln[1 - F(V)] = k\ln(V) - k\ln(c) \quad (9)$$

So we obtain a straight line equation:

$$y = ax + b \quad (10)$$

Where x and y are the variables, a is the slope and b is the intercept of the line on the y-axis.

$$y = \ln[-\ln(\ln(1 - F(V))] \quad (11)$$

$$a = k$$

$$x = \ln(V)$$

And

$$b = -k\ln(c)$$

The parameters in the resulting equation are obtained using the least squares method. The scale and shape parameter estimators are

$$\hat{k} = a$$

And

$$\hat{c} = \exp(-b/\hat{k}).$$

To determine the energy capture of the turbine over a time period T, we can just multiply the power Pe by f (V) * T so that the energy captured over a time period T (ignoring down time) will be:

$$E = T\int_{Vi}^{Vo} Pe(V) * f(V)dV \quad (12)$$

With Vi is the wind cut in speed (4m/s [13] [8]) and Vo is the cut out wind speed (25 m/s [13] [14]).
Unfortunately, the integral does not have a closed mathematical form in general and so a numerical integration is required, such as the trapezoidal rule or Simpson's rule [14] [15].
Within one year time period and for 10 data wind points, the energy capture will be, using the trapezoidal rule,

$$E = 365 * 24 * \sum_{i=1}^{9} ((Pe(Vi+1) f(Vi+1) + Pe(Vi) f(Vi))(Vi+1-Vi)) / 2 \quad (13)$$

Obtained results for a wind turbine with 9 m² swept area appear in the histograms of figures (1, 2 and 3). They confirm the annual and inter-annual variability of wind energy. For example, in the National Technology Center – Colorado, January 2006 was very windy comparing with the other months.

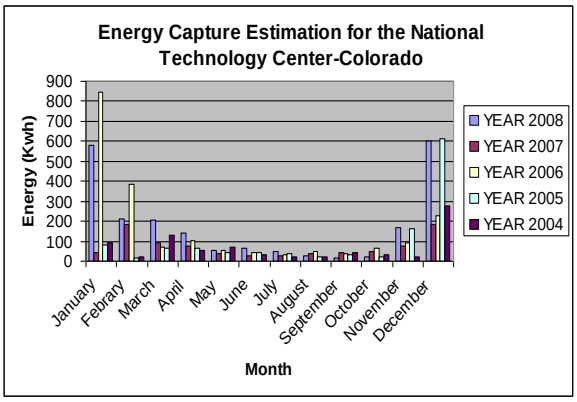

Fig.1. Energy Capture Estimation for the National Technology Center - Colorado using weibull distribution

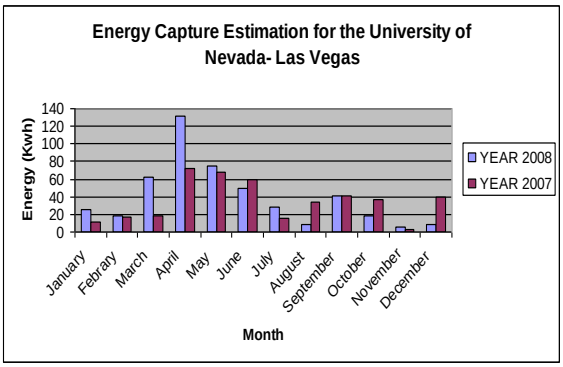

Fig.2. Energy Capture Estimation for the University of Nevada – Las Vegas using Weibull distribution

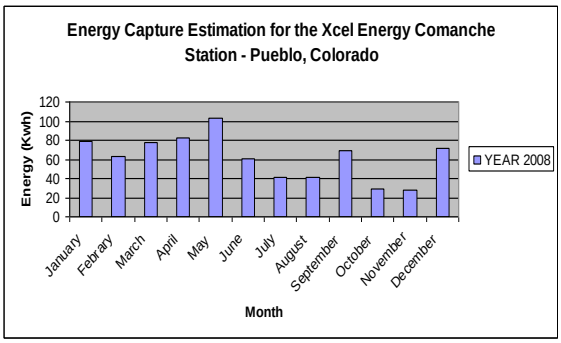

Fig.3. Energy Capture Estimation for the Xcel Energy Comanche Station- Pueblo, Colorado using Weibull distribution

Estimation of wind energy depends on the goodness of weibull distribution fitting and consequently in the estimation of weibull parameters. The goodness of fit can be evaluated knowing: - Summed Square of residuals (SSE), - the square of the correlation between the response values and the predicted response values (R-square), - Degrees of freedom (Adjusted R-square) and – the Root Mean Squared Error (RMSE).
As an example, for January 2007 of the National technology center - Colorado, we have as parameters of goodness of fit:
SSE: 0.04532
R-square: 0.9596
Adjusted R-square: 0.9595
RMSE: 0.01352
Although these figures indicate a global good fit (SSE and RMSE close to zero, R-square and Adjusted R-square close to one), the probability plot (fig.4) shows that the adjusted Weibull distribution is not adequate to model wind data of this month especially for wind speeds between 4 m/s and 25 m/s :

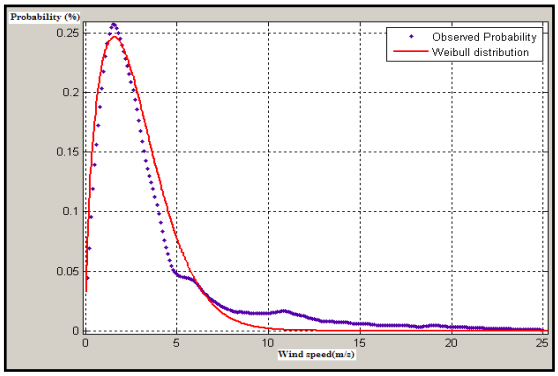

Fig.4. Probability plot and Weibull distribution curve fitting of wind data January 2007- National Technology Center-Colorado

This ascertainment is confirmed by calculating the coefficient of determination R-Square for wind speeds between 4m/s and 25 m/s:

$$R - Square = 1 - \frac{\sum_i (fmes(v) - fest(v))^2}{\sum_i (fmes(v) - mean(fmes(v)))^2} \quad (14)$$

fmes(V) and fest(v) corresponds respectively to observed and modelled probability values.
We find: R2 = 0.5665.
So, the fit of weibull distribution of wind speed data is not always a good approximation. Consequently, utilizing the weibull parameters to estimate wind energy may give biased values.
Our analysis of Weibull parameters shows that:
- For the National Wind Technology Center –Colorado the shape parameter k varies between 1.155 and 2.127 while the scale parameter C varies between 2.7878 and 7.1118.
- For the University of Nevada –Las Vegas the shape parameter k varies between 1.007 and 1.713 while the scale parameter C varies between 1.426 and 3.7787.
- For Xcel Energy Comanche Station - Pueblo, Colorado the shape parameter k varies between 1.543 and 2.153

while the scale parameter C varies between 2.9916 and 4.322.

The scale factor 'c' is closely related to the mean wind speed and the shape parameter 'k' is inversely related to speeds' variance about the average value .i.e. high value of 'k' means low variance and low value of 'k' means high variance (σ^2).

It should be noted from Weibull parameter analysis that there is a wide variation in the parameters estimation over months. This suggests very different distribution patterns of wind speed over months at selected stations.

C. *Energy Estimation using computational method (Numerical integration of the power)*

Produced energy can be estimated by numerical integration of the wind power Pe. Several methods of numerical integration such as the trapezoidal method or also the method of Simpson can be implemented at this stage.

In this paper, we have developed a program to draw the power curve. Graphically, the energy output can be given by the area under this curve. This area is calculated using the trapezoidal method with the function Energy = trapz (Time, Power):

$$E(estim) = \frac{1}{3600} \sum_{i=1}^{744*24*60} \frac{1}{2}(Pe(Vi) + Pe(Vi+1)).60 \qquad (15)$$

Results are shown on figures 5 to 7 for different sites:

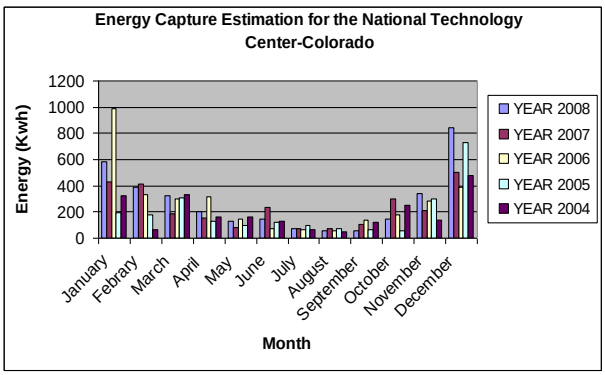

Fig.5.Energy Capture Estimation for the National Technology Center – Colorado using computational method

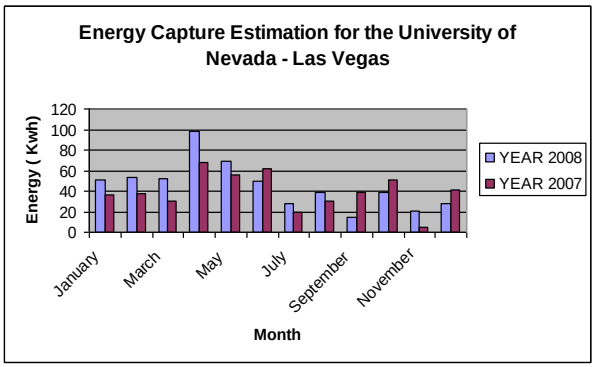

Fig.6.Energy Capture Estimation for the University of Nevada – Las Vegas using computational method

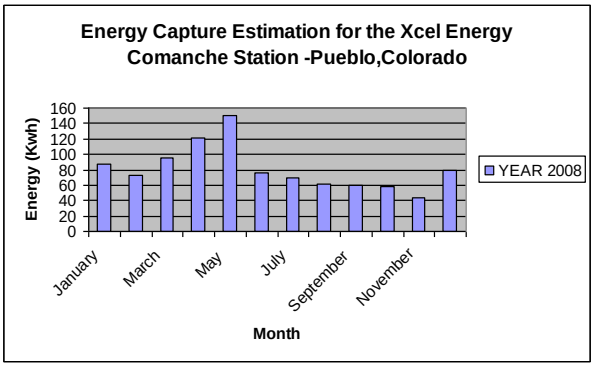

Fig.7. Energy Capture Estimation for the Xcel Energy Comanche Station- Pueblo, Colorado using computational method

In that context, results shows that weibull distribution use does not estimate wind energy output accurately. A significant difference between calculations made with weibull distribution and direct integration of the power is underlined.

The method of integrating the power versus time is easier to implement. It takes into account almost all the factors of the site (gusts, changes in wind direction, etc...) as it can use a huge data of wind speed. The calculation of energy by integrating the power takes its justification from the definition of the energy itself. That validates the use of this method for a precise estimation of wind generation. It gives more accurate estimations than method using weibull distribution because in its case we do not have to estimate any parameter. It is almost a direct calculation.

IV. Solar Photovoltaic Energy Assessement

Solar photovoltaic power output can be calculated as:

$$Ppv=Ig*e*Apv \qquad (16)$$

Where e is the power conversion efficiency of the module (power output from the system divided by power input from the sun), A is the surface area of the solar cells of the system [m²], Ig is the solar irradiance [W/ m²] [16].

The total monthly electricity output from a PV system can be assessed by integrating Ppv.

Power and energy output relies heavily on photovoltaic panels'type because of efficiency variations with materials and manufacturers [17]. As such, in our work, analysis has been carried for three locations with a general efficiency of 13.5 % independently from module type or model and for an installed PV system of 9 m² area. Total monthly energy output is estimated-such as for wind energy- using trapezoidal method.

Results are shown on figures 8 to 10 for different sites:

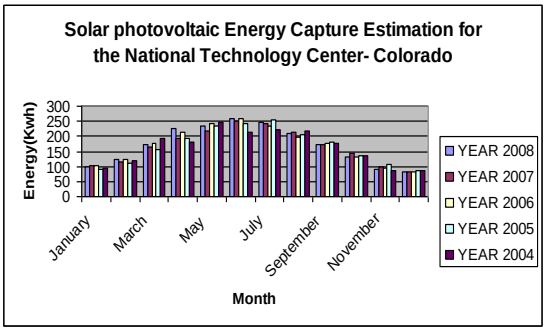

Fig.8. Solar Photovoltaic Energy Capture Estimation for the National Technology Center – Colorado

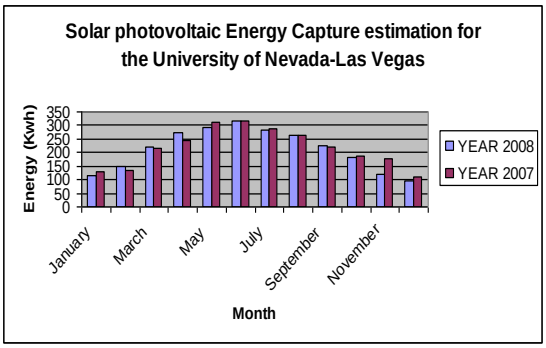

Fig.9.Solar Photovoltaic Energy Capture Estimation for the University of Nevada- Las Vegas

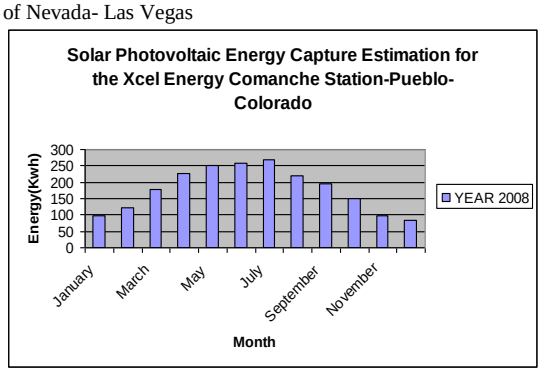

Fig.10. Solar Photovoltaic Energy Capture Estimation for the Xcel Energy Comanche Station- Pueblo

We note that, unlike wind energy, solar photovoltaic energy does not vary much from one year to another. In addition, in the three sites, overall, the photovoltaic potential (Kwh/m²) is more important than wind energy potential per m².

V. STATISTICAL STUDY OF THE INFLUENCE OF THE DATA SAMPLING INTERVAL IN THE ESTIMATION OF ENERGY CAPTURE

A. Principle

Using the available data of wind speed and global irradiation, we made the estimation of energy using different time steps between one minute and two hours. We supervised the influence of sampling intervals on the accuracy of the estimation. The study has been made twice: initially directly with the data available and in a second time with filtered data respecting Shannon. Filtering is made by a Butterworth structure. The filter frequency is adjusted to be half of the sampling frequency.

B. Results and discussion

*a) **Wind Turbine Case***

Results indicate that-for the different sites and for all months- there is no significant difference between energy values obtained with a sampling interval one minute and those obtained with sixty minutes (difference less than 10 %). The hourly time resolution, compared to one minute resolution provides satisfactory accuracy in wind energy estimation. Consequently, it is sufficient to just take a sample every hour in a month to get a good estimation of the production of a wind turbine. However, the values of estimated energy vary randomly with the sampling interval.

By comparison, if we filter the data of wind speed while respecting Shannon using a Butterworth filter, we note that the energy decreases when the vesting period of the wind increases. Also, a loss of energy (maximum 10 %) at one minute using filtered data comparing to unfiltered data at the same resolution was detected. Besides, using filtered data, for sampling intervals between one minute and thirty minutes, the energy decreases linearly (Fig.11).

As an illustration, Table 1 presents all results for the National Wind Technology Center-Colorado during January 2008:

TABLE I.
ENERGY CAPTURE ESTIMATION FOR THE MONTH OF JANUARY 2008 (NATIONAL WIND TECHNOLOGY CENTER-COLORADO) USING FILTERED AND NO FILTERED WIND SPEED DATA

YEAR 2008 (National Wind Technology Center- Colorado)				
Month	January			
Sampling interval (minute)	Energy estimated using direct acquired data (Kwh)	last unit	Energy estimated using filtered data (Kwh)	last unit
1	581,1559	1	565,8551	1
2	583,7693	1,0044969	557,1366	0,98459235
3	580,0885	0,99816332	552,0488	0,975601
4	585,1442	1,0068627	548,7073	0,96969578
5	579,939	0,99790607	546,2214	0,9653026
6	582,6262	1,00252996	544,1639	0,96166651
10	610,483	1,0504634	537,7807	0,95038589
12	588,4921	1,01262346	535,099	0,94564669
16	581,5675	1,00070824	530,396	0,93733537
20	586,3385	1,00891774	525,4259	0,92855203
24	578,5109	0,99544873	520,8522	0,92046922
30	560,967	0,96526078	514,8246	0,90981702
60	558,9274	0,96175123	484,1794	0,85565969
120	555,1622	0,95527241	437,3421	0,77288709
240	542,2533	0,93305996	363,7512	0,64283453

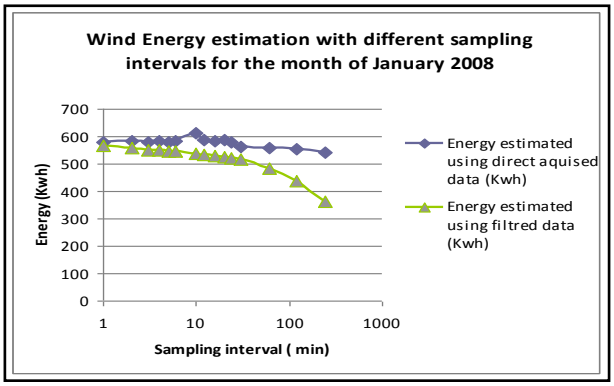

Fig.11. Wind Energy estimation with different sampling intervals for the month of January 2008 (National Wind Technology Center-Colorado) using filtered and no filtered wind speed Data

Results can be explained by the fact that for high frequencies (between (1/60) Hz and (1/3600) Hz), the wind speed, a random variable, has the same behavior as a white noise. Besides, for periods of acquisition of wind between 60 s and 3600 s, the statistical characteristics of the data (max, min, mean, variance, etc.) are almost invariant. Indeed, as an example for wind data of January 2008 (National Wind Technology Canter-Colorado):

- Using one minute sampled Data, we have:

Mean = 5.45 m/s, Variance = 18.52, min = 0.32 m/s and max=25.46 m/s,

- Using hourly sampled Data, we have:

Mean = 5.43 m/s, Variance = 17.92, Min = 0.32 m/s and Max= 23.53 m/s.

b) Photovoltaic Case

Results indicate that-for different sites and for all months-there is practically no difference between energy values obtained with a sampling interval one minute and those obtained with sixty minutes (difference less than 0.5 %).

However, unlike wind energy estimation, if we filter the data of irradiation while respecting Shannon using a Butterworth filter, we do not note an important change on results (Fig.12). Energy does not decrease linearly for sampling intervals between one minute and thirty minutes. This is can be explained by the fact that irradiation varies slowly during time.

As an illustration, Table 2 presents all results for the University of Nevada – Las Vegas in May 2007:

TABLE II.
SOLAR PHOTOVOLTAIC ENERGY CAPTURE ESTIMATION FOR THE MONTH OF MAY 2007 (UNIVERSITY OF NEVADA- LAS VEGAS) USING FILTERED AND NO FILTERED IRRADIATION DATA

YEAR 2007 (University of Nevada- Las Vegas)				
Month	May			
Sampling interval in minute	Energy estimated using direct acquired data (Kwh)	last unit	Energy estimated using filtered data (Kwh)	last unit
1	311,2113	1	311,2113	1
2	311,2225	1,00003599	311,2185	1,00002314
3	311,2402	1,00009286	311,2259	1,00004691
4	311,295	1,00026895	311,2337	1,00007198
5	311,5278	1,00101699	311,2416	1,00009736
6	310,9853	0,99927381	311,2476	1,00011664
10	311,4965	1,00091642	311,2804	1,00022204
12	310,5257	0,997797	311,2995	1,00028341
16	311,1175	0,9996986	311,3499	1,00044536
20	311,9496	1,00237234	311,4115	1,00064329
24	310,6005	0,99803735	311,4773	1,00085472
30	309,956	0,99596641	311,5869	1,0012069
60	310,7218	0,99842711	312,6566	1,00464411
120	313,3439	1,00685258	315,9659	1,01527772
240	318,9522	1,02487345	327,3578	1,05188276

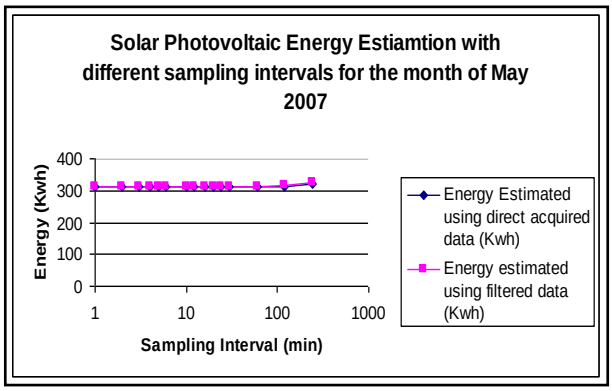

Fig.12. Solar Photovoltaic Energy estimation with different sampling intervals for the month of May 2007 (University of Nevada- Las Vegas) using filtered and no filtered Irradiation Data

VI. CONCLUSION

Estimation of wind and solar photovoltaic energy output for small-scale systems is the focus of our paper. We have also studied the influence of the sampling interval on energy estimation accuracy. To achieve this objective, we have estimated the monthly output energy in three different American sites.

Investigations have showed that:

* The computational method based on integrating power versus time is more accurate to estimate Wind Energy.
* There is a very different distribution pattern of wind speed over months at selected stations.
* Solar Photovoltaic Energy does not vary much from one year to another.
* Photovoltaic potential (Kwh/m²) is more important than wind energy potential per m² in all sites.

* If wind speed data with an average one minute value is used, estimated energy varies randomly with sampling interval.
* The hourly time resolution, compared to one minute resolution provides satisfactory accuracy in wind or solar photovoltaic energy estimation.
* It is sufficient to choose an hourly sample period to get good energy estimation both for wind or solar photovoltaic energy estimation.
* In case of data filtered respecting Shannon (for i.e. using a Butterworth filter), wind energy estimated decreases when the vesting period of the wind increases. However, it is practically invariant in case of photovoltaic energy.
* With filtered data, for sampling intervals between one minute and thirty minutes, the energy decreases linearly. This result may be interesting in wind energy prediction.

To finish, these results allow better design of wind or hybrid systems, taking in consideration the difference between renewable sources energy potential and minimizing measurement equipments. Indeed, it is sufficient to use hourly data. Therefore, it does not require high acquisition frequency measuring instruments. Besides, note that in most cases, people use the Weibull distribution to estimate wind potential and choose appropriately their turbine. We have shown through our research that this is not always accurate. It may rather integer power versus time and have a better energy estimation that takes into account all the characteristics of the site.

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