Statistical Analysis of Solar-Wind-Biomass Hybrid System Installed at R.G.T.U., Bhopal M.P., India*

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ABSTRACT

This article describes the linkage that exists among the various alternative power sources in the hybrid system. The wind energy system, along with solar photovoltaic panels and a biomass gasifier for the production of electricity, is more suitable among the alternatives available. Wind, solar and biomass energy systems can be used in remote areas. Keeping this in mind, a statistical analysis of the hybrid energy system has been developed for a remote area. Wind and solar data are obtained from a weather monitoring station installed at Energy Park, R.G.T.U., Bhopal, India.

Keywords: PV-wind-biomass hybrid system, multiple correlations, statistical correlations, sustainability

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*The authors previously published this article in *Clean Technologies and Environmental Policy*, March 2009. Reprinted with the authors permission.

INTRODUCTION

As we know, during the summer solar radiation is generally at its peak and when the winds are the weakest. During the winter season, sunrays are the weakest and winds are the strongest. Therefore, solar photovoltaic, along with a wind turbine and biomass gasifier, would ultimately increase the overall power produced from the solar panels during the summer. Whereas, the wind turbine produces more output in the winter. If any shortage of power is there, it could be fulfilled by power from a biomass gasifier. Thus the demand curve can be smoothed over the year. Thus, a hybrid system can be a better option than wind, solar or biomass alone.

Many similar systems are already in use, but they vary in size from a few watts to many kilowatts. It depends on the energy needs. Further, for proper assessment calculation for every hour of the year, the solar and wind energy generated by the energy conversion devices must be done (Powel 1980).

As far as the electrification level in rural areas in Southeast Asia is concerned, it is about 51%, compared to 90% in urban areas. (Shrestha, et al. 2004). Situations where this is true include cases where brunt demand profile are present, and where the resources required by each generator complement each other.

The solar-wind hybrid system was installed at the Energy Centre of Rajeev Gandhi Technological University, Bhopal. Madhya Pradesh, India (Figure 1). While designing this project, it was observed that major power sources, i.e., solar and wind, are strongly complementary (Markvart 1996). Because both are not present at the same time, another major contributor (i.e., biomass) is integrated into the existing solar-wind hybrid system (Figure 2).

The biomass "Julliflora" wood pieces, 50- to 55-mm in length, were cut using a commercially available saw cutting machine. The wood, having a fairly uniform diameter (50- to 55-mm) was selected for preparation of feed for gasification. The rectangular strip and other wood logs were cut into the desired size in the saw mill and segregated manually into the desired size for gasification. Then, the biomass was converted into clean and combustible producer gas in the presence of steam and air. The producer gas was used in diesel engines in dual-fuel mode for power generation application. This pilot project shows a successful mixing of different power sources in the functioning area. Different size

Figure 1. Existing 1.6 kW Solar-wind Hybrid System (RGTU 2007)

Figure 2. Existing 10 kW Biomass Gasification System (RGTU 2007)

wood pieces may be required for the system to be used in other locations, depending on nature of the load, and the potential of the renewable energy resources in the proposed location. By developing such a hybrid system, the future electricity demand of the consumers can be achieved. Further, it is energy efficient, eco friendly and economical.

RESEARCH METHODOLOGY

Several correlations among these subsystems and the interrelated parameters have been thoroughly studied for modeling and optimization of hybrid system of wind, solar and biomass. Various options to optimize a complete hybrid system and environment limitations are considered. The mathematical modeling consists of statistical correlation analysis, and multiple associations are done based on the interrelation of various parameters and their effects on each other.

EXPERIMENTAL SETUP OF SOLAR-WIND-BIOMASS HYBRID SYSTEM AND DATA MEASUREMENTS

The major components of typical 11.6-kWe solar photovoltaic (PV), wind and biomass hybrid system are as follows:

- Solar photovoltaic modules
- Mounting structures for solar
- Photovoltaic modules
- Junction boxes
- Solar charge controller
- Photovoltaic batteries
- Biomass gasifier
- Wind generator
- Wind charge controller
- Inverter unit
- Installation kits
- Interconnecting cables
- Earthing kit

The 11.6-kW solar-wind and biomass hybrid system installed at the Energy Park of Rajeev Gandhi Technological University Bhopal, Madhya Pradesh (MP), India is schematically shown in Figure 3. The system consists of a 1.3-kW wind electric generator, 0.3-kW solar arrays and 10-kW electric-generating biomass gasification units. The output from the system is fed to a street lighting system at the Energy Park powering the system for over 8 hours every night. The weather monitoring station is located in the Energy Park at RGTU Bhopal. It determines the local potential of both solar and wind energy.

Devices used for data collection from the solar-wind-biomass hybrid system consist of anemometer, radiation pyranometer, temperature recorders, wind speed recorder, thermocouple, etc.

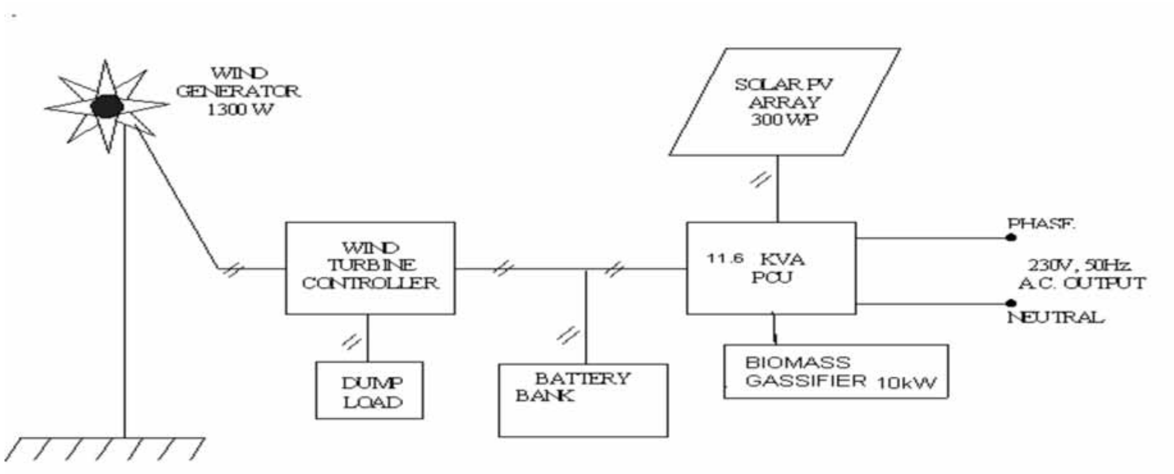

Figure 3. Block diagram of 11.6-kW solar, wind and biomass hybrid system installed at Rajeev Gandhi Technological University Bhopal (M.P.) India.

Wind power (Khan 2006) is calculated as

$$Pw = 1/2\ \rho\ AV^3 \qquad \text{(eq 1)}$$

The design variables of a wind turbine, PV arrays, batteries and the electric grid are the total wind rotor area (m^2), the total solar panels' area (m^2), the size of the batteries (kWh) and the rating of the substation (kW), respectively. Full details about the implementation are given in Chedid, et al. (1998).

The data collection was made at 1-hour intervals. All measurements were obtained with an anemometer at ground level as stated earlier in Ulgen and Hepbasli (2003).

Previously in the Energy Park of R.G.T.U., there was a solar-wind hybrid system with a capacity of 300- and 1300-watt, respectively. Because of an increase in electric load from street lights, an additional 10-kW biomass gasifier was added, as shown in Figure 3. Because of this addition, there is no shortage of power. The University gets continuous sustainable electricity power supply. Monthly variance is minimized by combining the existing system with a 10-kW biomass gasifier and a project being taken under the guidance of Ministry of Non Conventional Energy Sources (MNES) and sponsorship from All India Council of Technical Education (AICTE) under a research promotion scheme (RPS). By using a standard deviation approach, optimum mix has been determined. Because a solar photovoltaic system is too expensive, its size is limited to meet only the base load. Figure 4 provides variation of power generation of solar panel, wind generator and biomass power in the hybrid system over the year.

STATISTICAL CORRELATION ANALYSIS

The relationship between solar power, wind power and biomass power availability can best be explained by calculating the correlation coefficient that is given by Montgomery and Runger (1994). The solar radiation and wind speed data, as well as their statistical analysis, are necessary for the correct sizing of the energy system and have also been the object of several studies (Knight et al., 1991; Pissimanis et al. 2000).

Here n is the number of data to be correlated. The correlation can take values from (–1) to (+1). The best correlation for complementary data, such as solar and wind power would be (–1). As the correlation

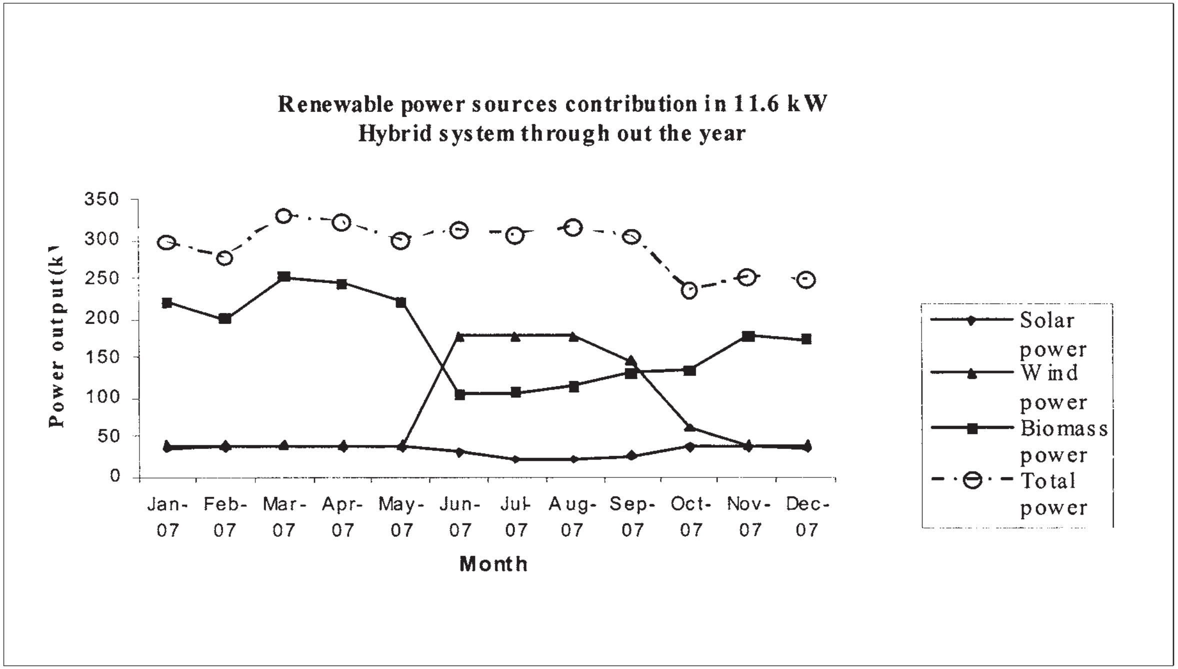

Figure 4. Power output of solar, wind and biomass power source in 11.6-kW hybrid systems throughout the year (Source: Data plotted above is recorded from weather monitoring station located in Energy Park UIT-RGTU Bhopal, 2007)

approaches (+1), the complementary nature of the data disappears (Sahin 2000). For performing correlation analysis of various subsystems of the hybrid system (i.e., solar, wind and biomass), first of all correlation among various subsystems (i.e., solar-wind, wind-biomass, and solar-biomass) is calculated. The purpose of this is to find out correlation between two power sources according to its power availability over the year. In a solar-wind combination, both the power sources are of complementary nature. Therefore, a single power source is mostly available at a given time. By using a statistical correlation formula, correlation coefficient for solar-wind hybrid system is given below:

The covariance (cov) for solar-wind hybrid system is given by (Sahin 2000).

$$\mathrm{Cov}\ (P_s, P_W) = 1/n \sum_{i=1}^{n} [(P_s)_i - P_s]\ [(P_W)_i - P_W] \qquad \text{(eq 2)}$$

Standard deviations for solar and wind are,

$$\sigma_S = \{1/n \sum_{i=1}^{n} [(P_S)_i - P_S]^2\}^{1/2} \text{ and } \sigma_W = \{1/n \sum_{i=1}^{n} [(P_W)_i - P_W]^2\}^{1/2} \qquad \text{(eq 3)}$$

Where, mean powers for solar and wind are given by

$$P_S = 1/n \sum_{i=1}^{n} (P_s)_i \quad \text{and} \quad P_W = 1/n \sum_{i=1}^{n} (P_W)_I \qquad \text{(eq 4)}$$

Then correlation coefficient for solar-wind hybrid system is

$$r_{SW} = \frac{\mathrm{Cov}\ (P_S, P_W)}{\sigma_S\ \sigma_w} \qquad \text{(eq 5)}$$

$$r_{SW} = -\ 345.50/(\sqrt{38.30})\ (\sqrt{3735.23}) = -\ 0.913$$

After calculating correlation coefficient between solar and wind power sources, correlation coefficient between solar and biomass power source is calculated to check the correlation between them according to their power source availability. Generally, moisture content in the biomass is greater in the rainy season, so it affects the power production. The statistical correlation formula is used to calculate the correlation coefficient between solar and biomass.

The covariance for a solar-biomass hybrid system is given by Sahin (2000).

$$\mathrm{Cov}\ (P_s, P_B) = 1/n \sum_{i=1}^{n} [(P_s)_i - P_s]\ [(P_B)_i - P_B] \qquad \text{(eq 6)}$$

Standard deviations for solar and biomass are

$$\sigma_S = \{1/n \sum_{i=1}^{n} [(P_s)_i - P_s]^2\}^{1/2} \quad \text{and} \quad \sigma_B = \{1/n \sum_{i=1}^{n} [(P_B)_i - P_B]^2\}^{1/2} \qquad \text{(eq 7)}$$

Where, mean powers for solar and biomass is given by

$$Ps = 1/n \sum_{i=1}^{n} (P_s)_i \quad \text{and} \quad P_B = 1/n \sum_{i=1}^{n} (P_B)_i \qquad \text{(eq 8)}$$

Then correlation coefficient for solar-biomass hybrid system is

$$r_{SB} = \frac{\mathrm{Cov}\ (P_s, \sigma_B)}{\sigma_s\ \sigma_B} \qquad \text{(eq 9)}$$

$$r_{SB} = 248.56/(\surd 38.30)\ (\surd 2722.05) = 0.77$$

The need for calculating the correlation coefficient between wind-biomass is that both supplement each other. Only power production from wind and biomass is considered while calculating correlation coefficient between them.

The covariance for wind-biomass hybrid system is given by Sahin (2000).

$$\mathrm{Cov}\ (P_B, P_W) = 1/n \sum_{i=1}^{n} [(P_B)_i - P_B]\ [(P_W)_i - P_W] \qquad \text{(eq 10)}$$

Standard deviations for wind and biomass is

$$\sigma_B=\{1/n \sum_{i=1}^{n} [(P_B)_i - P_B]^2\}^{1/2} \text{ and } \sigma_w =\{1/n \sum_{i=1}^{n} [(P_W)_i - P_W]^2\}^{1/2} \quad \text{(eq 11)}$$

Where, mean powers for wind and biomass is given by

$$P_B = 1/n \sum_{i=1}^{n} (P_B)_i \quad \text{and} \quad P_w = 1/n \sum_{i=1}^{n} (P_w)_i \qquad \text{(eq 12)}$$

Then correlation coefficient for a wind-biomass hybrid system is

$$r_{BW} = \frac{Cov\ (P_B, P_W)}{\sigma_B\ \sigma_w} \qquad \text{(eq 13)}$$

$$r_{BW} = (-2705.57)/[(\sqrt{3735.23})\ (\sqrt{2722.05})] = -\ 0.85$$

MULTIPLE CORRELATION ANALYSIS OF HYBRID SYSTEM

Correlation techniques that utilize partialing in its derivation is a basic multiple correlation analysis. The main purpose of multiple correlations is to be able to predict some criterion variable power sources better. The monthly power available data set from various power sources (i.e., solar, wind and biomass), shown in Tables 1 and 2, represent a situation in which multiple correlation analysis is used. These data relate to the situation where we have information on the monthly power available data set and want to use that information to predict future adjustments in the combination of the solar, wind and biomass power source data. Here we considered the combined influence of two or more variants (solar, wind and biomass power) upon variants not included above. The influence among them can be determined by this technique.

Case 1: The multiple correlation $R_{S.BW}$, where S (solar) is the criterion power source that is being predicted by a best weighted combination of predictor power sources B (biomass) and W (wind) (Ray et al. 2001).

Table 1. Monthy Standard Deviation Calculation of Renewable Power Sources

Sr. No.	Month	$[(P_s)_i - \bar{P}_s]$	$[(P_s)_i - \bar{P}_s]^2$	$[(P_w)_i - \bar{P}_w]$	$[(P_w)_i - \bar{P}_w]^2$	$[(P_B)_i - \bar{P}_B]$	$[(P_B)_i - \bar{P}_B]^2$
01	Jan 07	2.62	6.86	-45.46	2066.61	48.23	2326.13
02	Feb 07	4.82	23.23	-45.46	2066.61	26.78	717.17
03	Mar 07	6.31	39.82	-45.46	2066.61	78.92	6228.37
04	Apr 07	3.94	15.52	-45.46	2066.61	70.78	5009.80
05	May 07	4.45	19.80	-45.46	2066.61	48.23	2326.13
06	Jun 07	-2.24	5.02	92.94	8637.84	-70.22	4930.85
07	Jul 07	-10.76	115.78	92.94	8637.84	-66.78	4459.57
08	Aug 07	-11.9	141.61	92.94	8637.84	-58.1	3375.61
09	Sep 07	-7.33	53.73	62.54	3911.25	-42.62	1816.46
10	Oct 07	4.12	16.97	-23.06	531.76	-38.26	1463.83
11	Nov 07	4.29	18.40	-45.46	2066.61	3.28	10.76
12	Dec 07	1.69	2.856	-45.46	2066.61	-0.31	0.02
Total			459.6		44822.8		32664.7
Avg.			38.30		3735.23		2722.05

Table 2. Monthy Covariance Deviation Calculation of Renewable Power Sources

Sr. No.	Month	$((P_s)_i - \overline{P}_s)((P_w)_i - \overline{P}_w)$	$((P_s)_i - \overline{P}_s)((P_B)_i - \overline{P}_B)$	$((P_w)_i - \overline{P}_w)((P_B)_i - \overline{P}_B)$
01	Jan 07	-119.10	126.36	-2192.53
02	Feb 07	-219.12	129.08	-1217.42
03	Mar 07	-286.85	497.98	-3587.70
04	Apr 07	-179.11	278.87	-3217.66
05	May 07	-202.30	214.62	-2192.53
06	Jun 07	-208.18	157.29	-6526.25
07	Jul 07	-1000.03	718.55	-6206.53
08	Aug 07	-1105.99	691.39	-5399.81
09	Sep 07	-458.42	312.40	-2665.45
10	Oct 07	-95	-157.63	882.27
11	Nov 07	-195.02	14.07	-149.11
12	Dec 07	-76.83	-0.22	5.91
Total		-4145.95	2982.76	-32466.86
Avg.		-345.50	248.56	-2705.57

$$R_{S.WB} = \sqrt{[\{R_{SW}^2 + R_{SB}^2 - 2\ R_{SW}\ R_{SB}\ R_{WB}\}/\{1 - R_{WB}^2\}]} \quad \text{(eq 14)}$$

$$= \sqrt{[[(-0.913)^2 + (0.779)^2 - 2\{(-0.913)\ (0.779)\ (-0.85)\}]/\{1-(0.85)^2]}$$

$$= \sqrt{[\{0.833 + 0.606 - 2\ (0.604)\}/0.277]}$$

$$= \sqrt{[\{1.439 - 1.209\}/0.277]}$$

$$= \sqrt{(0.23/0.277)}$$

$$= \sqrt{0.83}$$

$$= 0.911$$

Case 2: The multiple correlation $R_{W.SB}$ in which W (wind) is the criterion power source that is being predicted by a best weighted combination of predictor power sources B (biomass) and S (solar).

$$R_{W.SB} = \sqrt{[\{R_{SW}^2 + R_{WB}^2 - 2R_{SW}\ R_{SB}\ R_{WB}\}/\{1 - R_{SB}^2\}]} \quad \text{(eq 15)}$$

$$= \sqrt{[[(-0.913)^2 + (-0.85)^2 - 2\{(-0.913)\ (0.779)\ (-0.85)\}]/\{1-(0.779)^2\}]}$$

$$= \sqrt{[\{0.833 + 0.72 - 2\ (0.604)\}/0.4]}$$

$$= \sqrt{[\{1.55 - 1.209\}/0.4]}$$

$$= \sqrt{(0.342/0.4)}$$

$$= \sqrt{0.855}$$

$$= 0.924$$

Case 3: The subscripts for $R_{B.SW}$ simply means that B (biomass) is the criterion power source that is being predicted by a best weighted combination of predictor power sources S (solar) and W (wind).

$$R_{B.SW} = \sqrt{[\{R_{SB}^2 + R_{WB}^2 -2\ R_{SW}\ R_{SB}\ R_{WB}\}/\{1 - R_{SW}^2\}]} \quad \text{(eq 16)}$$

$$= \sqrt{[[(0.779)^2 + (-0.85)^2 - 2\{(-0.913)\ (0.779)\ (-0.85)\}]/\{1-(-0.913)^2\}]}$$

$$= \sqrt{[\{0.606 + 0.72 - 2\ (0.604)\}/0.167]}$$

$$= \sqrt{[\{1.326 - 1.209\}/0.167]}$$

$$= \sqrt{(0.118/0.167)}$$

$$= \sqrt{0.706}$$

$$= 0.84$$

RESULTS AND DISCUSSION

Monthly values of the solar power output, wind energy and biomass power data shown in Figure 4 indicate that the solar energy values are larger in the summer season and smaller in the winter season because they are of complimentary nature. The monthly average value of solar power availability shows a consistent variation, but the wind power potential variation has a large scatter as a result of wind velocity and ambient temperature variations. The total power potential shows little variation throughout the year, but it is totally dependent on atmospheric conditions to obtain sustainable power according to desired power. One more power element is added, thus making it solar-wind-biomass hybrid system. This illustrates that by using a solar-wind-biomass hybrid system, a continuous and nearly constant sustainable power output could be generated that can utilize the solar, wind and biomass potentials in an optimum way. It is quite important to note that maximum average solar energy output of 39.29 kWh/month occurred in the month of March, when wind power potential is at a minimum (39.2 kWh). The minimum solar power output (21.1 kWh/month) occurred in the month of August; the maximum wind power potential (177.6 kWh) occurred in August. The correlation between the solar and wind energy availability is calculated to be –0.913, between solar and biomass it is 0.77, and between wind and biomass it is –0.85. The negative sign indicates a complementary nature and positive sign means they supplement each other.

We are interested in the best possible prediction of criterion power source (i.e., biomass). If we use only one predictor variable power source (either solar or wind), the predictor variable that correlates most positively with biomass is solar, with a correlation of 0.77. And the predictor variable that correlates most negatively with biomass is wind, with a correlation of –0.85. As a measure of how predictable the biomass values are from solar, we could simply use the correlation coefficient, or we could use the coefficient of determination, which is simply r^2. r^2 represents the proportion of the criterion biomass power source variance that is predictable. That value or coefficient of determination is $r^2_{SB} = 0.772 = 0.593$. Approximately 59.3% of the criterion biomass power source variance is predictable based on using the information available to us by having solar power source data. To do better, not with one of the two predictor power sources, the correlation we find between solar and biomass is

0.77. It is obvious that we have a second predictor, wind, that, while not correlating positively with biomass as solar, it has a negative correlation of –0.85 with biomass. Solar is somewhat better. Perhaps it would make sense to explore the possibility of combining the two predictors together in some way to take into account the fact that both do correlate with the criterion of biomass negatively and positively. It is possible that by combining solar and wind together in some way that we can improve on the prediction that is made when only selecting solar. By using both solar and wind together in some fashion as a new variable, we can find a better correlation with the criterion biomass power source.

The three correlations are the inter-correlations among the three primary variable power sources: the two predictor power sources and the criterion power source.

Further, when we used the single predictor that most positively correlated with biomass, we selected solar because it had the higher positive of the two predictor-criterion correlations: 0.77 versus –0.85 for wind. Also, recall that solar accounted for approximately 59.3% ($\{0.77\}^2$ = 59.3 %) of the criterion variance.

The multiple correlations $R_{B.SW}$ combining both predictors together (i.e., solar and wind) is 0.84, a difference of 0.07 in the higher direction. As for the proportion of predictable variance or r squared value, $(0.84)^2$ = 70.5% or a gain of (70.5 – 59.3 =) 11.2% in predictable variance. Whether we consider the increase in the correlation or the increase in the r squared value (r squared versus R squared), there is some improvement in the prediction of the criterion power source. Here is an instance where the combination of two predictors does a better job of estimating the criterion power source than only using one predictor variable. There is some improvement in the predictability in this case.

Combining two or more predictor variables will enhance or increase the predictability of some criterion variable. In the first case, we should recognize that in order for even one predictor to be used to estimate some criterion, there must be some reasonable correlation (either + or –) with the criterion power source. The combination of the two predictor power sources added about 11.2 percent predictable variance over and beyond what only one predictor power source would do.

If there are several power sources that we are considering for the prediction of some criterion power source, the main reason why we select these "potential" predictor power sources is that we know that each of them correlates with the criterion power source. This indicates that some of these power sources are very similar to one another. Hence, the predictor power sources will correlate with each other at a moderate level. Thus, it is better to select the predictor power source that correlates reasonably well with the criterion power source but does not correlate very highly with each other.

The optimum size of a solar-wind–biomass hybrid system that could produce a constant total power throughout the year continuously is 0.3-kWe solar, 1.3-kWe wind and 10-kWe biomass power. As the size of solar power generator increases, the required size of the wind generator decreases however, this decrease is not linear for the whole range of hybrid power generators. There exists a minimum total size of hybrid power generators. Because a solar-photovoltaic system is too expensive, its size is limited to supply the base load only.

CONCLUSION

For obtaining sustainable power throughout the year, partial correlation analysis shows that the hybrid of solar-wind power source keeping biomass power source constant appears to be a better combination in implementing stand alone electricity generation systems for remote areas.

The chemistry between various subsystems of a hybrid system can be cleared by statistical analysis. The integration of a biomass gasification unit to the PV-wind hybrid system provides power on demand, improves reliability, is sustainable and environment friendly system thus improving the economic attributes of the power source. It can be applied to various geographical locations and in remote areas, where electricity is not available.

Notations

A	Array area (m^2)
P_s	Power output from a solar generator (kWh)
P_w	Power output from a wind generator (kWh)
P_B	Power output from a biomass gasifier (kWh)
R	Radius of rotor (m)
V	Wind velocity (m/s)
r_{SW}	Correlation coefficient between solar-wind hybrid system.
r_{SB}	Correlation coefficient between solar-biomass hybrid system.

r_{WB} Correlation coefficient between wind-biomass hybrid system.

$R_{B.SW}$ Multiple Correlation coefficient where B (biomass) is the criterion power source that is being predicted by a best weighted combination of predictor power sources S (solar) and W (wind).

$R_{W.SB}$ Multiple correlation coefficient in which W (wind) is the criterion power source that is being predicted by a best weighted combination of predictor power sources B (biomass) and S (solar).

$R_{S.BW}$ Multiple correlation coefficient where S (solar) is the criterion power source that is being predicted by a best weighted combination of predictor power sources B (biomass) and W (wind).

Acknowledgements

The authors are very much thankful to the All India Council of Technical Education (AICTE) for sponsoring under research promotion scheme (RPS). The authors gratefully acknowledge Vice Chancellor Dr. P.B. Sharma and Director Energy Centre Dr. V.K. Sethi of the Technical University of M.P. India for their kind permission and directions to conduct the experimentation and research work on integrated renewable energy system (biomass gasifier/gas engine gen-set) located at Green Power Technology Center of RGTU, M.P. India.

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