Journal of Engineering Science and Technology Review 5 (4) (2012) 24 -29
Special Issue on Renewable Energy Systems

Research Article

JOURNAL OF
**Engineering Science and Technology Review**

www.jestr.org

# A Review of Wind-PV Sizing Algorithms and a Case Study

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Received 28 August 2012; Revised 24 September 2012; Accepted 6 October 2012

***Abstract***

In this study, various sizing algorithms developed to size hybrid (wind/PV) renewable energy systems are reviewed as a first step. Then a case study is performed to find optimum size of a small hybrid (wind/PV) system considered to be built at Afyonkarahisar region of Turkey. Finally, size results are presented, optimality of results and accuracy of optimality are discussed.

*Keywords: Wind, PV, Sizing Algorithms*

## 1. Introduction

Cost effective sizing of wind-PV (Photovoltaic) systems is very important to decrease initial cost of the system. In general hybrid systems are composed of two main generators. In renewable applications wind and solar systems are widely used in a hybrid hierarchy. The main reason of this combination is the discrete behavior of wind and solar energy generations. It is not possible to generate electricity via sun at noon times whereas it is not possible to generate electricity from wind turbines if the wind speed values are less than 3m/s in general. However, from the view of energy reliability in case of hybrid usage of these systems, reliability increases, considerably. There are a lot of studies performed in literature to determine the size of hybrid (wind-PV) system.

Here some of them are reviewed:

Borowy and Slameh performed an optimization and obtained PV array size for a hybrid wind-PV system [1]. In this study, electrical models of system components are considered and generation outputs of renewable systems computed, accordingly. Yang and Zhou developed a novel optimization sizing model for hybrid solar-wind power generation system [2]. In their study optimization model is considered within three parts: the model of the hybrid system, the model of loss of load supply probability and the model of levelised cost of energy. Finally, Technical and economical system is obtained by proposed algorithm. Following this study Yang et al. developed an optimal sizing method for stand-alone hybrid solar-wind system. In this study they used genetic algorithm together with loss of power supply probability concept. [3]. Similarly Koutroulis et al. employed genetic algorithm to obtain optimum sizing results [4]. On the other hand Hong and Lian used Markov based genetic algorithm technique to calculate optimum size of wind-PV systems [5]. Çelik used different sizing methods for techno-economic analysis of autonomous PV-wind hybrid energy systems [6]. Kaabeche et al. recommended an iterative technique for wind-PV system sizing [7]. In a recent study Hocaoğlu et al. searched the effect of model generated solar radiation data in wind-PV energy system sizing studies [8]. In a different study Roy et al. incorporated resource uncertainty in wind-PV system sizing [9]. On the other hand in another study Roy et al. applied design space methodology for optimum sizing of wind-battery systems [10]. Hocaoğlu et al. developed a very effective and novel method to size wind-PV systems [11]. Kaldellis and Zafirakis recommended a sizing technique for wind-PV system from the view of firs initial cost [12]. Diaf et al. proposed a methodology that uses more accurate models for characterizing PV module, wind generator and battery for optimum sizing of wind-PV systems [13]. In a different study Hocaoğlu developed novel mathematical models for PV based system sizing procedures [14]. In this study Hocaoğlu suggested that usage of model generated data instead of data itself gives more cost effective size results. Kellogg et al. performed and optimization for wind-PV systems for a hypothetical site of Montana [15]. Nelson et al. considered fuel cell besides wind-PV hierarchy and performed an optimization to obtain the optimum size of the system for a typical home in the Pacific Northwest [16]. Kaplani and Kaplanis developed a stochastic simulation model for reliable PV system sizing providing for solar radiation fluctuations [17]. Similarly Cabral et al. proposed a stochastic method for standalone PV system [18]. Mellit et al. reviewed artificial intelligent techniques used for PV system sizing [19]. In an interesting study Erdinc and Uzunoğlu considered power output degradation of renewable energy sources due to aging during their pre-defined operating life time and proposed an observe and focus algorithm [20]. Chen proposed an efficient sizing method for a standalone system [21] Luna-Rubio reviewed

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ISSN: 1791-2377 

the methodologies used in hybrid system sizing studies [22]. Belfkira et al. presented a method to calculate the optimum size of a stand alone wind-PV-diesel energy system [23]. In past time Markvart had described a procedure to find optimum size of wind-PV systems [24]. Bilal et al. considered the Loss of power supply probability together with annualized cost to design a wind-PV system [25]. In a different study Zhou et al. considered management strategy besides system sizing [26]. Bagul et al. used three-event probability density approximation to size stand alone wind-PV system [27]. Yang and Liao developed an computed aided design for wind-PV system [28]. In an interesting study Zhou et al. predicted battery behaviors and analyzed battery working states of solar-wind systems [29]. In this study, a case study is performed to determine the size of a hybrid system that is considered to built at Afyon Kocatepe University. First the main parts of the system is introduced in Section 2, briefly. Second, mathematical models used for PV and Wind power calculations are provided in Section 3. Moreover a hybrid system size procedure is presented in this section. Finally a case study is performed for Afyonkarahisar region in Section 4. The results are presented and discussed.

## 2.Hybrid (wind-PV) Systems

Hybrid systems are widely used to increase energy reliability. A simple hybrid system consist of a wind generation unit, PV modules and batteries, basically. The energy stored in batteries should be directly used to meet DC (Direct Current) loads. However to use generated power from hybrid system in AC (Alternative Current) loads, an appropriately sized inverter must be employed. These systems are widely used at rural areas because of their simple constructions and effectiveness. However, first construction costs of such systems are considerably high. Therefore, the system as whole must be sized cost effectively before investment

## 3. Size optimization of wind photovoltaic hybrid systems (WPHS)

In this section first general procedures used for calculation of PV and Wind power are mentioned than well known optimization procedure is presentedOverview of Test System

### 3.1 Calculation of PV output

It is of vital importance to find optimum size of hybrid wind/PV system from the view of economy. The solar radiation and wind speed data must be analyzed as an initial step. Following this a time interval must be determined. Finally change of charge state of batteries must be analyzed step by step. To perform this final step it is mandatory to calculate the renewable generations, accurately. There exist two kind of PV output calculation technique in the literature. These techniques are known as electrical parameter based techniques and efficiency based techniques. Both techniques are reviewed and presented in equations 1-9. However equation 1 is employed in this study

$$P_{PV} = A_m \eta_m P_f \eta_{pc} I \tag{1}$$

where; $A_m$ is the array area, $\eta_m$ is the module reference efficiency (assumed to be 0.12), $P_f$ is the packing factor (assumed to be 0.9), $\eta_{pc}$ is the power conditioning efficiency (assumed to be 0.86), and $I$ is the hourly insulation in Wm-2. On the other hand it is well known that the PV modules must be located with an angle to the surface. Furthermore it was experimentally proven that temperature effect the PV output negatively. Therefore a more detailed and accurate model must be used to calculate hourly outputs of PV modules. For this case to calculate hourly output of a PV module following equations should be used.

$$P_{PV} = A_m \eta_{pv} I \tag{2}$$

Here as distinct from equation 1 in this equation $\eta_{pv}$ represents the PV generator efficiency and it should be calculated from equation 3

$$\eta_{pv} = \eta_r \eta_{pc}[1 - \beta(T_c - T_{ref})] \tag{3}$$

Here $\eta_r$ represents the reference module efficiency whereas $\eta_{pc}$ is known as power conditioning efficiency. If a MPPT (Maximum power point tracker) is used power conditioning efficiency should be assumed to be 1. On the other hand $\beta$ represents generator efficiency temperature coefficient. It is generally assumed to be constant. For silicon based cells $\beta$ alters from 0.004 to 0.006 per 0C. $T_{ref}$ in equation 3 is the reference cell temperature and finally $T_c$ represents the actual cell temperature. Here $T_c$ should be calculated from equation 4:

$$T_c = T_a + [(NCOT - 20)/800]I \tag{4}$$

Here $T_a$ is the ambient temperature and NCOT is the nominal cell operating temperature both temperatures in the equations are in 0C. In the equations above the parameters: $\eta_{pc}$, $\beta$, NCOT and $A_m$ determines the characteristic of a PV module. [30-34].

The solar module equivalent circuit based models to calculate the PV output are also available:
A typical equivalent circuit for a solar cell is given in Fig. 1.

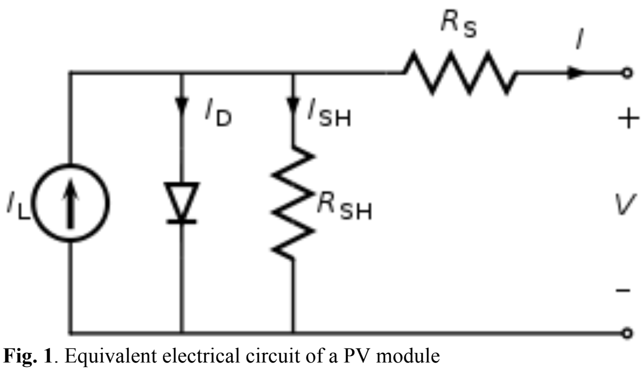


**Fig. 1**. Equivalent electrical circuit of a PV module

The module equivalent circuit current can be calculated by the help of module voltage V as given in Equation 5:

$$I = I_{sc}[1 - C_3(e^{C_4 V^m} - 1)] \tag{5}$$

Here $C_3$ equals to 0.01175 whereas the other constants had defined by Browy and Salameh as given in Equations 6-9 [1].

$$C_6 = In[(1+C_3)/C_3] \quad (6)$$

In Browy et al. C3 was assumed to be 0.01175 (see [1] for details).

$$C_4 = \frac{C_6}{(V_{OC})^m} \quad (7)$$

$$C_5 = In\left\{\frac{I_{SC}(1+C_3)-I_{mp}}{C_3 I_{SC}}\right\} \quad (8)$$

And finally m can be calculated from Equation 10

$$m = \frac{In\left(\frac{C_5}{C_6}\right)}{In\left(\frac{V_{mp}}{V_{OC}}\right)} \quad (10)$$

### 3.2 Calculation of Wind Generator output

Wind speed is the most important parameter to be known or predicted accurately to calculate the power output of a wind turbine. Wind turbines differ from each other by the specifications of cut-off, cut-in wind speed parameters and the generation values per wind speed intervals, in general. The other important parameters that affect the power output are height of the region and turbine and the air density. A simplified but accurate model to calculate the power output of a wind generator is presented in Equation 11

$$P_w = \begin{cases} P_r \dfrac{V-V_{ci}}{V_r - V_{ci}} & V_{ci} \le V \le V_r \\ P_r & V_{ci} \le V \le V \\ 0 & V \le V_{ci} \text{ and } V \ge V_{co} \end{cases}, \quad (11)$$

where $P_r$ is the rated power; $V_{ci}$ is the cut-in wind speed; $V_r$ is the rated wind speed and $V_{co}$ is the cut-off wind speed.

Optimization procedure

In a renewable application the selection of appropriate battery type is important. To find the optimal size of a wind-PV system the model of the batteries should be considered as a start point. Once the state of the batteries simulated accurately it is possible to find the number of PV and wind generator. Simplest and accurate way to determine the charge state of batteries is to calculate the renewable generation in comparison with the battery state with previous state. State of charge should be calculated using 12.

$$SOC(t) = SOC(t-1) + [(N_{Wg}E_{Gw}(t) + N_{Pv}E_{GP}(t) - E_{LD}/\eta_{inv})]\eta_C \quad (12)$$

where $SOC(t)$ and $SOC(t-1)$ are state of charge of batteries at time t and $t-1$, respectively. $N_{Wg}$ is the number of wind generators, $N_{Pv}$ is the number of photovoltaic modules, $P_{Gw}(t)$ and $E_{GP}(t)$ are generated energies from wind generator and photovoltaic module at time t, respectively. $E_{LD}(t)$ is the demand of load at time t. Finally $\eta_C$ and $\eta_{inv}$ represents charging and inverter efficiencies. During system operation at any time interval, one of the 3 following situations can occur:

1-) The total energy generated from wind turbine(s) and Photovoltaic module(s) can be greater than the demand of load: In this situation the remaining energy will charge the batteries. However the fallowing constrains must be satisfied;

$$SOC(t) \le SOC_{Max} \quad (13)$$

2-) The load demand can be equal to the total energy generated from PV modules and wind turbines: This situation can be called as the balance circumstance.

3-) The demand of the load can be greater than the total energy generated from wind turbine(s) and Photovoltaic module(s): In this situation the load must be met by the energy stored in batteries, so the batteries will discharge about the amount of deficient energy. However, because of the physical constraints of batteries the following inequality must be met

$$SOC(t) \ge SOC_{Min} \quad (14)$$

During running the algorithm, power failure times are counted to obtain LLP which is expressed as the ratio of failure time $T_f$ to estimated period of the time $T$ (given in Equation 15).

$$LLP = T_f / T \quad (15)$$

In optimization last step is to calculate the total cost of the system. A simple model to calculate the cost of the system is presented in equation 16.

$$C_{tot} = \sum_{i=1}^{3} C_i = C_R + C_{Bat} = C_{Pv} + C_{Wg} + C_{Bat} \quad (16)$$

Here Cpv, Cwg and CBat represent initial costs of photovoltaic panels, wind generator and batteries, respectively.

### 4. Case Study: Sizing For Afyonkarahisar Region

It is considered that a small building used as an office and will be met by a hybrid wind PV system. In an office the main units that consume energy and their hourly energy consumptions are presented in Table 1. Using table 1 a load profile is built as given in Fig. 2.

**Table 1.** Hour by hour electricity consumptions of the units considered to be used in the office

| Hours | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Laptop (W)** | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
| **Modem (W)** | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **Printer (W)** | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| **TV (W)** | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 |
| **Illumination** | | | | | | | | 50 | 50 | 50 |
| **Total (W)** | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 200 | 200 | 200 |

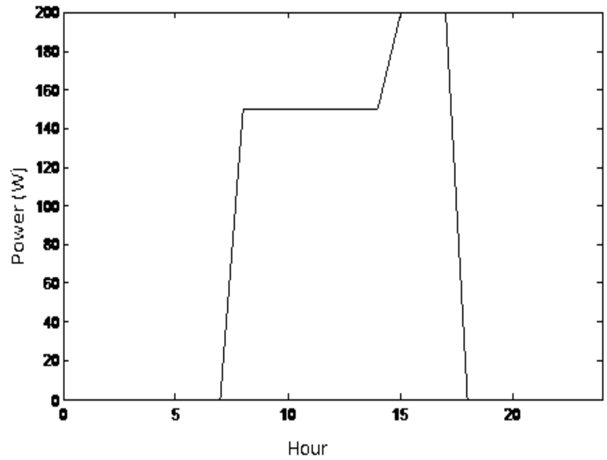


**Fig. 2.** Considered load profile

LLP is selected as to be 0.2, 60W solar panels and 300W wind generator is selected as the renewable part of the system to meet the load profile presented in Fig. 2. Moreover 2 battery banks with 120Ah are selected for the simulation. The simulation is performed using hourly measured and collected solar radiation and wind speed data from Afyonkarahisar region in 2004. Hourly alterations of solar radiation and wind speed data are presented in Fig. 3 and 4 respectively.

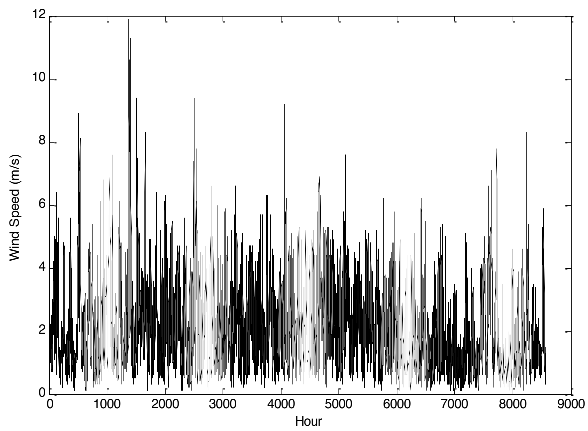


**Fig. 3.** Hourly alterations of wind speed data measured from Afyonkarahisar region

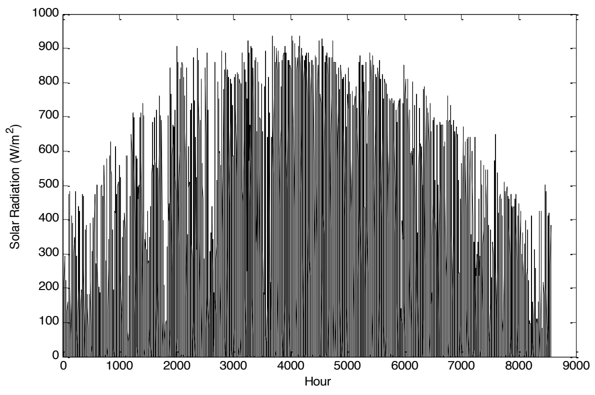


**Fig. 4.** Hourly alterations of solar radiation data measured from Afyonkarahisar region

Instead of calculation the wind power from a model in this study the data obtained from the characteristic curve (presented in Fig. 5) of wind turbine is used.

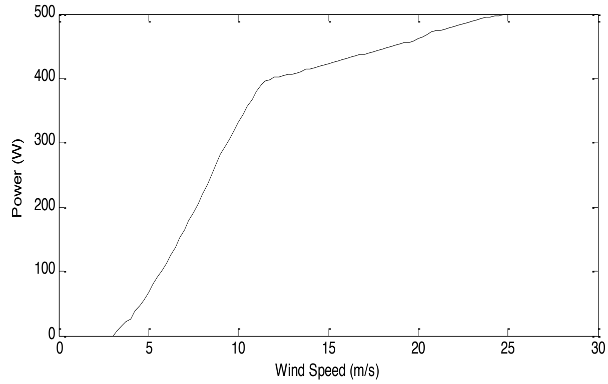


**Fig. 5.** Characteristic curve of wind generator used.

Finally iterative algorithm based on state of charge is used to find optimum solution that will meet the system with a LLP value at most 0.1 and 0.2. Possible solutions with minimum costs are marked for LLP=0.1 and 0.2 cases in Figs 6 and 7, respectively.

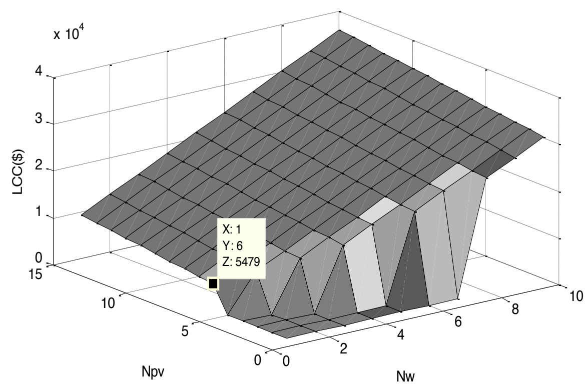


**Fig. 6.** Possible solutions an optimum system with minimum cost for LLP=0.1.

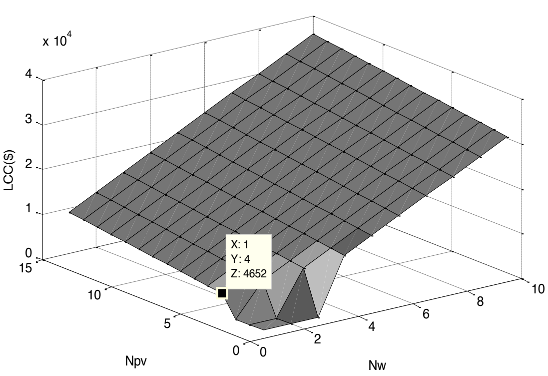


**Fig. 7.** Possible solutions an optimum system with minimum cost for LLP=0.2.

It is obvious from Fig.6 and 7, that there exist a lot of solutions however just one have minimum cost. These configurations can be considered as the optimum ones. Therefore in the region it is possible to meet the load with considered profile (see Fig. 2) can be met using 4 PV generators each has 60W peak power and 1 wind generator having 300W peak power for LLP=0.2 whereas for LLP=0.1 case two additional PV must be used with same power.

## 5. Conclusion

In this paper, it is aimed to review the existing studies performed on hybrid (wind-PV) sizing. The studies should be categorized into three main titles: First category uses nonlinear techniques such as genetic algorithms and neural networks whereas in the second and third categories it is aimed to find optimum solution via iterative optimization techniques. The second and third category differs from each other in calculation of photovoltaic and wind generations. There exist a large number of studies on the subject of renewable prediction. Some of these studies from each category are exemplified and reviewed. Furthermore to show the application of a sizing algorithm a case study is performed. In this section as a first step a meaningful load profile that characterizes the energy consumption of an office room is considered. As a second step hourly measured wind speed and solar radiations are employed to calculate renewable generations. While computing wind generations the characteristic of the turbine considered to be used is employed. However the generations from PV are calculated using basic solar energy models presented by equations 2 and 3. Finally an iterative algorithm based on LLP concept is applied to find optimum size of the system. In conclusion the optimal system that met the load within desired LLP limits with minimum cost is obtained. Since the proposed algorithm uses an iterative technique the size results are optimum. However, the technique should be improved using real generations of PV modules instead of model generated generation values. This situation is not valid for wind generations since the generations are calculated directly by turbine specifications. On the other hand since the hourly variations of solar radiation and wind data changes year by year, as suggested by the author in a different study, model generated data usage should give more accurate size results in state of using the data itself. However in this case the modeled data must include the general behavior of the data, accurately. In conclusion, it is thought that this paper should be used as a good reference for those who are related and concerned to renewable system sizing issue.

**Acknowledgement**

The author gratefully acknowledges to Scientific Research Project Fund of Afyon Kocatepe University for the financial support of this work through projects 11ARŞMER01 and 12HIZDES10. Moreover the author also thanks to the Turkish State Meteorological Service (DMI) for the supply of hourly wind speed and solar radiation data.

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