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Sizing PV-wind hybrid energy system for lighting

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Abstract

Sizing of wind and photovoltaic generators ensures lower operational costs and therefore, is considered as an important issue. An approach for sizing along with a best management technique for a PV-wind hybrid system with batteries is proposed in this paper, in which the best size for every component of the system could be optimized according to the weather conditions and the load profile. The average hourly values for wind speed and solar radiation for Izmir, Turkey has been used in the design of the systems, along with expected load profile. A hybrid power model is also developed for battery operation according to the power balance between generators and loads used in the software, to anticipate performances for the different systems according to the different weather conditions. The output of the program will display the performance of the system during the year, the total cost of the system, and the best size for the PV-generator, wind generator, and battery capacity. Using proposed procedure, a 1.2 kWp PV-wind hybrid system was designed for Izmir, and simulated and measured results are presented.

Keywords: PV-wind hybrid system, PV, Wind turbine

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1. Introduction

A stand-alone solar energy system cannot provide a continuous source of energy due to the low solar radiation periods. Also, stand-alone wind energy systems cannot satisfy load demands due to the significant fluctuations in the magnitude of wind speeds from one hour to another, or throughout the year. Therefore, an energy storage system will be required for each of the two systems in order to satisfy the power demands. Usually storage systems are very expensive and need to be reduced to their minimum possible storage size for a renewable energy system to be cost effective. Hybrid energy systems can be used to reduce the energy storage requirements as they rely on multiple sources of energy to ascertain continuous operation with one or more inactive power sources. While the total system output may be less than the hybrid components' individual capabilities, the reduction of battery size is economically significant. Solar and wind energy which are two random sources of renewable energy are individually less reliable. However, in many regions, the sum of solar and wind energy has approximately constant value during all seasons. Combining these two renewable energy sources could make the system more reliable and depending on the regional conditions, the system costs might stay constant or slightly decrease. However, the energy system sizing procedure and operation control strategies are getting more complex. Configuration of the PV-wind hybrid energy system depends on the wind speed and solar insolation at the considered site.

Graphical solution (Markvart, 1996) defines PV-wind hybrid system configuration using only seasonal variations instead of hourly variations. This method defines the size of PV arrays and wind generator according to the supply-demand criteria and then it can be optimized according to the cost criteria. Seeling-Hochmuth (1997) takes interdependency between sizing and operation strategy into account. Seeling-Hochmuth and Marrison (1997) have solved the non-linear sizing problem using genetic algorithm. Beyer and Langer (1996) have determined the size of hybrid system using limited meteorological parameters. Kellogg et al. (1998) have developed a simple iterative technique that is based on energy balance for sizing PV-wind hybrid energy systems. Green and Manwell (1995) and Morgan et al. (1997) presented software tools for assessing hybrid system performance for pre-determined system configuration.

In this paper, hybrid system model that covers costing and system performance variables is identified. Decision variables, objective function, and constraints are determined for this model. Using simple iterative technique, sizing variable and performance variables are optimized according to the objective function under constraints.

2. Solar evaluation instruments and measurements

The Solar-Wind Meteorological Station is located on the roof of the Solar Energy Institute Building in Ege University for determining the local potentials of both solar and wind energy, as shown in Figure 1. This station consists of four main sections, namely (i) sensors unit, (ii) data logger unit, (iii) electric power unit, and (iv) tripod kit. Table 2 gives the specification of the equipment used for the solar radiation and wind energy measurements. The station is operated with PV-battery hybrid power supply and hereby the auxiliary energy is not required. The data gathering is made at every second and all variables` monthly averages are also logged. The Solar-Wind meteorological station was installed in October 1993 and the measurements have been taken since then (Ulgen and Hepbasli, 2002).

Figure 1. The solar-wind meteorological station at Ege University, Bornova, Izmir, Turkey

3. Hybrid energy system performance model

PV-wind hybrid energy system's main components are shown in Figure 2. PV array and wind turbine generate energy for the load. Battery stores excess energy and supplies to the load when the generated energy is not enough for the load. Battery charge controllers keep battery voltage within specific voltage window and thus, they prevent over-discharge or over-charge regimes. To protect the battery against overcharging, PV array and wind generator is disconnected from the system, when the DC bus voltage increases above $V_{max\text{-}off}$ and when the current required by the load is less than the current generated by the PV array and wind generators. They are connected again when DC bus voltage decreases below $V_{max\text{-}on}$. To protect the battery against excessive discharging, the load is disconnected when the DC bus voltage falls below $V_{min\text{-}off}$ and when the current required by the load is greater than the current generated by the PV array and wind generators. The load is connected again when DC bus voltage increase above $V_{min\text{-}on}$. Inverter converts generated energy from DC to AC for AC load.

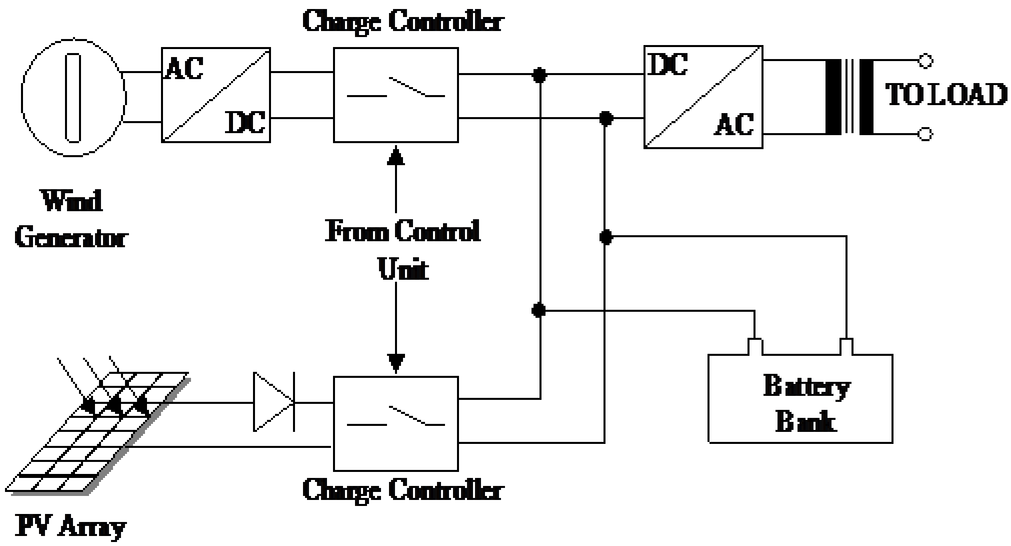

Figure 2. Hybrid energy system components.

3.1. PV module performance model

The most important electrical characteristics of a PV module are short circuit current, open-circuit voltage, and maximum power point. These characteristics depend on temperature and irradiance. The temperature coefficient for the open circuit voltage is negative and large, approximately equal to –2.3 mV/°C for an individual cell. On the other hand, the current coefficient is positive and small, approximately +6 μA/°C for a square centimeter of the module area. In practical calculations, current variations with temperature can be neglected, and the voltage variations with temperature can be defined for a PV module consisting N_c cells connected series using equation 1 (Markvart, 1994).

$$dV_{OC}/dt = -2.3 \times N_c \text{ mV/°C} \quad (1)$$

The operating temperature of the cell which differs from the ambient temperature, determines the open-circuit voltage. Operating temperature can be calculated using equation 2 for a given ambient temperature (Lorenzo, 1994).

$$T_C = T_a + 0.03 \cdot G_a \quad (2)$$

where T_c is operating cell temperature, T_a is the ambient temperature and G_a is irradiance. Open-circuit voltage of the cell can be calculated using equation 3.

$$V_{OC}^{C} = V_{OC,0}^{C} + \left(-2.3\,\mathrm{mV/C}\right)\left(T_C - T_0^{C}\right) \tag{3}$$

For the PV cell, the short-circuit current is proportional to the irradiance where the open-circuit voltage is a logarithmic function of the current. Using equation 4, PV cell short-circuit current can be calculated for given irradiance (Hansen et. al., 2000).

$$I_{SC}^{C} = I_{SC,0}^{C} G_a / G_{a,0} \tag{4}$$

PV module's short-circuit current is proportional to the number of parallel connected PV modules.

$$I_{SC}^{M} = N_{PC} \cdot I_{SC}^{C} \tag{5}$$

PV module's open-circuit voltage can be calculated using equation 6.

$$V_{OC}^{M} = N_{SC} \cdot V_{OC}^{C} \tag{6}$$

The equivalent series resistance of the module can be calculated as below:

$$R_S^{M} = \frac{N_{SC}}{N_{PC}} \cdot R_S^{C} \tag{7}$$

The PV module's current I^M under arbitrary operating condition can be described as (Hansen et. al., 2000);

$$I^{M} = I_{SC}^{M}\left[1 - \exp\left(\frac{V^{M} - V_{OC}^{M} + R_S^{M} \cdot I^{M}}{N_{SM} V_t^{C}}\right)\right] \tag{8}$$

The necessary number of PV modules to be connected in series is derived by the number of modules needed to match the bus operating voltage.

$$V_{PV} = V_{OC}^{M} \cdot N_{SM} \tag{9}$$

The current output of a PV array at time t, I^M (t), is related to the number of parallel strings as below (Hansen et. al., 2000):

$$I_{PV}(t) = I^{M}(t) \cdot N_{PM} \cdot f_{MM} \tag{10}$$

3.2. Wind turbine performance model

Characteristic curves for wind turbines are given as power output versus wind speed at the hub height. Wind turbines are never connected in series (Seeling-Hochmuth, 1998). Several wind turbines can be connected in parallel to match the system current requirements. This can be done with parallel strings of the same wind turbine type or with strings of a different wind turbine type. It is assumed here that at most two different turbine types are used at the same time in one system. Yearly energy densities for wind are calculated using equation 11. If we assume the average yearly energy demand as *D*, we can determine average wind turbine diameter using equation 12, so that wind turbine type can be defined easily (Bagul et al., 1996).

$$P_{WT}=0.5 \, . \, C_p \, . \, \rho_{air} \, . \, \nu^3 \tag{11}$$

$$D = \sqrt{\frac{D_{av,year}}{\cdot hours / year \cdot P_W \cdot \pi \cdot \frac{1}{4}}} \tag{12}$$

The power output of the wind turbine array at time t,

$$P_{WT}(t) = \sum_{i=1}^{N_{wt,type}} I_{WTi}(t) \cdot V_{WTi} \cdot N_{PWTi} \tag{13}$$

3.3. Battery performance model

Batteries in a hybrid system are connected in series to obtain the appropriate nominal bus voltage. Therefore, the number of batteries connected in series for the same type of battery in a battery bank is calculated as below:

$$N_{SBat}=V_{PV}/V_{Bat} \tag{14}$$

The hybrid system can have several different types of battery banks. The battery state of charge of a battery bank at time t is calculated based on adding the charge current (positive sign) or discharge current (negative sign) to the battery bank state of charge at the previous time instant. When adding the battery current to the battery state of charge, self discharge losses and battery charging losses should be taken into account (Seeling-Hochmuth, 1997).

$$SOC(t+1) = \sum_{i=0}^{BatBan} \left[SOC_i(t) \cdot \sigma_i + I_{Bat}(t) \cdot \Delta t \cdot \eta_{i(I_{kolbat}(t))} \right] \cdot N_{PBat} \qquad (15)$$

3.4. Inverter, charger, and loads performance model

The inverter characteristics can be described by the inverter input-output relationship. Some of the power going into the inverter will be lost due to transformation losses that are named inverter efficiency losses.

$$P_{inv-,ip} \cdot \eta_{inv} = P_{inv-op}, \quad \eta_{inv} = f(P_{inv-op}) \qquad (16)$$

In fact, charge regulators can be modeled as a switch which connects and disconnects generator to battery or load according to battery state of charge, temperature or load demand (Engin, 2002). The output power, $P_{BC\text{-}OP}$ of the battery charger equals to the input power $P_{BC\text{-}IP}$ multiplied with the efficiency losses during the energy conversion. Efficiency losses depend non-linearly on the DC output power and therefore, non-linearly on the DC output current of the battery charger.

$$P_{iBC-ip} \cdot \eta_{BC} = P_{BC-op}, \quad \eta_{BC} = f(P_{BC-op}) \qquad (17)$$

Efficiency losses can be calculated from efficiency losses versus output power curves that are given by the manufacturers. In most cases, two types of loads are present, DC appliances 12V, 24V, 48V or AC appliances 220V. The estimated power consumption should be given in intervals of hourly, daily, or yearly. If both a DC and an AC generator exist, some of the DC generator energy can be routed through the inverter to the AC loads.

$$I_{Gdc} \geq I_{dcL}, \quad or \quad I_{Gdc} = I_{dcL} + I_{inv-ip} \qquad (18)$$

3.5. Costing model of hybrid system

It is stated by Seeling-Hochmuth (1998) that in the life cycle costing equipment and operation costs are compiled and discounted over the assumed project life. The hybrid system life cycle costs are defined as the initial investment and future discounted operation costs.

$$LCC = \left[C_C + \sum_{i=1}^{Number of Compenents} Discounted\ C_{OP,i} \right] \tag{19}$$

The hybrid system operation costs are in general non-linear, and depend largely on component size and type, and the way the system is operated. As they depend on future operations, they can only be estimated roughly (Seeling-Hochmuth, 1998).

The sizing variables are sizes of component types and their number to be installed. From the PV module, wind turbine, battery, battery charger and inverter performance models sizing variables are defined as follows:

N_{SBat}, N_{PBat}, N_{SM}, N_{PM}, N_{PWT}, N_{Pin}, PV_{type}, WT_{type}, IN_{type}, BC_{type}, BAT_{type}

Hybrid system must include operation strategies that describe the energy flow between the generator and the load. The operation decision variables to be optimized represent routing and operation decisions that are based on the power flow modeled for the hybrid system. The main operation decision variables of the hybrid system model are presented as follows: (Engin, 2002).

CS_{CPV}, CS_{CWT}, CS_{IN}, SOC_{min}, SOC_{max}, CS_L

Some of these decision variables may be set before optimization of hybrid system. The hybrid system model has many constraints including technological, socio-economic, legal or physical. The constraints in the presented approach are given by technical characteristics of battery operation and by matching demand and generated energy. Constraints can be formulated as follows:

$$SOC(t) \geq SOC_{min} \tag{20}$$

$$I_{PV}\,(t) + I_W\,(t) + I_{BD}\,(t) \geq I_{load}(t) + I_{BC}\,(t) \tag{21}$$

Equation 21 cannot always be proved. According to various applications, load may not be served with desired amount of energy. This situation is described as loss of load probability (LLP). LLP of the energy system can be calculated using equation 22. Also, LLP is the size of system reliability.

$$LLP = \frac{Energy\_Demand}{Energy\_Served} \tag{22}$$

The objective of the optimization procedure is to achieve hybrid system that generates energy with the lowest cost. The hybrid system model needs to be optimized with respect to the decision variables and operation strategies such that a minimum of the life cycle costs is achieved (Seeling-Hochmuth, 1998).

4. Results and discussion

The load on the system is an experimental lighting of Solar Energy Institute. Load demand changes according to night period. The monthly means of daily loads are shown in Figure 3. Daily energy densities were calculated using yearly mean irradiation and wind speed, and results are shown in Figure 4.

Using MATLAB hybrid system components performance models initial values of sizing variables and type of system components were defined as follows: N_{SM}=2, V_{DC}=24 V, V_{BAT}=2 V, N_{SBAT}=12, N_{Pin}=400 W_{peak}, PV_{type}=M65, WT_{type}=400 W, IN_{type}= square wave output, BAT_{type}= 2 V and 210 Ah stationary type battery (Engin, 2002). Equation 15 was optimized with respect to the N_{PBat}, N_{PM}, N_{PWT}, BC_{type}, and operation strategies to minimize the life cycle costs (Seeling-Hochmuth, 1998). Using simple iteration technique, sizing variables were defined and results are shown on Figure 5. Because of economical constraint N_{PWT} is set to 1 instead of 2, and then LLP value revised to be 0.0738. Using defined sizing variables and operation strategies hybrid system model simulated according to hourly weather data and SOC is shown in Figure 6. Life cycle costs per kWh are calculated as $1.0076.

Configured hybrid system was installed in Izmir during January 2009. Battery voltage, load voltage, load current, battery current, PV output and wind generator output currents were measured every 10 minutes during one year. Inverter and charge regulator efficiencies were calculated as 80% and 98%, and overall system efficiency was calculated as 72%. Life cycle costs per kWh were calculated as $0.89 and LLP=0.0428. Using measured variables hourly changes of SOC was calculated and the result is shown in Figure 7.

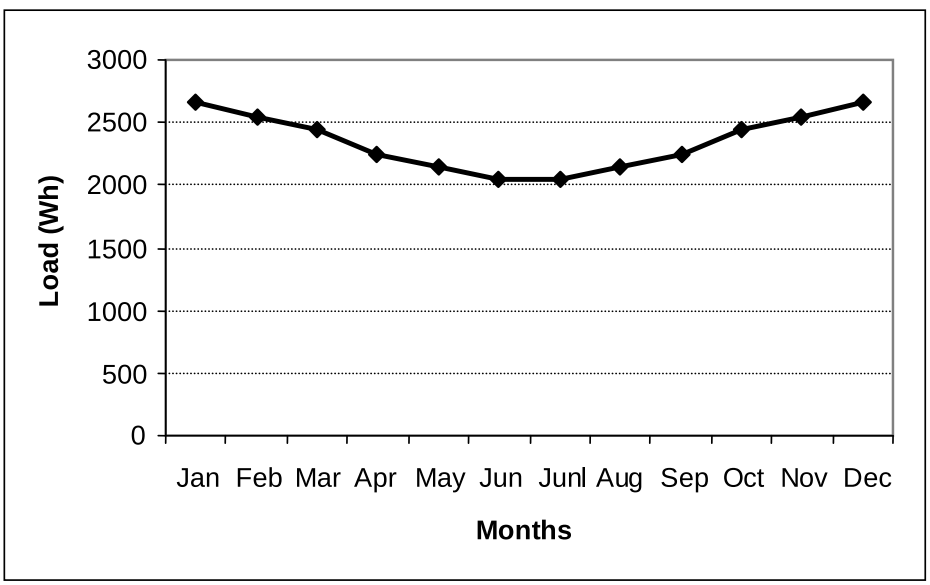

Figure 3. Load profile of hybrid system.

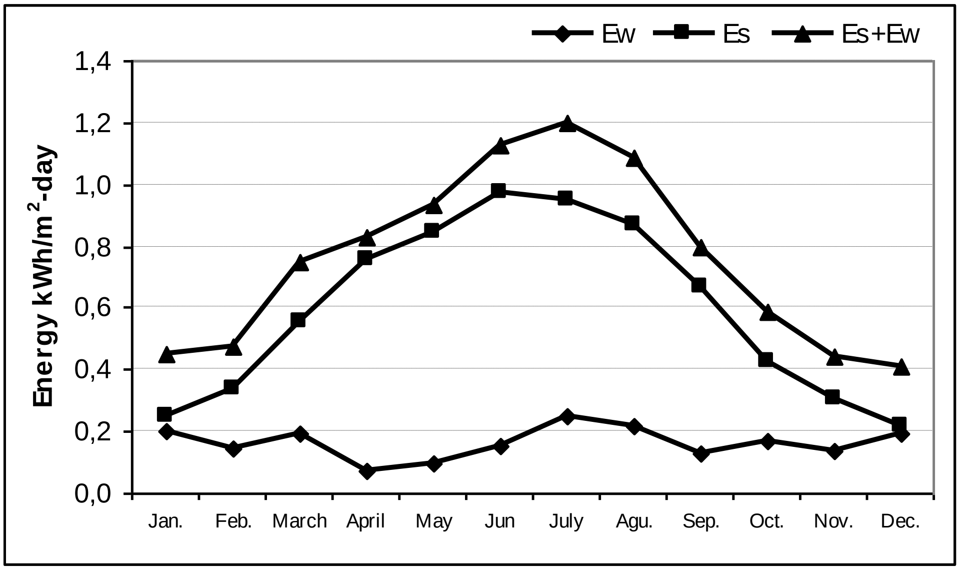

Figure 4. Daily energy densities for Izmir.

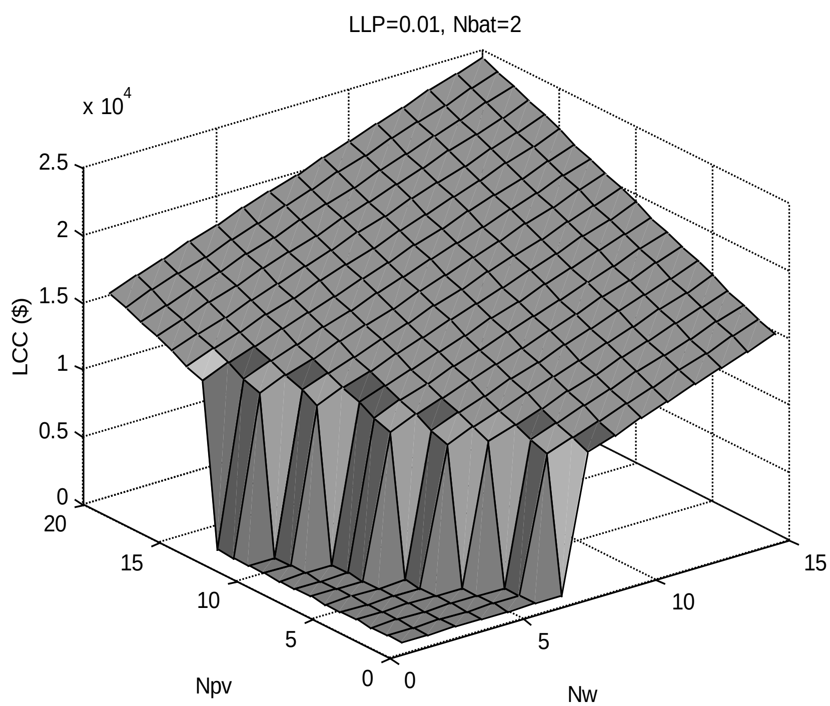

Figure 5. LCC versus NPWT, NPV for LLP = 0.01 and Nbat=2.

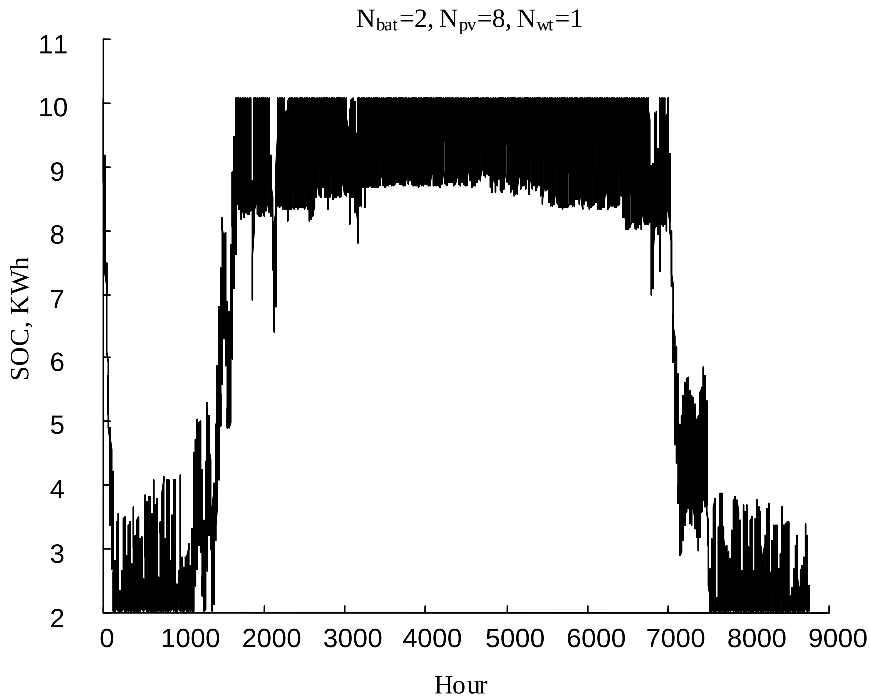

Figure 6. Simulation result of SOC.

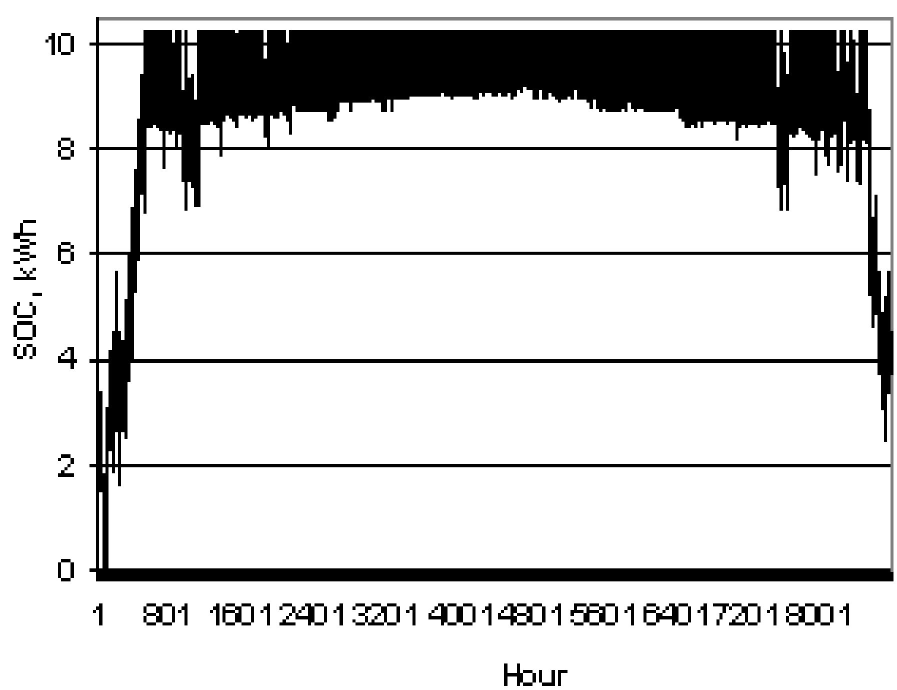

Figure 7. Measured results of SOC.

5. Conclusions

A sizing procedure of a hybrid PV-wind energy system was presented. The outlined procedure defines optimum hybrid energy system configuration and control criteria. It needs hourly changing meteorological data as input, and gives cost-effective hybrid system configuration with the highest reliability. The procedure was applied for the sizing of PV-wind hybrid energy system that is considered to lighting Solar Energy Institute Building. Hybrid energy system was settled; configured hybrid system was installed in June 2000, and the system variations were measured every 10 minutes during one year. From the measured values, life cycle costs per kWh were calculated as $0.89, LLP=0.0428, and also hourly changes of SOC is shown in Figure 7. The validation of procedure was performed through the comparison between simulation results and measured results.

Nomenclature

Cp	Power coefficient
C_C	Capital cost of hybrid system.
C_{OP}	Operation cost.
CS_{CPV}	PV battery charger control switch.
CS_{CWT}	WT battery charger control switch.
CS_{IN}	Inverter control switch.
CS_L	Load control switch.
f_{MM}	Miss-match factor for different type of module
$G_{a,0}$	Reference ambient irradiation
G_a	Ambient irradiation
$I^C_{SC,0}$	Short-circuit current of cell for reference working condition.
$I^C_{SC,0}$	Short-circuit current of cell.
$I^M_{SC,0}$	Short-circuit current of module.
I^M	Module current.
I_{PV}	PV array current.
I_W	Wind turbine current.
I_{BD}	Battery discharge current.
I_{Load}	Load current.
I_{BC}	Battery charge current
R_S^M	Equivalent serial resistance of module
R_S^C	Equivalent serial resistance of cell
η_{BC}	Efficiency losses of the battery charger.
η_{inv}	Inverter efficiency losses.
N_{SBat}	Number of serial connected batteries.
N_{SC}	Number of serial connected cells.

N_{PC} Number of parallel connected cells.
N_{SM} Number of serial connected modules.
N_{PM} Number of parallel connected modules.
N_{PBAT} Number of parallel connected batteries.
$P_{BC\text{-}op}$ The output power of the battery charger.
σ_i Self-discharge losses of the battery.
SOC Battery stage of charge.
SOC_{min} Minimum SOC
SOC_{max} Maximum SOC
V_{Ba} Voltage of a battery.
V_t^c Thermal voltage, mkT^C/e
v Wind speed (m/s),
ρ_{air} Air density

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