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Optimal Energy Management for off-Grid Hybrid Renewable Energy Systems

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ABSTRACT

A photovoltaic (PV)/wind/battery/Generator-Set hybrid power system's energy dispatch is discussed in this research, along with the ideal solution. The optimization model enables the hybrid power system's generating devices to share power appropriately. The main goals are to minimize fuel consumption and costs and maximize the usage of Renewable Energy Sources (RES). The proposed simulation plan succeeds in lowering fuel costs because the diesel generator only kicks on at night and in the early morning when the energy from RES is insufficient to supply the load. The load is supplied with power, and the battery is charged throughout the day, when the production of electricity from the wind and solar generators is highest. The use of diesel is minimal. However, based on their particular characteristics and the operational limitations of the system, the generating devices effectively share the power needed from the hybrid power system.

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INTRODUCTION

Typically, off-grid power systems employ Renewable Energy Resources (RES). The smooth operation of the entire power system can easily be compromised by disturbances such as abrupt power fluctuations or over/underproduction. Hybrid Energy Storage Systems (HESS), which incorporate parts from many technologies, has been proposed as a solution to this limitation because no energy storage technology can meet these needs while remaining cost-effective (Himri Y et al. 2008). Additionally, it has been investigated how generators (G-set) may be integrated into autonomous power systems despite their detrimental environmental impact and high operating and maintenance costs (World energy outlook: Executive summary 2009), (Getachew and Getnet 2012), (World Bank 2008).

Numerous research works on this subject, and optimization strategies employing various methodologies have been published in the literature. The first method proposes a model of predictive control in the demand profiles and RES output for both seasons (Fadaee and Radzi 2012). While maximizing the use of RES, accounts for the effect of daily variations in energy consumption and the output power fluctuation of the RES on the system. This control reduces operational costs by reducing G-Set power generation and BESS charge-discharge cycles. The investigation of an optimal energy management strategy for a photovoltaic/wind/battery/G-set hybrid (, . 2009; World energy outlook: Executive summary 2009)power system is presented in this paper The first strategy is to minimize fuel consumption, and the second is to maximize the usage of RES, whereas the third strategy employs the Particle Swarm Optimization (PSO) method to reduce the overall cost of the hybrid PV/G-Set/battery system, the total amount of greenhouse gases produced by the G-set and the chance of load loss (Himri Y et al. 2008).Finally, one of the answers is optimum energy management based on heuristic control approaches. (Sharma and Tiwari 2012). In actuality, each power plant connected to a power network receives daily updates on the amount of electricity that will be provided over the next 24 hours period. A renewable energy power plant's reference power should be set while considering the outlook period's forecasting data. All these should be taken into account for the power reference, which is the rated power, and the forecasted data on the energy system that is accessible (World energy outlook: Executive summary 2009), (Getachew and Getnet 2012), (World Bank 2008), (Himri Y et al. 2008), (Sharma and Tiwari 2012).This study aims to develop a power flow management optimization strategy for a PV, wind, G-sets and battery hybrid power system that maximizes the use of RES while minimizing the fuel cost of the system by taking into account the load profile, the forecast RES energy generation, and other operational constraints on the energy system.

MODELING OF AN AUTONOMOUS PV/WIND/BATTERY/G-SET HYBRID SYSTEM

Overall system description

The main layout of a hybrid PV/Wind//Battery/ G-Set system is that it consists of a PV system, wind generation (WG) system, BESS, and G-Set as its four subsystems. Combining the separate models of various devices creates a model of the entire system. Energy models for each system are adequate for our investigation. This system's power output helps to meet the electricity demand. The function of load profile and weather conditions, as well as the RES and BESS, significantly influence the G-Set fuel consumption. Therefore, when RES production is sufficient, the battery should be charged, and the load should be satisfied by RES. If the battery works within its operational parameters, it will drain and supply the load.

Solar PV Model

The power produced by the PV array during one hour is equivalent to the hourly energy output from the PV generator, which may be represented as follows: (Fadaee and Radzi 2012).

$$P_{pv} = \eta_{pv} A_c I_{pv} \tag{1}$$

The efficiency of the PV generator is computed by:

$$\eta_{pv} = \eta_R \left[1 - 0.9\beta \left(\frac{I_{pv}}{I_{pv.NT}} \right) \left(T_{c.NT} - T_{A,NT} \right) - \beta \left(T_A - T_B \right) \right] \tag{2}$$

The time of day and the location of the PV array installation affect the hourly solar irradiation. The PV array's azimuth, tilt and hour angle are used to describe the time of day, while the latitude, hourly global sun irradiation and diffuse fraction are used to determine where the PV array is located (Ahmed and Salam 2015). The following formulas provide the PV array's hourly sun irradiation: (Fadaee and Radzi 2012)

$$I_{pv} = \left(I_B - I_D \right) R_B + I_D \tag{3}$$

At any instant k, the power output of PV system is subject to the following inequality constraints:

$$0 \le P_{pv}\left(k\right) \le P_{pv}^{\max} \tag{4}$$

Hwhere$P_{PV}^{max}$is the rated power of the PV energy system.$P_{PV}$is Hourly energy output from a PV generator of a given array area at the kth hour.

Wind turbine model

The wind speed pattern at aparticular site, air density, rotor diameter and energy

conversion efficiency from wind to electrical energy all affect the hourly energy production of a wind turbine. Knowing the wind speed at a reference height, the following formula may be used to calculate the wind speed at any time k:
Source:(Carpentiero, Langella, and Testa 2012).

$$V_{hub}(k) = V_{ref}(k)\left(\frac{H_{hub}}{H_{ref}}\right)^{\alpha} \tag{5}$$

In this work, α is considered equal to 1/7.
The hourly energy output of a wind turbine is given by (Fadaee and Radzi 2012),(Ahmed and Salam 2015):

$$P_{wind} = 0.5\eta_w \rho_{air} C_p A v^3 \tag{6}$$

At any time of day, the power output of the wind generator system is constrained by:

$$0 \le P_w(k) \le P_w^{\max}(k) \tag{7}$$

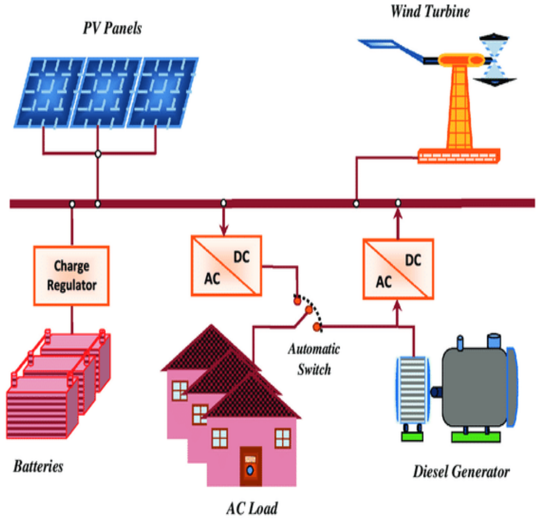

Figure 1: Configuration of the PV/wind/battery/G-Set hybrid power system, (Chel and Tiwari 2011).

Battery Model

In essence, a single battery's rated voltage and current cannot fulfil most power smoothing applications. To get over these restrictions, battery strings are used to provide a certain voltage, and several strings are connected in parallel to generate a certain current level.

The dynamic equation approximates the energy capacity of the complete battery subsystem at a certain hour k.
While overcharging can harm the devices, deep draining of batteries has the greatest impact on their lifespan. As a result, the available battery capacity never exceeds its working limits, i.e., the maximum permissible capacity ($E_B^{\max}$)and the minimum allowable capacity ($E_B^{\min}$)
Source (Carpentiero, Langella, and Testa 2012).

$E_B^{\min} \le E_B(k) \le E_B^{\max}$ and

$$E_B^{min} = E_B^{\min} = (1 - DOD)E_B^{\max} \tag{8}$$

The charging and discharging powers of the batteries are subjected to the following constraints:

$$0 \le P(k) \le P_B^{\max} \tag{9}$$

$$0 \le P_4(k) \le P_B^{\max} \tag{10}$$

Diesel Model

Due to their inexpensive initial cost, G-sets have historically been the preferred option for decentralized electricity delivery. The G-sets are employed as a backup in hybrid power supply systems and are required to carry the load when the PV, wind and BESS cannot do so. The following limitation illustrates how the G-set must operate between its rated power and a set minimum value advised by the G-Set manufacturer: (Salas, Suponthana, and Salas 2015).

$$P_{G-Set}^{\min} = P_1(k) \le P_{G-Set}^{\max} \tag{11}$$

OPTIMIZATION MODEL

The goal of the optimization task is to determine the best time of day to schedule generating to maximize the usage of RES, and satisfy load demand and other operating constraints while minimizing fuel consumption costs and battery-delivered power. The latter are expressed in terms of operational constraints made up of the abovementioned equations. An extra constraint is thus necessary and is mentioned because the batteries should be charged primarily by the RES (Hafez and Bhattacharya 2012).

This dispatch problem's optimization challenge may therefore be stated as follows (Hafez and Bhattacharya 2012).

$$\min J_1 = \min \sum_{k=1}^{N} \left(C_f \left(aP_1^2(k) + bP_1(k) \right) + P_5(k) - P_2(k) - P_3(k) \right) \qquad (12)$$

$$P_{pv} = \eta_{pv} A_c I_{pv}$$

Subject to the following constraints:

$$P_2(k) + P_3(k) + P_4 \le P_{pv}(k) + P_w(k) \qquad (13)$$

$$P_1(k) + P_2(k) + P_3(k) + P_5(k) = P_L(k) \qquad (14)$$

$$P_i(k) \ge 0, i = 1,2,3,4,5...$$

Anon-linear optimization problem was formulated in the manner shown below to be solved using MATLAB's "quadroon" function: those specifications and parameters (Ahmed and Salam 2015).

$$\min \frac{1}{2} x^T H x + f^T x \qquad (15)$$

Subject to:

$$Ax \le b \qquad (16)$$

$$A_{eq} x \le b_{eq} \qquad (17)$$

$$l_b \le x \le u_b \qquad (18)$$

CASE STUDY

For demonstration purposes, the suggested power control scheme's performance is assessed using the load profile shown in Table 1 (Salas, Suponthana, and Salas 2015). Literature has been searched for the specifications of the PV module, wind turbine, G-Set, and BESS, as well as the remaining characteristics (Chel and Tiwari 2011),(Hafez and Bhattacharya 2012). These details and parameters are listed in Table 2.

Table 1:Weekday and weekend demand profile for both winter and summer

Time (hours)	Winter Load (kW)		Summer Load (kW)	
	Weekend	Weekday	Weekend	Weekday
00:30:00	1.50	1.500	1.50	1.50
01:30:00	1.50	1.500	1.50	1.50
02:30:00	1.50	1.500	1.85	1.85
03:30:00	1.50	1.500	1.95	1.95
04:30:00	1.95	1.650	1.50	1.50
05:30:00	0.15	0.625	0.90	0.90
06:30:00	1.95	1.650	1.65	1.65
07:30:00	1.65	1.350	1.65	1.65
08:30:00	1.35	1.350	1.70	1.70
09:30:00	3.25	3.000	1.75	1.75
10:30:00	3.25	3.000	1.75	1.75
11:30:00	2.15	1.950	1.75	1.75
12:30:00	2.15	1.950	1.25	1.25
13:30:00	2.15	1.950	1.32	1.32
14:30:00	2.15	1.950	1.35	1.35
15:30:00	2.15	1.950	1.35	1.35
16:30:00	2.15	1.650	1.45	1.45
17:30:00	1.80	1.650	2.10	2.10
18:30:00	2.31	3.250	2.40	2.40
19:30:00	3.81	3.250	3.80	3.80
20:30:00	2.31	2.310	3.80	3.80
22:30:00	2.31	2.150	1.50	1.50
23:30:00	2.31	2.150	1.50	1.50

SIMULATIONS AND RESULTS

The parameters provided in the literature (World energy outlook: Executive summary 2009), (Tawfeek, Ahmed, and Hasan 2018), (Carpentiero, Langella, and Testa 2012) were utilized to estimate the data used in this research for simulations for both PV and wind output energy. The sampling period was set at one hour; thus, the hourly energy equals the power produced or consumed during that time.

The optimization issue is resolved for four load profiles, as shown in Table 1, to present a variety of scenarios for the debate.Figures 2 to 5 show the few samples of energy flow from different suppliers and the load profile satisfied as obtained from MATLAB simulations. Likewise, Table 2 and Table 3 depict the parameters and specifications of different devices and fuel cost savings, respectively.

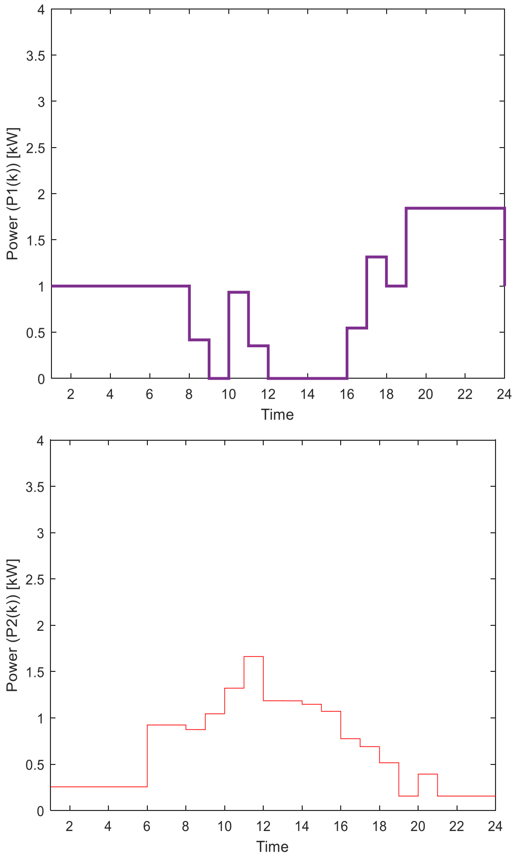

Figure 2: Winter weekend power flow and load profile

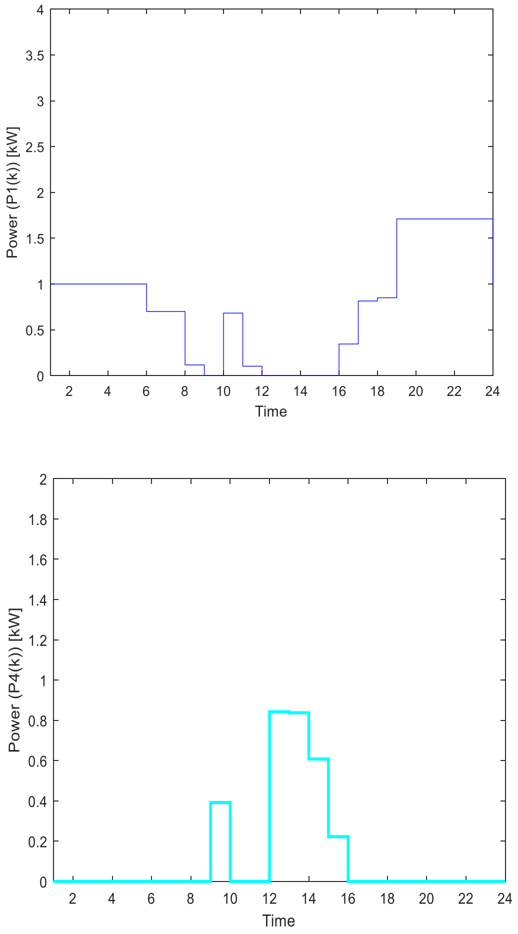

Figure 3: Winter weekday power flow and load profile

Table 2: Parameters and specifications of different devices

Parameters	Specifications
a	US$ 0,246/h
b	US$ 0,1/kWh
Fuel Cost	US$1,2/I
DG capacity	5 kVA
Nominal battery Capacity	54,5 kWh
Battery charge efficiency	85%
Battery discharge efficiency	100 %
Battery allowable depth of discharge	50%
PV array capacity	4 kW
Reference cell temperature	25°C
Average solar irradiation incident	0.8 kWh/m^2
$T_{c,NT}$	45°C
$T_{A,NT}$	20°C
The coefficient for cell efficiency	0.004-0,005/25°C
Wind turbine capacity	5 kW

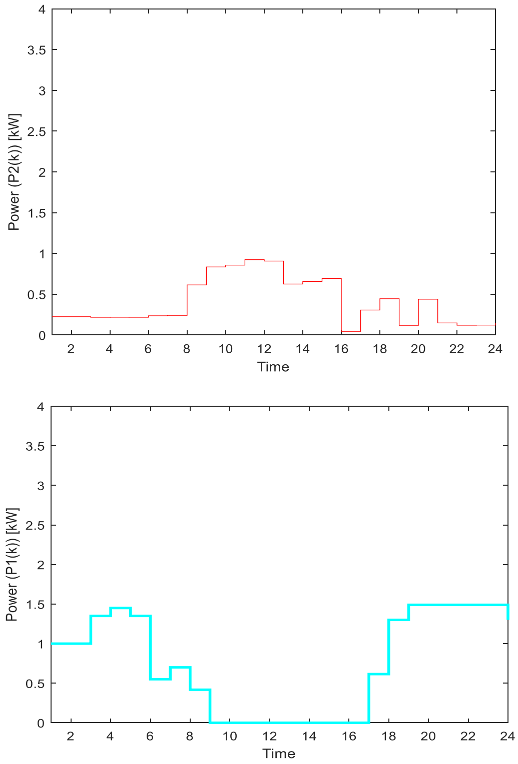

Figure 4: Summer weekend power flow and load profile

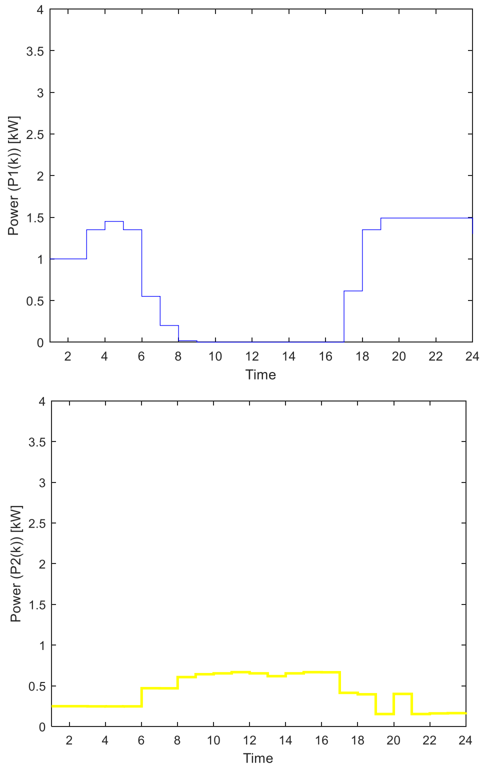

Figure 5: Summer weekday power flow and load profile

According to the modelling results, the load requirement seems to be met during both the Summer and Winter seasons. The G-Set and wind generator handle the load overnight and early in the morning. The constraint (Hafez and Bhattacharya 2012) is met by the output of the PV and wind generators, which provide the load and recharge the battery bank. When the PV, wind generator and battery fail to fulfill the demands of the load, the G-Set is turned on. As a result, it is evident that the expense of diesel use is being decreased, and the utilization of RES is being maximized. Given that demand is higher in the Winter than it is in the Summer and that it is lower during the weekdays than it is during the weekends;therefore, more fuel is consumed in the Winter than in the Summer.

When the output from the RES is insufficient to support the load, the battery is charged during the day and supplies the load at night. The proposed control scheme appears to achieve the expected results. One could propose introducing disturbances in demand profiles and RES output for both the Winter and Summer seasons to approximate the effect of daily energy consumption variations and RES output power fluctuation on the system.

Table 3: Fuel Cost Savings

Time (hour)	Winter	Summer		
	Weekend	Weekday	Weekend	Weekday
Diesel only scenario	39.40	35.2	33.0	28.0
Hybrid model	9.02	7.2	6.3	4.4
Savings	30.38	28.0	26.7	23.6

CONCLUSIONS

In this study, a power control approach for a photovoltaic/wind/battery/G-set hybrid system is developed. It aims to reduce the cost of fuel while maximizing the usage of RES. Using the presented results of optimization, it is easy to say that more savings are made with the optimization model than with the diesel-only scenario. It has been suggested that the optimization problem be solved for four load profiles to fully benefit from the analysis of the study.

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