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OPTIMAL SIZING OF GRID-CONNECTED HYBRID WIND-PV SYSTEMS WITH BATTERY BANK STORAGE

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ABSTRACT

Conventionally a battery bank is used as the backup system in standalone Hybrid Renewable Energy Systems (HRES) while in grid-connected systems the grid performs as the backup during power shortage periods. For the latter, different prices of electricity during peak and off-peak hours raises a question about the cost effectiveness of using the grid as a backup. Adding a small storage system to maintain the shortage of electricity produced by renewable resources at peak hours may prove to be more cost effective backup. This paper focuses on the design of an optimised grid connected small-scale HRES, incorporating a battery bank to store electricity during off-peak periods and uses this storage to support the HRES during peak demands. This system is intended to be cost effective (taking into consideration the Feed-In-Tariff) and make building self sufficient with regard to energy use.

The performance of the proposed design method is evaluated based on a case study for a typical household in UK.

Keywords: grid-connected hybrid systems, hybrid PV-wind-battery, long-term storage,

1. INTRODUCTION

Increase in energy demand has made the renewable resources more attractive. Common drawback of using renewable resources is constant challenge with their unpredictable nature which is completely dependent on climate changes and may result in load rejection at some points. Conventionally the balance between demand and HRES is obtained by grid in grid-connected systems and overproduction is sent into the grid. In these systems, the grid performs as the storage system with infinite capacity which makes the HRES reliable at any time. However different grid electricity prices in peak and off-peak hours could become an economical challenge in maintaining power shortage in peak hours from the grid. In this paper a new method in design of HRES is introduced by adding a small battery storage system to cover the power shortage during peak hours.

Normally battery bank is used as a backup in standalone systems. Bernal-Agustín and Dufo-López [1, 2] put their effort in analyzing the main strategies in optimisation of hybrid systems with battery bank as storage. Balamurugan et al. [3] proposed a hybrid energy system consisting of biomass, wind, solar photovoltaic and battery to deliver energy at optimum availability, considering proper energy storage to meet the peak load demand during low or no solar radiation periods or during low wind periods. Ould Bilal et al.[4] & Yang [5] & Kaabeche [6] proposed methods for sizing a hybrid solar–wind-battery system with the aim of minimizing cost system with maximum reliability.

Recently some research has been carried out in which the hybrid system is grid-connected but still includes a battery bank as storage. Castillo-Cagigal et al [7] developed a prototype of a self-sufficient solar house equipped with grid connection, PV generation, lead–acid batteries, controllable appliances and smart metering. Mudler [8] proposed a method to determine the optimal storage size for grid-connected dwelling with PV panels. Particularly increase in grid electricity prices for example in peak hours will change the status of complete dependency on grid during shortage times.

The presented study addresses the optimisation of a grid-connected HRES based on wind and solar energy considering different grid electricity prices with a storage system to cover the power shortages during peak hours.

2. COMPONENTS MODELLING

The concept block diagram of the designed system in this study is presented in Fig. 1.

Different mathematical models have been proposed by researchers to estimate the output power of wind turbine, photovoltaic panel and batteries. The models implemented in this study are chosen with consideration of giving a realistic estimation of the output of each system without getting involved with too much of details.

2.1 Wind Turbine Model

The wind power generated by a wind turbine can be obtained by:

$$P_{WT} = \frac{1}{2}\rho C_p V_w^3 A_{WT} \qquad (1)$$

where P_{WT} is wind turbine power in W, $\rho = 1.225 kg/m^3$ is the air density, C_p is the wind turbine power coefficient, A_{WT} is the rotor disk area in m^2 and V_w is hourly average wind velocity in m/s at the hub elevation.

The wind speed at the hub height can be calculated:

$$V_w = V_{ref}\,\frac{\ln\left(z_{hub}/z_0 \right)}{\ln\left(z_{ref}/z_0 \right)} \qquad (2)$$

where z_{hub} is the hub height, V_{ref} is the wind speed at the reference height z_{ref} and z_0 is the surface roughness length in m.

The power coefficient depends on the wind turbine characteristics and varies with wind speed. Fig. 2 shows the power coefficient variation used in this study. This curve has been extracted from the data of different wind turbines in the range applied to the case study reported.

2.2 Photovoltaic (PV) Panel Model

The PV array model used in this study is given by Equation 3:

$$P_{PV} = I A_{PV} \eta_{PV} \qquad (3)$$

in which, P_{PV} is the PV array output power in W, I is the horizontal solar irradiance in W/m^2, A_{PV} is the PV panel area in m^2 and η_{PV} is the efficiency of the PV array and corresponding converters. In this study it is assumed that η_{PV} is constant and equals to 12.3%.

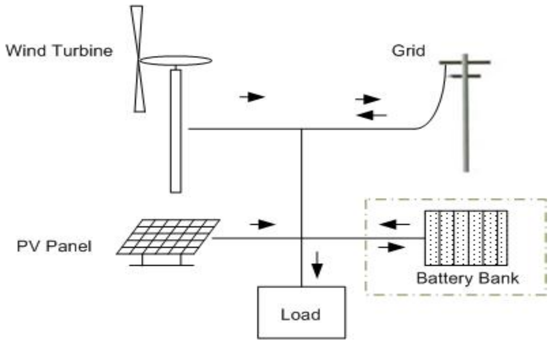


Fig. 1: Concept diagram of HRES

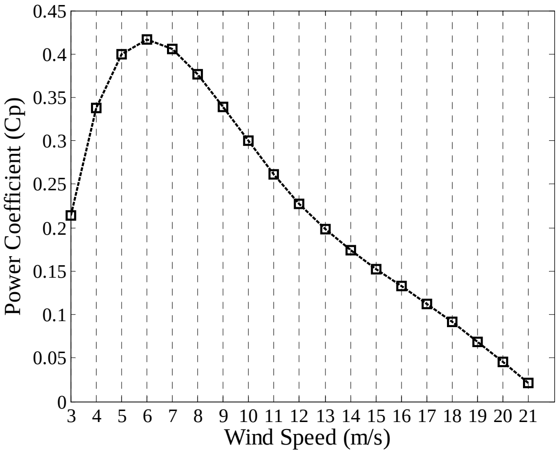


Fig. 2: Power coefficient curves

2.3 Battery Bank Model

The battery used in this study is a lead acid battery .The selection of an appropriate size of a battery bank requires complete analysis on the charge and discharge process of the battery.

The battery SOC is simulated during the charging process by [5]:

$$\mathrm{SOC}(t+1) = \mathrm{SOC}(t)(1-\delta(t)) + \frac{I_{Bat}(t)\Delta t \eta_C}{C_{Bat}} \qquad (4)$$

where, $\delta(t)$ is the hourly self-discharge rate and the proposed average approximation of 0.02% is used. Δt is the time step in which the SOC is calculated, in this study Δt is equal to one hour. C_{Bat} is the nominal battery bank capacity in Ah and η_C is the charge efficiency factor. The battery current I_{Bat} can be calculated by:

$$I_{Bat}(t)=\frac{P_{PV}(t)+P_{WT}(t)-P_{load}(t)}{V} \qquad (5)$$

where, V is the battery voltage.

During the discharge, SOC is calculated by [5]:

$$SOC(t+1)=SOC(t)(1-\delta(\mathrm{t}))-\frac{I_{Bat}(t)\Delta t}{C_{Bat}} \qquad (6)$$

in which

$$I_{Bat}(t)=\frac{P_{load}(t)-P_{PV}(t)-P_{WT}(t)}{V} \qquad (7)$$

Charge and discharge processes are subjected to the following constraints:

$$SOC_{\min}=1-DOD_{\max} \qquad (8)$$

where $DOD_{\max}$ is maximum depth of discharge of the battery.

$$SOC_{\min}\le SOC(t)\le SOC_{\max} \qquad (9)$$

3. ECONOMIC ANALYSIS

Economic analysis has a leading role in size optimisation of HRES to result in a reasonably profitable investment. In this study the Return On Investment (ROI) of the design candidates is calculated as the economical measure which is calculated using Equation 10.

$$ROI=\frac{TI-TC}{TC}\times 100 \qquad (10)$$

TI, the total income of the system takes into account the present value of feed-in tariff income I_{FIT} and present value of selling excess electricity to the grid $I_{Sell,grid}$.

$$TI=I_{FIT}+I_{Sell,grid} \qquad (11)$$

TC, the total cost of the system takes into account the initial capital cost C_{IC}, the present value of replacement cost C_{rep} and present value of maintenance cost $C_{O\&M}$ and present value of buying electricity from grid $C_{buy,grid}$.

$$TC=C_{IC}+C_{rep}+C_{O\&M}+C_{buy,grid} \qquad (12)$$

3.1 Income Modelling

3.1.1 Income of feed-in tariff

$$I_{FIT}=L_P(FIT_{WT}P_{WT,load}+FIT_{PV}P_{PV,load}) \qquad (13)$$

where FIT_{WT} and FIT_{PV} are feed-in tariff of wind turbine and PV panels respectively . $P_{WT,load}$ and $P_{PV,load}$ are the wind turbine and PV panels production which is used domestically.

3.1.2 Income of selling to grid

$$I_{Sell,grid}=L_P T_{sell,grid}(P_{WTt,excess}+P_{PV,excess}) \qquad (14)$$

where $T_{sell,grid}$ is tariff of selling unit power to the grid. $P_{WT,excess}$ and $P_{PV,excess}$ are excess power of wind turbine and PV panel which are calculated after load satisfaction and charging the battery (if existed).

3.2 Cost Modelling

3.2.1 Initial capital cost

The initial capital cost consists of the components cost and their installation cost [6].

$$C_{IC}=\left(A_{PV}C_{Unit,PV}\right)+\left(A_{WT}C_{Unit,WTt}\right)+(N_{Bat}C_{Bat}C_{Unit,Bat})+C_0 \qquad (15)$$

A_{PV} and $C_{Unit,PV}$ are the total PV Area m^2 and unit cost $\$/m^2$ of the PV array, A_{WT} and $C_{Unit,WT}$ are the total rotor disk area and unit cost of the wind turbine respectively N_{Bat}, C_{Bat} and $C_{Unit,Bat}$ are the total number, nominal capacity Ah and the unit cost $\$/Ah$ of the battery bank. C_0 is the total constant cost including the cost of installation of the wind turbine and PV panels and is considered 20% of cost of wind turbine and 40% of cost of PV panels [6].

3.2.2 The present value of replacement cost:

In this study the only component which needs to be replaced during life time of the HRES is assumed to be the battery bank so this cost is only calculated when the battery bank exists in the configuration.

Lifetime of the battery is limited by two independent factors, the battery float life and the battery cycle life. The battery float life is the maximum duration that the battery will last before being replaced even if it has not been used at all. Dispatch strategy has direct effect on the battery lifetime, and by each charge and discharge cycle some depletion happens in battery. In each individual discharge and the charge cycle the battery equivalent No. of cycle [9] is calculated first and later the total EFC of the battery is then calculated. When the EFC reached to the battery maximum number of cycles specified by the manufacturer the battery needs to be replaced. Hence the battery needs to be replaced either because of the use or its age depending on which of them reached to their limits faster.

The replacement cost of the battery bank can be calculated with following equation [6]:

$$C_{rep}=N_{Bat}C_{Bat}C_{\mathrm{Unit,Bat}}\sum_{i=1}^{N_{rep}}\left[\frac{1+f}{1+k_d}\right]^{N_i/N_{rep}+1} \qquad (16)$$

N_{Bat}, C_{Bat} and $C_{Unit,Bat}$ are the total number, nominal capacity and the unit cost of the battery bank N_{rep} is the number of replacements over the system life period which is calculated based on EFC of the battery

f inflation rate

k_d annual real interest rate

3.2.3 The present value of operation and maintenance cost

The present value of operation and maintenance cost of the hybrid system is expressed as [6]:

$$C_{O\&M,HRES} = \begin{cases} C_{(O\&M)_0} \left(\frac{1+f}{k_d - f}\right)\left[1 - \left(\frac{1+f}{1+k_d}\right)^{L_p}\right], & k_d \neq f \\ C_{(O\&M)_0} L_p, & k_d = f \end{cases} \tag{17}$$

f inflation rate, k_d annual real interest rate, L_p system life period in years, $C_{(O\&M)_0}$ is the operation and maintenance cost in the first year. It can be given as a fraction k of the initial capital cost C_{IC} . $C_{(O\&M)_0}$ is expressed as:

$$C_{(O\&M)0} = kC_{IC} \tag{18}$$

The value of k is assumed to be as 1% for PV panels, 3% for wind turbine and 1% for battery bank as suggested in reference [6].

3.2.4 The present value of buying electricity from grid

$$C_{buy,grid} = \begin{cases} L_p (LCE_{offpeak,grid} P_{shortage,offpeak} + LCE_{peak,grid} P_{shortage,peak}) & (a) \\ L_p (LCE_{offpeak,grid} P_{shortage,offpeak}) & (b) \end{cases} \tag{19}$$

L_p system life period in years

(a) if there is no battery bank

(b) when there is battery bank

4. PROBLEM FORMULATION & DESIGN SCENARIOS

The objective is to find the optimum configuration of a grid-connected HRES with maximum ROI while satisfying the load demand. The optimisation problem can be formulated as:

$$\max\ ROI = \frac{TI - TC}{TC} \times 100 \tag{20}$$

In this paper the wind turbine/PV system sizing optimisation is performed following a deterministic design approach. The averages hourly of weather data and load profile are used as inputs of the design. The power from each resource is calculated at each time step (every hour) based on the capacity of power generator. The overall performance of each design candidate configuration is simulated during the entire year.
In sizing of HRES components, two design scenarios are followed.

Scenario 1: Considering grid as the backup system in peak and off-peak hours and selling excess of produced electricity to the grid. The total power of HRES is calculated with below equation:

$$P_{Total,HRES} = \begin{cases} P_{WT} + P_{PV} & (a) \\ P_{WT} + P_{PV} + P_{grid} & (b) \end{cases} \tag{21}$$

(a) if total power generated by wind turbine and PV is sufficient to cover the load demand.
(b) if P_{WT} and P_{PV} is not sufficient to cover the load demand.

Scenario 2: Considering grid as the backup system in off-peak hours and battery bank for peak hours.
The flow of excess power in this scenario is toward the battery bank if the battery is not fully charged and in case that the battery is fully charged then the excess will be sent to the grid.

To size the battery bank the amounts of excess energy and the peak hour power shortage of each individual day is calculated and based on that data the battery bank is sized. The battery is sized based on the worst day data using Equation 22.

$$N_{Bat} = \frac{P_{shortage}\Delta t}{V_{Bat} DOD_{\max} C_{Bat}} \tag{22}$$

The performance of whole system is then simulated with equation:

$$P_{Total\_HRES} = \begin{cases} P_{WT} + P_{PV}, & (a) \\ P_{WT} + P_{PV} + \begin{cases} P_{grid} & (b) \\ P_{Bat} & (c) \end{cases} \end{cases} \tag{23}$$

(a) if total power generated by wind turbine and PV is sufficient to cover the load demand otherwise
(b) where P_{WT} and P_{PV} is not sufficient during off-peak hours
(c) where P_{WT} and P_{PV} is not sufficient during peak hours and state of charge the battery :

$$SOC \geq SOC_{\min} \tag{24}$$

Feasible solutions of scenario 2 are compared with scenario 1 solutions and the most satisfactory solution is then selected.

5. CASE STUDY

The proposed methodology is used to design a grid-connected HRES for a household in Kent,UK . Inputs of the design are typical summer and winter load profiles and hourly average of wind speed and solar irradiance data for 12 months of the year which are presented in Fig. 3-5.

Technical and economical characteristics of the system

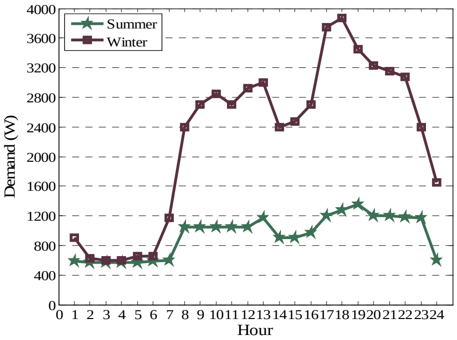


Fig. 3: Domestic Load Demand

TABLE 1: BATTERY BANK'S SPECIFICATION

	Nomial Capacity (Ah)	Nominal Voltage (V)	DOD (%)	Number of Cycles
Battery Bank	40	24	90	535

TABLE 2: GRID ELECTRICITY PRICES IN UK

Grid	Off-peak price (c/kWh)	Peak price (c/kWh)
First 900kWh	29	NA
Consumptions after first 900kWh	17	NA
Selling electricity to grid (c/kWh)	5	5

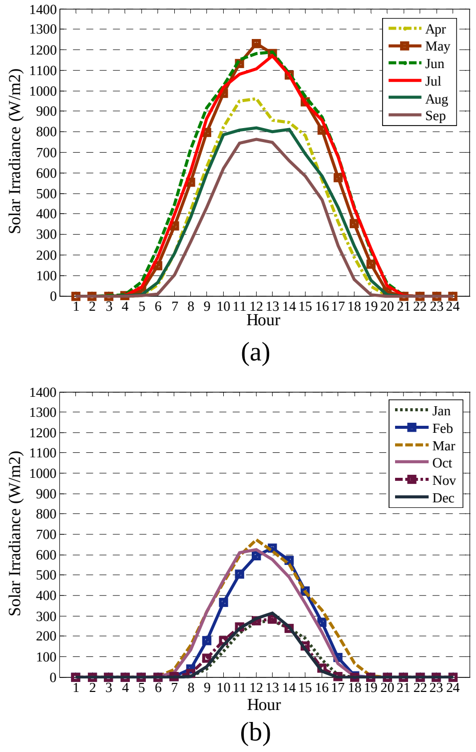
components and grid prices are given in Tables 1-3.

As can be seen in Table 2, the grid electricity has similar price during peak and off-peak hours in the UK. Therefore in this study the system is designed under different assumptions for the peak hours price. Comparing the results comparison the peak hour rate at which adding a storage system to cover the power shortage would be more cost effective than buying the required electricity from grid will be obtained.

6. RESULTS

The results of design process for 10 assumptions for the peak hour price are presented in Table 4.

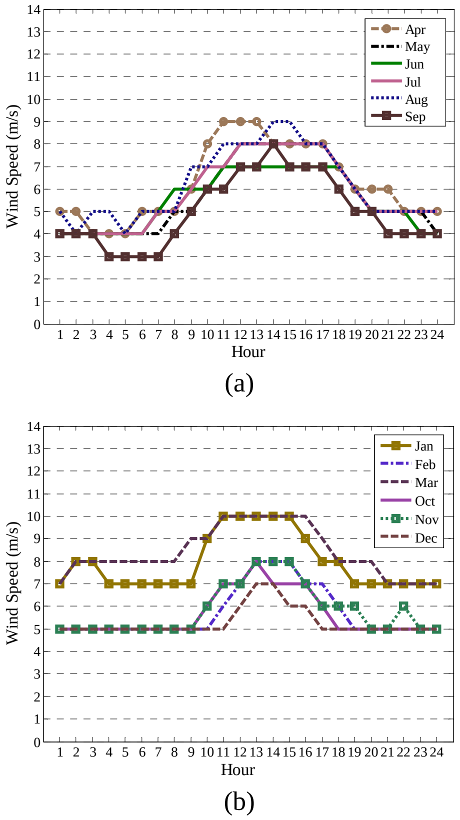
As expected the optimum size for PV is calculated as zero in all optimum solutions due to the fact that wind is dominant in the site under study. The further investigations showed that the configurations with PV arrays did not deliver the best performance considering



(a)

(b)

Fig. 4: Average Hourly Solar Irradiance:
(a) Summer, (b) Winter



(a)

(b)

Fig. 5: Average Hourly Wind Speed
(a) Summer, (b) Winter

TABLE 3: COMPONENTS DESIGN PARAMETERS

	Efficiency (%)	Lifetime (year)	Initial Cost	O&M Cost	Interest Rate(%)	Inflation rate (%)	Feed-in Tariff (c/kWh)
PV panel	12.3	25	600 ($/m2)	1% of price	8	4	27
WT		20	700 ($/m2)	3% of price	8	4	44
Battery Bank	90	8	1.5 ($/Ah)	1% of price	8	4	-

TABLE 4: OPTIMUM CONFIGURATION OF EACH PRICE RATE

Peak price/Off-peak price	WT Rotor Disk Area (m2)	PV Panel Area(m2)	Number of Batteries	Grid Supply for Peak hour
1.1	28.27	0	0	Yes
1.3	28.27	0	0	Yes
1.5	40.72	0	0	Yes
1.7	40.72	0	0	Yes
1.9	40.72	0	0	Yes
2.1	40.72	0	0	Yes
2.3	40.72	0	32	No
2.5	40.72	0	32	No
2.7	40.72	0	32	No
2.9	40.72	0	32	No

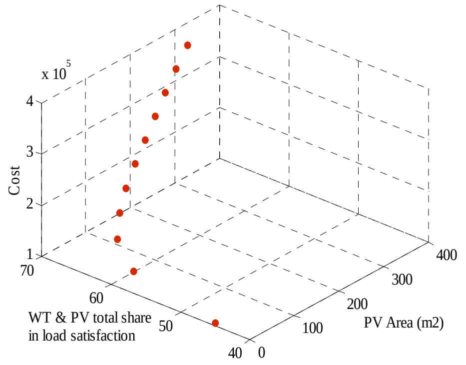


Fig. 6: PV Area vs. HRES Performance and Cost

the dramatic increase they make to the total cost of the system. Fig. 6 has a more detail look on the effect of adding PV panel on a sample for wind turbine with overall share of 45% in load satisfaction. It can be seen that by increasing the area of PV arrays from zero to 400 m^2 the HRES performance increases by 25% in the load demand satisfaction while the total cost of system increases dramatically.

The Fig. 7 demonstrates share of each power source when the peak hour price rate increases from 1.1 to 3 times of off-peak prices. It is shown that if the price of peak hours increases by 2.3 times or more than the off-peak price, then the optimum configuration contains the battery bank.

From result data in Table 4 the peak hour prices can be divided into three categories:

1. Peak Prices<= 1.3Off-peak hours
2. 1.3<Peak Prices< 2.3Off-peak hours
3. Peak Prices>= 2.3Off-peak hours

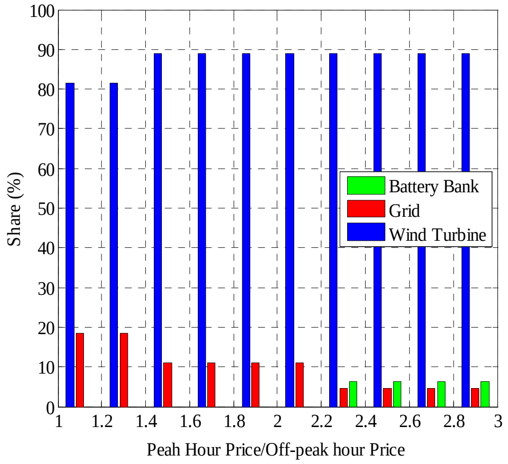
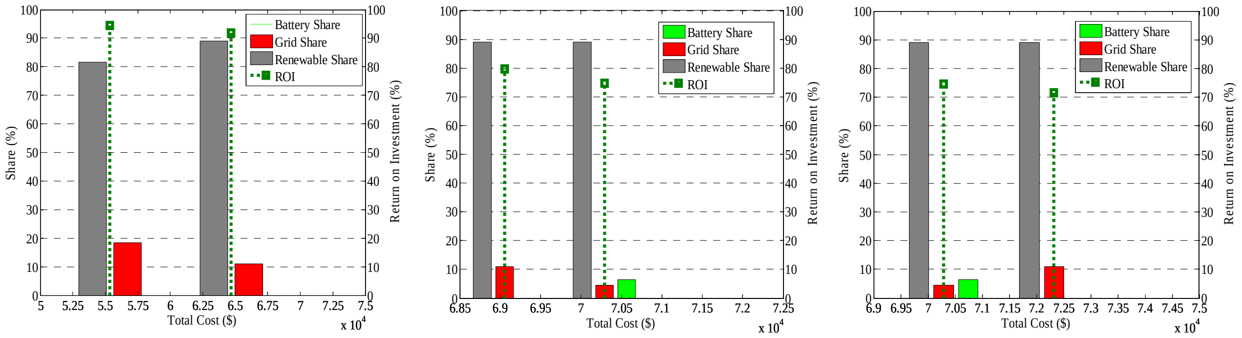


Fig. 7: Share vs. Peak Hour Price Rate

Fig. 8 compares the price and the share of each power resource for a sample rate in each of three above categories. The figure shows that at rates less than 1.5 there is no justification to add the battery bank. By comparing two best solutions of Fig. 8 (1) it is observed that the configuration with less share of HRES have less total cost comparing to next configuration which actually has more HRES share in load satisfaction. As the peak hour price increases to 1.5 times the off-peak hour the configuration with batteries appear as the second best options yet not the best one Fig. 8 (2). And eventually the configuration with the battery bank becomes the optimum configuration when the peak hour price reaches to 2.3 times more than the off-peak hour price Fig. 8 (3).

Fig. 9 shows the detail of produced power and demand of the months in which the battery bank is used. Apparently the battery bank is used in four months of the year in which the wind speed is low. In other months either the wind turbine produces sufficient power or the shortage occurs in off-peak hours and the shortage is maintained



(1) Peak price=1.1 Off-peak (2) Peak price=1.9 Off-peak (3) Peak price= 2.3 Off-peak

Fig. 8: Comparison between two best solutions of three different Peak prices

from the grid.

7. CONCLUSIONS

New concepts in buying electricity from grid such as different prices at different hours requires development of new design methods in grid-connected HRES those conventionally rely on grid to obtain their required electricity during the shortage hours. The method proposed in this study is based on investigating the possibility of adding a small storage system to cover the electricity shortage during peak hours. The proposed method takes into account adding battery bank to conventional grid-connected HRES configuration as an option to overcome the consequences of different electricity prices. The outcome of the design would be more profitable and at the same time the owner would be less dependent on the grid. The system configurations are evaluated in terms of power production and economical aspects. The amount of electricity bought from the grid is added as an economic factor to the design of the HRES.

8. ACKNOWLEDGEMENT

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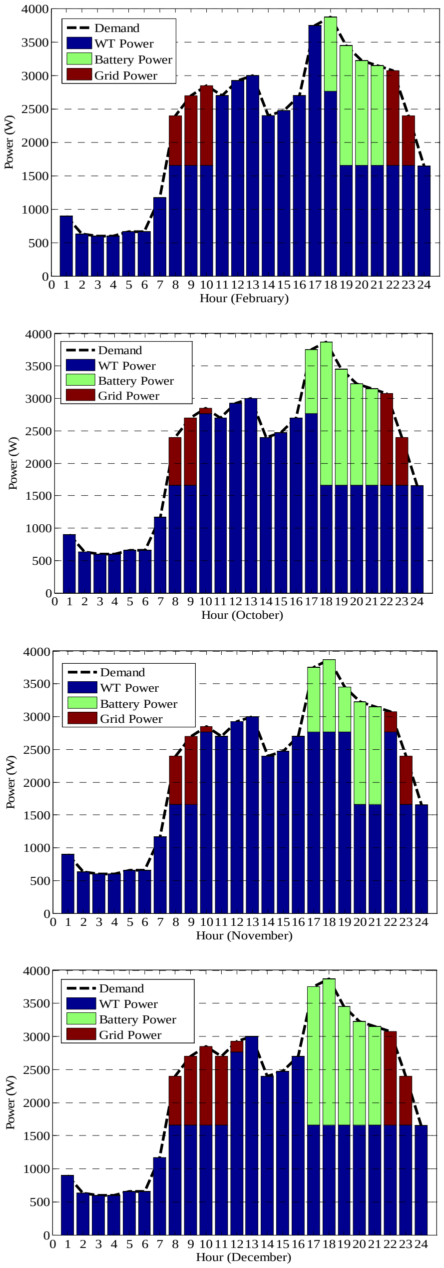

Fig. 9: The produced power of each source for typical months

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