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Optimisation of component sizes for a hybrid remote area power supply system

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Abstract

In this paper, an optimisation model for determination of the optimal sizes of various system components, including wind, diesel and energy storage, has been developed to obtain a reliable and cost-effective wind-diesel hybrid remote area power supply (RAPS) system. A linear programming based cost minimisation algorithm has been formulated for determination of optimal sizes of various components in a RAPS system with consideration of continually varying wind and system load. The system constraints, including power balance for both under-generation and over-generation scenarios, have been considered in the optimisation formulation. Optimisation model to minimize the total cost of the system based on hourly net present cost for both a one-day period and one-week period have been developed with allowance for unserved load during low wind conditions.

Keywords

Optimisation, component, sizes, for, hybrid, remote, area, power, supply, system

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Optimisation of Component Sizes for a Hybrid Remote Area Power Supply System

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Abstract— **In this paper, an optimisation model for determination of the optimal sizes of various system components, including wind, diesel and energy storage, has been developed to obtain a reliable and cost-effective wind-diesel hybrid remote area power supply (RAPS) system. A linear programming based cost minimisation algorithm has been formulated for determination of optimal sizes of various components in a RAPS system with consideration of continually varying wind and system load. The system constraints, including power balance for both under-generation and over-generation scenarios, have been considered in the optimisation formulation. Optimisation model to minimize the total cost of the system based on hourly net present cost for both a one-day period and one-week period have been developed with allowance for unserved load during low wind conditions.**

Keywords-optimisation; remote area power supply; wind; cost minimisation.

I. INTRODUCTION

The main reason for installing a remote area power supply (RAPS) system is the unavailability of the electricity grid. Other reasons include a desire to use renewable energy, or for independence, and in some instances the lower running costs of a RAPS system. A RAPS system can be operated solely using a diesel or petrol generator. However, in recent years, there has been an increasing trend towards combining the traditional diesel or petrol generator with one or more of the renewable energy generating sources such as PV modules, wind turbines, fuel cells or micro-hydro generation in a hybrid system.

A renewable energy system can be operated independently and therefore not have a need for a back-up generator if planned properly. The renewable energy system, however, may not always generate sufficient power required by the loads. For example, if wind power is used as the renewable energy source, there may be a time when the wind speed is insufficient to generate the required power for satisfying the load demand. As the RAPS system is isolated from the main grid, a back-up generator is, therefore, required to maintain uninterrupted power supply. A reliable back-up generator is a diesel generator which can used to provide the balance between the power from the renewable energy system and the power required by the loads. An example of an effective hybrid RAPS system is a combination of a renewable energy system that is made up of wind turbines and hydrogen fuel cells for required power generation and a back-up diesel generator to provide power during blackouts and excess power needs. A more efficient system is one in which the load is connected to a set of batteries and the excess power during over-generation is used to charge the battery bank. During over-generation due to excessive wind, a dummy load can be used to utilise the excess wind power. Further research is required to determine the possibility of replacing dummy loads with electrolysers as excess wind power has the characteristic of being highly variable with time.

A number of RAPS systems have been discussed in literature. A technical description and operational experience of the world's largest wind-hydrogen power plant that was put into operation at the small island of Utsira on the southwest coast of Norway has been reported in [1]. Authors in [2] have presented field experience of a small wind-hydrogen plant on the island of Unst in Shetland, which is 300km away from the Scottish mainland. A technical-economic optimisation study of a hybrid wind-solar-diesel RAPS system at six different sites in Algeria is presented by Saheb-Koussa *et al* in [3]. The cost and reliability of producing electricity by solar-only, wind-only and hybrid solar/wind/diesel systems were compared and the comparative studies indicated that the hybrid system is the best option for all the sites considered in the study. A linear programming model designed to choose the optimal system capacities and operation schedule for a microgrid connected to a larger national grid has been presented by Hawkes *et al* [4]. Zoka *et al* [5] formulated the unit commitment and system design problem for a single fuel cell (with electricity storage, and a boiler) microgrid using linear programming, and applied to a variety of load profiles for a typical system in Japan. They found that a set of commercial entities were better off economically when a single microgrid is installed compared with purchasing energy from a utility, taking into account power interruption costs. The particular issue of determining the optimum sizes of system components for a hybrid RAPS system operating autonomously has not benefited from substantial investigation.

In this study, a dummy load, instead of an electrolyser, is used in the RAPS system to determine the sizes of various system components through optimisation. This paper studies a RAPS system set up in a coastal area with the assumption that sufficient wind energy is available to meet the local power demand majority of the time.

To design a reliable and cost-effective hybrid power plant with wind and diesel, an optimisation model to determine the optimum size of various RAPS system components has been developed. The objective is to determine the size of system components of a wind-diesel based hybrid energy system and optimize the operation over a given time span in order to obtain the lowest possible cost of energy ($/kWh).

II. Wind and Load Profiles

Many utilities have daily load patterns which exhibit extreme variation between peak and off-peak hours because people use less electricity on weekends than on weekdays, less on Sundays than on Saturdays, and at a lower rate between midnight and early morning than the rest of the day [6].

Figure 1 shows the variation of wind speed over the period of a month, where the average wind speed for the month is about 7.5 m/s. A yearly wind profile plot is shown in Figure 2.

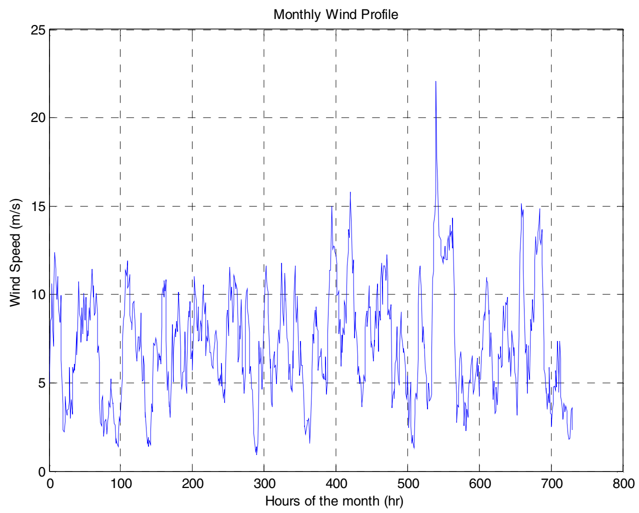

Figure 1. Monthly wind profile

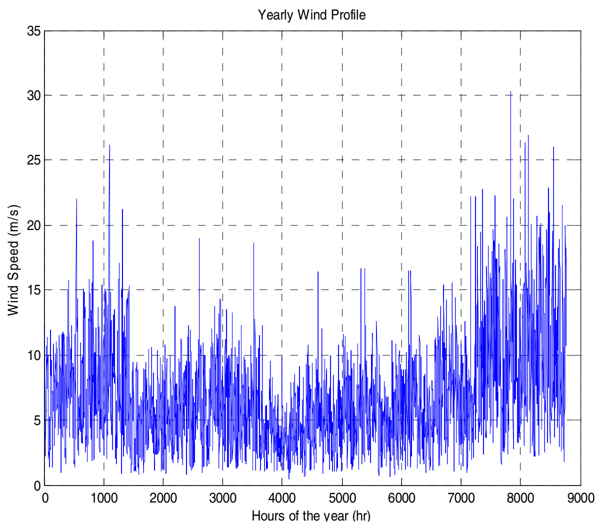

Figure 2. Annual wind profile

Figure 3 shows daily load demand at which the power demand in a day varies from 312kW to 775kW and the peak occurs approximately from 5p.m. to 8.30p.m. Scaling the standard day by a factor, which has a random component, generates a synthetic daily load duration curve for a month. Figure 4 shows a monthly load demand profile, where the energy demand in the weekends is seen to be low.

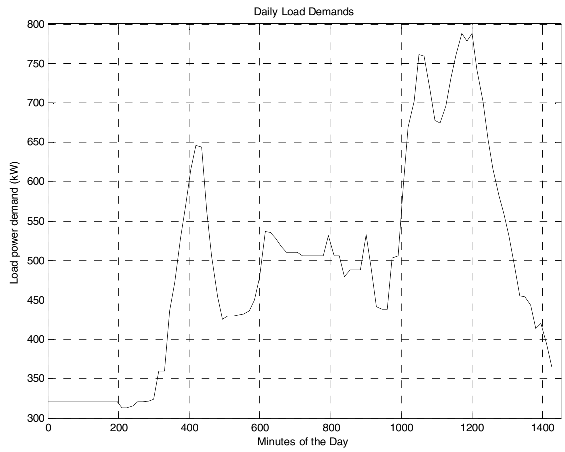

Figure 3. Daily load curve

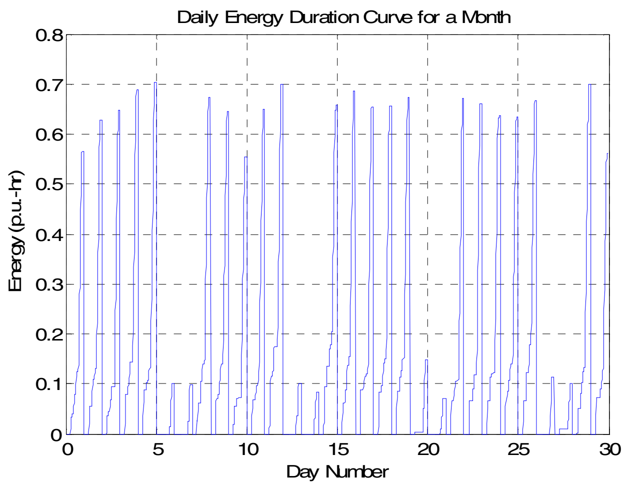

Figure 4. Montly load curve

III. Wind-Diesel Hybrid RAPS Model

The inputs to the optimisation model in this study are wind power production, electric load, dummy load, a battery bank and diesel power generation. Figure 5 shows the different components of the RAPS system under investigation. The arrows indicate direction of power flow.

The formulation of the optimisation problem is based on the net present cost of the individual components that make up the RAPS system being studied. The formulation of the hourly net present cost of the different components, made up of capital cost and operation & maintenance cost, are described below.

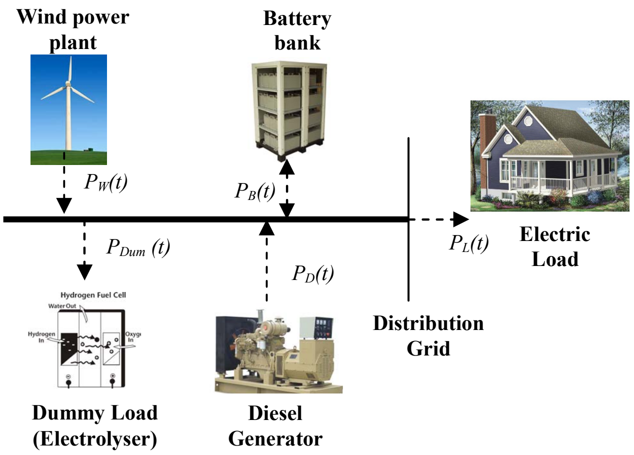

Figure 5. General model of a wind-battery-diesel plant

A. Wind turbine

The net present cost of the wind power plant is defined as:

$$NPC_{wind} = \$(\frac{C_{wind}}{l_{wind}/8760} + r_{wind} \times E_{wind}) \tag{1}$$

where C_{wind} is the cost of wind turbine (including installation cost), l_{wind} is the lifetime of the installed wind turbine, r_{wind} is the running/operation cost of the turbine per kWh, E_{wind} is the power produced by the turbine in kW and NPC_{wind} is the net present cost of the wind turbine.

B. Diesel generator

The net present cost of the diesel generator is defined as:

$$NPC_{diesel} = \$[\frac{C_{diesel}}{l_{diesel}/8760} + (r_{diesel} + F_{diesel} \times Int_{diesel}) * E_{diesel}] \tag{2}$$

where C_{diesel} is the capital cost of diesel generator(s), l_{diesel} is the lifetime of the diesel generator(s), r_{diesel} is the running cost of the generator (\$/kWh), F_{diesel} is price of diesel per litre, Int_{diesel} is the intercept coefficient in litre/hr/kW, E_{diesel} is the power produced by the generator in kW and NPC_{diesel} is the net present cost of the diesel generator.

C. Battery bank

The net present cost of the battery bank is defined as:

$$NPC_{battery} = \$(\frac{C_{battery}}{l_{battery}/8760} + r_{battery} \times E_{battery}) \tag{3}$$

where $C_{battery}$ is the cost of the battery bank (including installation cost), $l_{battery}$ is the lifetime of the installed batteries, $r_{battery}$ is the charging and discharging cost of the battery bank per kW, $E_{battery}$ is the power stored in or discharged from the battery bank (kW) and $NPC_{battery}$ is the hourly net present cost of the battery bank.

D. Dummy load

The net present cost of the dummy load, which could possibly be replaced by electrolysers in future studies for hydrogen generation for fuel cells, is defined as:

$$NPC_{dummy} = \$(\frac{C_{dummy}}{l_{dummy}/8760} + r_{dummy} \times E_{dummy}) \tag{4}$$

where C_{dummy} is the cost of dummy load (including installation cost), l_{dummy} is the lifetime of the installed dummy load, r_{dummy} is the running/operation cost of the dummy load per kWh, E_{dummy} is the power absorbed by the dummy load in kW and NPC_{dummy} is the net present cost of the dummy load.

IV. Optimisation Model

The problem of determining the optimal sizes of different components in a hybrid RAPS system is a challenging area of research which has not been frequently visited. It is desirable to have optimal sizes of the components so that the capital and operating costs are minimized and the net return is maximized.

A. Objective function

The optimisation problem is formulated as a linear programming (LP) problem. The objective function has been developed to find the optimal combination of components of various sizes that minimises the total cost of the system. The objective function to be minimised for an optimum solution is the total net present cost, as shown in (5).

$$Total\ NPC = (NPC_{wind} + NPC_{diesel} + NPC_{battery} + NPC_{dummy}) \times \frac{1}{CRF(ir, R)} \tag{5}$$

where

$CRF(ir, R) = \frac{ir(1+ir)^R}{(1+ir)^R - 1}$ is the capital recovery factor;

R = lifetime of project; and

ir = interest rate.

Each NPC component consists of fixed and variable cost, namely the capital cost and operation & maintenance cost, respectively. The optimisation model is implemented in MATLAB and solved with the *fmincon* function subject to power balance and various other constraints, outlined in the next subsection. The *fmincon* function determines the optimum power that need to be supplied by the diesel generator(s) (E_{diesel}), battery ($E_{battery}$) and wind (E_{wind}) to satisfy the load demand in order to minimise the total net present cost (5).

In this paper, optimisation models were developed for component optimisation over a day and a week using hourly data. This can easily be extended to obtain a longer term (monthly/yearly) optimisation model.

B. Constraints for optimisation

Two main scenarios that were considered for the optimisation model are excessive wind, where wind generators can generate excessive power, and low wind where wind-diesel hybrid operation is required.

1) Excessive wind (Over-generation)

In this situation, the produced power of the wind power plant exceeds the demand. Wind turbine should supply and support the whole system. Battery will be charged with excess power from wind power plant. Any excess power that exceeds the battery rating will be absorbed by the dummy load.

2) Wind-diesel - hybrid operation

When wind generation profile reduces and drops below load demand, diesel generator needs to be started up and battery power is fed to the load.

The electric energy balance for time step *t* is given as

$$P_L(t) + P_{Dum}(t) = P_W(t) + P_D(t) + P_B(t) \qquad (6)$$

where, at time step *t*,

P_L(t) is the load power demand;

P_{Dum}(t) is the excess power dump;

P_W(t) is the wind power;

P_D(t) is the diesel power; and

P_L(t) is the battery power (negative for charging and positive for discharging).

Equations to express energy balance under the two different scenarios stated above are given below in (7) and (8), where P_{excess} represents excess power.

Under-generation:

$$\begin{aligned} &P_L(t) - P_W(t) > 0 \\ &P_L(t) - P_W(t) = P_{excess} \\ &P_{excess} = P_D + P_B \end{aligned} \qquad (7)$$

and over-generation:

$$\begin{aligned} &P_L(t) - P_W(t) < 0 \\ &P_W(t) - P_L(t) - P_B(t) > 0 \\ &P_W(t) - P_L(t) - P_B(t) - P_{Dum} = 0 \end{aligned} \qquad (8)$$

The battery is assumed to be able to provide a maximum of 50kW of power to load for a duration of 2 hours, and the rest of the power demand is met by the diesel generator during under-generation. During over-generation, battery charge limit is set to 50kW.

$$-50kWh < P_B < 50kWh \qquad (9)$$

V. Results and Discussions

The optimisation model, developed based on various power balance constraints as outlined in the previous section, was implemented in MATLAB. The outcome of the optimization model developed to minimise the objective function for minimum cost of meeting power demand over the period of a day (24 hours), subject to the constraints outlined in the previous section, is shown in Figure 6. Both under- and over-generation scenarios are observed in Figure 6. A positive demand mismatch indicates over-generation, where the battery charges (shown negative in figure) and diesel generator output is zero. If the excess power exceeds the battery power limit, it is dumped into the dummy load. When the demand mismatch is negative (under-generation), the battery discharges and the remaining deficit power to the load is provided by the diesel generator. The dummy load power is zero during under-generation as there is no excess power. The corresponding hourly net present cost for the 1-day period is shown in Figure 7. It can be seen in Figure 6 that the net present cost closely follows the trend of the diesel generator output curve. This is because of the relatively high cost of diesel fuel and operating cost of the diesel generator.

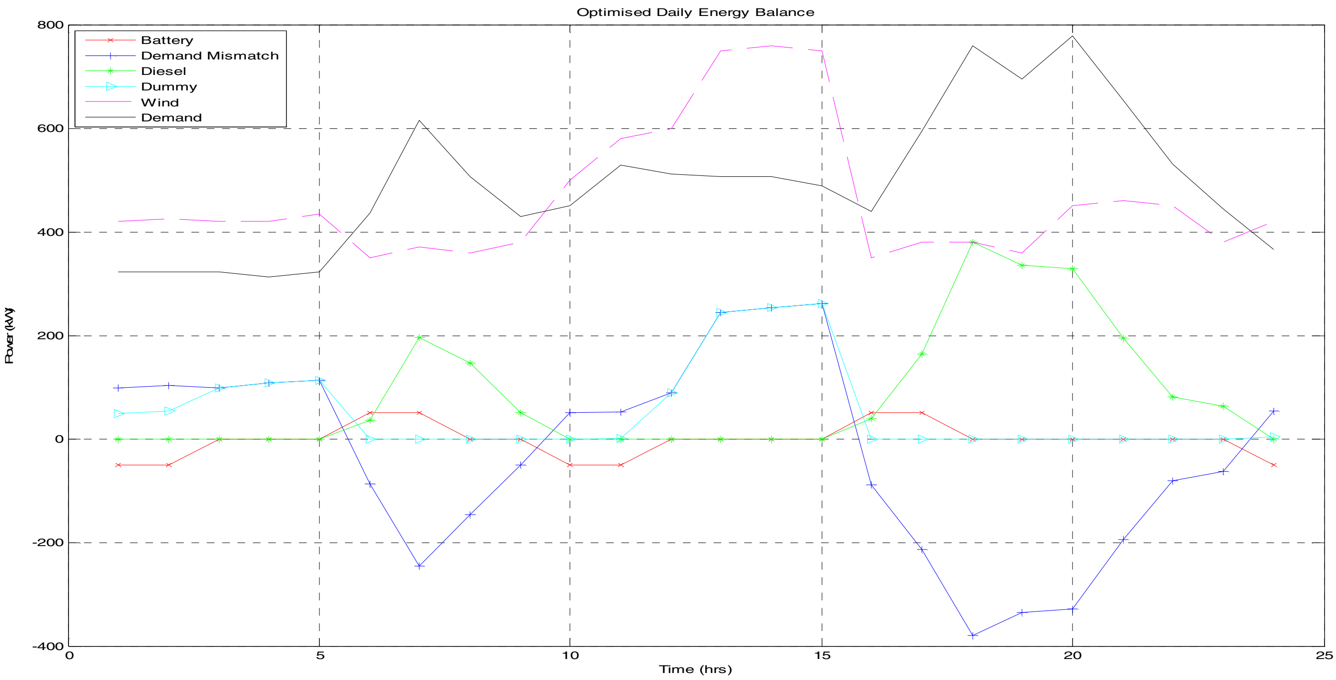

Figure 6. Optimised energy balance for a one-day (24 hrs) period

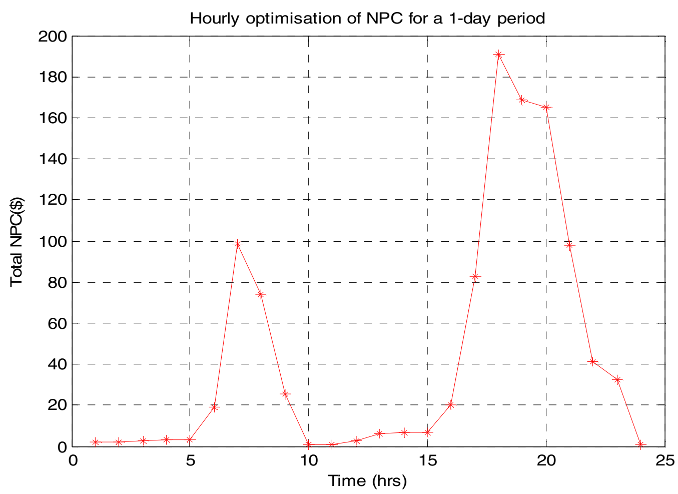

Figure 7. Hourly optimisation of Net Present Cost (NPC) for a one-day period

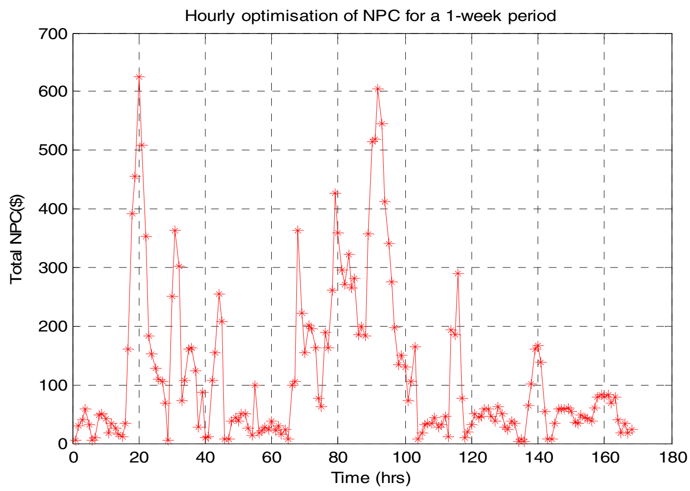

Figure 9. Hourly optimization of Net Present Cost (NPC) for a one-week period

The results of the optimisation model developed to consider optimisation for a 1-week period is shown in Figure 8. The power demand for the week is made up of the daily load profile shown in Figure 3 for all five weekdays, 35% of weekdays for Saturday and 29% for Sunday, in accordance with the weekly load trend shown in Figure 4. The amount of load that is allowed to be unserved when the wind turbine produces less power than the demand is set to zero for the model in Figure 8. The corresponding hourly net present cost for the 1-week period made up of 168 hourly values is shown in Figure 9. Similar to that seen in Figure 7, the waveform of net present cost shows a similar trend to that of the optimised diesel generator output curve shown in Figure 8. The total cost of the optimised system for the 1-week period is calculated to be $19,898.

Based on the optimisation results for the one-week period seen in Figure 8, the optimum sizes of diesel generator and dummy load can be determined. In this paper, the size of the battery bank is pre-determined so that both the charging and discharging limits are 50kW. The peak load demand is 778kW and the maximum and minimum wind power outputs are 760kW and 84kW, respectively. The size of diesel generator needs to be chosen such that it can supply the maximum power required to satisfy peak load during low wind conditions, which in this case is 637kW. The dummy load, for this particular scenario, has to be capable of handling power input of at least 496kW to utilise all the excess wind power.

During low wind and high demand conditions in a RAPS system, a certain amount of load can be allowed not to be served, referred to as unserved load in this paper. The 1-week NPC for various unserved load allowances is shown in Table 1 and plotted in Figure 11. When a load of 150kW is allowed to be unserved, the diesel output is significantly lower, as seen in the results of the optimisation model given in Figure 10. The

TABLE I. WEEKLY COST VS. UNSERVED LOAD ALLOWED

Unserved Load Allowed (kW)	Total NPC over a week($)
0	19,898
50	16,255
100	12,926
150	10,258
200	8,325
250	6,975
300	5,880

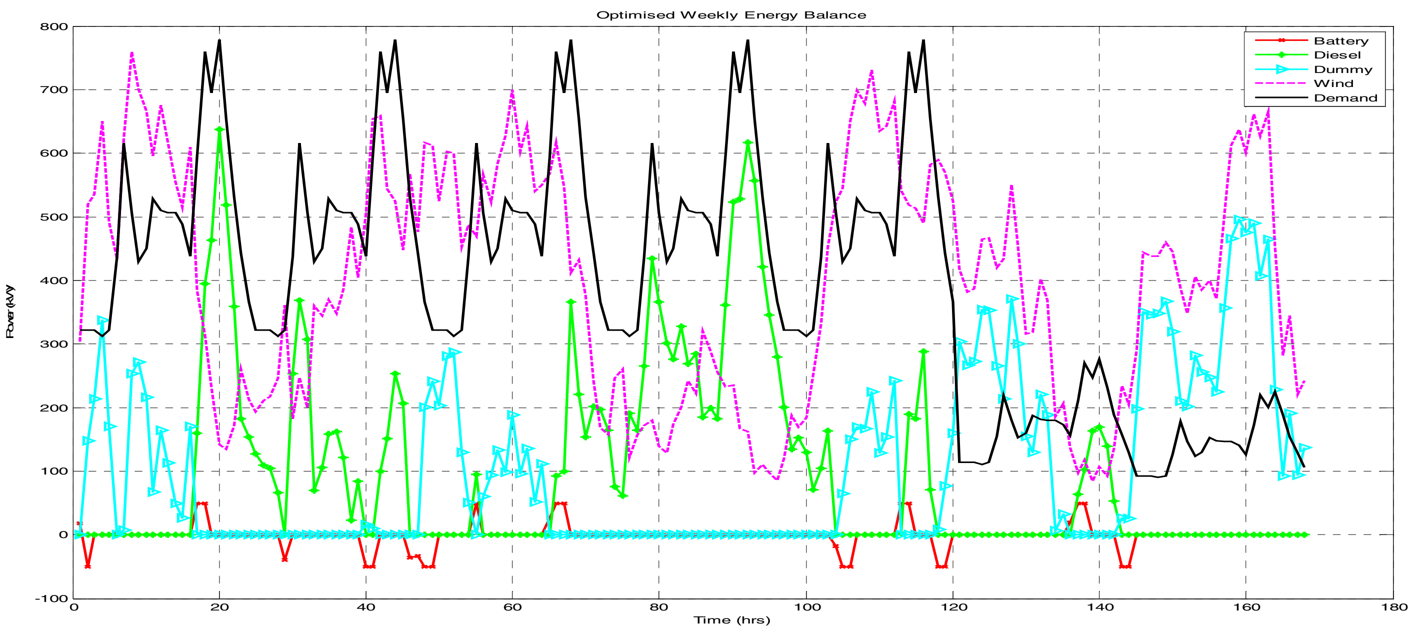

Figure 8. Optimised energy balance for a one-week (168 hours) period

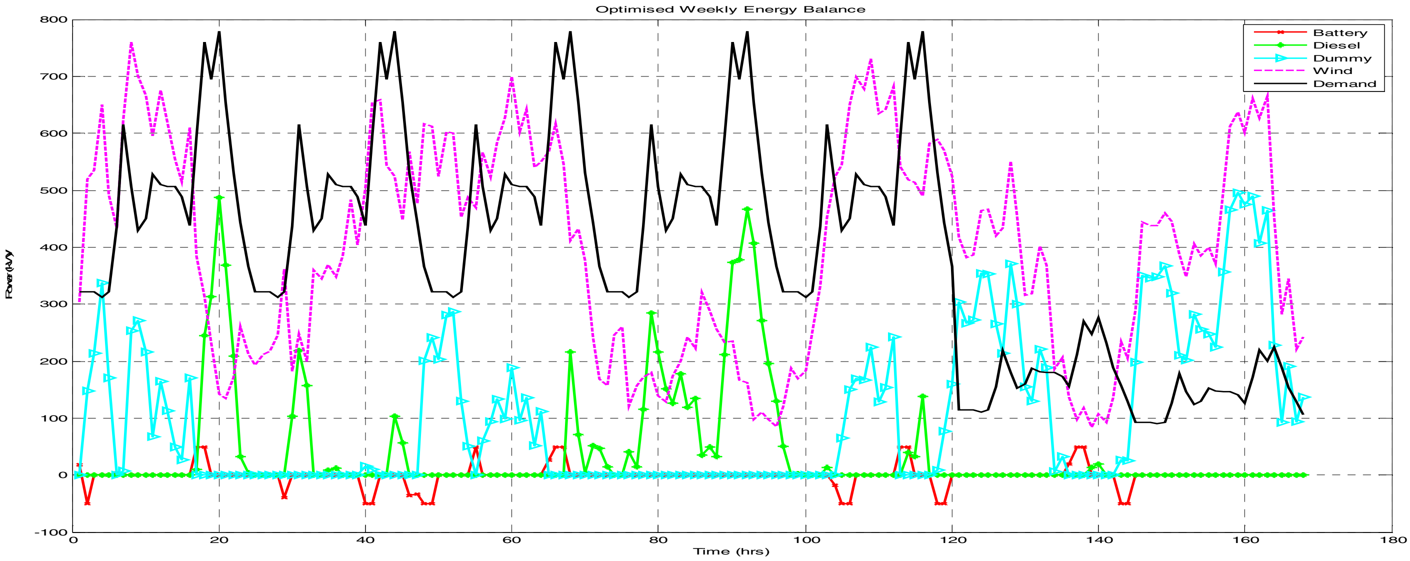

Figure 10. Optimised energy balance for a one-week period with 150kW unserved load allowance

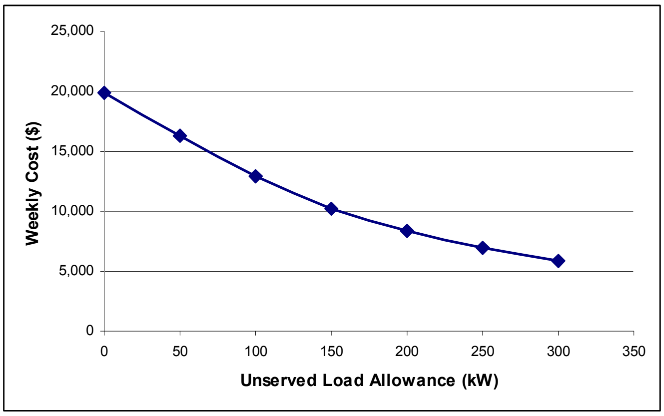

Figure 11. Weekly system cost vs. unserved load allowance

rating of diesel generator(s) required to satisfy peak load during low wind conditions has to be at least 487kW.

VI. Conclusions

The RAPS system studied in this paper consists of wind turbines, electric load, dummy load, a battery bank and diesel generator. Optimisation for the sizing of components for a given wind and load power profile, based on total cost minimisation, has been achieved using a linear programming model. The formulation of the optimisation problem is based on the net present cost, made up of capital cost and operation and maintenance cost, of the individual components that make up the RAPS system. Optimisation models were developed for component optimisation over a day and a week using hourly data taking into account both over-generation (excessive wind) and under-generation (hybrid operation) scenarios. The extent of cost savings by allowing different amount of loads not to be served during low wind and high demand conditions has also been analysed.

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References

[1] T. Nakken, L. R. Strand, E. Frantzen, R. Rohden, P. O. Eide. "The Utsira wind-hydrogen system – operational experience", European Wind Energy Conference Proceedings, Athens, March 2006.

[2] R. Gazey, S. K. Salman, D. D. Aklil-D'Halluin, "A field application experience of integrating hydrogen technology with wind power in a remote island location", Journal of Power Sources, Vol.157, 2006, pp.841-847.

[3] D. Saheb-Houssa, M. Haddadi, M. Belhamel, "Economic and technical study of a hybrid system (wind-photovoltaic-diesel) for rural electrification in Algeria," Journal of Applied Energy, vol. 86, 2009, pp. 1024-1030.

[4] A. D. Hawkes, M. A. Leach, "Modelling high level system design and unit commitment for a microgrid," Journal of Applied Energy, vol. 86, 2009, pp. 1253-1265.

[5] Y. Zoka, K. Koeda, A. Sugimoto, N. Yorino and K. Kawahara, "An economic evaluation for an autonomous independent network of distributed generators," International Power Engineering Conference, IPEC 2005, Nov/Dec 2005, vol. 2, pp 657-662.

[6] K. Ayoub and A. D. Patton, "Optimal thermal generating unit commitment," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-90, Issue 4, July 1971, pp. 1752-1756.