# Reliability Evaluation of Integrated Wind/Diesel/ Storage Systems for Remote Locations

W. Y. Li
Electric Power College
Inner Mongolia University of Technology
Huhhot, P. R. China
lwyyyll@vip.sina.com

B. Bagen
System Planning Department
Manitoba Hydro
Winnipeg, Canada
bbagen@hydro.mb.ca

***Abstract*— One of the most promising applications for wind energy is its use in electric power systems for remote isolated locations. Currently most remote and isolated communities depend on conventional diesel fuel for their electricity supply. Diesel generations in these locations are expensive mainly due to the escalating fuel costs. The associated maintenance costs and transportation costs are also relatively high in many areas. On the other hand, the wind speed in those remote areas is usually fairly high and hence wind energy has huge potential. Wind energy based systems have no fuel cost and can, therefore, be included in these conventional small isolated systems in order to replace the costly diesel fuel by renewable energy. Wind power generation is, however, intermittent in nature, and therefore, energy storage systems are often considered to smooth out the fluctuations and improve the supply continuity. The energy available for storage, and the stored energy that can be used at any time is highly dependent on the system operating constraints. In this paper, some of these important constraints are incorporated in a sequential Monte Carlo Simulation technique for the adequacy evaluation of integrated wind/diesel/storage systems for remote locations. The impact of wind and energy storage on integrated wind/diesel/storage system reliability performance is examined. Potential problems associated with utilization of wind energy and energy storage in small isolated systems are also discussed.**

**Keywords- Diesel Generator; Energy storage; Monte Carlo Simulation; Reliability Evaluation; Wind energy**

## I. INTRODUCTION

Power from renewable energy is becoming a significant fraction of total energy generation due to the limited reserve of fossil fuels and global environmental concerns associated with those conventional energy sources. Particularly rapid advances in wind turbine generator technologies have brought opportunities for increased utilization of wind energy for electric power generation around the world. By the end of January 2007, world wide installed wind nameplate capacity was 71, 476 MW [1]. The major utilization of these wind capacity installations is in large grid connected electric power systems. The technological and economical advantages associated with wind energy would, however, also justify their use in small scale stand alone applications for remote isolated communities.

There are many remote communities around the world that are physically or economically difficult to be connected to an electricity grid. Currently most remote and isolated communities depend on conventional diesel fuel for their electricity supply. Diesel generations in these locations are expensive mainly due to the escalating fuel costs. The associated maintenance costs and transportation costs are also relatively high in many areas. On the other hand, the wind speed in those remote areas is usually fairly high and hence wind energy has huge potential. Wind energy based systems have no fuel cost and can, therefore, be included in these conventional small isolated systems in order to replace the costly diesel fuel by renewable energy. From an energy-production point of view, it is desirable to have as much wind energy production as possible in order to save fuel consumption of the diesel engines and to reduce the level of pollution. Considerable power fluctuations can be expected from a wind turbine generator (WTG) unit due to the highly variable nature of the wind speed. Energy storage capability could, therefore, be a very significant component in power systems utilizing wind especially in remote isolated applications.

A great deal of effort, especially in recent years, has been devoted to reliability performance assessment of small isolated power systems including wind energy and/or energy storage. Reliability performance assessment of small stand-alone renewable energy based systems is presented in [2-10]. An approximate method for reliability evaluation of a stand-alone system consisting of one wind turbine feeding a load via a battery was presented in [2]. Reference [3] presents a method, which is similar to the one described in [2] for the computation of the loss of load probability (LOLP) and the expected energy not supplied (EENS) of a stand-alone system based on wind energy operating in parallel with a storage battery. The method modeled the generation, the load and the battery as Markov chains. Reference [4] presents an evaluation technique for wind energy based systems with storage and this technique assumes that the wind speed follows a Weibull distribution. Probabilistic methods for the evaluation of the performance of hybrid systems containing wind energy, conventional diesel-fueled units and energy storage were presented in [5] and [6]. All of the above mentioned works are focused on the use of approximate analytical methods. The major disadvantage of

978-1-4244-5721-2/10/$26.00 ©2010 IEEE

This work is supported by the National Natural Science Foundation of China (Project # 50967002) and the Inner Mongolia Natural Science Major Project Foundation (Project # 200711020702).

these approaches is that the chronological random nature of wind speed, its effect on the power output of renewable energy based generating units and the system load pattern cannot be completely recognized and incorporated. Reference [7] considers the use of Monte Carlo Simulation (MCS) for the reliability and production cost evaluation of small isolated power systems consisting of both renewable sources and conventional diesel generation. Energy storage was, however, not considered in this research. Due to the highly variable nature of the wind, the utilization of energy storage devices could enhance the reliability of a small isolated power system. References [8], [9] and [10] present a technique utilizing Monte Carlo simulation (MCS) for the reliability evaluation of generating systems including wind and energy storage. This method incorporates an energy storage model appropriate for sequential simulation, and considers the chronological random nature of wind speed, their impact on the power output of WTG units, and the system load pattern.

This paper extends the MCS approach to include the system operating constraints, and to analyze the adequacy of integrated wind, diesel and storage systems for remote isolated applications. The studies are conducted by adding wind power and energy storage to conventional diesel plants. The results from a wide range of studies considering variations in key factors, such as the wind penetration levels, different wind regimes, energy storage capacities, and system operating constraints are also presented.

## II. EVALUATION METHODOLODY

This research is primarily focused on generating capacity adequacy evaluation of small isolated power system applications. The main objective in generating capacity adequacy evaluation is to assess the ability of the generation facilities to satisfy the system load demand. In a sequential MCS method, the capacity model is the available system capacity at points in time established chronologically, considering random generating unit failures [11]. The load model is a chronological hourly load profile. The available system reserve during a time interval is the difference between the available capacity and the load. A negative margin means a load loss situation. System reliability indices, such as the loss of load expectation (LOLE) and the loss of energy expectation (LOEE) [11], can be calculated by simulating the available system reserve profile over a sufficiently long period of time.

The sequential simulation of small isolated power systems including wind energy involves the generation of hourly wind power from the installed WTG units for a large number of samples. The hourly power output from a WTG is determined by the hourly wind speed at a specific location. The wind speed at any given time for a particular geographic location can be simulated using the appropriate time series model developed using historical data collected over several years for a given site [12].

In the time series model [12], the simulated wind speed $SW_t$ can be obtained from the mean wind speed $\mu_t$ and its standard deviation $\sigma_t$ at time $t$ as follows:

$$SW_t = \mu_t + \sigma_t y_t \tag{1}$$

The original data series set $y_t$ can be used to create a wind speed time series referred to as an ARMA (n, m) series model (Auto-Regressive and Moving Average Model). This is shown in Equation (2).

$$y_t = \sum_{i=1}^{n} \phi_i y_{t-i} + \alpha_t + \sum_{j=1}^{m} \theta_j \alpha_{t-j} \tag{2}$$

Where $\phi_i$ ( i=1,2,…,n ) and $\theta_j$ ( j=1,2,…,m ) are the auto-regressive and moving average parameters of the model respectively, $\{\alpha_t\}$ is a normal white noise process with zero mean and variance of $\sigma_a^2$ , i.e., $\alpha_t \in NID(0, \sigma_a^2)$ , where NID denotes Normally Independent Distributed. Equation (2) permits new values of $y_t$ to be calculated from current random white noise $\alpha_t$ and previous values of $y_{t-i}$ . The hourly wind speeds incorporating the wind speed time series can be generated using Equation (1).

The wind speed ARMA models and data for two different sites located in Inner Mongolia were developed and used in the studies presented in this paper. The hourly wind speed obtained from the time series model is used with power curve of the wind turbine to determine the available power output from a WTG. The power curve provides the relationship between the WTG power output and the wind speed. The main parameters of this function are the cut-in, rated and cut-out wind speeds. The cut-in, rated, and cut-out wind speeds of the WTG unit used in the studies described in this paper are 12, 38, and 80 km/hour respectively. The name plate capacity for a single WTG is assumed to be 30 kW.

## III. IMPACTS OF WIND POWER

A simple and common method of using wind energy in remote areas is to operate the wind turbine generator in parallel with diesel generators in order to reduce the average diesel load. Studies were performed to investigate the reliability impacts of wind additions to a diesel power plant. The diesel power plant is assumed to consist of 4x60 kW generating units and each diesel unit has a forced outage rate of 5%. The system peak load is assumed to be 180 kW. The hourly chronological load shape of the IEEE-RTS [13] has been used in the studies described in this paper. The LOLE and LOEE indices of the original diesel plant are 6.03 hours/year, and 144.47 kWh/year respectively.

Figures 1 and 2 respectively show the relationship between the wind power capacity added and the resulting system LOLE and LOEE. It can be seen from Figure 1 that the LOLE decreases with increasing wind additions to the system. Figure 1 also shows that identical wind turbine generators located at different sites provide different system reliability. Site #1 has higher average wind speed and as expected, the adequacy at this location is better than that of systems located at Site #2. The wind data from Site #1 is, therefore used in all of the other studies presented in this paper. Similar effects are observed in terms of the LOEE index in Figure 2.

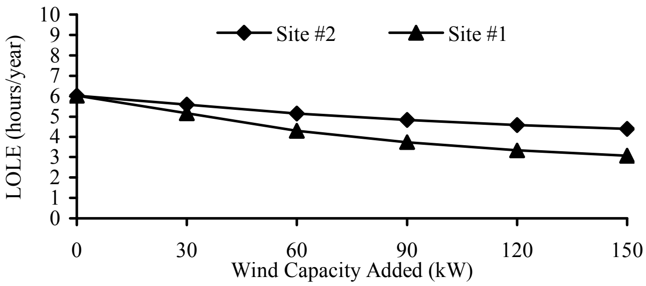


Figure 1. LOLE versus wind capacity additions

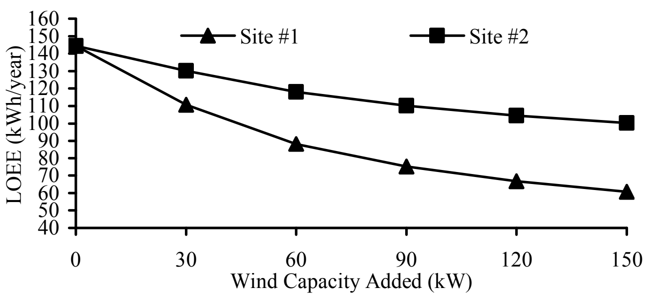


Figure 2. LOEE versus wind capacity additions

Parallel wind and diesel operation is particularly suitable for systems with relatively small renewable energy penetrations. This mode of operation could result in some energy wastage when there is sufficient wind energy available, especially at high renewable energy penetrations. For wind-diesel systems, stability may also be a problem if the wind turbine generator output is large. The application of energy storage in small isolated systems may smooth the fluctuations in power output from WTG and improve the continuity in power supply [9]. The reliability benefits obtained from a combination of wind power and energy storage are illustrated in the following section.

## IV. Impact of Wind Power and Energy Storage

Energy storage facilities have a significant positive effect on the reliability performance of small isolated power systems [8, 9, 10]. It is, therefore, important to investigate the impacts of energy storage on the reliability of integrated wind/diesel/storage systems for remote locations. In this study the effect of the storage facility has been incorporated in the simulation process using the proposed technique presented in [8, 9, 10]. The energy stored in the storage facility is calculated by comparing the load time series and the total generation time series. Excess energy from the entire generating system is used to fully charge the storage facility. The stored energy is dispatched when the total system generation fails to meet the system load.

The results from studies considering wind farm additions to systems with different storage capability are shown in Figure 3. Case 1 considers wind capacity additions to the system without any storage facility. The wind farm is assumed to be located at Site 1. Cases 2 and 3 consider a 10 kWh storage facility added to the system. Case 2 assumes no operating constraints associated with the charging and discharging of the stored energy. A linear charging and discharging rate proposed by the Power System Research Group at the University of Saskatchewan [10] is assumed in Case 3, considering a 5-hour charging time from the minimum to the full storage capacity. The energy storage has its maximum and minimum energy limitations in kWh, and the minimum energy storage is assumed to be 20% of maximum capacity.

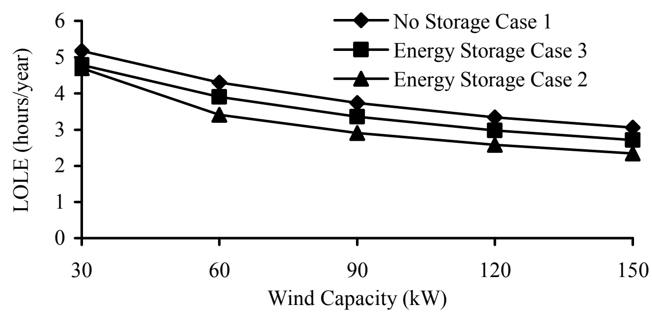


Figure 3. Effect of wind power and energy storage on LOLE

The top curve in Figure 3 shows the decrease in system LOLE with increasing wind farm capacity when there is no storage facility. The lower curve in Figure 3 for Energy Storage Case 2 shows the reliability benefits assuming no operating constraints. In this case, it is assumed that all the extra energy available during a time interval can be stored, and then used to serve the system load during the next time interval in the simulation process. The power output from the generating system and the system load are assumed to be constant during each time interval.

The surplus energy available in a generating system at any time may not be fully stored, and all the stored energy may not be available to supply the load in the next time interval due to the system operating constraints associated with the charging and discharging characteristics of the energy storage facility. A sequential simulation process is used to model the chronology of energy storage charging and discharging based on the co-relation of wind and load variation. Energy Storage

Case 3 is considered in this study to investigate the effect of the operating constraints associated with the energy storage on the reliability benefit obtained from the energy storage and wind energy. The middle curve in Figure 3 shows the relationship between the system LOLE and the added wind capacity for this case. It can clearly be seen from Figure 3 that the charging and discharging constraints of energy storage can limit the reliability benefits.

Further studies were conducted to appreciate the impact of energy storage capacity on the adequacy of integrated wind/diesel/storage systems. Figure 4 shows the LOLE as a function of energy storage capacity ranging from 0 to 50 kWh for Case 2 and Case 3. It is assumed that both cases contain 90 kW wind capacity. It can be seen from Figure 4 that the addition of energy storage capability improves the reliability of an integrated wind/diesel/storage system. Figure 4 also shows that the reliability benefit degrades when restrictions are placed on the maximum charging and discharging rate of the energy storage facility.

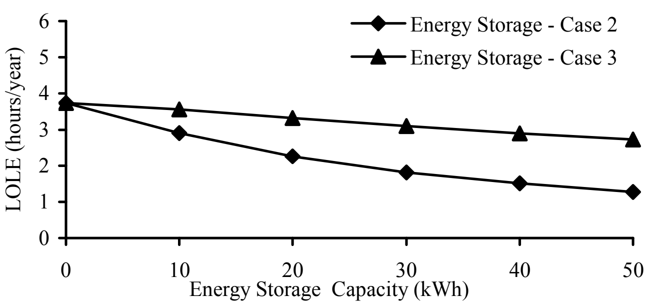


Figure 4. LOLE versus energy storage capacity

The results presented in this section were obtained assuming that electric energy generated by both the WTG units and the diesel units can be stored. The basic purpose of adding energy storage to a wind-diesel generating system is to smooth out the power fluctuations from the WTG units. It is not normally practical to store energy from conventional units for future use. It is assumed in the following study that only energy generated by WTG units will be stored for future use. Since the WTG units have priority to serve the system load, there will be extra wind energy available for storage only when the power output from the WTG units exceeds the system load during a time interval in the simulation.

Figure 5 shows the effect of energy storage on the system LOLE if only wind power can be stored. The results from the three different case studies described earlier in this section are presented. The resulting curves in Figure 5 from the three different case studies almost overlap for wind capacity less than the system minimum load of 61 MW, and branch out as the wind capacity exceeds the minimum system load. The upper curve in Figure 5 shows that the system reliability is improved continuously as wind capacity increases. Figure 5 shows that there is almost no difference between the three curves when the added wind capacity is less than 61 MW. This is because there is no surplus wind energy available for storage, and the 10 kWh storage facility cannot provide any reliability benefit to the system. There are additional reliability benefits from the storage facility when the added wind capacity is greater than 61 MW as shown by the curves for Cases 2 and 3 in Figure 5. The extra reliability benefits from energy storage are limited if the charging and discharging restrictions of energy storage are considered as shown in Figure 5. Unfortunately, this is generally the case that there are charging and discharging restrictions. Consequently, there may not be much benefit in providing storage, especially considering the added cost and maintenance of an integrated wind/diesel/storage system. The actual benefits of utilization of energy storage in small isolated systems are site dependant and system dependent. Further investigations especially economic analyses are in progress considering the savings of the diesel fuel due to wind and/or storage, operating considerations of diesel units and the potential outage costs.

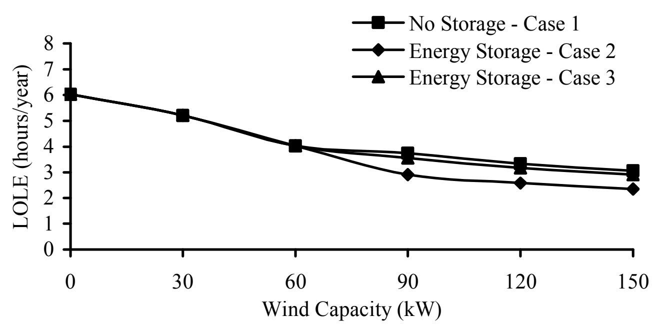


Figure 5. Effect of energy storage on LOLE if only wind power can be stored (Energy storage capacity is 10 kWh)

Figure 6 shows that increased wind capacity can affect the reliability contribution from an energy storage facility. In the following studies, two wind penetration levels are selected and compared. The first case is 12.5% penetration when 30 kW wind is added to the original diesel system. The second case is 37.5% penetration with the addition of a 90 kW wind. The relationship between the system LOLE and the added energy storage capacity is shown in Figure 6. The charging and discharging constraints of energy storage are considered in these studies.

Figure 6 shows that the system LOLE changes from 6.03 hours/year to 5.17 hours/year with 12.5% wind penetration, and to 3.74 hours/year with 37.5% wind penetration without considering any energy storage. It can be seen that there is little or no benefit in system reliability from adding energy storage capacity when the system wind penetration is 12.5%. The system LOLE remains virtually constant at 5.17 hours/year as the added energy storage capacity is increased at this wind penetration level. When the wind penetration is 37.5%, the system reliability improves as the energy storage capacity is increased. The incremental benefit, however, decreases as shown by the lower curve in Figure 6, which tends to saturate as more energy storage capacity is added. Appropriate reliability and cost analysis is necessary to determine the optimal energy storage capacity to maintain an acceptable system reliability.

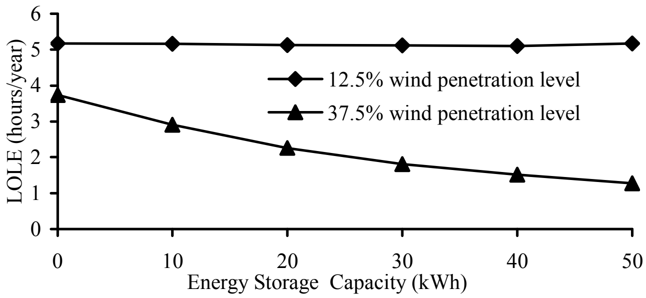


Figure 6. LOEE versus energy storage capacity when only wind power can be stored

## V. CONCLUSIONS

A time sequential Monte Carlo simulation method for reliability evaluation of integrated wind/diesel/storage systems is presented in this paper. The method takes into account the operating constraints associated with the charging and discharging of the storage facility. Generally, the addition of wind energy and/or the provision of energy storage to diesel systems can have significant positive impacts on the integrated system reliability performance. These impacts can be quantitatively evaluated using the model and the procedure described in this paper.

## REFERENCES


[1] R. Thresher, M. Robinson and P. Veers, “To Capture the Wind”, *IEEE Power and Energy*, Vol. 5, pp. 35-36, November/December 2007.

[2] I. Abouzahr and R. Ramakumar, “Loss of power supply probability of stand-alone wind electric conversion systems: A closed form solution approach”, *IEEE Transactions on Energy Conversion*, Vol. 5, No. 3, 1990, pp. 445-451.

[3] A. G. Bakirtzis, “A probabilistic method for the evaluation of the reliability of stand-alone wind energy systems”, *IEEE Transactions on Energy Conversion*, Vol. 7, No.1, 1992, pp. 99-107.

[4] S. H. Karaki, R. B. Chedid and R. Ramadan, “Probabilistic performance assessment of wind energy conversion systems”, *IEEE Transactions on Energy Conversion*, Vol. 14, No. 2, 1999, pp. 217-224.

[5] E.S. Gavanidou, A.G. Bakirtzis and P.S. Dokopoulos, “A Probabilistic method for the evaluation of the performance of wind-diesel energy systems,” *IEEE Transactions on Energy Conversion*, Vol. 8, No. 2, pp. 418-425, September 1992.

[6] A.J. Bowen, M. Cowie and N. Zakay, “The performance of a remote wind-diesel power system,” *Renewable Energy*, Vol. 22, pp. 429–45, 2001.

[7] R. Billinton and R. Karki “Reliability/cost implications of PV and wind energy utilization in small isolated power systems”, *IEEE Transactions on Energy Conversion*, Vol. 16, No.4, 2001, pp.368-373.

[8] Bagen and R. Billinton, “Incorporating well-being considerations in generating systems using energy storage” *IEEE Transactions on Energy Conversion*, Vol. 20, No. 1, March 2005, pp. 225-230.

[9] Bagen and R. Billinton, “Evaluation of different operating strategies in small stand-alone power systems” *IEEE Transactions on Energy Conversion*, Vol. 20, No. 3, September 2005, pp. 654-660.

[10] P. Hu, R. Karki and R. Billinton, “Reliability evaluation of generating systems containing wind power and energy storage”, IET Generation, Transmission and Distribution, 2009, Vol. 3, Issue 8, pp. 783–791.

[11] R. Billinton and R. N. Allan, Reliability Evaluation of Power Systems. Plenum Press, New York, 1996.

[12] R. Billinton, H. Chen and R. Ghajar, “Time-series models for reliability evaluation of power systems including wind energy”, *Microelectron. Reliab.* Vol. 36, no. 9, 1996, pp. 1253-1261.

[13] IEEE Committee Report, “A reliability test system”, *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No. 6, Nov./Dec. 1979.