Reliability/Cost Implications of PV and Wind Energy Utilization in Small Isolated Power Systems

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***Abstract*—The application of renewable energy in electric power systems is growing rapidly due to enhanced public concerns for adverse environmental impacts and escalation in energy costs associated with the use of conventional energy sources. Photovoltaics and wind energy sources are being increasingly recognized as cost effective generation sources in small isolated power systems primarily supplied by costly diesel fuel. The utilization of these energy sources can significantly reduce the system fuel costs but can also have considerable impact on the system reliability. A realistic cost/reliability analysis requires evaluation models that can recognize the highly erratic nature of these energy sources while maintaining the chronology and interdependence of the random variables inherent in them. This paper presents a simulation method that provides objective indicators to help system planners decide on appropriate installation sites, operating policies, and selection of energy types, sizes and mixes in capacity expansion when utilizing PV and wind energy in small isolated systems.**

I. INTRODUCTION

THE ESCALATION in electric energy costs associated with fossil and nuclear fuels, and enhanced public awareness of potential environmental impacts of conventional energy systems has created an increased interest in the development and utilization of alternate sources, such as wind and solar energy. The use of these energy sources are increasingly promoted by governmental policies that provide financial support in different forms, and penalize conventional energy generation facilities that emit greenhouse gases.

It is important to assess the actual benefits of utilizing PV and wind energy and the key variables that dictate or affect the economics involved. A realistic evaluation of the monetary benefits associated with these energy sources also requires an assessment of the level of system reliability that can be obtained when using these sources. It is quite evident that limitations in the energy available from renewable energy sources and their intermittent behavior degrade system reliability. Cost/benefit analysis associated with the application of PV and wind energy is incomplete without a corresponding reliability assessment.

The reliability aspects of utilizing renewable energy sources have largely been ignored in the past due the relatively insignificant contribution of these sources in major power systems, and consequently due to the lack of appropriate techniques. A relatively high penetration of these energy sources in small isolated power systems (SIPS) can create significant impacts on cost and reliability.

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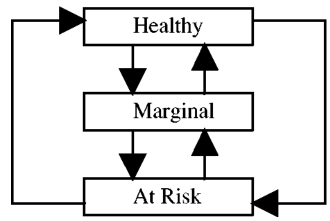

Fig. 1. System well-being model.

II. ADEQUACY EVALUATION OF SIPS

SIPS planners routinely evaluate generation capacity requirements using deterministic methods such as, percent reserve margin, the loss of the largest unit (LLU), etc. [1]. These techniques associate fixed capacity outputs to generating units and cannot be extended to include PV or wind energy sources that have highly fluctuating capacity values. The number of random variables and system complexities increase tremendously when renewable energy sources are added to SIPS. Deterministic methods cannot recognize the random behavior of the system. Probabilistic techniques must be applied to respond to these complexities and provide a realistic evaluation.

Existing probabilistic methods provide useful quantitative risk assessments and are widely used in large systems. These methods, however, have not been readily accepted in SIPS mainly due to concerns about the ability to interpret a single numerical risk index such as the loss of load expectation (LOLE) [2] and the lack of system operating information contained in a single risk index. SIPS planners are used to capacity planning based on physical and observable reserve margins, which cannot be obtained by the conventional probabilistic risk indices.

Deterministic and probabilistic methods can be combined into a system well-being approach [3], [4] to provide a practical solution to the adequacy problems encountered in SIPS. A selected deterministic criterion can be used in a probabilistic framework in order to determine the system healthy, marginal and at risk states as shown in Fig. 1. A system operates in the healthy state when it has enough capacity reserve to meet a deterministic criterion such as the LLU. This can be extended to include more than one unit, or the largest unit plus a fixed margin. The degree of comfort associated with operating the system within the accepted deterministic criterion is given by the probability of residing within the healthy state or the Healthy State Probability $P(H)$. The system is not in any difficulty but does not have sufficient margin to meet the specified deterministic criterion in the marginal state. In the at risk state, the load exceeds the available capacity. The actual

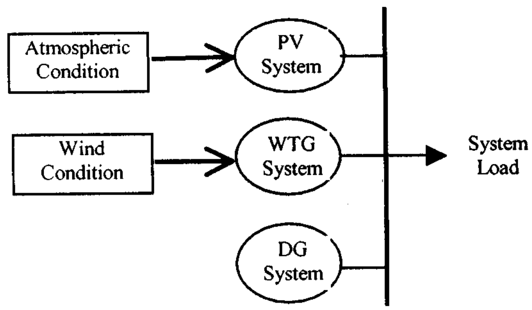

Fig. 2. Reliability evaluation model.

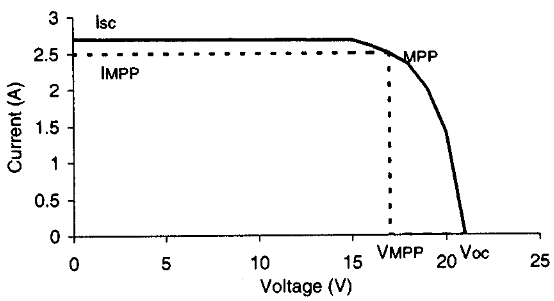

Fig. 3. PV Cell I–V characteristics.

risk associated with the inability of the generating system to satisfy the load requirement is measured by the probability of being in the risk state. A reliability/cost evaluation model applicable to SIPS containing PV and/or wind energy sources is presented in the following section.

III. Evaluation Model

The adequacy assessment of SIPS containing PV and/or wind energy sources has been developed in three steps. The necessary atmospheric data is generated for the system site in the first step. In the second step, the power delivered by the renewable energy source is calculated, and depends on the weather data provided in the first step. The power generated in the second step is combined with the system load data in the final step to obtain various adequacy and energy indices. The evaluation model is shown in Fig. 2.

A. Modeling PV Systems

The amount of solar intensity at a particular site dictates the power output of a PV system. Recorded solar radiation data are not available for many locations around the world. It is necessary to generate synthetic hourly data for satisfactory evaluation of PV power generation for reliability studies.

A widely used computer program called WATGEN [5] was used in order to generate hourly weather data from monthly mean values available at a given location. The program provides hourly synthetic data for global irradiation using the concepts described in [6], [7] and hourly ambient temperature data as described in [8].

The power output from a PV cell can be estimated from its current and voltage (I–V) curves, as shown in Fig. 3, the data for which is available from the manufacturer. The curve is the locus of the operating point of the PV cell. The largest rectangle that fits under the I–V curve will touch the curve at the maximum power point (MPP). The curve shifts vertically upwards (the output current increases) with increase in solar insolation and extends horizontally outwards (the voltage level increases) with a decrease in temperature. The I–V curve for a PV module can be constructed by adding the I–V curves of the individual cells contained in it.

The computer program called WATSUN-PV [9] decomposes the hourly global irradiation on the horizontal earths surface into diffuse, beam, and reflected components and evaluates the total radiation incident on the tilted array surface [10]. An iterative method is used to calculate the array output power with an initial estimate calculated using (1), where $V_{MPP_{REF}}$ and $I_{MPP_{REF}}$ are the reference module voltage and current at MPP, $H_{T_{REF}}$ is the reference insolation level, H_T the insolation level for the hour, and A the module area

$$P = (V_{MPP_{REF}})(I_{MPP_{REF}}).H_T/(H_{T_{REF}}.A). \tag{1}$$

The power estimate from 1 is used to obtain an estimate of cell temperature using the PV cell thermodynamic model described in [9]. An I–V curve is constructed for the estimated insolation level and cell temperature for the particular hour using the module ratings. The program then calculates the maximum power from the I–V curve using (2), where P_{MPP} and $P_{MPP_{REF}}$ are the maximum and the reference module power, $V_{OC_{REF}}$ and $I_{SC_{REF}}$ the reference open circuit voltage and short circuit current

$$P_{MPP} = (P_{MPP_{REF}}.V_{OC}.I_{SC})/(V_{OC_{REF}}.I_{SC_{REF}}). \tag{2}$$

The output power calculated using (2) further affects the cell temperature. An iterative calculation of cell temperature and output power finally provides a steady output power for that particular hour. The total power delivered by a PV array is the sum of the power delivered by all the modules existing in it.

B. Modeling Wind Systems

The wind speed at a specific site dictates the amount of energy that can be extracted from the wind. Historical wind speed data are required for the specific site, based on which, future hourly data are predicted using a time series model. The simulated wind speed SW_t can be obtained from the mean wind speed μ_t and its standard deviation σ_t at time t using (3)

$$SW_t = \mu_t + \sigma_t * y_t. \tag{3}$$

The data series y_t is used to establish the wind speed time series model in (4), where $\phi_i (i = 1, 2, \ldots, n)$ and $\theta_j (j = 1, 2, \ldots, m)$ are the auto-regressive and moving average parameters of the model, respectively,

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \cdots + \phi_n y_{t-n} + \alpha_t - \theta_1 \alpha_{t-1} - \theta_2 \alpha_{t-2} - \cdots - \theta_n \alpha_{t-n}. \tag{4}$$

An appropriate wind model should be selected to represent the wind characteristics at a particular site [11]. A computer program was developed to implement an ARMA(4,3) model and read annual site specific hourly data for mean wind speed and

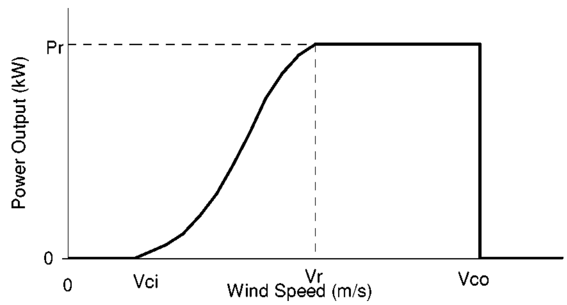

Fig. 4. Power curve of a WTG.

standard deviation and generate hourly wind speed data for a desired number of sample years.

The design parameters of a wind turbine generator (WTG) determine the amount of energy it can harvest from the wind. A power curve, which is a plot of output power against the average wind speed, can be constructed for a WTG design as shown in Fig. 4.

WTG are designed to start generating at the cut-in wind speed, V_{ci}. Fig. 4 shows that the power output increases nonlinearly as the wind speed increases from V_{ci} to the rated wind speed V_r. The rated power, P_r, is produced when the wind speed varies from V_r to the cut out wind speed, V_{co}, at which the WTG will be shut down for safety reasons. The electrical power generated hourly can be calculated from the wind speed data using the power curve of the WTG.

C. Overall System Evaluation

The complexity due to the effects of the numerous random variables inherent in renewable energy sources and their interactions can be resolved by simulating the atmospheric conditions and the corresponding system operation while recognizing the chronology of the actual events in the overall power system. A Monte Carlo simulation technique developed for conventional SIPS [12], which generates both conventional risk indices and well-being indices, was modified to include PV and wind energy sources that are energy limited, intermittent and sporadic in nature.

An outage history of each unit can be generated by simulating its failure and repair with respect to time using (5) and (6), respectively, where MTTF and MTTR are the mean times to failure and repair, respectively, of the unit

$$\text{Up Time} = -MTTF * \ln(x_1) \quad (5)$$

$$\text{Down Time} = -MTTR * \ln(x_2). \quad (6)$$

The generation models for PV and wind sub-systems are the chronological variation in their power outputs, respectively. The wind system generation model also depends on the load level due to the operating constraints applied to maintain system stability. The inclusion of WTG in SIPS introduces system stability problems. The power imbalances in supply and demand normally caused by load variations tend to accelerate or retard the rotating generators causing frequency and voltage fluctuations. Conventional units, such as diesel generators, respond to solve these stability problems by changing the supply power to match the demand through excitation and governor controls, respectively. The WTG units, however, cannot provide the proper power balance since their power supply fluctuates randomly and at a higher rate relative to the load variations. On the contrary, the rapid fluctuations in the WTG supply become the root cause for power imbalance instead of the load variations in conventional systems. A common practice to solve this problem is to impose an operating constraint of limiting the wind system to only a specified fraction of the total demand.

A wind to diesel energy dispatch ratio has been used as an operating constraint to build the generation model for the wind sub-system. The simulation algorithm first compares the system load level with the PV sub-system capacity and dispatches all the available PV energy in that interval. The remaining load is then shared jointly by the wind and diesel systems in the specified ratio, always dispatching wind energy to allow a maximum of its share. In this way, the useful capacity of the WTG sub-system is calculated.

The power available from all the generating units are combined to create the generation model, which is compared with the hourly load and the accepted deterministic criterion to identify the healthy, marginal and at risk states. The simulation proceeds chronologically from one hour to the next for repeated yearly samples until specified convergence criteria are satisfied. The number of healthy states $n(H)$, risk states $n(R)$ and their durations $t(H)$ and $t(R)$ are recorded for the entire simulation. The system health and risk indices are evaluated using (7)–(9), where N is the total number of simulated years

$$P(H) = \frac{\sum_{i=1}^{n(H)} t(H)_i}{N * \text{Year in hrs}} \quad (7)$$

$$LOHE = [1 - P(H)] * \text{Year in hrs} \quad (8)$$

$$LOLE = \frac{\sum_{i=1}^{n(R)} t(R)_i}{N}. \quad (9)$$

The fuel energy saving due to the renewable energy sources is equal to the total energy supplied by them. If PC_i, WC_i and DC_i are the PV, wind and diesel power output in hour i and L_i the load, the expected energy supplied (EES) by the PV and wind sub-systems can be obtained using (10) and (11), respectively, when the simulation is run for N sample years with a wind to diesel energy dispatch ratio of x

$$EES \text{ by PV} = \frac{\sum_{i=1}^{N*\text{yearly hours}} PC_i}{N} \quad (10)$$

$$EES \text{ by Wind} = \frac{\sum_{i=1}^{N*\text{yearly hours}} WL_i}{N} \quad (11)$$

where

$$WL_i = DC_i * x, \qquad \text{for } WC_i > DCi * x$$

and

$$WL_i = L_i, \qquad \text{for } WC_i < DCi * x.$$

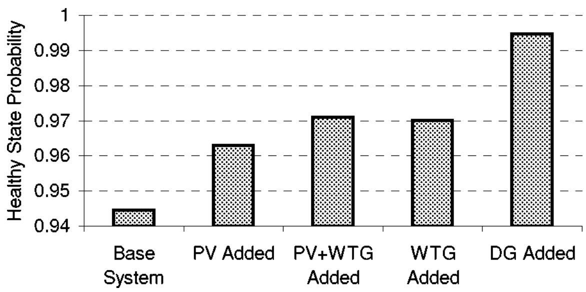

Fig. 5. System health for different energy types.

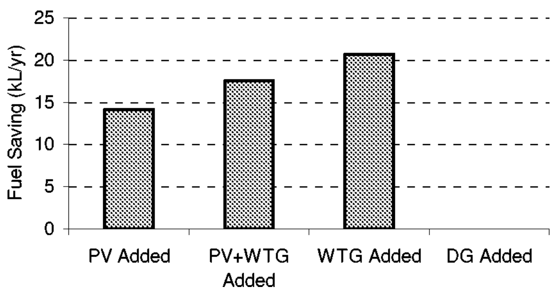

Fig. 6. Fuel savings for different energy types.

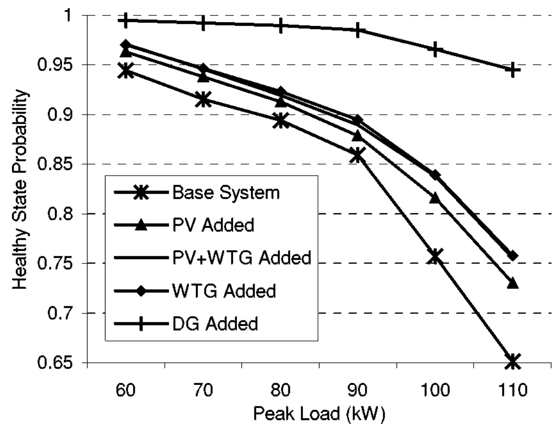

Fig. 7. System health with load growth.

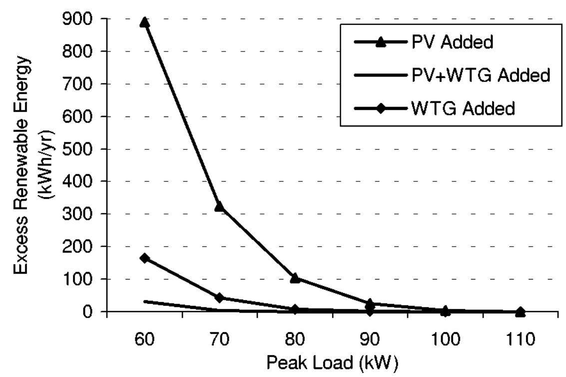

Fig. 8. Excess renewable energy with load growth.

IV. Application of the Evaluation Model

The developed evaluation model is applied to a base system with two 40 kW and one 70 kW diesel generating units (with 5% FOR, MTTF = 950 hours, MTTR = 50 hours). The hourly chronological load shape of the IEEE-RTS [13] was used with a peak load of 60 kW. The system was assumed to be located at a 43.4°N latitude site in Canada with atmospheric conditions that can be represented by the Toronto solar radiation data and the Saskatoon wind speed data. Cases involving adding 40 kW diesel units (similar to the existing units in the base system), 810 Wp PV arrays (built by assembling 9 groups of 3 series Canrom 30 Wp modules with 4% FOR, MTTF = 1920 h, MTTR = 80 h) and/or 10 kW WTG units (FOR = 4%, MTTF = 1920 h, MTTR = 80 h, cut-in, rated, and cut-out wind speeds of 14.4, 45, 90 km/h, respectively) were considered.

A total capacity of 40 kW was added to the base system in four different cases; one diesel unit, 50 PV arrays, 4 WTG, and a mix of 25 PV arrays and 2 WTG units. Fig. 5 compares the system degree of comfort in meeting the LLU criterion for the four cases with the base case. It can be observed that the system health increases for each capacity addition case but not to the same degree. Fig. 5 shows that conventional energy sources are much superior to renewable energy sources in terms of system reliability. A major benefit in utilizing PV or WTG is a significant reduction in the system operating costs due to fuel savings. Fig. 6 compares the fuel saving for the four cases considering a heat-rate of 3.2 kWh/liter.

System reliability degrades with increase in load. Fig. 7 compares the decrease in reliability with increase in peak load for the four cases of capacity addition. The relative reliability benefit from conventional unit addition is higher at higher loads.

A renewable energy source can offset maximum fuel when all of its generated energy can be utilized. The renewable energy available from these sources may not always be consumed due to a lower instantaneous demand or applied operating constraints. Fig. 8 compares the excess energy wasted for the three cases of renewable energy additions. It can be seen that most of the energy generated has been consumed except for the lower loads in the case when only PV arrays are added to the system. The excess energy evaluation provides a valuable indicator when deciding the types of energy sources that can be added and the expected benefits.

The variation in the system load in the above studies was modeled by increasing the peak load while maintaining the same load shape. Changes in load factor or in the shape of the load curve will also affect the system reliability and cost indices. Maximum benefit in utilizing renewable energy can be achieved by injecting an appropriate mix of energy sources in order to generate a power output profile that closely matches the load profile. Demand side management techniques can be applied to shape the load curve in order to maximize the utilization of the renewable energy available.

Fig. 9 illustrates the increase in system health with increase in renewable energy penetration. The marginal increase in system reliability decreases with further additions. There comes a point when the curves in Fig. 9 will saturate. The study suggests that adding only renewable energy to meet load growth may not be able to provide the desired reliability. Fig. 10 illustrates the increase in fuel savings with increasing renewable energy penetration. The benefit, however, decreases with further penetration.

It is very important to obtain reliable atmospheric data for a system location since realistic reliability and cost analysis strongly depend on the validity of the available data. Fig. 11

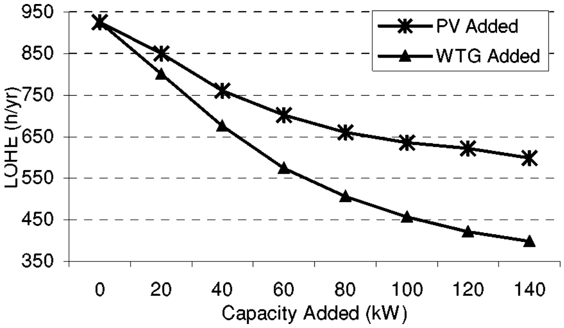

Fig. 9. System health with increasing penetration.

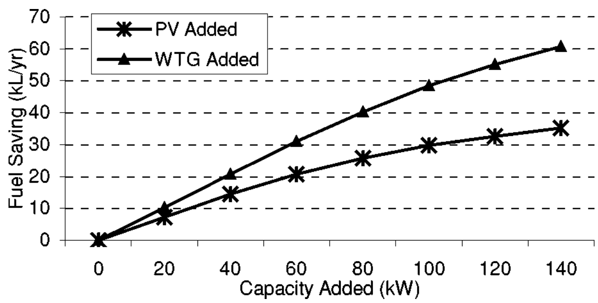

Fig. 10. Fuel savings with increasing penetration.

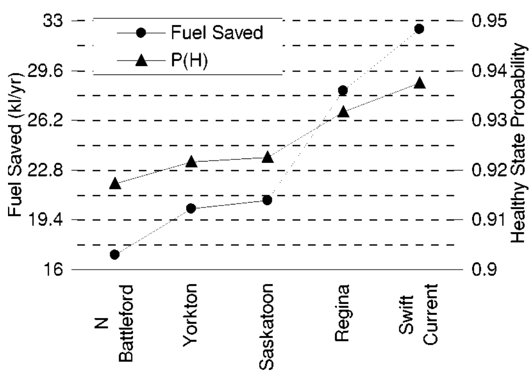

Fig. 11. Effects of location wind data.

illustrates the variation in system reliability and fuel savings at five different locations in Saskatchewan, Canada for the WTG addition case. The hourly mean wind speed and standard deviation data for the five locations were obtained from Environment Canada. Similar studies can be conducted for PV systems using site specific solar data.

The above studies assume that all the wind energy available can be consumed to satisfy the system demand. This assumption provides an unrealistically optimistic evaluation of the wind energy. The benefits of adding WTG units in a system are significantly curbed by operating constraints that must be satisfied in order to maintain system stability.

The base system was modified by removing one 40 kW diesel generating unit. The other system parameters remain the same. A capacity of 80 kW was added to the base system using the following five different mixes of PV : WTG; $80:0$, $60:20$, $40:40$, $20:60$ and $0:80$.

The fuel savings for the five different system configurations are compared in Fig. 12 for the three different operating

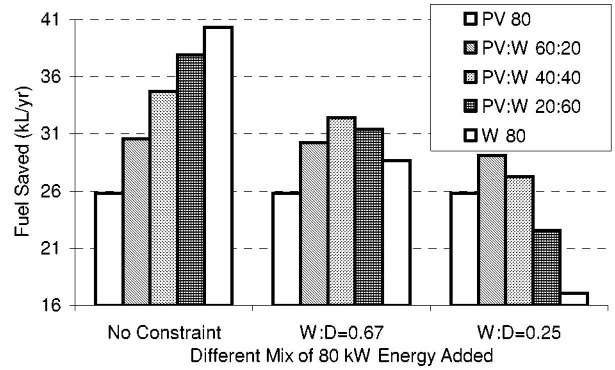

Fig. 12. Effect of wind operating constraints.

conditions of; no constraint, a wind to diesel load dispatch ratio ($W:D$) of 0.67, and a wind to diesel load dispatch ratio of 0.25. The constraint "$W : D = 0.67$" indicates that the wind energy cannot exceed 40% of the total system load.

The more stringent the constraint, the lower will be the benefits achieved from higher wind energy penetration. The results indicate that diesel units must accompany WTG additions at the right times in capacity expansion. The cost of investing in alternative methods to alleviate the operating constraints can also be compared with the annual savings in fuel costs as a result of the investment.

V. Conclusion

The rapid growth of renewable energy utilization and the immense potential for future use dictates a need to seriously consider the reliability of supply that can be obtained in addition to the associated cost benefits that can be achieved. Techniques have been developed to utilize site specific relevant atmospheric data, to model renewable energy conversion, and to conduct overall reliability/cost evaluation of renewable energy utilization in small isolated systems.

The dependence of renewable energy sources on a large number of random variables necessitates the utilization of probabilistic techniques for realistic cost/adequacy studies. The existing deterministic criteria used in SIPS can be embedded in a probabilistic approach using system well-being analysis. A Monte Carlo simulation approach has been utilized to incorporate the numerous random variables and their interactions. The developed evaluation model can be used to conduct a wide range of system cost and reliability studies in order to analyze the actual benefits that can be obtained. The concepts presented can be applied to analyze the effects of various factors that influence the utilization of renewable energy in electric power systems and use the results as valuable inputs to system planning.

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