Steady-State Performance of a Grid-Connected Rooftop Hybrid Wind–Photovoltaic Power System with Battery Storage

Francois Giraud, *Student Member, IEEE* and Zyiad M. Salameh, *Senior Member, IEEE*

***Abstract*—This paper reports the performance of a 4-kW grid-connected residential Wind–Photovoltaic system (WPS) with battery storage located in Lowell, MA. The system was originally designed to meet a typical New-England (TNE) load demand with a loss of power supply probability (LPSP) of one day in ten years as recommended by the Utility Company. The data used in the calculation was wind speed and irradiance of Login Airport Boston (LAB) obtained from the National Climate Center in North Carolina. The present performance study is based on two-year operation. (May 1996–Apr 1998) of the WPS.**

Unlike conventional generation, the wind and the sunrays are available at no cost and generate electricity pollution-free. Around noontime the WPS satisfies its load and provides additional energy to the storage or to the grid. On-site energy production is undoubtedly accompanied with minimization of environmental pollution, reduction of losses in power systems transmission and distribution equipment, and supports the utility in Demand Side Management (DSM). This paper includes discussion on system reliability, power quality, loss of supply, and effects of the randomness of the wind and the solar radiation on system design.

***Index Terms*—Battery storage, grid-connected residential system, hybrid wind–photovoltaic system, loss of supply, system reliability.**

I. Introduction

If ENVIRONMENTAL concerns keep growing, and restrictive guidelines constrain the use of the pollutant sources, wind and solar power can be considered as viable options for future electricity generation. Besides being emission-free, the energy coming from the wind and the sunrays is available at no cost. In addition, they offer a solution for power supply to remote areas that are not accessible by the Utility Company, and to developing countries that are poor in fossil-based resources. The interest in renewable energy forms is indeed growing worldwide. Today, more than 28 000 wind turbines, and more than 100 000 off-grid PV systems are installed all over the world. Since 1970, the PV price has continuously dropped. In 1970, the installed PV peak watt cost $100, during the 80s, it fell to $10; at the present time, the price is around $4 per installed peak watt. Nowadays, the price for the generation of a kWh Photovoltaics is estimated at 15 cents and a kWh wind energy cost 5 cents. These prices are still high when compared to conventional generation. However, with massive production of PV modules and small-scale wind turbines, with farther progress in research and development, and continuous government financial support, future price drops are expected, which will encourage the widespread application of interactive small-scale residential WPS.

The operation of a residential 4-kW WPS installed at the University of Massachusetts Lowell has been monitored for two years. In the original design, the system was intended to satisfy a simulated TNE load with a LPSP of one day in ten years as suggested by the Utility Company. Since on-site historical wind speed and irradiance measurements were not available at design time, long-term LAB data was used instead. LAB located on the East Coast approximately 40 miles South East of Lowell. The data was obtained from the National Climatic Center in North Carolina.

To determine the probability density functions (PDF) characterizing the wind speed and the irradiance, frequency histograms were generated with 30 years of data hourly recorded. Considering a 31-day-long month, 930 pieces of data are processed to engender the PDF for every hour of a typical day in each month. In the prediction of long-term hourly average power of a typical day in each month, the wind speed was assumed to be a Weibull distribution and the irradiance was modeled using one of the following PDF: Beta, Weibull, and Log-Normal. The goodness of fit test was performed with the Kohnogorov–Smirnov, or the Chi-Square tests [1].

Given the TNE load profile, the 1.5-kW wind turbine, and the LPSP of one day in ten years, it was found that 2.5 kW of PV and 44 kWh of battery storage is the optimum combination that yields the minimum cost for the system with the desired LPSP.

This paper reports the results of the system performance during two years of operation. Since the data used in the original calculation is not the data of the site, the analysis will also reveal how well both sites are correlated A discussion on power quality, long-term loss of supply probability assessment, system reliability, and effects of the variability of the wind speed and the irradiance on system design is also included.

II. The WPS Configuration

The WPS as configured in Fig. 1 is composed of the following:

A. The PV Modules

The 2.5-kW solar generator is made of 70 modules installed on the roof of the College of Engineering. They are assembled to form three PV arrays: one array with 20 modules and two with

Manuscript received March 23, 1999.

The authors are with the Department of Electrical Engineering, University of Massachusetts, Lowell, MA 01854.

Publisher Item Identifier S 0885-8969(01)02649-3.

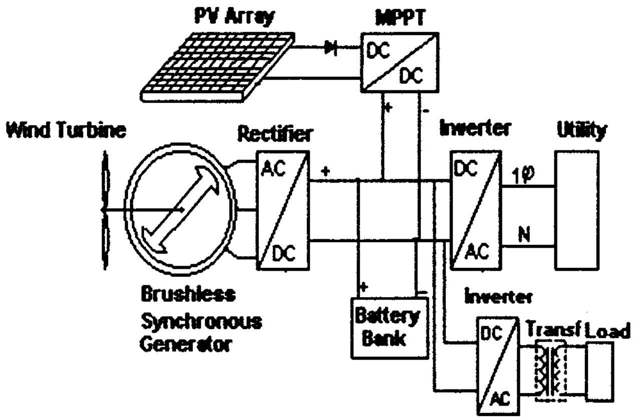

Fig. 1. Configuration of the WPS in the lab.

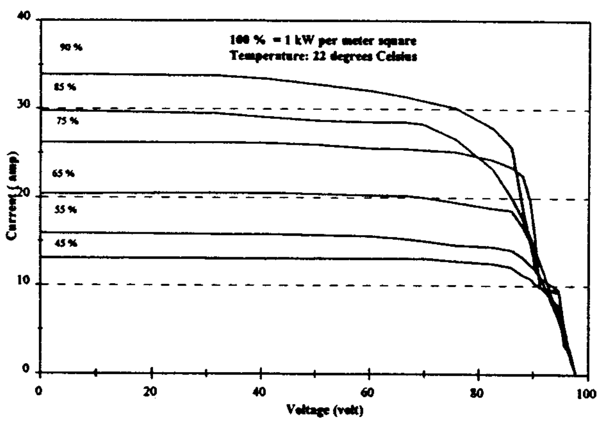

Fig. 2. Voltage/current characteristics of the solar generator at various irradiance levels.

25 modules. Every module is built up electrically from 36 individual 600-millivolt solar cells. The module manufacturer rating is 53 W. Due to aging, the module performance has dropped. Some of the modules experienced over time a discoloration from blue to brown due to oxidation occurring at high temperatures between the actual solar cells and the front glass cover. Likewise, this phenomenon vitiates the module efficiency. The actual current–voltage characteristics of the solar generator are illustrated in Fig. 2.

These curves are taken at 22 degrees Celsius at different insolation levels. The solar generator is characterized at each insolation by one operating point where it delivers maximum power. The arrays are fixed in orientation with an inclination of 42 degrees. This angle corresponds to the optimum tilting in spring for the considered location. As opposed to LAB, the sun power on the site has a higher availability than wind power. The PV power can be estimated via Fig. 3 taken at 20 degrees Celsius. The power is also dependent on the temperature, and the wind speed. Linear modeling or Neural Networks are among methods that can be used to predict PV performance under various temperature, and wind conditions [1], [2].

B. The Wind Turbine

A 1.5-kW wind turbine installed next to the PV arrays ensures wind energy conversion into electricity. The wind

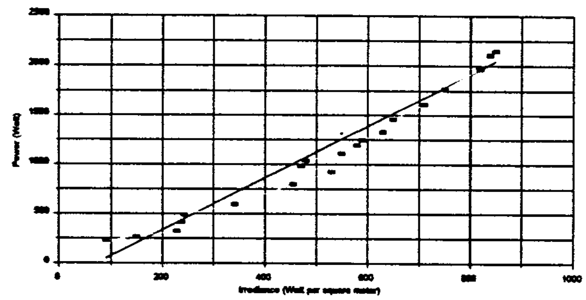

Fig. 3. PV output power versus irradiance at 20 degrees celsius.

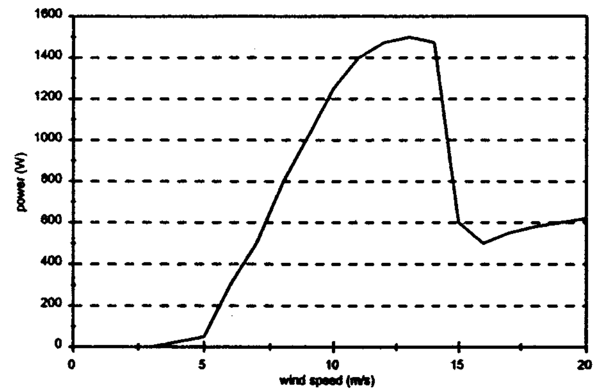

Fig. 4. Power curve of the wind turbine.

power that is extracted from the turbine can be predicted by the curve in Fig. 4. It is an upwind three-bladed, horizontal axis, maintenance-free wind turbine. After the rotor system has captured the energy from the wind, and converted it into rotational forces, the alternator converts the mechanical energy into electrical energy. The alternator is a permanent-magnets brushless synchronous generator. It has inverted configuration in that the outside housing rotates, while the stator windings are internal. The turbine has the capability of aligning itself to the wind direction until it reaches the furling wind speed of 13 m/s. To protect the wind turbine in high winds against mechanical stress, upon reaching the furling wind speed, the turbine will face away, out of the direction of the wind It will repeatedly furl and unfurl. As a result, in high winds, the output power of the turbine is significantly reduced (Fig. 4).

The wind is a more dynamic source than the sun. It can produce energy during periods of little or no sunshine, thus extending the batteries life by protecting them against deep discharges.

C. The Power Conditioning Units

The PV and the synchronous machine voltages follow the variability in the wind speed and in the insolation. The modules produce dc power and the wind generator produces ac power. This requires the need to condition the power at a fixed dc or ac voltage. A microprocessor-controlled Maximum Power Point Tracker (MPPT) maximizes the solar generator output; it separates the array terminals from the battery voltage and sets the solar generator at its optimum operating voltage at each insolation level. A converter rectifies the alternating current generated by the wind generator and protects the batteries from being overcharged by the wind turbine. A bi-directional inverter-charger links the system to the grid. A second inverter and a transformer condition the power for the emulated TNE load. These components constitute the major sources of power quality problems in the system

D. The Battery Storage

The 24 batteries installed have a total capacity of 44 kWh. They are configured in series of 4 to form the 24 volts dc bus voltage. The battery storage allows the displacement of the energy, i.e., the storing of excess energy produced at a favorable time and then the use of it at a time of no or low production. The batteries have a depth of discharge of 80% and a round-trip efficiency of 85%. In the study, the battery capacity represents the amount of retrievable energy, not the actually stored quantity.

III. System Analysis

A. The Energy Production

Fig. 5 shows typical profiles of the TNE load and the WPS energy production for each season. For part of the day, the production exceeds the demand (typically 8 hours in spring, 8 hours in fall, 6 hours in summer and 5 hours in winter).

These diagrams display also the important role of the battery storage. In most cases, between 9:00 AM and 3:00 PM, the system is able to produce more power than required by the load. The energy surplus is stored in the batteries in order to be used during time of insufficient production, or sold to the utility. Reserved energy in the batteries is instantaneously used as backup, if the supply is significantly reduced by random passage of clouds and/or absence of wind. In addition, the storage can also help reduce the utility peak hours requirements by storing energy from the utility in time of low demand to use it when the residential load needs it in peak hours, thus reducing the scheduling of expensive generation units at time of peak demand.

The highest system performance is recorded in March and April. Spring days are indeed not hot, (the PV module efficiency decreases with temperature), and windy. The sun paths are relatively long. This represents a good environment for system operation.

Winter is the worst period characterized by short and cloudy days, in which the daily TNE load is at its highest level. Summer is the season of the lowest wind energy production.

The load voltage reaches 120 V as the sun peaks, goes down to 117 V at night. The frequency remains within the 59–60 Hz range. As for total voltage harmonic distortion, the highest level measured at the point of connection to the utility is 1.27%.

Lowest level: 0.80%. Typical value: 1.17%. These values are far below the 5% limit recommendation of IEEE 519. Passing clouds and gusty winds do not cause any significant voltage fluctuation owing to the stability effect produced by the battery bank [3], [4].

Table I summarizes the annual energy production for both period intervals. The production covers around 47–48% of the residential load. In Table II, the wind energy represents only 10.51% of the PV production in the first annual period and 7.47% in the second based.

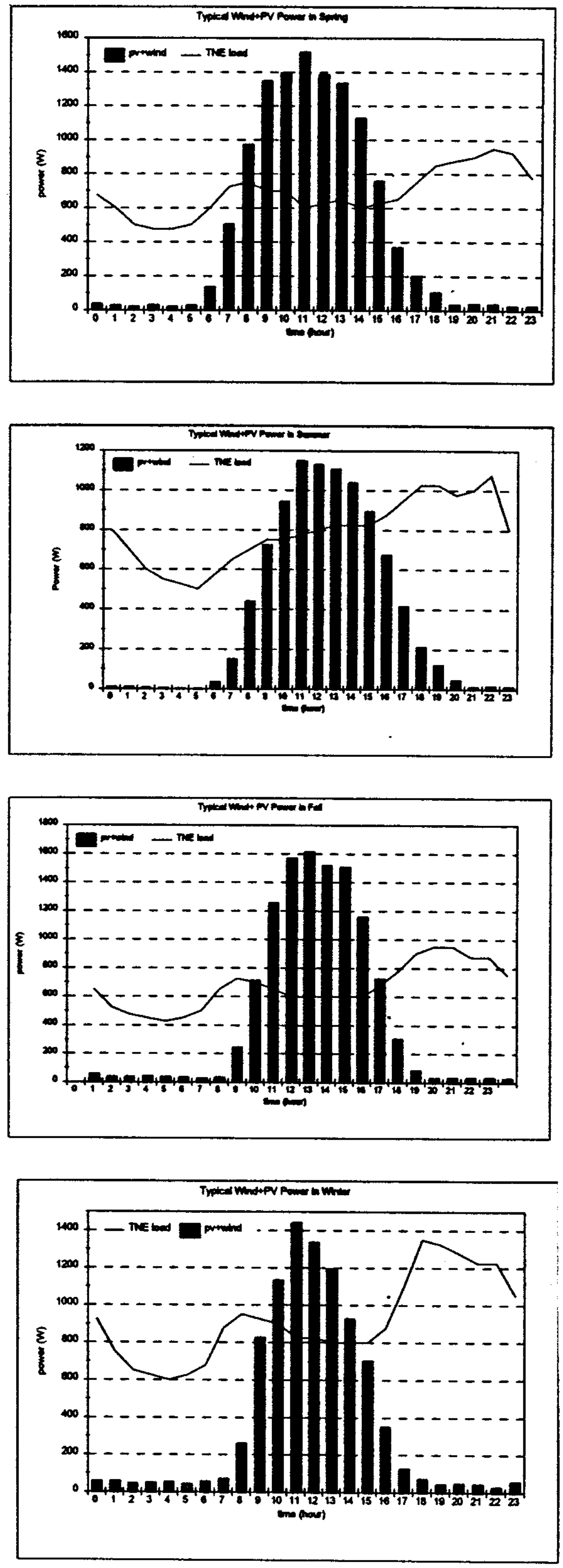

Fig. 5. Typical profiles of the power production and TNE load for each season.

A significant deviation between the theoretical values based on the Logan data and the system performance is pointed out.

TABLE I
COMPARISON OF THE ANNUAL ENERGY PRODUCTION TO THE ANNUAL LOAD DEMAND

Period	Annual Energy Production in kWh	Annual Load Demand in kWh	Total Energy / Load in %
May 96-Apr 97	3052.5	6364.6	47.96%
May 97-Apr 98	3001. 0	6364.6	47.15%

TABLE II
WIND ENERGY PRODUCTION COMPARED TO PV PRODUCTION

Period	Wind Energy Production in kWh	PV Production in kWh	Wind / PV in %
May 96-Apr 97	290.3	2762.2	10.51%
May 97- Apr 98	208.5	2792.5	7.47%

TABLE III
LOWELL ENERGY PRODUCTION EXPRESSED AS A PERCENTAGE OF THE CORRESPONDING ENERGY EXPECTED AT LOGAN

Period	Wind Energy Lowell/ Logan	PV energy Lowell/Logan	Total Energy
May 96-Apr 97	6.12%	77.71%	36.77%
May 97- Apr 98	4.39%	78.56%	36.15%

In Table III, during the first annual period, the wind energy production is only 6.12% of the wind energy expected at Logan.

Wind power has a higher availability at LAB than at Lowell, because LAB is bordering on the Atlantic Ocean, whereas Lowell is situated further in land. The air along coastlines is subject to higher temperature differences than air in land due to absorption differences between land and water. So the wind, which is due to uneven heating of the atmosphere, is more available at Logan than on the site. The hourly wind power extracted from the 1.5-kW turbine never exceeds 100 W, although, under gusty conditions, instantaneous power levels of up to 2000 Watts have been recorded. The turbine rated speed is 28 mph. The on-site mean wind speed is 10 mph. A better utilization of the wind power generator would occur if the wind power generator rated speed were closer to the site mean wind speed [5].

In the first annual period, the PV reaches 77.71% of the expected PV energy at Logan (Table III). This value indicates that the radiation patterns on both sites have a high degree of similarity. The 77.71% are a normal deviation that can be expected between the actual and the long-term averages of a location.

The total power in Lowell for the first period amounts only to 36% of the total energy expected at Logan (Table III). This is to be explained by the high dissimilarity between the wind data of both sides. While at LAB more power from the wind (134% of PV) was expected, the actual site is characterized by higher solar power availability than wind power (Table II).

TABLE IV
NEEDED ADDITIONAL BATTERY AND PV CAPACITY TO SATISFY THE DESIRED LPSP FOR EACH MONTH

Month	Batt. Cap. in kWh	PV Cap in kW
May-96-97	72.1-49.6	1.6-1.4
Jun-96-97	0-0	2.4-2.5
Jul-96-97	0-8	3.1-3
Aug-96-97	5-0	2.1-2.1
Sep-96-97	2-0	1.9-2
Oct-96-97	62.2-82.2	1.4--2
Nov-96-97	122-117.1	2.7-3
Dec-96-97	105-116.1	8.5-4
Jan-97-98	30.4 - 87.5	5.1-7.5
Feb-97-98	40-62	4.1-5
Mar-97-98	13-17	2.1-2.5
Apr-97-98	5.2-9.5	1.1--1.4

B. The System Component Reliability

The highest loss of power production (estimated through the irradiance data) occurred in November 1996 through the beginning of December 1996 as a result of short-circuits in PV cables and fuse burning on the DC bus. It took 36 days before complete PV operation resumed. The problem was that on cold, sunny days the PV system has delivered power that has exceeded its rating up to 40%. The reason is that, in the pn-junction recombination activities, which decrease the cell efficiency, decline as the temperature goes down. After replacement of the damage components with higher rating ones, the system has since then been operating trouble-free. Despite failure, the system was still capable of delivering power. This highlights the advantage of the modularity in PV systems.

C. The Unit Sizing

The wind and the solar radiation are stochastic by nature. So, when designing systems with random variables, one of the major problems encountered is that the primary energy quantity to be converted into electricity cannot be predetermined.

Conventionally, one has recourse to probabilistic techniques, where an assessment of the resources is made by processing historical data [1], [6], [7]. Due to variation in the wind and solar radiation from year to year, their daily/hourly values for each month is averaged over past years (typically 30 years) to provide long-term data. The collection of all averages will form a typical profile for a time period, which can be a year, a season, a month, or a day. The data of the typical time period is used to assess resource availability of this particular time period. For instance, assuming the years are statistically equivalent, a typical year can be used to predict the system long-term performance and economics. In case of nonavailability of site-specific data, one uses data taken from the nearest meteorological station, which will reproduce the on-site environmental conditions with unknown degree of similarity [1].

TABLE V
NEEDED ADDITIONAL BATTERY AND PV CAPACITY TO SATISFY THE DESIRED LPSP FOR EACH ANNUAL PERIOD AND BOTH PERIODS TOGETHER

Year	Batt. Cap. in kWh	PV Power in kW
May 96-Apr 97	88	7.5
May 97- Apr98	153	7
Both years together	120	7.3

The system component ratings are usually found by optimizing a certain objective function to satisfy the energy needs at a minimum capital cost, and at a pre-selected reliability defined as LPSP [1], [8], [9]. In the case of wind–solar system with storage, the LPSP is the probability the combined action of the storage, the PV and the wind is not able to meet the demand, thus requiring part of the power to be drawn from the grid. The point of design optimization is conditional upon the resource availability of the site.

Nonetheless, the randomness in the wind, and the solar radiation introduces a great deal of uncertainty in the determination of a long-term LPSP (for instance one day in ten years, or 2.4 hours in a year), and in the optimal sizing that will satisfy this requirement. Normally, the typical data, which describes the resources availability of the selected site, is the basis upon which reliability assessment and component ratings are calculated. Even if the years of operation are assumed statistically identical different profiles in the yearly energy production will likely lead to distinct component combinations (storage, wind turbine and PV ratings) that would satisfy the long-term probability at a minimum cost. That also means that the use of long-term averages in computing the optimum system design will not guaranty the long term reliability requirement.

Given the 1.5-kW turbine, and the resources that were available during the 24-month operation, different scenarios are calculated. Table V gives the amount of additional storage and PV capacity that would have satisfied the desired long-term LPSP at a minimal cost with no grid intervention for each month. That means each month is taken separately and unit combination for this particular month is determined. For instance, in May 1996, the system would have needed an additional 72.1 kWh battery storage and 1.6 kW PV to satisfy the LPSP, while in May 1997, the additional capacity is 49.6 kWh and 1.4 kW.

Also, when the 12 consecutive months of each annual period are considered in sequence, the design parameters again change. Table VI reports the optimum combination for each annual period. These results are also different from the combinations obtained in their corresponding worst month of energy production (Dec 1996, Jan 1998 in Table V). The combination that satisfies one annual period does not satisfy the other one, and combination found by using data averaged over both annual periods fails to meet the desired long-term LPSP. That demonstrates how the volatility of the resources influences the design parameters.

The impact of the randomness on the LPSP would disappear only in case of unlimited energy storage capacity. Excess energy accumulated in a given subperiod will be stored in totality to compensate deficit in another subperiod. Thus two periods with

TABLE VI
COST DISTRIBUTION IN THE WPS

Components	Cost ($)	Life Cycle (in years)	Annual Interest rate (%)	Monthly payment ($)
Solar panels	10,000	20	6	50.00
1.5 kW wind turbine	6,200.	20		31.00
Battery Bank	2,400	5	6	12.38
4 kW Inverter	3,300	20	6	16.50
BOS	600	20	6	3.00
Total	22,500		6	112.88

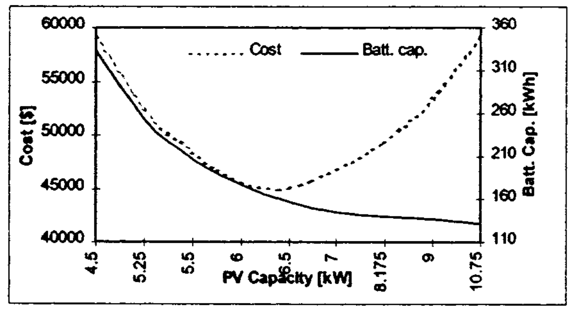

Fig. 6. Additional battery capacity and additional costs versus PV capacity needed to satisfy the LPSP for the second annual period (May 1997–Apr. 1998).

statistically identical energy production would have the same LPSP. However with limited storage capacity, depending upon the energy production pattern, it can happen that some of the excess cannot be stored; therefore cannot be retrieved from the batteries in time of deficit. Subperiods characterized by consecutive days of low availability of energy tend to increase the need for battery capacity; on the contrary, subperiods characterized by consecutive days of clear sky sunshine tend to lower the needed PV and battery capacity. As a result, the less the energy production is uniformly distributed, the more difficult it is to satisfy a long term LPSP.

However, by composing a year data out of the worst months of both periods, an optimum solution is found that satisfies the long-term LPSP over both periods. For example, to select January, the months of January of both periods are compared and the one with the worst resources is chosen. The results for the twelve consecutive worst months are reported in the third row of Table V. However, this procedure has a limited character in that it has been used for data spanning only over two years. Its validity over longer period of time (for example 30 years) remains to be tested.

Fig. 6 illustrates different combinations of PV capacity and battery storage that would satisfy the LPSP for the second year and their corresponding costs. The search algorithm yields only one combination for the optimum solution, where the cost is at a minimum. During the search, the cost of battery storage is assumed linear at 123$/kWh. The PV costs $4000/ kW. The installation costs are assumed fixed. The WPS needs an additional 6.3 kW PV and a 170 kWh supplementary storage to satisfy the LPSP in the second period (Fig. 6). For the same period, and

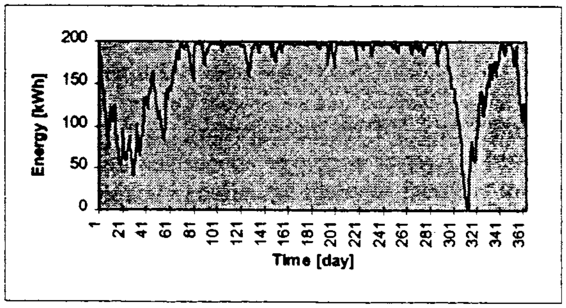

Fig. 7. Profile of the retrievable battery energy to satisfy the LPSP for the second annual period (May 1997–Apr. 1998).

for the optimum solution, Fig. 7 shows the quantity of the retrievable energy in the batteries for each day. On the 312th day, the amount of energy retrievable from the batteries without violating the depth of discharge sank to almost zero.

IV. Cost of Energy From the WPS

The cost of energy ($/kWh) from a battery backup wind-pv system will vary from site to site, since it largely depends on a number of factors that are site-related. These are the average solar radiation, the average wind speed as well as the assistance programs available at that location. In other words, the average cost of a kWh will decrease the more the system is used to produce energy. Also, the larger the wind turbine size used, the lower the cost of the installed kW wind power. The WPS under investigation includes:

- A 2.5 kW solar panel @ $4 per watt
- A 1.5 kW wind turbine including rectifier and guyed lattice tower for $6200.
- A 4 kW Inverter for $3300.
- The balance of system (BOS) which is the dc disconnect, conduit boxes, circuit breakers, fuses, battery cables, etc. costing $600.

An analysis of the costs of the system is made in Table VI.

This system would cost the customer $112.88 per month (with no down payment), if the local electric utility would offer their assistance by assuming the low installation and maintenance costs. Also, the federal, state and local governments would have to promote those projects with low-interest loans, exemptions from sales and property taxes. In the calculation we assumed that the system has a life cycle of 20 years and the batteries have to be replaced every 5 years. With an average annual energy production of 3025 kWh (Table I), the average cost of a kWh would be $0.41, which is still more than the $0.12 paid for conventional electricity in Massachusetts. However, in other states with more favorable solar radiation and wind speed conditions, we can anticipate the cost of the kWh renewable energy to halve to $0.19 Moreover, if the efforts to further reduce the cost of PV to $1 per watt are successful, the price of the kWh from a battery-backup WPS can easily reach today's rate for conventional electricity. Other intangible incentives for the customer to install such systems would be the ability to independently satisfy his or her energy needs in case of extreme emergency, the long-term health benefits associated with pollution reduction and a decrease of the dependence on exhaustive foreign sources. Being less dependent on foreign energy also means a decline in military expenditure to protect those sources and a less volatile energy market.

V. Concluding Remarks

This paper has discussed the experience with a residential wind–solar power system with storage during two years of operation. The conclusions drawn from the analysis are the following:

- Hybrid wind–solar power generation with battery storage form a complementary system: the wind is a more dynamic source than solar; it also provides energy during periods of little or no sunshine; the battery storage allows for the displacement of the energy by storing at a favorable time and then using the excess energy when necessary. This complementary feature is favorable to system reliability.
- In utility-interactive mode, the residential storage can also help reduce the burden of the utility during peak hours by storing energy from the utility during period of low demand and retrieve it to the load in time of peak demand, reducing the need for expensive generation units.
- If data of the nearest meteorological station is to be used in system designing, the degree of similarity of both sites must be taken in to account.
- While the primary resources (wind speed, irradiance) averaged over several years are helped in predicting system performance for a long period of time, the fluctuations in the resources from year to year, however, is a handicap in the determination of system component ratings that would satisfy a long-term objective like a LPSP at a minimum cost. Basing the calculation on the worst months of the past years instead may help reduce design uncertainty.
- The total voltage distortion, the frequency, and voltage level at the point of connection to the grid remains within acceptable levels. That is, the connection of the system to the grid is not a source of concern in terms of power quality.
- Further improvements in PV and battery technologies, and continuous reduction in prices, besides the environmental benefits are likely to facilitate the widespread use and acceptance of such systems by Utility Companies in Demand-Side Management.

Acknowledgment

The authors gratefully acknowledge Dr. J. Bzura of the New England Power Service for having provided funding for this study.

References

[1] B. S. Borrowsy and Z. M. Salameh, "Methodology for optimally sizing the combination of battery bank and PV array in a wind/PV hybrid system," *IEEE Trans. on Energy Conversion*, vol. 12, no. 1, Mar. 1997.

[2] T. Hiyama and K. Kitabayashi, "Neural network based estimation of maximum power generation from PV module using environmental information," in *IEEE '96 SM 550-4 EC*.

[3] F. Giraud and Z. M. Salameh, "Neural networks modeling of the gusts effects on a grid-interactive wind energy conversion system with battery storage," Electric Power Systems Research, to be published.

[4] ——, "Analysis of the effects of a passing clouds on a grid-interactive photovoltac system with battery storage using neural networks," IEEE Transactions on Energy Conversion, to be published.

[5] I. Safari and Z. M. Salameh, "The effect of windmill's parameters on capacity factors," *IEEE Trans. on Energy Conversion*, vol. 10, no. 4, Dec. 1995.

[6] R. Ramakumar and I. Abouzhar, "Loss of supply probability of stand-alone wind electric conversion systems," *IEEE Trans. on Energy Conversion*, vol. 5, no. 3, Dec. 1990.

[7] S. Rahman and R. Chedid, "Unit sizing and control of hybrid wind–solar power systems," in *IEEE 96 Sm 572-8 EC*.

[8] R. Ramakumar and I. Abouzhar, "An approach to assess the performance of a utility interactive photovoltac systems," *IEEE Trans. on Energy Conversion*, vol. 8, no. 2, June 1993.

[9] R. Ramakhumar, I. Abouzahr, and K. Ashenayi, "A knowledge-based approach to the design of integrated renewable energy systems," *IEEE Trans. on Energy Conversion*, vol. 7, no. 4, Dec. 1992.

Francois Giraud received the Diplom-Engineer in electrical engineering at the Fachocschule Coburg, Germany, in 1991 and the Ph.D. degree at the University of Massachusetts in June 1999. His research interests are in the fields of renewable energy systems.

Zyiad M. Salameh (S'78–M'82–SM'88) was born in Agraba, Jordan on May 4, 1944. He received the B.S. degree in electrical engineering from Moscow Power Engineering Institute, USSR, in 1974 and the M.S. and Ph.D. degrees from the University of Michigan, Ann Arbor, in 1980 and 1982, respectively. Zyad Salameh taught in the department of electrical engineering at Yarmouk University in Irbid, Jordan from 1982 to 1985. Since 1985, he has taught at the University of Massachusetts Lowel. He is a Member of IEEE Power Engineering, Industry Applications and Power Electronics societies. His areas of interest are power electronics, solid state electrical drive systems, modeling of electrical machines, photovoltaics and wind energy conversion systems. He has authored over 70 research papers.