2008

Reliability-based Stand-alone Photovoltaic System Sizing Design- A Case Study

Haifeng Ge
University of Nebraska-Lincoln

Liqin Ni
University of Nebraska-Lincoln

Sohrab Asgarpoor
University of Nebraska-Lincoln, sasgarpoor1@unl.edu

Ge, Haifeng; Ni, Liqin; and Asgarpoor, Sohrab, "Reliability-based Stand-alone Photovoltaic System Sizing Design- A Case Study" (2008). *Faculty Publications from the Department of Electrical and Computer Engineering*. 141.
http://digitalcommons.unl.edu/electricalengineeringfacpub/141

Published in PMAPS '08. Proceedings of the 10th International Conference on Probabilistic Methods Applied to Power Systems, 2008, pp.1–8. Copyright 2008 IEEE. Used by permission.

Reliability-based Stand-alone Photovoltaic System Sizing Design- A Case Study

Haifeng Ge, Liqin Ni, Sohrab Asgarpoor*
Department of Electrical Engineering
University of Nebraska – Lincoln
sasgarpoor1@unl.edu

Abstract: ***This paper introduces a method for designing a stand-alone photovoltaic system to improve the load point reliability, extend the operation life, and minimize the design cost. This approach examines the impacts of solar panel sizes, tilt angles and battery volumes toward load point reliability, as well as the expected system life, by using real insolation data in a given location and random load burdens. The reliability evaluation incorporating solar insolation variations and load point uncertainty is performed. Life evaluation of battery is included in this paper with consideration of the battery State of Charge (SoC) history. The Economical analysis to examine the investment cost, potential reliability cost and benefit is also studied. An application selecting Lincoln, Nebraska as the site is utilized to illustrate proposed methods. This work is valuable for practical stand-alone photovoltaic system sizing designs with reliability, life and economy consideration.***

Index Terms -- **Battery storage, Load Point Reliability, Photovoltaic, Reliability Evaluation, Stand-alone power system**

I. NOMENCLATURE

I_0	Total energy solar-cell collected
θ	Incident angle
α	Solar elevation angle
β	Tilt angel
I_d	Diffusion radiation
I_b	Direct beam/normal radiation
η	Solar-cell efficiency
Φ	Latitude. 0.71239 radians for Lincoln
δ	Declination angle
d	The day of the year from Jan. 1st.
θ_S	Sun azimuth
θ_P	Panel azimuth
HRA	The hour angle
LST	Local solar time
LT	Local time
T	Solar-cell panel temperature (in Celsius)
T_{amb}	Ambient temperature (in Celsius)
TC	Time correction
ΔGMT	Greenwich Mean Time difference. Lincoln is -6
E_0T	Eccentricity of orbit

II. INTRODUCTION

With the penetration of renewable energies into the conventional energy fields, there are growing concerns of the reliability and stability of these systems.

Previous researches are available on how to construct alternative energy systems, combine them into the traditional power grid [1-3], and how to size the storage volume or the energy source capacity to meet the loads' needs [4]. The impact of the alternative energy on the traditional power grid is also examined in order to improve systems' stability [5] [6]. But most of the design rules are based on the "meeting the need" strategy, not based on the reliability.

There are also some results available, for reliability evaluation of alternative energy systems [7-10]. In these papers, wind, photovoltaic, or their hybrid system were evaluated, to calculate the reliability indices at both the generation and transmission level [10]. These indices are very useful for the planning and operation. However, these studies are based on high level performance studies, and do not give a clear guide on how to improve the system's reliability during design phase.

Moreover, different applications have different reliability requirements, as well as different budgets. The economical analysis during system design is indispensable. In economical analysis, not only the capital investment needs to be included, the cost related with reliability due to the potential lost of energy, and the potential benefit of selling extra energy back to utilities should also be considered. Therefore, in order to design a cost-effective system, the economical analysis is also needed in practical application.

In order to meet the needs of the reliability and economical evaluation in practical application, this paper includes following works:

1) Evaluation of the load point reliability of a stand-alone solar system, with real solar insolation data. For example, given a random load and the stand-alone solar system's panel size and energy storage volume configuration, calculating its basic reliability indices, such as load point availability, failure rate, and average duration of outages;
2) Sensitivity studies of the solar panel size, storage volume, tilt angles, in stand-alone system reliability evaluations;
3) Evaluating expected life of this solar system, especially the expected life of storage (take lead-acid type batteries as an example);
4) Studying how to improve both the reliability and battery life by choosing a combination of a solar panel size and a storage volume;
5) Economical analysis of a given stand-alone solar system, including investment cost, potential reliability cost, and potential benefit.

In this paper, an example is provided for illustration, choosing Lincoln, Nebraska as the selected site. This work is valuable for practical stand-alone photovoltaic system sizing design, in which reliability, economics, and expected life are taken into consideration.

III. SYSTEM DESIGN

Figure 1 is the configuration of a typical stand-alone photovoltaic system [11].

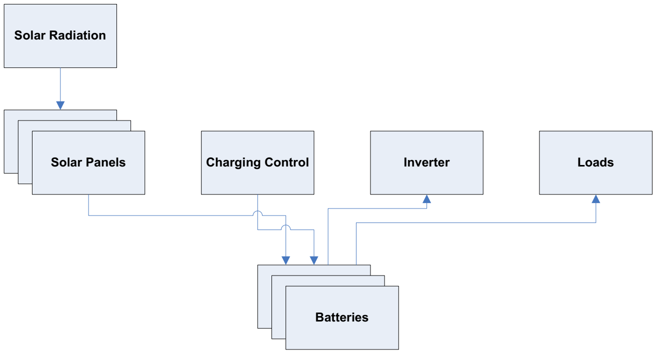

Fig.1. Configuration of a typical Stand-alone photovoltaic system

In these components, usually the solar panels size and the battery volume are needed to be determined based on different applications. Besides, the position of solar panels, such as the tilt angle and the azimuth angle, also need to be evaluated base on the location of this system. In evaluating of the expected life, because of the deterioration of battery during operation and its life is comparably shorter than other components, only the life of battery is evaluated. Following is the description of models for each individual component in Figure 1.

IV. INDIVIDUAL COMPONENT MODELS

A. Solar radiation with a given solar panel position

Solar radiation is defined as how much energy that an 1m^2 horizontal area can receive. Solar radiation includes direct insolation (energy received directly from sunrays), diffusion insolation (energy received from diffused rays in the air), and ground-reflected radiation [11]. For fixed solar panels, the insolation energy it receives can be expressed by equation (1).

$$I_0 = I_b \cdot \cos\theta + I_d \cdot (1-\beta/\pi) + I_r \qquad (1)$$

Where,

I_0 is the total insolation energy on 1m^2 horizontal area;

I_b is the direct beam radiation;

I_d is the diffusion radiation;

I_r is the ground-reflected radiation;

θ is the incident angle;

β is the tilt angle.

The data for I_b, I_d and I_r are available from National renewable energy laboratory [12]. Compared with direct beam radiations and diffusion radiations, ground-reflected radiations are much smaller. Therefore, ground-reflected radiations are not considered in this paper.

One advantage of this paper is the using real solar insolation data for evaluation, rather than simulating. Simulating is an easy and efficient method for reliability studies in similar systems [10]. However, though in simulation methods, geography positions (latitude & longitude) and temperatures can be included, there are other factors, such as climate varies and season changes, which are not easily or cannot be accurately incorporated in modeling. For example, usually the daytime in high latitude region is longer than equators region, which means longer insolation times. But in some regions or seasons, an equator area has higher accessibility and larger solar intensity than a higher latitude area. It is difficult to use a simple model to simulate all these varying in reliability studies. Therefore, it is reasonable and necessary to use real insolation data rather than the simulation.

Following are descriptions of parameters that are related with modeling with the real solar radiation data.

1) Direct beam radiation

Figure 2 illustrates the relationship of solar panels and solar positions. In Figure 2, α is the elevation angle between sunray and horizontal plane.

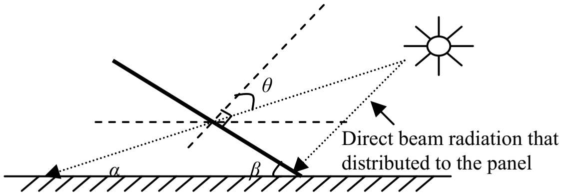

Fig.2. Direct beam insolation on the panel

i) Tilt angle β

Initially, the tilt angle is calculated to maximize the direct beam radiation, at worst solar insolation conditions, which are usually around Feb.14th in Lincoln, NE. The tilt angle will be changed slightly later, to find the optimum value. The definition of tilt angle is shown in Figure 3.

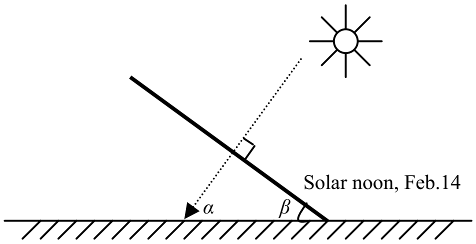

Fig.3. The tilt angle to maximize the direct normal radiation in mid of Feb.

At the time point of the solar noon, on Feb, 14th, the elevation angle at solar noon equals $\alpha = 90^{\circ} - |\Phi| + \mathrm{sign}(\Phi)\cdot\delta$,

where,

Φ is the latitude, which is 0.71239 radians for Lincoln;

δ is the declination angle;

"sign" is the symbolic function: If $\Phi>0$, $\mathrm{sign}(\Phi)=1$, otherwise -1;

δ is calculated by equation (2)

$$\delta = 23.45^{\circ}\sin\left[\frac{360}{365}\cdot(d-81)\right] \qquad (2)$$

In equation (2), d is day of the year from Jan. 1st. Thus, on Feb. 14th, $d = 45$, δ (Feb, 14th) = -0.238 Then the initial tilt angle is:

$$\beta = 90^{\circ} - \alpha = |\Phi| - \delta = 53.436^{\circ} = 0.9501 \qquad (3)$$

When it is not the solar noon, equation (4) is used to calculate α.

$$\alpha = \sin^{-1}(\sin\delta\sin\Phi + \cos\delta\cos\Phi\cos HRA) \qquad (4)$$

Where,

HRA is the hour angle;

In equation (4), *HRA* is used to converts the local solar time into the number of degrees. Equation (5) is the definition of HRA

$$\begin{aligned} &HRA=15^{\circ}\,(LST\text{-}12)\\ &LST = LT + TC\\ &TC = 4(-\Delta\mathrm{GMT}\cdot 150\text{- Longitude})+E_0T \qquad (5)\\ &E_0T = 9.87\sin(2B)\text{- }7.53\cos B\text{-}1.5\sin B\\ &B = 360/365\cdot(\mathrm{d}\text{-}81) \end{aligned}$$

Where,

LST is the local solar time;

LT is the local time;

TC is time difference;

E_0T is eccentricity of orbit;

ΔGMT is Greenwich Mean Time difference, -6 for Lincoln

"Longitude" is the longitude, which is 96.7° for Lincoln

ii) Incident angle θ

Another parameter which determines the solar panel position is the incident angle θ. θ is the angle between solar-cell panel's normal line and incident ray. θ determines how much energy is distributed to the solar-cell from direct beam radiation. Directed beam radiation collected by the solar-cell is calculated by $I_b\cdot\cos\theta$, as show in Figure 2.

The incident angle θ could be calculated by equation (6):

$$\theta = \cos^{-1}[\,\sin\alpha\cdot\cos\beta + \cos\alpha\cdot\sin\beta\cdot\cos(\theta_S\text{- }\theta_P)\,] \qquad (6)$$

Where,

θ_S is sun azimuth angle;

θ_P is solar panel azimuth angle.

Figure 4 describe the relationship among the angles in equation (6).

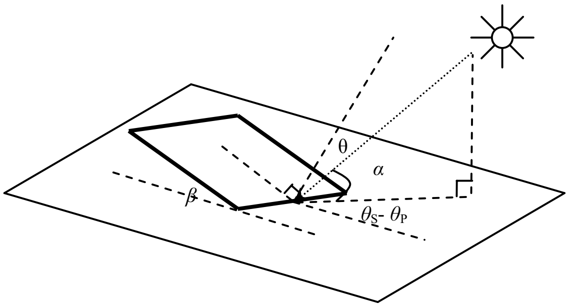

Fig. 4. Relationships between angles

θ_S can be calculated by equation (7),

$$\theta_S = \pi + \mathrm{sign}\,(HRA)\cos^{-1}[\sin\Phi\cdot\sin\alpha\text{-}\sin\delta/(\cos\alpha\cdot\cos\Phi)] \qquad (7)$$

In fixed solar panel system, θ_P is a constant value of π. It should be noted that in some application, the solar panel rotated constantly, in order to track the position of sun and to increase the direct beam insolation. For example, if an axis rotation solar system changes 15° each hour, the θ_P can be calculated approximated as equation (8)[11]:

$$\theta_P = \pi + (LT\text{-}12.4467)\cdot[(15^{\circ}\cdot 2\pi)/360^{\circ}] \qquad (8)$$

In this paper, the fixed panel solar system is selected, and θ_P equals π.

2) Diffusion radiation

Figure 5 illustrates how to calculate the diffusion insolation. In this paper, it is assumed that the global diffusion radiation is equally distributed from all parts of the sky.

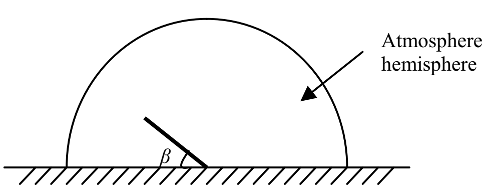

Fig.5. Diffusion radiation on a tilted panel

From Figure 5, the fraction of the hemisphere the panel sees by the tilted panel is $1\text{-}\beta/\pi$, and the energy the panel receives from diffusion radiation equals $I_d\cdot(1\text{-}\beta/\pi)$ [11].

Previous research has simulated the solar insolation, and considered the varying values by choosing different distribution functions [7]. In this research, the real insolation is given for one year. Therefore, there are two ways to model the solar radiation:

1) Utilize this specific year's insolation for all year through out the simulation, or, assuming for every year the solar insolation of every hour is all the same. In practice, these values may change randomly because of weather varying and slightly climate changes. But on average, these values in a given year will not change considerably.
2) Using the specific year's data as mean values, generating new solar insolation data by adding random difference, which follows normal distributions.

For simplicity, in this paper, the data used for every year are all the same.

B. Solar panel efficiency

The efficiency η is defined as the portion of energy that is transmitted into electricity from solar energy collected from the panel.

There are many factors that have influence on solar panel efficiency, such as sunlight intensities, panel temperatures, series resistances, and shunt resistances. Theoretically, solar panel efficiency can be calculated by equation (9) [11].

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}} \qquad (9)$$

Where, V_{oc} is the open circuit voltage; I_{sc} is the short circuit current; *FF* is the filling factor , which is determined by V_{oc}, I_{sc}, series resistance, shunt resistance, etc.

Like all semiconductors, temperature has impact on the electrical characteristics. In Equation (9), the open circuit voltage V_{oc} decreases about 2.2 mV and the short circuit current I_{sc} increases 0.0006mA, respectively, when the panel temperature increase 1 Celsius degree. The change of sunlight intensity also has influence on V_{oc}, I_{sc}, serial and shunt resistance, which in turn has impact on solar panel's efficiency. However, for reliability evaluation purpose, the solar panel efficiency is modeled with temperature variations only.

In this paper, the solar panel selected is Matrix Photowatt Solar Models PW750 80W [13]. Each panel has a size of 1237mm×556mm, which is 0.687772m^2. For economical analysis, the cost of each panel is $425. Assuming that there is no deterioration and defect on solar panel, it can works 20 years without breaks; after 20 year, it has no surplus meaning.

C. Modeling of battery

The purpose of the battery is to collect and store the generated electricity from the solar panel. It also is the link between the solar panel and the power converter.

Different types of batteries have different life curves. Usually the battery life or the cycling of a battery is proportional to the State of Charge (SoC hereafter). The deeper of the discharge, the shorter life it has. In this paper, a typical lead-acid battery, Deka 8G8D LTP Gel Battery [14] is selected for example. The volume of each battery is 264 Ampere hour (Ah hereafter). The points in Figure 6 are the life data provided from the manual. In order to calculate the cycles of the battery given state of charge values, a polynomial curve is generated by regression, which is shown in the equation in Figure 6. This battery has a charge efficiency of 85% and a discharge efficiency of 90%.

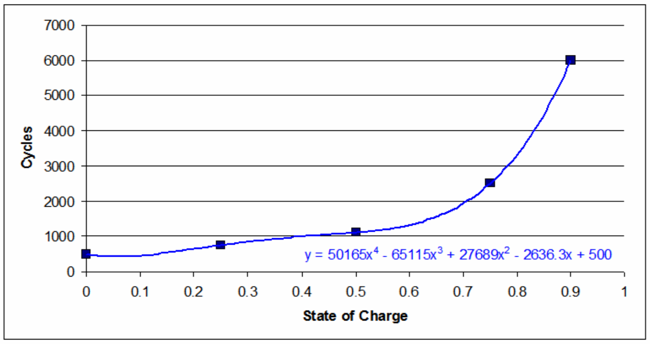

Fig.6. The battery cycles curve

D. Modeling of load

The modeling of load varies greatly, depending on different applications. Usually, there are three loads: constant load with slight changes, predictable loads, and random loads. The date of load is chosen from a typical residential house [15]. This load is represented by a vector of values, which means the power used in each hour of a day. In order to reflect the real load changes, artificial load values are generated from the real value, which follows a normal distribution. Figure 7 shows the real load values for a single day [15].

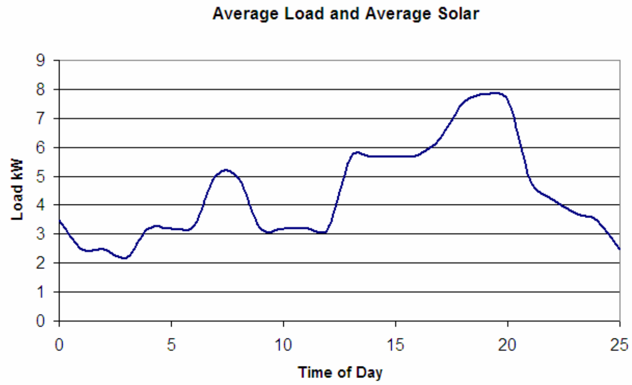

Fig. 7. Real load of a typical residential house over 24 hours.

Considering the randomness in this paper, artificial load values is generated by normal distribution, in which the mean values equals the real value, and the variance is chosen manually. The paper also studies the sensitivity of the variance values, which shows the changes of the load.

E. Economical Analysis

Economical analysis is an indispensable step in stand-alone solar system design, as the optimum design always requires a minimum cost, or most cost-effective design.

In traditional power system reliability cost analysis, the cost of reliability includes two parts: Utility Cost of Reliability and Customers Cost of Reliability [16]. Here we extend the concept of traditional reliability cost into stand-alone solar system. The Following costs should be considered during economical analysis:

1) *Investment cost*. Investment cost includes the cost of investment of solar panels, batteries, chargers, converters, necessary accessories, and the cost of mountings. Usually, solar panels and batteries take a large portion of cost, therefore the sizing of solar panel size and battery volume will influence the investment cost. Moreover, based on the assumption that only the battery will deteriorate and may need replacement, the investment cost will also include the cost of additional batteries and additional mounting cost. In this paper, it is assumed that after 20 years, the surplus values of all equipment are zero.

2) *Reliability cost*. In addition to investment cost, the cost associated with the loss of energy or outages should also be considered. Similar to traditional power system reliability cost [16], the cost of stand-alone solar system can also be expressed by equation (10):

$$\text{Cost of Reliability/year} = n \cdot C_{\text{outage}} + P_{\text{lost}} \cdot C_{\text{kWh}} \qquad (10)$$

Where,

n is the number of outages;

C_{outage} is the cost per outage ($/outage);

P_{lost} is the total energy lost (kWh);

C_{kWh} is the customer's cost of interrupted energy ($/kWh).

The value of C_{outage} and C_{kWh} can be obtained from past histories and surveys.

In this paper, as the application of the stand-alone solar system is for a typical residence usage, it is assumed that every interruption will cost $100 ($C_{\text{outage}}$=$10), and the cost of interrupted power is $10/kW ($C_{\text{kWh}}$=$1).

3) *Reliability benefits*. Similar to traditional power system, the normal operation of stand-alone power system will bring in benefit for customers. In addition, because of the promotion of the application of renewable energies, many governments will provide various incentives back for the usage of renewable power. One of which is by buying back electricity from customers who generate alternative energy, with higher price. In this paper, the reliability benefit is given as equation (11):

$$\text{Benefit of Reliability/year} = P_{\text{usage}} B_{\text{usage}} + P_{\text{extra}} B_{\text{extra}} \qquad (11)$$

Where,

P_{usage} is the energy used by load (kWh);

B_{usage} is the benefit from using 1kWh of energy ($/kWh);

P_{extra} is the extra energy generated, that can be sold to utilities (kWh);

B_{extra} is the benefit by selling 1kWh of energy ($/kWh).

In this paper, B_{usage} is assumed to be the same as the price of electricity bought from utilities, which is $0.07/kWh for

Lincoln; B_{extra} is assumed to be twice of the price of B_{usage}, which is \$0.2/kWh.

In this paper, in order to illustrate the proposed approach, several assumptions are made: 1) The cost of battery chargers, converters, wirings, mounting fees are neglected; 2) The cost of additional battery is neglected.

Based on these assumptions, the total cost of this application is: Investment Cost + Reliability Cost +Reliability Benefits.

V. CALCULATION PROCEDURE

Figure 8 shows the procedure for calculating reliability and battery life. Assuming the solar panel's controllers and inverters for charging and discharging the battery are 100 % reliable, there is no maintenance on all of these components. Calculation of the simulated operation history, including battery state of charge, energy used by load, outages and its durations, extra energy sold follows these cases:

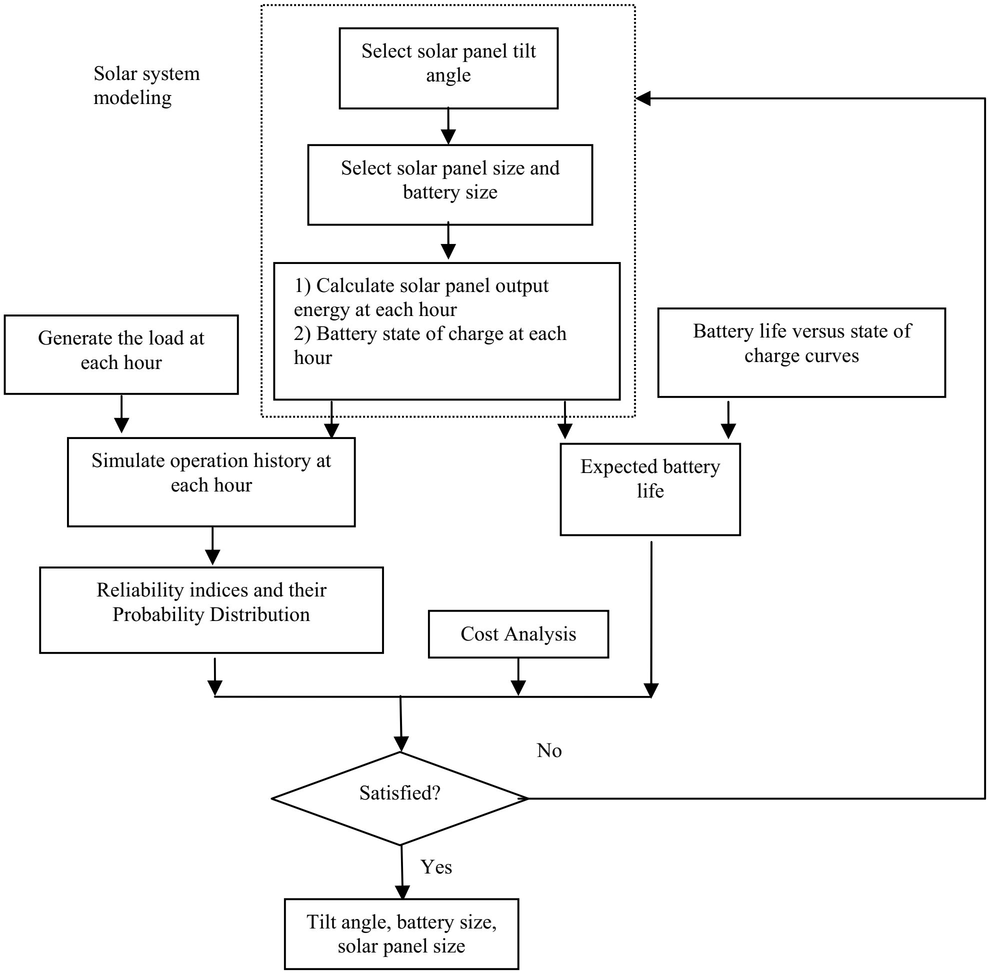

Fig.8. The flowchart of the stand-alone solar system of reliability and battery life calculation

Define,

G_{i_solar}= Current generated solar energy at current hour i;
$B_{i\text{-}1}$= Energy stored in battery at previous hour i-1;
B_i= Energy stored in battery at current hour i;
B_{volume} = Battery volume;
L_i= Amount of load at current hour i;
E_{i_sold}= Extra energy sold at current hour i;
E_{i_used} = Energy used at current hour i;
E_{i_lack}= Energy lacked at current hour i.

Case 1:

If solar energy generated in current hour plus the battery stored energy in previous hour is higher than the current load, and the extra energy is *less* than battery volume, which can be expressed as

$$G_{i\_solar} + B_{i\text{-}1} > L_i, \text{ and } G_{i\_solar} + B_{i\text{-}1} - L_i < B_{\text{volume}}$$

Then:

There is no outage;
E_{i_lack} =0;
$B_i = G_{i\_solar} + B_{i\text{-}1} - L_i$;
$E_{i\_\text{used}} = L_i$;
E_{i_sold} =0.

Case 2:

If the solar energy generated in current hour plus the battery stored in previous hour is higher than the load in current hour, and the extra energy is *larger* than battery volume, which can be expressed as:

$$G_{i\_solar} + B_{i\text{-}1} > L_i, \text{ and } G_{i\_solar} + B_{i\text{-}1} - L_i > B_{\text{volume}}$$

Then:

there is no outage;

$E_{i\_\text{lack}} = 0$;

$B_i = B_{\text{volume}}$

$E_{i\_\text{used}} = L_i$;

$E_{i\_\text{sold}} = G_{i\_solar} + B_{i\text{-}1} - L_i - B_{\text{volume}}$.

Case 3:

If the load in current hour is larger than the solar energy generated in current hour plus the battery stored energy in previous hour which can be expressed as

$$G_{i\_solar} + B_{i\text{-}1} < L_i$$

Then:

there is outage;

$E_{i\_\text{lack}} = 0$;

$B_i = 0$;

$E_{i\_\text{used}} = G_{i\_solar} + B_{i\text{-}1}$;

$E_{i\_\text{sold}} = 0$.

After obtaining the operation history data, the reliability indices, expected battery life/cycle, and expected cost/benefit can be calculated.

VI. RESULTS

In a stand-alone solar system, there are various parameters that need to be determined to maximize the reliability and minimize the load. In this paper, the solar panel tilt angle, the battery size, and the solar panel size, are chosen to be studied, because those parameters are usually difficult to determine, in a given application. This paper also studies the impact of load variance toward the model results.

A. Impact of solar panel tilt angle

Assuming the load variance is 10%, the battery size is $250 \cdot 265 = 795000$ Ah, the solar panel size is $400 \cdot 0.687772 = 275$ m^2, the tilt angle is changed from latitude minus 20º to latitude plus 20º. The reliability and battery life are studied. Table 1 shows the results of the reliability, battery life, and expected cost. Figures 9 and 10 show the results of battery state of charge curves under tilt angle equals latitude minus 10º and plus 10º degrees.

Figures 9 and 10 shows that the slightly varying of tilt angle will greatly change battery SoC curve, especially during winter time. This is true as the in the winter time, the directly beam insolation is less comparing with summer time. The less generated solar out will result in the lower SoC value for battery. From economy perspective, Table 1 also shows that various tilt angle values will bring in different benefits.

TABLE 1 VARYING THE SOLAR PANEL TILT ANGLE

Tilt angle	Expected cost			Reliability			Expected Battery life	
	Investment ($)	Benefit ($)	Total Cost ($)	Availability	Fail.Rate(/year)	Durations	Mean of SOC	Life (cycles)
Φ + 20	280000	4345.320749	198896	0.992808219	6	10.5	0.83685	4126.73309
Φ + 10	280000	4974.289863	186320	0.992808219	6	10.5	0.842035	4255.81408
Φ +0	280000	5418.93539	179783	0.990296804	8	10.625	0.833472	4044.82342
Φ -10	280000	5678.200113	179242	0.983447489	12	12.08333	0.805721	3433.63463
Φ- 20	280000	5759.174251	185372	0.973401826	20	11.65	0.755658	2578.93421

TABLE 2 RESULTS OF CHANGING OF THE BATTERY SIZE AND PANEL SIZE

Solar Panel Size (m2)	Battery Size (Ah)	Expected cost			Reliability			Expected Battery life	
		Investment ($)	Benefit ($)	Total Cost ($)	Availability	Fail. Rate (/year)	Durations	Mean of SOC	Life (cycles)
275	79500	280000	5419.350923	179768	0.990296804	8	10.625	0.833453	4044.35672
261	699600	258300	4940.838079	175631	0.979452055	15	12	0.792381	3176.61196
288.8	731400	279700	5924.384094	165649	0.994406393	5	9.8	0.852756	4535.85559
247.59	604200	236600	4463.392724	171544	0.968721461	20	13.7	0.74827	2476.46481

TABLE 3 THE SYSTEM RELIABILITY AND BATTERY LIFE UNDER DIFFERENT LOAD VARIANCE VALUES

Load Variance	Expected cost			Reliability			Expected Battery life	
	Investment ($)	Benefit ($)	Total Cost ($)	Availability	Failure Rate (/year)	Durations	Mean of SOC	Life (cycles)
0.01	280000	5220.541166	182342	0.991780822	7	10.28571	0.839422	4190.25202
0.05	280000	5220.435264	182343	0.991780822	7	10.28571	0.83945	4190.9464
0.1	280000	5220.627957	182332	0.991780822	7	10.28571	0.839504	4192.30177

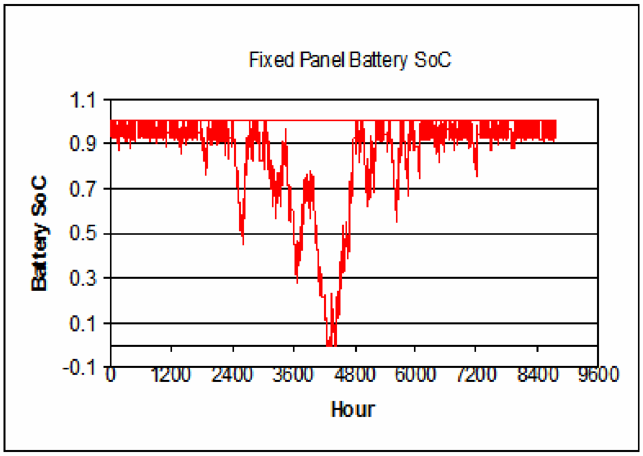

Fig.9. The battery SoC history curve. The tilt angle is $\Phi + 10^{o}$

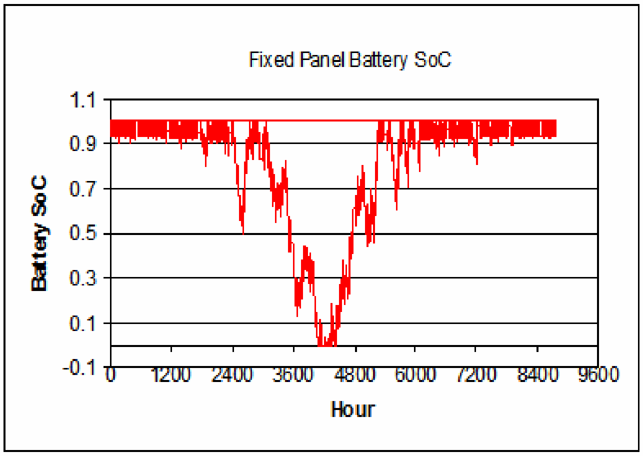

Fig.10. The battery SoC history curve. The tilt angle is Φ -10^{o}

B. *Impact of battery size and panel size*

Table 2 shows the results of changing the battery size and panel size, when the load variance is 0.1, and the tilt angle is Φ degrees. Figures 11 and 12 are the corresponding Figures of battery SoC curves.

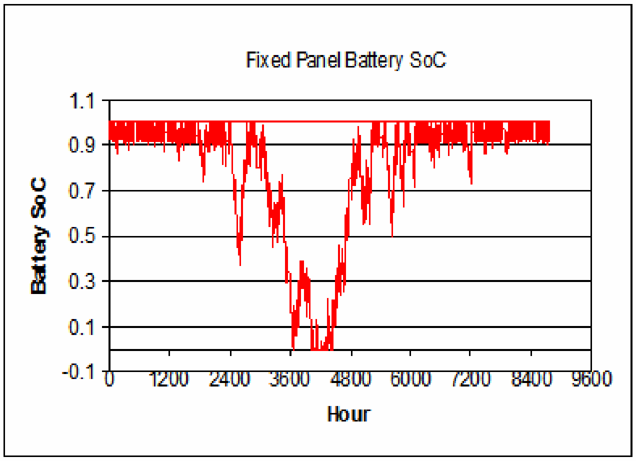

Fig.11. The battery SoC history curve, when the battery volume is 699600 Ah and solar panel size is 261 m^2

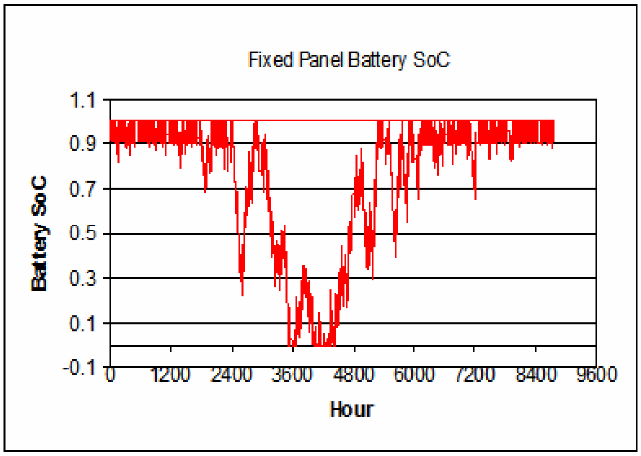

Fig.12. The battery SoC history curve, under battery volume of 604200Ah and solar panel size of 247.59m^2

Figures 9 and 10 demonstrate that the selection of battery and solar panel size will greatly influence the battery SoC. Under the same size of battery, the higher solar panel size will result in higher average SoC values, as well as the benefits. In the mean while, it will also improve the investments cost. Therefore, it is important for design engineers to varying the solar panel size and battery volume data for this model, and determine the optimum values, based on specific application, such as economy orientated, life orientated, or reliability orientated.

C. *The impact of the load variance*

The load variance should also be examined in order to make sure the system is reliable when the load is different from the design. Table 3 shows the system reliability and battery life under various load variance values. Assuming battery number is 400 (total 795000Ah), solar panel number is 250(total 275.1088m^2), and the tilt angle is latitude plus 5 degrees.

From Table 3, the variation of load does not change the battery life, reliability, or economical values greatly. The reason is, comparing with the mount of the variation of solar insolation input and temperature, the variation of load is much less. Therefore, during practical design, the focus should be imposed on solar panel & battery size, and solar panel position (tilt angle) determination.

VII. CONCLUSION

The stand-alone solar system sizing design depends on many variables such as solar panel size, battery volume, tile angle, which needs to be determined during design. The variation of variables will have direct impact towards the system reliability, the battery expected life/cycles, and the expect benefit/cost. For different applications, such as reliability-orientated designs or cost-orientated designs, the selections of optimum combinations of those parameters are different.

In addition, similar as traditional power system design, reliability evaluations as well as economical analysis should be considered during the planning and design phases of the system, rather than after the system has been built.

ACKNOWLEDGEMENT

The authors are grateful to Dr. Dean Patterson at UNL for valuable insights and advices.

REFERENCE

[1] Burgio, A.; Menniti, D.; Picardi, C.; Pinnarelli, A., "A novel integrated configuration of Grid-connected photovoltaic plant with UPS: reliability estimation," *Clean Electrical Power, 2007. ICCEP '07. International Conference on* , vol., no., pp.142-147, 21-23 May 2007

[2] Kenji Otani; Takumi Takashima; Kosuke Kurokawa, "Performance and Reliability of 1 MW Photovoltaic Power Facilities in AIST," *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on* , vol.2, no., pp.2046-2049, May 2006

[3] Adelstein, J.; Sekulic, B., "Performance and reliability of a 1-kW amorphous silicon photovoltaic roofing system," *Photovoltaic Specialists Conference, 2005. Conference Record of the Thirty-first IEEE* , vol., no., pp. 1627-1630, 3-7 Jan. 2005

[4] Saengthong, S.; Premrudeepreechacham, S., "A simple method in sizing related to the reliability supply of small stand-alone photovoltaic systems," *Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE* , vol., no., pp.1630-1633, 2000

[5] Jain, A.; Jaeho Choi; Byoungjin Kim, "Impact of integrating the photovoltaic and wind energy sources on generation system reliability and operation economics," *Power System Technology, 2002. Proceedings. PowerCon 2002. International Conference on* , vol.4, no., pp. 2437-2442 vol.4, 2002

[6] Wohlgemuth, J.H.; Conway, M.; Meakin, D.H., "Reliability and performance testing of photovoltaic modules," *Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE* , vol., no., pp.1483-1486, 2000

[7] Bagen; Billinton, R., "Evaluation of Different Operating Strategies in Small Stand-Alone Power Systems," *Energy Conversion, IEEE Transaction on* , vol.20, no.3, pp. 654-660, Sept. 2005

[8] Bagen; Billinton, R., "Incorporating well-being considerations in generating systems using energy storage," *Energy Conversion, IEEE Transaction on* , vol.20, no.1, pp. 225-230, March 2005

[9] Billinton, R., Bagen, "Incorporating reliability index distributions in small isolated generating system reliability performance assessment," *Generation, Transmission and Distribution, IEE Proceedings-* , vol.151, no.4, pp. 469-476, 11 July 2004

[10] Billinton, R., Bagen, "Reliability Considerations in the Utilization of Wind Energy, Solar Energy and Energy Storage in Electric Power Systems," *Probabilistic Methods Applied to Power Systems, 2006. PMAPS 2006. International Conference on* , vol., no., pp.1-6, 11-15 June 2006

[11] Stuart R. Wenham, Martin A. Green, Muriel E. Watt, and Richard Corkish, *Applied Photovoltaics*, Earthscan Publications Ltd. Feb, 2007

[12] User’s Manual for TMY2s. http://rredc.nrel.gov/solar/pubs/tmy2/tab3-2.html

[13] Matrix PW 750-12V PV Module http://www.solarelectricsupply.com/Solar_Panels/Matrix/PW750.html

[14] Deka 8G8D LTP Battery http://www.mrsolar.com/pdf/MK_Battery/MK_8G8D-LTP.pdf

[15] Corrigan P. M., Heydt G.T., “Optimized Dispatch of a Residential Solar Energy System”, IEEE NAPS07 Conference

[16] Brown R. E., Venkata S.S., “Predictive Distribution Reliability and Risk Assessment”, *IEEE Tutorial Course Probabilistic T&D System Reliability Planning*, 07TP182, pp:29-36, 2007