# A new methodology for sizing hybrid photovoltaic-wind energy system using simulation and optimization tools

**Carlos Eduardo Camargo Nogueira[1]*, Hans Helmut Zürn[2] and Samuel Nelson Melegari de Souza[1]**

*[1]Centro de Ciências Exatas e Tecnológicas, Universidade Estadual do Oeste do Paraná, Rua Universitária, 1619, Jardim Universitário, 85814-110, Cascavel, Paraná, Brasil. [2]Centro Tecnológico, Laboratório de Sistemas de Potência, Universidade Federal de Santa Catarina, Campus Universitário, Trindade, 88040-900, Florianópolis, Santa Catarina, Brasil. *Autor para correspondência. e-mail: cecn@correios.net.br*

**ABSTRACT.** This paper presents a new methodology for sizing an autonomous photovoltaic-wind hybrid energy system with battery storage, using simulation and optimization tools. The developed model is useful for energizing remote rural areas and produces a system with minimum cost and high reliability, based on the concept of Loss of Power Supply Probability (LPSP) applied for consecutive hours. Some scenarios are calculated and compared, using different numbers of consecutive hours and different LPSP values. As a result, a complete sizing of the system and a long-term cost evaluation are presented.

**Key words:** hybrid energy system, sizing methodology, system optimization.

**RESUMO. Uma nova metodologia para dimensionamento de sistemas híbridos de energia (solar-eólica) utilizando ferramentas de simulação e otimização.** Este trabalho apresenta uma nova metodologia para dimensionamento de sistemas híbridos de energia (solar-eólica) com armazenamento em banco de baterias, utilizando ferramentas de simulação e otimização. O modelo desenvolvido é útil para a energização de áreas rurais isoladas e resulta num sistema com custo mínimo e alta confiabilidade, baseado no conceito de perda de fornecimento de energia à carga (LPSP) aplicado para horas consecutivas. Alguns cenários são calculados e comparados, utilizando-se diferentes períodos de horas consecutivas e diferentes valores de LPSP. Os resultados apresentam um dimensionamento completo do sistema e uma avaliação de custos ao longo de vários anos.

**Palavras-chave:** sistemas híbridos de energia, metodologia de dimensionamento, otimização de sistemas.

## Introduction

Renewable energy resources, as solar radiation and wind power, are vast, and unlike the fossil fuels, they are very well distributed all over the world. The main problem associated with them is their diluted nature and the consequent necessity of high cost equipment to convert them into usable forms. In spite of the energy resources being free, their extraction is not. Economic considerations, quality and type of necessary energy to supply the final consumer needs have an important role in the selection of the technology.

Much work has been done to calculate the sizing of renewable energy systems. Optimization models of systems are proposed by Ramakumar *et al*. (1986), Khella (1997) and Cormio *et al*. (2003). Probabilistic calculations, involving the loss of power supply probability (LPSP) as a measure of reliability, are used by Ofry and Braunstein (1983), Klein and Beckman (1987) and Borowy and Salameh (1996). Methods for sizing hybrid energy systems (photovoltaic/wind), with emphasis on the cost and/or performance of the system, are presented by Beyer and Langer (1996), Protogeropoulos *et al*. (1997) and Celik (2003).

The solar radiation and wind speed data, as well as their statistical treatment, are necessary for the correct sizing of the energy system and have also been object of several studies (Knight *et al*., 1991; Pissimanis *et al*., 2000; Santos *et al*., 2003).

This paper presents a new methodology for sizing hybrid energy systems (photovoltaic/wind), using tools that guarantee a minimum cost and a desired reliability. Hourly data of load, solar radiation, wind speed, and parameters regarding PV modules, wind turbines and batteries, as well as economic parameters, are used in the sizing methodology. The details used for sizing equipment, associated with the developed methodology, give the present model great robustness and very reliable results.

## Material and methods

### Model formulation

The developed sizing model minimizes the total cost of the energy conversion equipment (PV modules, wind turbines and batteries), taking into account the desired reliability of the system. This reliability is represented by the maximum loss of power supply probability (LPSPmax) desired for the project. A loss of power supply probability equal to zero means that the consumer demand will always be satisfied, while a value equal to one means that it will never be satisfied (Ofry and Braunstein, 1983).

An iterative procedure to calculate the optimal sizing of the energy system was developed in MATLAB 6.0, and a flowchart is presented in Figure 1. The procedure presents the following steps:

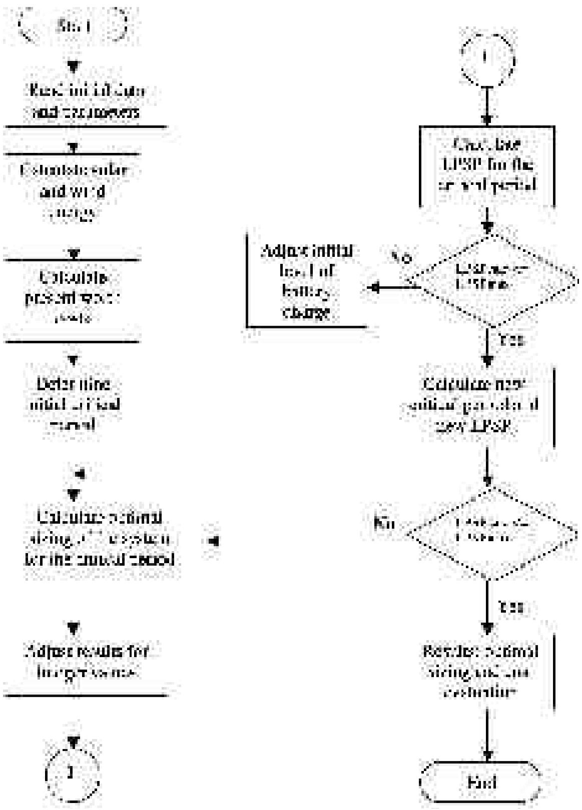

**Figure 1.** Procedure for the energy system optimal sizing

I) Read hourly data of load, solar radiation and wind speed, as well as the energy conversion equipment parameters and economic parameters that will be used in the methodology.

II) Calculate for every hour of the year the solar and wind energy generated by the energy conversion devices (Rauschenbach, 1980; Powel, 1980).

III) Calculate the present worth costs of the equipment (Willis and Scott, 2000).

IV) Determine the initial critical period for the procedure, considered as being a number of consecutive hours where the largest loss of power supply occurs, using a preliminary comparison between the available load data and the calculated solar and wind energy.

V) Calculate the optimal sizing of the system (number of PV modules, wind turbines and batteries) for the established critical period. The optimization model uses linear programming to minimize the system cost and to comply with the desired LPSPmax, as presented in Item 2.1. The algorithm used to solve the linear programming is based on a primal-dual interior point method. The use of the LPSP for critical periods is important to avoid those eventual energy deficits that become concentrated on short periods, causing possible inconveniences to the consumer. Thus, along the whole year, there will be no single period - with an established number of consecutive hours - presenting a LPSP larger than that desired for the project.

VI) Adjust the results for integer values, using the bifurcation and limit algorithm (Bronson, 1982).

VII) Calculate the LPSP for the critical period (Borowy and Salameh, 1996), using the results obtained in step VI and all available data of load and energy generation. If $LPSP_{CALC} \le LPSP_{MAX}$ go to step IX. Otherwise, go to step VIII.

VIII) Adjust the level of battery charge, defined for the beginning of the critical period. The parameter used to represent the battery charge level can vary from 1 (initial value for completely charged batteries) to zero (completely discharged batteries), in intervals of 0.005. This adjustment is necessary because the optimal sizing of the system is carried out for the critical period, and the batteries are considered as being completely charged in the beginning of this period. As this fact may be not true, it is important that the initial level of the battery charge decreases progressively, so that the equipment sizing and the calculated LPSP can also be adjusted, increasing the first and decreasing the second. With the adjustment settled, return to step V.

IX) Calculate the new critical period, comparing deficits of energy for all periods of the year, using the results obtained in steps V, VI and VII. With this new period, calculate LPSP again. If

$LPSP_{CALC} \leq LPSP_{MAX}$ go to step X. Otherwise, return to step V.

X) Results: optimal sizing of the system and cost evaluation.

## Optimization model

The optimization model is:

Minimize $c\,x'$ (1)

$$\text{Subject to} \begin{cases} A\,x' \leq b \\ x \geq 0 \end{cases} \quad (2)$$

The objective function to be minimized consists of the sum of the present worth costs of all energy conversion devices (PV modules, wind turbines and batteries). It is expressed as:

$$c_{(1,2n+3)} = \begin{bmatrix} c_1 & c_2 & c_3 & \overbrace{0 \cdots 0}^{2n} \end{bmatrix} \quad (3)$$

$$x_{(1,2n+3)} = \begin{bmatrix} x_1 & x_2 & x_3 & \overbrace{x_4 \cdots x_{n+3}}^{n} & \overbrace{x_{n+4} \cdots x_{2n+3}}^{n} \end{bmatrix} \quad (4)$$

where:

$\mathbf{c_1}$, $\mathbf{c_2}$ and $\mathbf{c_3}$ are the present worth costs of the PV module, wind turbine and battery, respectively;

$\mathbf{x_1}$, $\mathbf{x_2}$ and $\mathbf{x_3}$ are the quantities of this equipment;

**n** is the number of consecutive hours for which the LPSPmax is considered;

$\mathbf{x_4}$ to $\mathbf{x_{n+3}}$ are the variables that control the LPSPmax ;and

$\mathbf{x_{n+4}}$ to $\mathbf{x_{2n+3}}$ are the variables that allow the occurrence of energy surplus.

The constraints are represented by matrix **A** and **b**, expressed as follows:

$$A_{(2n+1,2n+3)} = \begin{bmatrix} -AA' & -BB' & -(ka.CC)' & -DD & DD \\ AA' & BB' & (ka.CC-CC)' & DD & -DD \\ & & KK & & \end{bmatrix} \quad (5)$$

$$b_{(2n+1,1)} = \begin{bmatrix} -LL' \\ LL' \\ LPSPmax.\sum_{i=1}^{n} Lh_i \end{bmatrix} \quad (6)$$

where:

$$AA_{(1,n)} = \begin{bmatrix} Eh1_1 & \sum_{i=1}^{2} Eh1_i & \sum_{i=1}^{3} Eh1_i & \cdots & \sum_{i=1}^{n} Eh1_i \end{bmatrix} \quad (7)$$

$$BB_{(1,n)} = \begin{bmatrix} Eh2_1 & \sum_{i=1}^{2} Eh2_i & \sum_{i=1}^{3} Eh2_i & \cdots & \sum_{i=1}^{n} Eh2_i \end{bmatrix} \quad (8)$$

$$CC_{(1,n)} = \begin{bmatrix} \overbrace{Eb \cdots Eb}^{n} \end{bmatrix} \quad (9)$$

$$Eb = Cbat \,.\, Ddbat \,.\, Efbat \quad (10)$$

$$DD_{(n,n)} = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 1 & 1 & 0 & \cdots & 0 \\ 1 & 1 & 1 & \cdots & 0 \\ \vdots & & & \ddots & \vdots \\ 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \quad (11)$$

$$LL_{(1,n)} = \frac{\begin{bmatrix} Lh_1 & \sum_{i=1}^{2} Lh_i & \sum_{i=1}^{3} Lh_i & \cdots & \sum_{i=1}^{n} Lh_i \end{bmatrix}}{Efinv} \quad (12)$$

$$KK_{(1,\,2n+3)} = \begin{bmatrix} 0 & 0 & 0 & \overbrace{1 \cdots 1}^{n} & \overbrace{0 \cdots 0}^{n} \end{bmatrix} \quad (13)$$

where:

**ka** is the value concerning the battery charge level (it may vary from 1 to zero);

**Lh** is the hourly energy consumption (kWh);

**Eh1** and **Eh2** are the generated hourly energy for the PV module and wind turbine, respectively (kWh);

**Cbat** is the energy storage capacity of the battery (kWh);

**Ddbat** is the discharge depth of the battery;

**Efbat** is the battery round-trip efficiency; and

**Efinv** is the inverter efficiency.

Observing matrices **A** and **b**, the existence of three constraints for the optimization model can be verified. The first constraint establishes that the process of discharging batteries, which occurs when the demanded energy exceeds the generated energy, should be limited to the maximum battery discharge depth. This procedure protects batteries against damages and drastic decrease of their lifetime. If this limit is reached, and the demanded energy goes on exceeding the generated energy, an energy deficit will occur. The second constraint establishes that the process of charging the batteries, which occurs when the generated energy exceeds the demanded energy, should be limited by the maximum level of energy supported by the battery. In this case, a surplus production of energy, which will not be stored, may occur. An electronic charge controller must be used to control the battery charge limits. The surplus energy production can be dissipated through resistors and used to heat water. The third constraint establishes the maximum deficit of energy allowed, quantified by the LPSPmax. Therefore, both deficit and surplus of energy may occur, due to the matrix DD. The deficit is controlled by the LPSPmax, which represents the reliability of the system, and the surplus is adjusted to guarantee the best resource-need combination along the year, resulting in a system with minimum cost.

## Results

The developed procedure is used to calculate the optimal size of a solar-wind hybrid energy system, for a small rural property located in Southern Brazil, with an hourly load varying from zero to 12 kW along the year. Long-term data of solar radiation and wind speed recorded for every hour of the day are used to calculate the generated energy. The parameters regarding the equipment of energy conversion, as well as economic parameters, are presented as follows:

I) PV module. Manufacturer and model: Kyocera LA51; maximum power: 0.051 kW; voltage at maximum power: 16.9 V; open circuit voltage: 21.2 V; current at maximum power: 3.02 A; short circuit current: 3.25 A; current coefficient at reference radiation: 0.0016 A/°C; voltage coefficient at reference radiation: 0.144 V/°C; initial cost: $ 5000 /kW; maintenance cost: $ 0.005 /kWh and lifetime: 20 years.

II) Wind turbine. Manufacturer and model: Vergnet GEV4; maximum power: 1.1 kW; generation voltage: 220 V; rotor diameter: 4 m; minimum wind speed for energy generation: 2.5 m/s; nominal wind speed, after which the generation is constant: 10 m/s; maximum wind speed for energy generation: 22 m/s; initial cost: $ 1800 /kW; maintenance cost: $ 0.012 /kWh and lifetime: 20 years.

III) Battery. Type: Deep cycle lead-acid; energy storage capacity: 1.2 kWh (100 Ah, 12 V); depth of discharge: 0.8; round-trip efficiency: 0.85; initial cost: $ 100 /kWh and lifetime: 4 years.

IV) Other parameters. Inverter efficiency: 0.9; annual discount rate: 0.12 and period of economic analysis: 20 years.

Using all these data and parameters, the optimal sizing of the system is calculated and the results are presented in Tables 1 and 2.

Table 3 presents a cost evaluation for Scenario 2, considering a period of 20 years. In this Table**, IC** is the initial cost of the equipment, **MC** is the system operation and maintenance annual costs, **TC** is the total cost of the system, obtained by the sum of the two previous columns, **PWF** is the present worth factor for each year, used to compute discounted annual costs and discounted annual energy consumption (Willis and Scott, 2000), **DC** is the result of the product of the two previous columns, **EC** is the annual energy consumption (kWh) and **DE** is the result of the product of PWF and EC.

**Table 1.** Results of the system optimal sizing for scenarios 1, 2 and 3 (period length of 50, 100 and 150 hours), considering a LPSPmax of 5%.

| | Scenario 1 (n=50h) | Scenario 2 (n=100h) | Scenario 3 (n=150h) |
|---|---|---|---|
| Number of PV modules | 1 | 0 | 1 |
| Number of wind turbines | 22 | 22 | 21 |
| Number of batteries | 66 | 58 | 56 |
| Generated energy (kWh/year) | 56462 | 56384 | 53902 |
| Useful energy (kWh/year) | 24783 | 24755 | 24738 |
| Surplus energy (kWh/year) | 31679 | 31629 | 29164 |
| Deficit of energy (kWh/year) | 12 | 40 | 57 |
| Total load (kWh/year) | 24795 | 24795 | 24795 |
| Total cost of the project ($) | 78260 | 74823 | 71935 |
| Evaluated cost ($/kWh) | 0.289 | 0.276 | 0.266 |

## Discussion

The sizing of the system was carried out considering different scenarios, presented in Tables 1 and 2. Scenarios 1, 2 and 3 (Table 1) are characterized by the different periods of consecutive hours (periods of 50, 100 and 150 hours) used for the optimal sizing of the system, considering an LPSPmax of 5%. Scenario 1 (n = 50 hours) presents a more robust sizing of the system (more equipment and higher costs) with a lower annual deficit of energy, when compared with other scenarios. It happens because scenario 1 uses a smaller critical period length, for which the LPSPmax must be respected. That is, for any period of 50 consecutive hours along the year, only 5% of the load can be unattended. In fact, most of the periods will present an energy deficit less than 5%, and only one (maybe more) will present a deficit equal to 5% (critical period). As the period length increases (scenarios 2 and 3, with periods of 100 and 150 hours, respectively), the energy deficit tends to become more concentrated in some hours of the year, permitting a less robust sizing of the system. In the case of an 8760 hours period, for example, the energy deficit would be equal to 309.94 kWh (5% of the total annual load), representing the least robust system (the cheapest one). However, this deficit would probably be too concentrated in some hours of the year, which may not be interesting to the consumer.

**Table 2.** Results of the system optimal sizing for scenarios 4, 5 and 6 (LPSPmax of 0%, 5% and 10%), considering a period length (n) of 72 hours.

| | Scenario 4 (LPSPmax=0%) | Scenario 5 (LPSPmax=5%) | Scenario 6 (LPSPmax=10%) |
|---|---|---|---|
| Number of PV modules | 1 | 0 | 0 |
| Number of wind turbines | 23 | 22 | 21 |
| Number of batteries | 72 | 63 | 57 |
| Generated energy (kWh/year) | 59022 | 56384 | 53824 |
| Useful energy (kWh/year) | 24795 | 24772 | 24742 |
| Surplus energy (kWh/year) | 34227 | 31612 | 29082 |
| Deficit of energy (kWh/year) | 0 | 23 | 53 |
| Total load (kWh/year) | 24795 | 24795 | 24795 |
| Total cost of the project ($) | 82998 | 76809 | 72072 |
| Evaluated cost ($/kWh) | 0.306 | 0.283 | 0.266 |

**Table 3.** Cost evaluation for Scenario 2.

| Year | IC | MC | TC | PWF | DC | EC | DE |
|---|---|---|---|---|---|---|---|
| 1 | 50520.00 | 676.46 | 51196.46 | 1.000 | 51196.46 | 22279.65 | 22279.65 |
| 2 | 0.00 | 676.46 | 676.46 | 0.943 | 638.17 | 22279.65 | 21018.54 |
| 3 | 0.00 | 676.46 | 676.46 | 0.890 | 602.05 | 22279.65 | 19828.81 |
| 4 | 0.00 | 676.46 | 676.46 | 0.840 | 567.97 | 22279.65 | 18706.42 |
| 5 | 6960.00 | 676.46 | 7636.46 | 0.792 | 6048.79 | 22279.65 | 17647.57 |
| 6 | 0.00 | 676.46 | 676.46 | 0.747 | 505.49 | 22279.65 | 16648.65 |
| 7 | 0.00 | 676.46 | 676.46 | 0.705 | 476.88 | 22279.65 | 15706.27 |
| 8 | 0.00 | 676.46 | 676.46 | 0.665 | 449.89 | 22279.65 | 14817.24 |
| 9 | 6960.00 | 676.46 | 7636.46 | 0.627 | 4791.21 | 22279.65 | 13978.53 |
| 10 | 0.00 | 676.46 | 676.46 | 0.592 | 400.40 | 22279.65 | 13187.29 |
| 11 | 0.00 | 676.46 | 676.46 | 0.558 | 377.73 | 22279.65 | 12440.84 |
| 12 | 0.00 | 676.46 | 676.46 | 0.527 | 356.35 | 22279.65 | 11736.64 |
| 13 | 6960.00 | 676.46 | 7636.46 | 0.497 | 3795.09 | 22279.65 | 11072.30 |
| 14 | 0.00 | 676.46 | 676.46 | 0.469 | 317.15 | 22279.65 | 10445.57 |
| 15 | 0.00 | 676.46 | 676.46 | 0.442 | 299.20 | 22279.65 | 9854.31 |
| 16 | 0.00 | 676.46 | 676.46 | 0.417 | 282.26 | 22279.65 | 9296.52 |
| 17 | 6960.00 | 676.46 | 7636.46 | 0.394 | 3006.07 | 22279.65 | 8770.30 |
| 18 | 0.00 | 676.46 | 676.46 | 0.371 | 251.21 | 22279.65 | 8273.87 |
| 19 | 0.00 | 676.46 | 676.46 | 0.350 | 236.99 | 22279.65 | 7805.54 |
| 20 | 0.00 | 676.46 | 676.46 | 0.331 | 223.58 | 22279.65 | 7363.71 |
| Total | | | 74822.98 | | | | 270878.57 |
| Evaluated cost ($/kWh): 0.276 | | | | | | | |

Table 2 presents scenarios 4, 5 and 6, characterized by the different LPSP values desired for the project (LPSPmax equal to 0, 5 and 10%), considering a period length of 72 hours. As expected, the more the LPSPmax increases, the more energy deficit will occur. Consequently, the project will become less robust, with lower costs and lower energy production.

In Table 3, the sums presented at the end of column 6 (DC) and column 8 (DE) represent, respectively, the total discounted cost of the system ($) and the total discounted energy consumption (kWh). The ratio of these values indicates the cost per unit of useful energy ($/ kWh) calculated for the system. This value can be used to compare economically all different scenarios.

A cost curve for photovoltaic and wind generation system, considering Scenario 2, is presented in Figure 2. In this figure, the cost of energy ($/ kWh) is calculated using the equipment initial cost, the maintenance cost, the lifetime, the load factor and the annual discount rate. The cost of energy calculated for the photovoltaic system is $ 0.271 / kWh and for the wind system is $ 0.076 / kWh, showing that the latter has a larger economic feasibility.

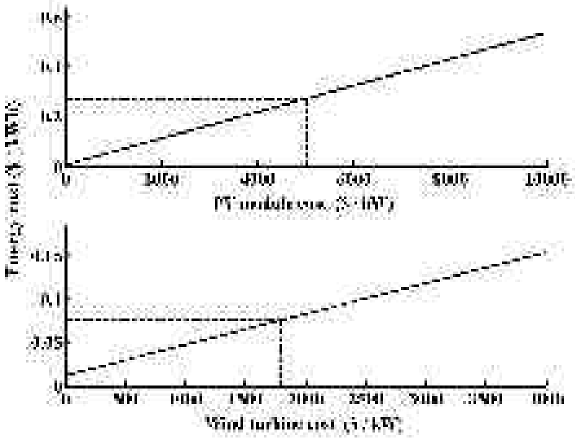

**Figure 2.** Costs for photovoltaic and wind generation system (Scenario 2).

The battery charge level for the critical period, considering Scenario 2, is presented in Figure 3. The zero charge level, located on the y-axis, represents the maximum discharge depth allowed for the battery. A charge level below that line indicates that no more energy is being supplied for the system (occurrence of energy deficit).

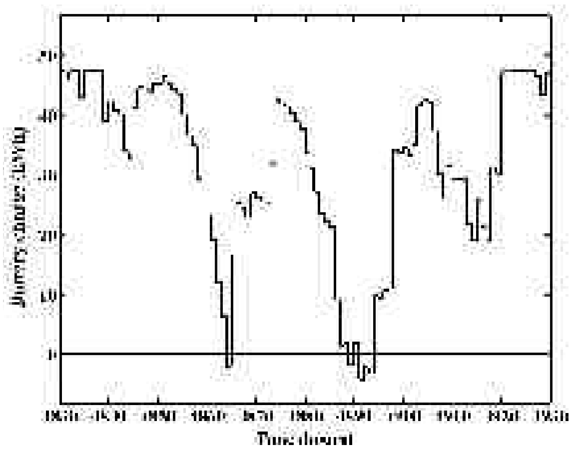

**Figure 3.** Level of battery charge for the critical period (Scenario 2).

## Conclusion

The developed model for sizing hybrid energy systems presents a new calculation methodology, based on simulation and optimization tools.

The model uses the concept of loss of power supply probability (LPSP) to establish the reliability of the system, which is applied for periods of consecutive hours, and guarantees a system with minimum cost.

Some examples to calculate the optimal sizing of the system are presented, varying the number of consecutive hours and the LPSPmax desired for the project. Increasing these parameters (period length and LPSPmax), an increase of the energy deficit will occur, resulting in a less robust sizing.

The obtained results are quite detailed, and include, besides the optimal sizing of the system, the total values of the generated, useful, surplus and lack of annual energy. A cost evaluation is also presented for the system, as well as the behavior of the battery charge for the critical period.

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