A Novel Method for Optimal Calculation of Stand-Alone Renewable Energy Systems

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Abstract: - Nowadays, the development and use of clean energy sources are receiving strong attention all over the world. However, the current methods used to calculate the design of these systems have proved unconvincing when the optimization is performed by "soft" optimization, and there are certain defects. In this paper, a new method for more robust optimization of independent renewable energy systems is proposed, in which the essential elements of the system such as energy characteristics are obtained in the reality of renewable energy generators or weather changes over time of the year are also considered to solve the problem of optimizing the energy system more efficiently, meet the demand for efficient energy use and optimize consumer investment costs.

Key-Words: Renewable energy generator, Stand-alone system, Linear programming problem, Battery, Simplex-method.

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1 Introduction

Currently, the use of independent renewable energy systems is gaining wide attention because of its undeniable advantages, such as reducing carbon emissions, environmental pollution, climate change, etc. This system can be found everywhere, such as power supply systems for remote areas, islands where the power grid is difficult to reach [1, 2]. In the transportation sector, they are used to build electric charging stations using renewable energy to charge electric vehicles, or in other fields [3-6], etc. There are many studies on optimizing these systems, but most of them are only done with "soft" optimization, i.e., systems that are optimized using control methods. based on previously selected system parameters [4-10]. The selection of installation parameters of these systems is mostly based on estimation because no specific calculation method is effective. That prompted us to find a more effective method in calculating the optimal design of the installation parameters of the independent energy system and this is also the main content of the paper.

In most of the research related to independent energy systems, we found [3,5-10] the authors gave different optimization methods, but most of them are soft optimization methods. The authors [3] performed a cost optimization calculation of the energy storage portion used in the stand-alone system. This has not shown the ability of the whole system to work effectively. The authors [5-11] have proposed optimal methods controlled by optimization algorithms or by combining different sources. However, in these articles, there is no mention of determining any installation parameters for the equipment used in the system. Soft optimization based on predetermined system parameters is just about finding the best performance of this system. Some other authors [9] mentioned the combined use of different energy sources but also did not give convincing calculation methods. In the work [10], some guidelines have been given for selecting lead-acid batteries for use in independent systems, and of course, a convincing calculation method has not been provided. All of this creates a defect in the overall optimization of the renewable energy system. In practice, it is not easy to determine the optimal system parameters. For an independent renewable energy system, this becomes even more difficult, because it is not possible to accurately determine the consumption characteristics of the load or the energy characteristics obtained in practice from renewable energy generators, which are highly dependent on weather conditions, and this is also the reason why it is difficult to find an efficient calculation method.

All the studies mentioned above on optimization of the systems are based on partial optimization (hard) or optimal control (soft). This is not convincing, to achieve complete optimization, all parameters of the system must be included in the specific calculation.

A thoroughly optimized energy system must include the optimization of installed equipment, and then incorporate intelligent control methods. In this paper, the authors present a more specific and detailed optimal calculation method used in the calculation and design of an independent renewable energy system, which compensates for the defect mentioned above. This method fully represents the calculation of the installed capacity of the storage devices and of the generators under a given load which is assumed to be predetermined. In practice, this assumption can be fully realized when the load graph can be built based on past energy consumption and future plans. In addition to calculating the installed capacity of the renewable energy generators, in this method, the captured energy characteristics of the wind and solar generators are included. These characteristics were obtained by the author from the electrical engineering laboratory of the Peter the Great St. Petersburg Polytechnic University and were used in the work [12]. This allows the optimal calculation of the system and the response to the energy consumption needs of the load more realistically and more suitable for different geographical areas. The optimal calculation of the investment cost of the system depends on many factors such as the manufacturer, the size of the system, etc. therefore the authors did not include it in this paper. However, this is completely possible based on the optimal installation parameters of the system.

The stand-alone system used to illustrate the proposed method consists of wind and solar generators, UPS, and consumer loads. To be more general, the consumed load consists of two parts, the fixed component is the important loads, and the variable component is the loads that can change the time of using electricity such as charging other equipment. For a simple problem description, the power loss on the device is considered negligible. This system is related to a project to study the possibility of installing a renewable energy system to replace gas turbine generators.

The results illustrating the proposed method shown in Figures 1-12 are extracted from countless relationships showing the system's ability to work in four seasons of the year. As can be seen easily in the next section, the system description function consists of 4 main variables (installed capacities of renewable energy generators and UPS capacity) which include a multitude of ingredient variables. For a graphical representation, some results are illustrated by specific parameters (installed capacity of wind and solar generators). From the results obtained, it is possible to accurately determine the optimal values of the devices used in the system. Combining this result with optimal control methods will allow the optimization of the energy system to be more thorough and rigorous.

2 Problem Formulation

The difficulties encountered in solving the energy problem as mentioned above are the nonlinearity of the energy problem. In this section, the linearization of the nonlinear energy problem and solving them by the linear programming method are presented in detail.

The mathematical model of the problem

- For batteries:

$$-P_{\text{sto min}} \le P_{\text{sto}}(t) \le P_{\text{sto max}}\,, \tag{1}$$

$$W_{\text{sto min}} \le W_{\text{sto}}(t) \le W_{\text{sto max}}\,, \tag{2}$$

here $P_{\text{sto}}(t)$ – total instant power of the batteries and $W_{\text{sto}}(t)$ – total instant capacity of the batteries; $P_{\text{sto min}}$; $P_{\text{sto max}}$; $W_{\text{sto min}}$ and $W_{\text{sto max}}$ – limits of power and energy of the batteries to its safety assurance.

$$W_{\text{sto}}(t) = \int_0^t P_{\text{sto}}(t)dt + W_{\text{sto}}(0)\,.$$

It should be noted that the maximum storage/converter capacity should be taken according to the charge/discharge limit of the. These limits are valid for each type of battery used [11-17]. $P_{\text{sto}}(t) > 0$ if at time t, the battery discharges electricity, and $P_{\text{sto}}(t) < 0$ if at time t, the battery charges.

If $W_{\text{sto}}(0) = 0$,

$$W_{\text{sto}}(t) = \int_0^t P_{\text{sto}}(t)dt \tag{3}$$

Limits of actual energy characteristics of generators:

$$0 \le P_{\text{solar}}(t) \le P_{\text{solar max}} \tag{4}$$

$$0 \le P_{\text{wind}}(t) \le P_{\text{wind max}} \tag{5}$$

where $P_{\text{solar max}}$ and $P_{\text{wind max}}$ – installed power of wind turbines and solar panels; $P_{\text{solar}}(t)$ and $P_{\text{wind}}(t)$ – actual power of wind turbines and solar panels.

$P_{\text{load}}(t)$ - The load instantaneous power consumption, consists of two components, as mentioned above $P_{\text{const}}(t)$, $P_{\text{var}}(t)$:

$$P_{\text{load}}(t)=P_{\text{const}}(t)+P_{\text{var}}(t) \tag{6}$$

Here $P_{\text{const}}(t)$ - Important load components; $P_{\text{var}}(t)$ - load element that can shift the moment of consumption.

The energy power consumption W_{load} from $t=0$ to $t=T$, here T - simulation interval, we have [16]:

$$W_{\text{load}}=\int_0^T P_{\text{load}}(t)dt=\int_0^T P_{\text{const}}(t)dt+\int_0^T P_{\text{var}}(t)dt=W_{\text{const}}+W_{\text{var}} \tag{7}$$

Equation of power balance [18]

$$P_{\text{solar}}(t)+P_{\text{wind}}(t)+P_{\text{sto}}(t)=P_{\text{load}}(t)$$

or

$$-P_{\text{var}}(t)+P_{\text{solar}}(t)+P_{\text{wind}}(t)+P_{\text{sto}}(t)=P_{\text{const}}(t) \tag{8}$$

Solving nonlinear equations with a variety of conditions as mentioned above by the analytic method has many difficulties, so we bring the above problem to a linear form.

We examine the column vectors $\mathbf{P}_{\text{sto}}$, $\mathbf{P}_{\text{solar}}$, $\mathbf{P}_{\text{wind}}$, $\mathbf{P}_{\text{var}}$ whose elements are values corresponding to the quantities $P_{\text{sto}}(t)$, $P_{\text{solar}}(t)$, $P_{\text{wind}}(t)$, $P_{\text{var}}(t)$, at discrete times. $t_k:\{t_1=0;\ t_k=t_{k-1}+h;\ t_N=T\}$, here h – Observed steps in the simulation process. To make it simpler to write quantities, we notation $P_{\text{sto},k}=P_{\text{sto}}(t_k)$, $P_{\text{solar},k}=P_{\text{solar}}(t_k)$, $P_{\text{wind},k}=P_{\text{wind}}(t_k)$, $P_{\text{var},k}=P_{\text{var}}(t_k)$. We have

$$\mathbf{P}_{\text{sto}}=\left[P_{\text{sto},1},P_{\text{sto},2},\cdots,P_{\text{sto},N}\right]^t;$$
$$\mathbf{P}_{\text{solar}}=\left[P_{\text{solar},1},P_{\text{solar},2},\cdots,P_{\text{solar},N}\right]^t;$$
$$\mathbf{P}_{\text{wind}}=\left[P_{\text{wind},1},P_{\text{wind},2},\cdots,P_{\text{wind},N}\right]^t;$$
$$\mathbf{P}_{\text{var}}=\left[P_{\text{var},1},P_{\text{var},2},\cdots,P_{\text{var},N}\right]^t.$$

The amount of energy consumed can change the time of use.

$$W_{\text{var}}=\int_0^T P_{\text{var}}(t)dt=\sum_{n=1}^{N}P_{\text{var},n}h=h\cdot\mathbf{1}^t\cdot\mathbf{P}_{\text{var}}=B_1=W_{\text{load}}-W_{\text{const}}$$

Here **1** – Unit vectors have corresponding dimensions. If $W_{\text{sto}}(0)=W_{\text{sto}}(T)=W_{\text{sto},N}$, we got:

$$W_{\text{sto}}=W_{\text{sto}}(0)+h\cdot\mathbf{1}^t\cdot\mathbf{P}_{\text{sto}}=W_{\text{sto},1}+B_2=W_{\text{sto},N} \quad \text{or}$$

$$h\cdot\mathbf{1}^t\cdot\mathbf{P}_{\text{sto}}=B_2=W_{\text{sto},N}-W_{\text{sto}}(0)$$

(8) in matrix form:

$$\begin{bmatrix}-\mathbf{E} & \mathbf{E} & \mathbf{E} & \mathbf{E}\end{bmatrix}\cdot\underbrace{\begin{bmatrix}\mathbf{P}_{\text{var}}\\ \mathbf{P}_{\text{sto}}\\ \mathbf{P}_{\text{solar}}\\ \mathbf{P}_{\text{wind}}\end{bmatrix}}_{\mathbf{X}}=\begin{bmatrix}P_{\text{const},1}\\ P_{\text{const},2}\\ \vdots\\ P_{\text{const},N}\end{bmatrix}=\mathbf{B}_3,$$

here **E** – the unit matrix. Finally, we have:

$$\underbrace{\begin{bmatrix}h\cdot\mathbf{1}^t & \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & h\cdot\mathbf{1}^t & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0}\\ -\mathbf{E} & \mathbf{E} & \mathbf{E} & \mathbf{E}\end{bmatrix}}_{\mathbf{A}}\cdot\underbrace{\begin{bmatrix}\mathbf{P}_{\text{var}}\\ \mathbf{P}_{\text{sto}}\\ \mathbf{P}_{\text{solar}}\\ \mathbf{P}_{\text{wind}}\end{bmatrix}}_{\mathbf{X}}=\underbrace{\begin{bmatrix}B_1\\ B_2\\ \mathbf{0}\\ \mathbf{B}_3\end{bmatrix}}_{\mathbf{B}}\Rightarrow\mathbf{AX}=\mathbf{B}$$

Here **0** – zeros vector has a corresponding size.

For (3)

$$0\le W_{\text{sto,n}}=W_{\text{sto}}(0)+\sum_{i=1}^{n}P_{\text{sto},i}h\le W_{\text{sto max}};\quad n=\overline{1,N}$$

Its matrix form

$$-\mathbf{1}\cdot W_{\text{sto}}(0)\le h\underbrace{\begin{bmatrix}1 & 0 & \cdots & 0\\ 1 & 1 & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 1 & 1 & \cdots & 1\end{bmatrix}}_{\mathbf{S}}\begin{bmatrix}P_{\text{sto},1}\\ P_{\text{sto},2}\\ \vdots\\ P_{\text{sto},N}\end{bmatrix}\le\mathbf{1}\cdot\left(W_{\text{sto max}}-W_{\text{sto}}(0)\right)$$

.

Or $-\mathbf{1}\cdot\dfrac{W_{\text{sto}}(0)}{h}\le\mathbf{S}\cdot\mathbf{P}_{\text{sto}}\le\mathbf{1}\cdot\dfrac{W_{\text{sto max}}-W_{\text{sto}}(0)}{h}$, from here

$$\begin{bmatrix}\mathbf{S}\\ -\mathbf{S}\end{bmatrix}\mathbf{P}_{\text{sto}}\le\frac{1}{h}\begin{bmatrix}\mathbf{1}\cdot\left(W_{\text{sto max}}-W_{\text{sto}}(0)\right)\\ \mathbf{1}\cdot W_{\text{sto}}(0)\end{bmatrix}.$$

So

$$\begin{bmatrix}\mathbf{0}\\ \mathbf{S}\\ -\mathbf{S}\\ \mathbf{0}\end{bmatrix}\cdot\begin{bmatrix}\mathbf{P}_{\text{var}}\\ \mathbf{P}_{\text{sto}}\\ \mathbf{P}_{\text{solar}}\\ \mathbf{P}_{\text{wind}}\end{bmatrix}\le\frac{1}{h}\begin{bmatrix}\mathbf{0}\\ \mathbf{1}\cdot\left(W_{\text{sto max}}-W_{\text{sto}}(0)\right)\\ \mathbf{1}\cdot W_{\text{sto}}(0)\\ \mathbf{0}\end{bmatrix}\Rightarrow\mathbf{CX}\le\mathbf{D}.$$

For clarity, we re-enumerate the conditions in the form of inequality as follows,

$$\begin{cases}0\le P_{\text{var}}(t)\le P_{\text{load}}\\ -P_{\text{sto min}}\le P_{\text{sto}}(t)\le P_{\text{sto max}}\\ 0\le P_{\text{solar}}(t)\le P_{\text{solar max}}\\ 0\le P_{\text{wind}}(t)\le P_{\text{wind max}}\end{cases},$$

And, in matrix form

$$\begin{bmatrix}\mathbf{0}\\ -\mathbf{1}\cdot P_{\text{sto min}}\\ \mathbf{0}\\ \mathbf{0}\end{bmatrix}\le\begin{bmatrix}\mathbf{P}_{\text{var}}\\ \mathbf{P}_{\text{sto}}\\ \mathbf{P}_{\text{solar}}\\ \mathbf{P}_{\text{wind}}\end{bmatrix}\le\begin{bmatrix}\mathbf{1}\cdot P_{\text{load}}\\ \mathbf{1}\cdot P_{\text{sto max}}\\ \mathbf{1}\cdot P_{\text{solar max}}\\ \mathbf{1}\cdot P_{\text{wind max}}\end{bmatrix}. \tag{12}$$

The investment cost of the system can be calculated according to the installed capacities

$P_{\text{solar max}}, P_{\text{wind max}}, P_{\text{sto max}}, W_{\text{sto max}}$ of the devices, so it can be optimized when the installed capacity of the devices is optimized, i.e. the objective function will be installed capacities to reach a minimum.

$$F_{(\mathbf{P}_{\text{solar}},\mathbf{P}_{\text{wind}},\mathbf{P}_{\text{var}},W_{\text{sto}})} = \begin{cases} P_{\text{solar max}} \\ P_{\text{wind max}} \\ P_{\text{sto max}} \\ W_{\text{sto max}} \end{cases} \rightarrow \min \qquad (13)$$

This is a multi-objective optimization problem, so in solving this problem, the multi-objective optimization methods are chosen.

Problem (13) with conditions in the form of equality (10), inequalities (11), and limits (12) related to the linear programming problem, and to solve this type of problem, we apply simple methods. (Simplex method) [18-20]. The total number of variables when simulating the system within a year can be up to dozens, hundreds of thousands of variables [15-16].

3 Problem Solution

The system simulations operate for a year with variable model functions, i.e., they are not that they fluctuate in a range that reflects the uncertainty of the actual energy consumption as well as the actual energy of the generators.

The obtained result is the ability (Prob %) to meet electricity consumption demand according to four installation parameters ($P_{\text{solar max}}$ $P_{\text{wind max}}$, $P_{\text{sto max}}$, $W_{\text{sto max}}$). They are the main parameters of the independent power system and have been described in mathematical equations, and participate in the optimization process as mentioned in the introduction part. For an intuitive look, some results are graphically depicted relative to the values of the generators.

The obtained results (Figures 1 to 12) have shown the reasonableness of the proposed method. When installed capacity/power is large, the system completely meets the energy consumption demand. This is very practical because when the installed capacity/power of the storage energy system is larger, more energy is stored, so they can completely always meet the electricity demand. In contrast, when they are small, the response is markedly reduced.

Figures 1 to 12 show the probability that the system can function perfectly, being able to meet the requirements of the load consumption corresponding to the installed power level of the generating sources. Figures 1 to 3 show the system's response capacity in spring, figure 4 to 6 - summer, figure 7 to 9 - fall and figure 10 to 12 – winter.

From the results illustrated in Figures 1 to 12, the installed capacity levels of the system can be selected and from there a specific investment cost can be calculated.

For example, in Figure 1, when the installed capacity of the generator P_{solar} = 3 kW, P_{wind} = 4 kW, at the power level of the battery is 3.5 kW and its capacity is 4kW.h, the system works almost perfectly (~96,7%) in spring, ie the sources supply enough for consumption needs. When the installed power of the generators is the same, but the installed power and (or) capacity of the storage system are reduced, the system cannot meet the consumption demand at a certain time. Because when the weather is bad and the installed power and (or) capacity of the battery is too low, it will not meet the electricity demand.

Figures 1 to 12 show the system working probabilities corresponding to the four seasons of the year. The choice of the installed capacity of the equipment must satisfy the consumption over the seasons. For example, when P_{solar} = 3 kW, P_{wind} = 4 kW (Figures 1, 4, 7, 10), at the power level of the battery of 3 kW and its capacity is 4 kW.h, the system works almost perfectly (~94.6%) in summer (Figure 4), but does not meet consumer demand (the probability less than 90%) in other seasons (Figures 1, 7, 10).

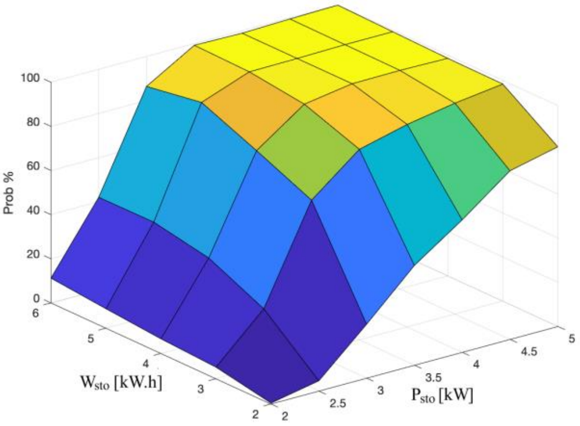

Fig. 1: Potential system performance in spring, when P_{solar} = 3 kW; P_{wind} = 4 kW.

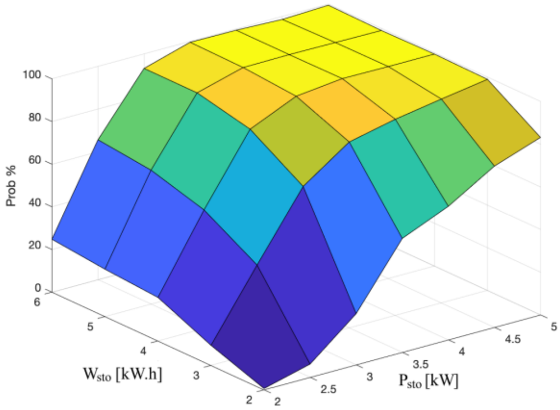

Fig. 2: Potential system performance in spring, when P_{solar} = 4 kW; P_{wind} = 3 kW.

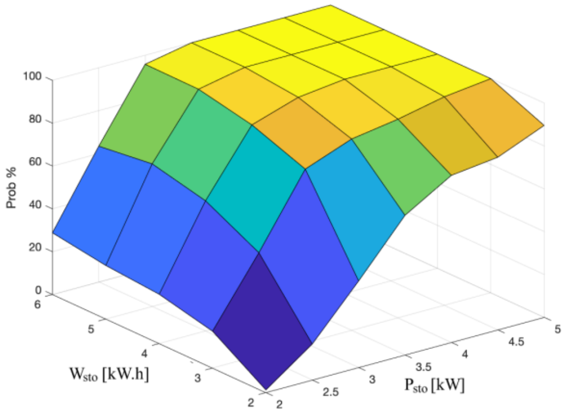

Fig. 3: Potential system performance in spring, when Psolar = 4 kW; Pwind = 3 kW.

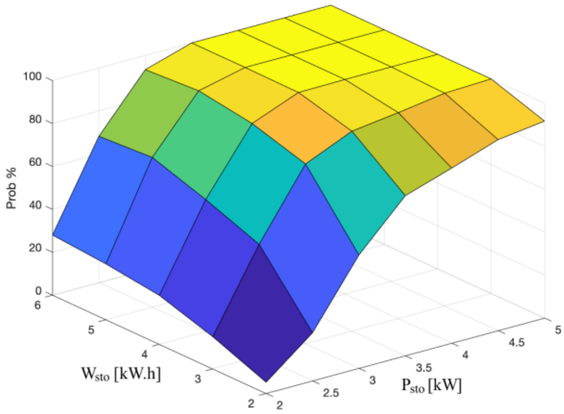

Fig. 4: Potential system performance in summer, when Psolar = 3 kW; Pwind = 4 kW.

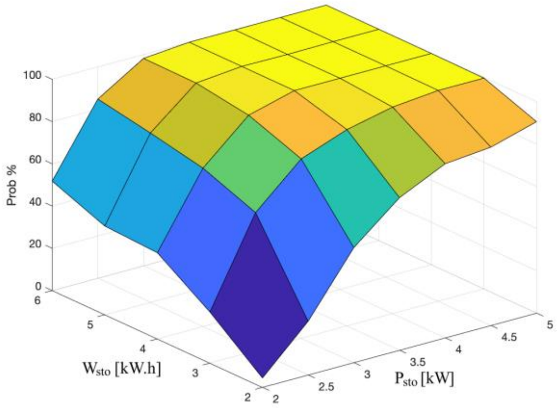

Fig. 5: Potential system performance in the summer, when Psolar = 4 kW; Pwind = 3 kW.

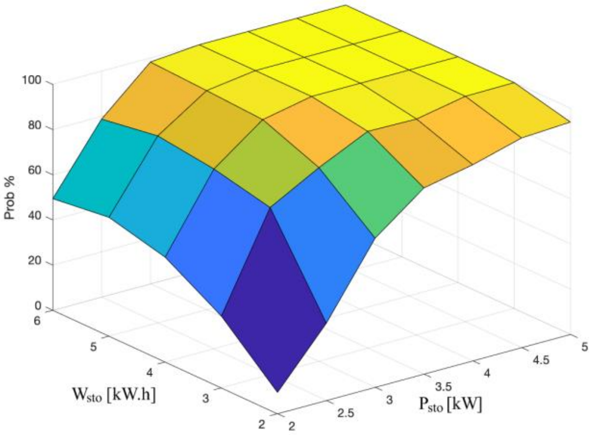

Fig. 6: Potential system performance in the summer, when Psolar = 4 kW; Pwind = 4 kW.

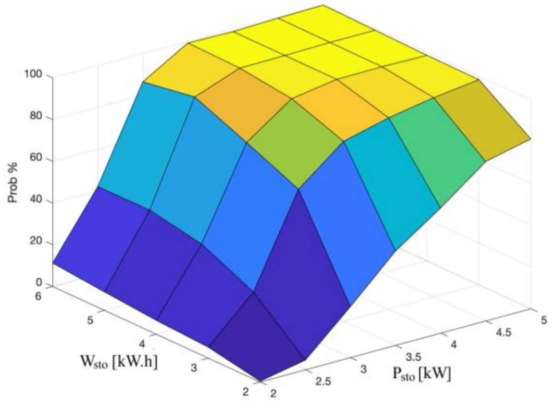

Fig. 7: Potential system performance in fall, when Psolar = 3 kW; Pwind = 4 kW.

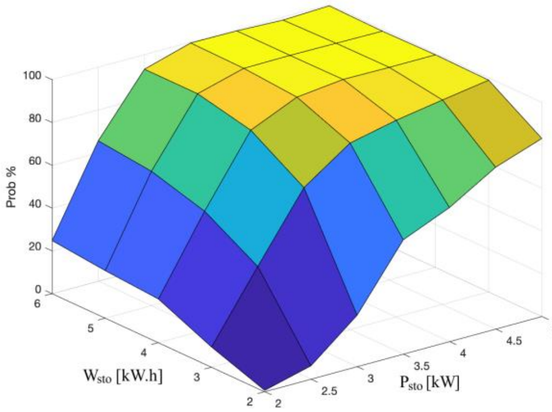

Fig. 8: Potential system performance in fall, when Psolar = 4 kW; Pwind = 3 kW.

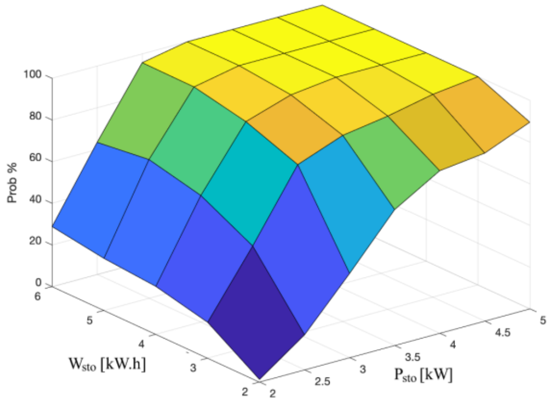

Fig. 9: Potential system performance in fall, when Psolar = 4 kW; Pwind = 4 kW.

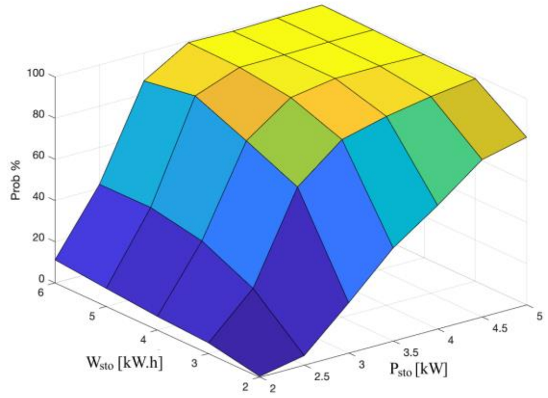

Figure 10: Potential system performance in the winter, when Psolar = 3 kW; Pwind = 4 kW.

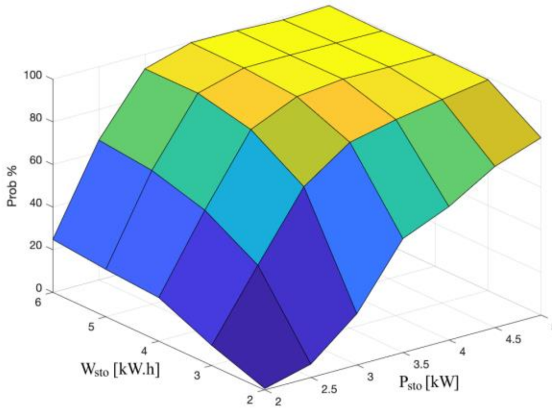

Fig. 11: Potential system performance in winter, when Psolar = 4 kW; Pwind = 3 kW.

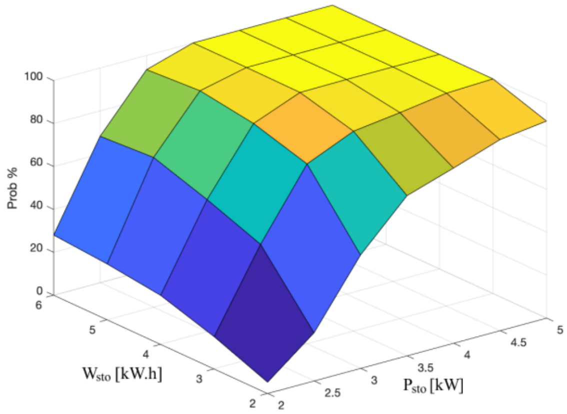

Fig. 12: Potential system performance in winter, when Psolar = 4 kW; Pwind = 4 kW.

The level of response to the energy consumption demand corresponding to the different installed power levels is clearly shown in Figures 1 to 12. From these graphs, it is not difficult to choose the optimal system values.

Clearly, the results obtained above (Figures 1 to 12) have shown the perfect working level of the system relative to the input parameters that are the installed powers of the stand-alone system. When the installation parameters of the system are optimized, it is not difficult to deduce that the cost of the system can also be optimized.

4 Conclusion

In this paper, the optimal installed capacity calculation has been solved by bringing the nonlinear problem to a linear form. This method is more convincing in calculating the design of the energy system independently than estimating installed capacity combined with optimal control in many previous studies. The simulation of the proposed method is performed on an independent renewable energy system. The results of the simulation showed clearly the installed capacities of the devices so that the energy system meets demand. Obviously from the graphs (Figures 1 to 12), choosing the optimal installation tool and inferred that the optimization of investment costs can be done easily. For example, for this system, when the installed capacity of wind power generator P_{wind} = 4 kW, solar power generator P_{solar} = 3 kW, battery P_{sto} = 3.5 kW, and the capacity of battery W_{sto} = 4 kW.h, the system always ensures the adequate power supply.

In the mathematical model of the problem in the previous section, including descriptive functions for energy sources, the charge/discharge, the capacity of the storage unit, and the consumed loads are the basic components of an independent energy system. Therefore, this method can be used in general for all independent energy systems using renewable energy generators with different electricity consumption requirements. This method required accurate load chart and weather characteristics where the system is installed. This can be considered a difficulty of the proposed method, especially for localities that have not yet completed the above information systems (including forecasting of energy consumption and weather).

The proposed method has eliminated the difficult calculation and replaced the estimation of the system's design parameters by calculating specific optimization. It allows the optimal calculation of installed capacities more precisely and specifically. This not only has great technical significance but also has special implications for transporting equipment to remote areas because the optimal calculation of the system components can be derived from the optimal calculation of the installed capacity

In addition, the life cycle of energy storage units is relatively short compared to other devices in the system and the substances used in their manufacture are also very harmful to the environment. So the optimization of installed capacity for this part also has great significance for environmental protection.

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