Power Coupling Characteristics Between Photovoltaic System and Remote Tourist Area

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\textbf{ABSTRACT} Nowadays, with the high development of photovoltaic (PV) technique and tourist industry, PV system is used in remote tourist area more and more widely. However, in practical application, the design, planning and layout involved in them are usually very difficult because the direct relationship between them is absent. To solve this problem, in this paper, some mathematical expressions and their constraint conditions are proposed by analyzing the power relationships between PV system and tourism facilities. By them, the power coupling characteristics between PV system and remote tourist area can be clearly shown. Finally, some simulation experiments are done to analyze the tourism facilities installed in two areas where the degree of difficulty in constructing the electricity grid is different. Meanwhile, a simulation experiment for a whole tourist area is also conducted. The simulation results not only show that the presented power coupling characteristics is accurate and reasonable, but also illustrate that the real-time simulation analysis based on them is feasible and available regardless of a single tourism facility or a whole tourist area.

\textbf{INDEX TERMS} PV system, tourist area, power coupling characteristics, tourism facility.

\section{I. INTRODUCTION}

Nowadays, with the high development of the tourism business and PV system, their combination is concerned more and more strongly. On the one hand, in remote tourist area, lots of fields on the top of the high mountain, in the dense primordial forest or in the deep valley are suffering from the power shortage. This phenomenon prevents the installation of the business facilities and civilian facilities in tourist area. It is obvious that, for the conventional energy, this problem is very difficult to be solved because of the environmental conservation. On the other hand, PV system can provide the continuous electricity supply. Meanwhile, its friendly environment, flexible installation and convenient expansion can just match with the mentioned-above fields. Therefore, in this paper, the theory combining PV system with remote tourist area is first studied on the basis of the relationship between power supply and power demand.

Hitherto, a lot of efforts have been taken to develop the tourism. For example, on the basis of Hong Kong’s political economy, the local models of the tourism governance and development planning are studied by Yim King Penny Wan and Bramwell [1]. For historic water town tourism in China, its tourism market structure is analyzed by Mingcao Ma et al. [2]. In order to solve the problem of water use efficiency, a market-based proposal is presented by Cashman and Moore [3]. The rural tourism experience economy is analyzed by Loureiro [4]. The effects of stricter environmental regulation in a tourism economy are examined by Chao et al. [5]. The relationship between tourism and income distribution is studied by Incera and Fernández [6]. However, the universal theoretical model or mathematical expression, which can reflect the real-time operational characteristics of a tourist area, do not exist now. Therefore, for a newly developing tourist area, its design, planning and construction can only depend on the operational experience of other similar tourist areas, but the simple, cheap and flexible simulation can not be used. In order to solve this question, in this paper, the expressions of every tourism facility are presented on the basis of the power relationships between PV system and tourism facilities. Combine these mathematical models with simulation technology, the virtual design, planning and
The construction of a new tourist area can be conveniently implemented, which can greatly contribute to the development of tourism.

With regard to the green tourism and environmental protection for tourist area, a lot of works have been done. A regional environment tourism economy system is analyzed by Yaoqing Yuan et al. [7]. The circular economy based on relationship between environmental and economic system is studied by Patrizia Ghisellini et al. [8]. The effectiveness of the policy of circular economy in China for 11th five-year plan is analyzed by Wua et al. [9]. According to the observed data of many hotels, guesthouses, tourist attractions and transit stations, an analysis of wasteful tourism in tourist area is completed by Manomaivibool [10]. A framework for a green economy transition in tourism destinations is proposed by Law et al. [11]. However, in these works, the proposed concrete measures to implement green tourism and environmental protection are not enough at all. Therefore, in this paper, PV system, which is one of the most widely used renewable energy systems, is selected as the concrete implementation of the ecological tourism and friendly environment, and then the power supply-demand relationships between it and remote tourist area are built. By this work, the important theoretical basis for application of the renewable system in remote tourist area is laid.

In practical application, the works to optimize the renewable system or tourist area are usually done individually. For example, in a remote area, the yearly system performance of the PV/wind hybrid system is studied by Celik [12]. In addition, the design and installation costs of the PV/wind hybrid system are analyzed by Bilal et al. [13] and Bakos and Tsagas [14], respectively. The cost of wind and solar energy is analyzed and the cost improvement is given by Braff et al. [15]. To compare the economic impacts, an intelligent energy management system algorithm is proposed by Nayak et al. [16]. By these works, it is obvious that the implementation of the complementary advantages are always suffering from the absence of their combination. Therefore, in this paper, the direct mathematical relationships between PV system and tourism facilities (including their constraint conditions) are built. By them, the combination of PV system and tourism industry is implemented and their complementary advantages are obtained. On the basis of them, the virtual analysis can be made again and again to reduce the design period, improve the management ability and increase the planning level. It is obvious that this work is good at the high development of PV system in remote tourist area.

The main innovations of this work can be illustrated as follows:

- The first attempt to seek the direct mathematical relationship between PV system and remote tourist area is made.
- The direct power expressions between PV system and tourism facilities are first built.
- The constraint conditions corresponding to these power expressions are also presented.

Some single tourism facilities and a whole tourist area are successfully analyzed by these relationships.

The following sections can be divided: in Section II, the power demand characteristics of tourism facilities are analyzed. In Section III, the power supply characteristics of PV system are studied. In Section IV, based on the relationships between power supply and power demand, the power coupling characteristics between PV system and remote tourist area are presented. In Section V, some simulation experiments are done to test these presented power coupling characteristics. Finally, some discussions and conclusions are given in Section VI and Section VII, respectively.

## II. POWER DEMAND OF TOURISM FACILITIES TO PV SYSTEM

### A. POWER DEMAND CHARACTERISTICS

The facilities in tourist area mainly include infrastructures, entertainment facilities, landscape facilities, service facilities and performance facilities. They mainly include water supply system, sewage treatment system, communication system, entertainment equipments, landscape equipments, management center, catering facilities, accommodation facilities, shopping facilities, leisure facilities. For the remote tourism areas, their power demand characteristics can be analyzed as follows:

#### 1) WATER SUPPLY SYSTEM (REPRESENTED BY WS)

It is well known that a lot of tourist areas stand on remote countryside and mountaintop, so the conventional water supply system is usually not applicable. In order to deal with this problem, constructing a water supply system whose electrical energy is supplied by PV system is an effective way. This argument can be confirmed as follows: firstly, lots of tourist areas are usually an acute shortage of water, the cascade pumping is needed, which means the big energy consumption and disperse power supply. Secondly, the cost to construct the electric wiring for remote countryside and mountaintop is usually very high and the period to finish this construction with the destruction of the fragile environment is usually very long. Finally, there exists a lot of sunlight in remote countryside and mountaintop, which is beneficial for PV system. Therefore, using PV system instead of electricity grid can avoid consuming the national electricity, cut down the cost of construction and protect the environment of tourist area.

#### 2) SEWAGE TREATMENT SYSTEM (REPRESENTED BY ST)

The sewage treatment system mainly includes two aspects. On the one hand, the medium-sized sewage treatment system can be built at the visitor center, hotels and large restaurants to prevent environmental pollution. On the other hand, at public toilets, rest sites and small restaurants, the small sewage treatment system should be built to implement water recycle. For the medium-sized sewage treatment system, if the electricity grid has been constructed, the PV system and electricity grid
hybrid system (represented by PV/grid system) should be selected to meet the big energy consumption. For the small sewage treatment system, the time period of the big energy consumption is usually concentrated in the forenoon, noon and afternoon of a fine day because of the characteristic of tourists. It is clear that PV system is very appropriate for this characteristic. Therefore, to avoid the high expense and environment disruption to construct the electricity grid, PV system is the most reliable, steady and environmental.

3) COMMUNICATION SYSTEM (REPRESENTED BY CS)
The communication system includes the mobile phone system, monitoring system and emergency system. The communication system of the mobile phone is usually designed, installed and repaired by the mobile operator. The monitoring communication system must be constructed and repaired by the tour operator. Their electrical energy must be supplied 24 hours a day to ensure the integrity and continuity of the monitoring data, so the continuity and stability are the essential qualification for power system. Therefore, in order to reduce the construction cost, protect the scenic and guarantee the good flexibility, PV system with batteries should be selected. Meanwhile, to supply the adequate electrical energy, the redundant batteries should be designed. The monitoring communication system is usually installed at miniature shops, rest sites and dangerous areas in favor of management. For the emergency system, their electrical energy must be also supplied 24 hours a day continuously and steadily. Therefore, PV system with redundant batteries should be used in remote areas while the electricity grid with batteries should be selected in urban areas.

4) ENTERTAINMENT EQUIPMENT (REPRESENTED BY EE)
The entertainment equipments are usually located in visitor center. Their energy consumption is greatly influenced by the number of visitors and the time period to consume the electrical energy, which can be used to design their power supply system. If they are used in day time, the PV/grid system should be selected. By this system, the high cost arising from the changing flow of visitors can be avoided, and the flexible and steady power supply can be implemented. If they are used at night, the electricity grid can be selected. If they are in remote countryside, PV system with some batteries should be used to reduce the cost constructing the electric wiring. Of course, the number of the storage batteries should be adequate to meet the uncertain demand of visitors.

5) LANDSCAPE EQUIPMENT (REPRESENTED BY LE)
Some landscape equipments in tourist area need consume electrical energy. If they run in day time, PV system with storage batteries should be selected, especially in a valley, mountaintop and forest. If they run at night, the large capacity batteries should be usually selected. Meanwhile, the electricity grid can be selected if it is easy to construct the electric wiring.

6) MANAGEMENT CENTER (REPRESENTED BY MC)
The management center is the center of the tourist area. It is usually located in visitor center with many people and big energy consumption. Because the energy consumption is greatly influenced by the number of visitors and its peak is usually in day time, the PV/grid system should be selected.

7) CATERING FACILITIES (REPRESENTED BY CF)
The catering facilities are the important part of tourist area, they mainly include hotels, restaurants, farmer’s houses and so on. The large and medium-sized hotels or restaurants are usually located at the visitor center or tourist station, while the small restaurants or farmer’s houses are usually located at other areas. Whatever their sizes are, the time period to consume the electrical energy (midday, afternoon and night) is relatively fixed. It is obvious that, to match this characteristic, the PV/grid system should be selected. That is to say, PV system should be mainly used in day time while the electricity grid should be mainly used at afternoon or night. In remote countryside, PV system with large capacity batteries should be used to reduce the cost constructing the electric wiring. Meanwhile, the number of the storage batteries should be adequate to meet the uncertain demand of visitors.

8) ACCOMMODATION FACILITIES (REPRESENTED BY AF)
The accommodation facilities mainly include all kinds of hotels. The time period to consume the electrical energy is concentrated in afternoon and night. At that time, the energy consumption is usually very big because lots of tourists have to eat and rest after a one-day trip is ended. It is obvious that the electricity grid should be mainly used. In remote countryside, the number of the storage batteries should be adequate to meet the demand of these tourists.

9) SHOPPING FACILITIES (REPRESENTED BY SF)
The shopping facilities mainly include large-scale shop, small-sized shop and miniature shop. The large-scale shops are usually located at the visitor center or tourist station, their electrical energy should be supplied by PV/grid system. That is to say, PV system should be mainly used and the electricity grid is regarded as the supplementary energy. For the small-sized shops, if they are located at the visitor center, the energy supply mode should be same as the large-scale ones. And if they are located at remote countryside, PV system should be selected as the main power system to reduce the cost. The miniature shops such as the vending machines are used by many business people more and more widely because of their flexible installation, low cost and simple maintenance. They are usually located in remote valleys, mountaintops or forests, so PV system whose merits include flexible installation, low cost and simple maintenance is the best choice to supply electrical energy.
10) LEISURE FACILITIES (REPRESENTED BY LF)
In tourist area, a lot of leisure facilities are positioned at intervals along the load to sightseeing, rest, phone charging and so on. They are usually disperse and is used by tourists only during their tour, so PV system is the best choice to match these traits. The merits include the low expense to complete the initial investment, the easy implementation to protect the scenic and the good flexibility to install equipments. It is well known that the customer satisfaction and comfort are greatly influenced by these leisure facilities. For the elderly, it is very importance to construct an adequate number of seats, drinking fountains and cool places. Nowadays, the number of the elderly tourists is large and steady, so their satisfaction and comfort is of uppermost priority. To the young, their mobile phones are carried and used at all times, so how they are charged conveniently and cheaply is a problem which should be solved quickly. Although the charger baby can solve this problem to a certain extent, it is very heavy and is not carried easily. It is clear that some platforms to charge the mobile phones should be built to improve the young tourists’ satisfaction and comfort. Of course, these drinking fountains, cool places and charging platforms should be supplied by PV system.

B. POWER DEMAND CURVES
According to the above-mentioned characteristics, the power demand curves can be used to express the load characteristics of tourism facilities. In Ref. [17], these curves are classified as four output shapes: “baseload”, “intermediate”, “bipeaker” and “peaker”. In this paper, these output shapes will be still used and a new output shape “mulpeaker” is defined. Figs. 1-5 show these five output shapes of the power demand curves.

According to these defined power demand curves, the main power demand characteristics can be shown in Table 1 and Table 2. Where pk, im, bl, mp and bp represent “peaker”, “intermediate”, “baseload”, “mulpeaker” and “bipeaker”, respectively. Meanwhile, we assume that the load types can be divided as “I type” load, “II type” load and “III type” load to reflect the importance of electricity supply (whether or not load can operate). “I type” load represents the load which needs the good electricity supply at any time, “II type” load represents the load which needs the general electricity supply, and “III type” load represents the load with no importance of electricity supply. In addition, L, LH and H represent the low, a little high and high energy consumption level, respectively.

Table 1 and Table 2 show that all tourism facilities can be expressed by the output shape “peaker”, “intermediate”, “baseload”, “mulpeaker” or “bipeaker”. Meanwhile, the power demand curves “peaker” and “intermediate” hold great majority. For the tourism facilities carrying the output shape “peaker”, the ranges of time interval $[t_1, t_2]$ are similar with each other. By contrast, for loads (or tourism facilities) with output shape “intermediate”, these ranges are very different with each other. In addition, the ranges of time interval
Power supply characteristics of PV system

After the power demand characteristics of tourism facilities in remote tourist area have been analyzed, the power supply characteristics of PV system should be analyzed to find the power coupling characteristics between PV system and tourist area. Here, we assume that the tourist area can be defined as “A area” and “B area” to reflect the degree of difficulty in constructing the electricity grid. “A area” represents the area where the electricity grid is constructed with difficulty, “B area” represents the area where the electricity grid is constructed easily. The power supply characteristics of PV system can be analyzed as follows:

Firstly, for the “III type” loads in “A area”, it is obvious that Eq. (1) can be given to reflect the power supply characteristics of PV system. Meanwhile, Eq. (2) is satisfied because the total power is supplied only by PV system.

\[ P_{PV} = \sum_{i=1}^{n} P_{oi} \]  
\[ P_{PV} = \sum_{i=1}^{n} P_{oi} \]

where \( P_{PV} \) represents the real-time output power of PV system (including PV cells and storage modules); \( P_{oi} \) represents the real-time output power of the whole power system; \( P_{oi} \) represents the real-time output power of PV cell marked No. \( i \). If these PV cells have the same type, Eq. (1) can be replaced as Eq. (3). Where \( P_o \) represents the real-time output power of a PV cell when PV system is operating around the maximum power point (MPP).

\[ P_{PV} = n \times P_o \]  
\[ P_{PV} = n \times P_o \]

Here, according to our previous research results in Ref. [18], the real-time value of \( P_o \) can be calculated by Eq. (4) when PV cell parameters \( I_{sc}, V_{oc}, I_m \) and \( V_m \) are selected as 9.19A, 22V, 8.58A and 17.5V, respectively. In Eq. (4), \( S \) and \( T \) represent the real-time values of solar irradiance and cell temperature, respectively. Therefore, \( P_o \) can be regarded as the function of \( S \) and \( T \), and represented by Eq.(5).

\[ P_o = 2.943 \times 10^{-8} S^3 - 2.992 \times 10^{-5} S^2 + 0.1497S \]
\[ + 2.664 - 0.045T \]  
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\[ + 2.664 - 0.045T \]

Secondly, for the “II type” loads or “I type” loads in “A area”, in order to ensure the good power supply, some energy storage modules (ESMs) must be added in PV system. Therefore, Eq. (6) can be given to reflect the power supply characteristics of PV system in this case.

\[ P_{\Sigma} = P_{PV} = \sum_{i=1}^{n} P_{oi} + \sum_{j=1}^{m} P_{Bj} \]  
\[ P_{\Sigma} = P_{PV} = \sum_{i=1}^{n} P_{oi} + \sum_{j=1}^{m} P_{Bj} \]

where \( P_{Bj} \) represents the real-time output power of the ESMs marked No. \( j \). If these PV cells and storage modules have their own same types, Eq. (6) can be replaced as Eq. (7).

\[ P_{PV} = n \times P_o + m \times P_B \]  
\[ P_{PV} = n \times P_o + m \times P_B \]

where \( P_B \) represents the real-time output power of an energy storage module (ESM) and can be expressed by Eq. (8).

\[ P_B = P_b + P_c \]  
\[ P_B = P_b + P_c \]

where \( P_b \) and \( P_c \) represent the real-time output powers of the batteries and super capacitors, respectively, in an ESM. Here, to make the analysis process simple, assume that the numbers of the batteries and super capacitors have been optimized.

Thirdly, for loads in “B area”, it is obvious that Eq. (9) should be satisfied. Meanwhile, it is well known that the electricity grid has the good power supply, so Eq. (10) is available for the “III type” loads or “II type” loads according to Eq. (1).

\[ P_{\Sigma} = P_{PV} + P_g \]  
\[ P_{\Sigma} = P_{PV} + P_g \]

where \( P_g \) represents the real-time power supplied by electricity grid. If all PV cells have the same type, Eq. (10) can be replaced as Eq. (11).

\[ P_{\Sigma} = n \times P_o + P_g \]  
\[ P_{\Sigma} = n \times P_o + P_g \]
For the “I type” loads in “B area”, in order to ensure the good power supply, some ESMs must be added in PV system. According to Eq. (6), Eq. (12) should be satisfied.

\[ P_\Sigma = \sum_{i=1}^{n} P_{oi} + \sum_{j=1}^{m} P_{Bj} + P_g \]  

(12)

If all PV cells and storage modules have their own same types, Eq. (12) can be replaced as Eq. (13).

\[ P_\Sigma = n \times P_o + m \times P_B + P_g \]  

(13)

Finally, for a few facilities such as PV lamps, Eq. (14) can usually reflect their power characteristics. In these loads, to reduce the cost as much as possible, the super capacitors in the ESMs are usually deleted. In addition, the energy stored in these storage batteries is rooted in PV cells operated at daytime.

\[ P_\Sigma = m \times P_B \]  

(14)

Eq. (1), Eq. (6), Eq. (10), Eq. (12) and Eq. (14) show the power supply equations of PV system with different topologies to match the different tourism facilities in different tourist areas. On the basis of them, the power demand characteristics of different tourism facilities (or loads) can be involved in studying the relationships between power supply and power demand.

### IV. RELATIONSHIPS BETWEEN POWER SUPPLY AND POWER DEMAND

#### A. POWER EXPRESSIONS

After the power demand characteristics of tourism facilities (or loads) and power supply characteristics of PV system have been studied, the relationships between power supply and power demand can be analyzed according to the power balance between PV system and different loads. These relationships reflect the main power coupling characteristics between PV system and remote tourist area.

According to the power balance theory, Eq. (15) is always satisfied for all tourism facilities (or loads) except “III type” loads in “A area”. Where \( P_R \) represents the real-time demand power of loads (or tourism facilities).

\[ P_\Sigma = P_R \]  

(15)

For “III type” loads in “A area”, an approximate equation shown by Eq. (16) can be given.

\[ P_R \approx \sum_{i=1}^{n} P_{oi} \]  

(16)

According to Eqs. (15) and (16), take Eq. (1), Eq. (6), Eq. (10) and Eq. (12) into account, Table 3 can be given. It shows the power expressions (equations or approximate equations) between tourism facilities and their corresponding power systems.

According to Table 3, it is obvious that these expressions have built a bridge between tourism facilities and PV system.

| Load types | Areas | Power equations (or approximate equations) | Corresponding equations with same PV cells |
|------------|-------|------------------------------------------|------------------------------------------|
| III        | A     | \( P_s = \sum_{i=1}^{n} P_{ai} \)         | \( P_s = n P_a \)                          |
| II         | A     | \( P_s = \sum_{i=1}^{n} P_{ai} + \sum_{j=1}^{m} P_{bj} \) | \( P_s = n P_a + m P_B \)              |
| I          | A     | \( P_s = \sum_{i=1}^{n} P_{ai} + \sum_{j=1}^{m} P_{bj} \) | \( P_s = n P_a + m P_B \)              |
| III        | B     | \( P_s = \sum_{i=1}^{n} P_{ai} + P_g \)     | \( P_s = n P_a + P_g \)                |
| II         | B     | \( P_s = \sum_{i=1}^{n} P_{ai} + P_g \)     | \( P_s = n P_a + P_g \)                |
| I          | B     | \( P_s = \sum_{i=1}^{n} P_{ai} + \sum_{j=1}^{m} P_{bj} + P_g \) | \( P_s = n P_a + m P_B + P_g \)         |

Therefore, they reflect the main power coupling characteristics between PV system and remote tourist area. Meanwhile, the constraint conditions of these equations (or approximate equations) can be regarded as the supplement to the power coupling characteristics.

#### B. CONSTRAINT CONDITIONS

1) POWER RELATIONSHIPS BETWEEN DIFFERENT LOADS AND PV CELLS

In order to find the constraint conditions of the power expressions shown in Table 3, the power supply curve of PV cells is compared with the power demand curves of the different load types and Figs. 7-11 are given. On the one hand, the power supply curve of PV cells can be assumed and shown by Fig. 6. Here, the area of the shaded part is represented by \( S_{PV} \). It is obvious that its value is equal to the electric energy generated by PV cells in one day (represented by \( W_o \)). Therefore, Eq. (17) and Eq. (18) are satisfied. Here, to make the analysis process simple, assume that all PV cells are the same type.

\[ W_o = n \int_{t_a}^{t_b} P_{o} \, dt \]  

(17)

\[ S_{PV} = W_o \]  

(18)

On the other hand, in Figs. 7-11, the area of the shaded parts can be represented by \( S_R \) and Eqs. (19) and (20) are satisfied. Where \( W_R \) represents the total electric energy that
It is obvious that, according to Figs. 7-9, Eq. (19) can be expressed as Eq. (21) to the “peaker” load, “intermediate” load or “baseload” load.

$$W_R = \int_{t_1}^{t_2} P_R dt$$  \hspace{1cm} (19)  

$$S_R = \int_{t_1}^{t_2} P_R dt$$  \hspace{1cm} (20)  

According to the relationships between different loads and PV cells shown in Figs. 7-11, the constraint conditions of the power equations (or approximate equations) shown in Table 3 can be analyzed from two aspects: constraint conditions in “A area” and constraint conditions in “B area”.

2) CONSTRAINT CONDITIONS IN “A AREA”

In “A area”, either the construction of the electricity grid is very difficult or its construction will damage the tourist area, so all tourism facilities (or loads) must be supplied only by PV system. Firstly, for the “III type” load, when the tourism facility is the “peaker” output shape, the storage batteries are usually not used to save the hardware cost of PV system and Eq. (25) can be given.

$$S_R \approx S_{PV}$$  \hspace{1cm} (25)  

Meanwhile, a constraint condition of Eq. (25) can be expressed by Eq. (26). Where $S_r$ represents the area of the shaded part in Fig. 12 and the positive number $\varepsilon$ represents the tolerance degree to power shortage for a tourism facility.

$$S_R - S_c \leq \varepsilon$$  \hspace{1cm} (26)  

Secondly, for the “III type” load, when the output shape of the tourism facility is the “bipeaker”, “mulpeaker” or “intermediate”, some storage batteries must be used and Eq. (25) should still be satisfied. However, the constraint condition of Eq. (26) must be revised as Eq. (27). Where

$$W_R = \int_{t_1}^{t_2} P_R dt + \int_{t_3}^{t_4} P_R dt + \int_{t_5}^{t_6} P_R dt$$  \hspace{1cm} (23)  

$$W_R = \int_{t_1}^{t_2} P_R dt + \int_{t_3}^{t_4} P_R dt$$  \hspace{1cm} (24)
TABLE 4. Power coupling characteristics between PV system and remote tourist area.

| Load types | Areas | Power equations (or approximate equations) | Corresponding equations with same PV cells | Main constraint conditions | Other constraint conditions |
|------------|-------|-------------------------------------------|-------------------------------------------|--------------------------|---------------------------|
| III        | A     | $P_S = \sum_{i=1}^{2} P_{st}$             | $P_S = nP_s$                              | $S_R - S_c \leq \varepsilon$ | peak load                |
| III        | A     | $P_S = \sum_{i=1}^{2} P_{st}$             | $P_S = nP_s + mP_{st}$                    | $S_R - S_c < W_B \leq S_{PV} - S_c$ | other loads              |
| I          | A     | $P_S = \sum_{i=1}^{2} P_{st}$             | $P_S = nP_s + P_{st}$                     | $S_R - S_c < W_B < S_{PV} - S_c$ |                           |
| III        | B     | $P_S = \sum_{i=1}^{2} P_{st}$             | $P_S = nP_s + P_{st}$                     | $C_{PV} + C_B \leq \zeta$ |                           |
| II         | B     | $P_S = \sum_{i=1}^{2} P_{st}$             | $P_S = nP_s + P_{st}$                     | $S_R \geq S_{PV}$ |                           |
| I          | B     | $P_S = \sum_{i=1}^{2} P_{st}$             | $P_S = nP_s + mP_{st} + P_{st}$           | $C_{PV} + C_B \leq \zeta$ | $W_B > \nu$              |

Fig. 12. Definition of $S_c$.

$W_B$ represents the maximum charging or discharging electric energy of the ESMs in one day.

$$S_R - S_c \approx W_B$$  \hspace{1cm} (27)

Thirdly, for the “II type” load in “A area”, the number of PV cells and the capacity of the ESMs must be enough. Therefore, Eq. (28) and Eq. (29) can be given.

$$S_R < S_{PV}$$  \hspace{1cm} (28)

$$S_R - S_c < W_B \leq S_{PV} - S_c$$  \hspace{1cm} (29)

Finally, for the “I type” load in “A area”, the number of PV cells and the capacity of the ESMs must be very adequate. Therefore, Eq. (30) should be satisfied and its constraint condition can be expressed by Eq. (31).

$$S_R \ll S_{PV}$$  \hspace{1cm} (30)

$$S_R - S_c \ll W_B < S_{PV} - S_c$$  \hspace{1cm} (31)

3) CONSTRAINT CONDITIONS IN “B AREA”

In “B area”, for all types of loads, Eq. (32) can be given to show the power relationships in this case. Where $W_g$ represents the electric energy supplied by the power grid in one day.

$$S_R - S_c = W_g$$  \hspace{1cm} (32)

In order to make full use of the electric energy generated by PV system and save the hardware cost, Eq. (33) can be expressed as the constraint condition.

$$S_R \geq S_{PV}$$  \hspace{1cm} (33)

Except Eq. (33), the hardware cost of PV system can be used as the constraint condition expressed by Eq. (34).

Where $C_{PV}$ and $C_B$ represent the total costs of PV cells and ESMs, respectively; $\zeta$ represents the maximum value of the construction cost of PV system.

$$C_{PV} + C_B \leq \zeta$$  \hspace{1cm} (34)

In addition, for the “II type” or “I type” load in “B area”, the adequate capacity of the ESMs should be ensured and the constraint condition can be expressed by Eq. (35) in this case. Where $\nu$ represents the critical capacity of the ESMs to ensure the necessary energy supply and electricity supply security.

$$W_B > \nu$$  \hspace{1cm} (35)

In brief, the constraint conditions of the power equations (or approximate equations) shown in Table 3 can be shown in Table 4. Although only the relationships between all tourism facilities and PV system are given by Table 4, these facilities are the key parts of the remote tourist area. Therefore, actually, these expressions and constraint conditions clearly describe the power coupling characteristics between PV system and remote tourist area. In practical application, when some special purposes such as cost optimization, tourism planning, investment and so on need be implemented, the objective functions corresponding to them can be built easily. In this case, these results shown in Table 4 can be used as the mathematical basis.

V. SIMULATION EXPERIMENTS

In order to verify the accuracy and rationality of the power coupling characteristics shown in Table 4, some simulation
experiments are conducted in Sections \( V(A) \) and \( V(B) \). The flowchart to implement these simulations can be shown by Fig. 13. Meanwhile, in Section \( V(C) \), a simulation experiment for a tourist area is done to thoroughly analyze its power coupling characteristics. In addition, to reflect the energy consumption characteristics of tourism facilities, some parameters including \( r_{pd} \), \( r_c \), \( r_p \) and \( r_u \) are defined by Eqs. (36)-(39), respectively. They represent the supply and demand ratio of renewable energy, the renewable energy coverage, the supply ratio and the utilization coefficient of renewable energy, respectively.

\[
\begin{align*}
  r_{pd} &= \frac{W_o}{W_R} \\
  r_c &= \frac{t_c}{t_w} \times 100\% \\
  r_p &= \frac{t_p}{t_w} \times 100\% \\
  r_u &= \frac{W_{Ro}}{W_o} \times 100\%
\end{align*}
\]

where \( t_w \) represents the total operating time of the tourism facility, \( t_c \) represents the operating time of the tourism facility when \( P_{PV} \geq P_R \), \( t_p \) represents the operating time of the tourism facility when \( P_{\sum} \geq P_R \), \( W_{Ro} \) represents the part of the consumed electric energy of load, which is supplied only by PV cells and ESMs charged by PV cells.

The relationship between electric energy generated by renewable energy system and electric energy required by load in a certain time can be expressed by \( r_{pd} \). \( r_c \) shows whether or not the renewable electric energy generated by renewable energy system can meet the demand of load. If it is equal to 1, then the electric energy generated by renewable energy system can always meet the demand of load. \( r_p \) shows whether or not the electric energy of load is sufficiently supplied. If it is equal to 1, then there is an adequate supply power for load. \( r_u \) shows the renewable energy efficiency generated by PV system. If it is equal to 1, then the electric energy generated by renewable energy system is completely used. That is to say, there is no electric energy changed from light energy to waste.

A. POWER COUPLING ANALYSIS OF “A AREA”

In “A area”, the electricity for the tourism facilities is provided only by PV system (including PV cells and ESMs), a small shop is selected as the research object and other facilities can be also analyzed by analogy. Some simulation experiments whose main parameters are shown by Table 5 can be done and their results can be given by Figs. 14-17. Where \( P_{PC} \) represents the power supplied only by PV cells; \( P_R \) represents the power demanded by the small shop. Meanwhile, to simplify the analysis process, we assume that the capacity of an ESM is 10Ah.

Fig. 14 shows that when the electricity for the tourism facility is provided only by PV cells, in time intervals [8:38,
the power supply fails because the power demanded by the shop is more than power supplied by PV cells. Fig. 15 shows that the adequate power supply can be guaranteed all the time when three PV cells are used. Meanwhile, according to Fig. 16, it is only in time interval [15:30, 17:38] that there is a failure of the power supply when two PV cells and an ESM are used. At this time the adequate power supply can be implemented by increasing the number of the ESMs from 1 to 2, just as Fig. 17 has been showing.

According to Figs. 14-17, it is clear that, in PV system, by fitting the reasonable number of PV cells and ESMs, the adequate power supply can be guaranteed. Meanwhile, the efficiency to use the generated power and the cost to construct PV system are very different because of their different system configuration. From the eyes of the efficiency to use the generated power, their values corresponding to Figs. 14-17 are 85.16%, 62.05%, 91.1% and 93.81%, respectively. It is obvious that the efficiency shown by Fig. 17 is the highest while there is the highest cost because of the large battery capacity. From the eyes of the cost to construct PV system, according to Table 5, it is obvious that the cost shown by Fig. 14 is the lowest because the cost of a PV cell is far less than that of an ESM. In addition, if the adequate power supply must be guaranteed, PV system shown in Fig. 15 has the lowest cost.

In these results, Figs. 14-17 show the power coupling characteristics of the “III type” load, “II type” load and “I type” load in “A area”, respectively. Fig. 15 shows that the “II type” load and “I type” load in “A area” can be still supplied well on the premise of the surplus PV cells, but it is not available because of the poor utilization efficiency to the electric energy generated by PV cells. Therefore, a conclusion can be drawn that, for loads in “A area”, the power coupling characteristics shown in Table 4 are accurate and reasonable and the real-time analysis using them is feasible and available.

B. POWER COUPLING ANALYSIS OF “B AREA”

In “B area”, when the electricity for the tourism facilities is provided by PV/grid system, a catering facility is selected as the research object and other facilities can be also
FIGURE 19. Supply and demand power curves under \( y \) condition.

TABLE 6. Main parameters of simulation experiments.

| Conditions | 1 | 2 | 3 | 4 |
|------------|---|---|---|---|
| Corresponding figures | Fig. 18 | Fig. 19 | Fig. 20 | Fig. 21 |
| \( n \) | 11 | 10 | 14 | 11 |
| \( m \) | 0 | 10 | 45 | 50 |

analyzed by analogy. Some simulation experiments whose main parameters are shown by Table 6 can be done and their results can be given by Figs. 18-21. Where \( P_R \) represents the power demanded by the catering facility.

Fig. 18 shows that when the electricity for the tourism facility is provided only by eleven PV cells, in time intervals \([7:00, 8:35]\) and \([17:15, 21:45]\), the power supply fails because the power demanded by the catering facility is more than the power supplied by PV system. In this time the power to compensate load is supplied by electricity grid, just as Fig. 18(b) has been showing. Fig. 19 shows that when the electricity for the tourism facility is provided by eleven PV cells and an ESM, the efficiency to use the generated power is higher. However, in time intervals \([7:27, 8:39] \) and \([18:30, 21:45]\), the power supply does still fail because of the inadequate capacity of the ESMs. In this time the power to compensate load is still supplied by electricity grid, just as Fig. 19(b) has been showing. In addition, the ESMs are charged in time intervals \([8:39, 10:09]\) and \([13:15, 13:56]\) while they will be discharged in time intervals \([6:58, 7:27]\), \([13:15, 13:56]\) and \([17:15, 18:30]\). It is clear that the efficiency to use the generated power will be improved by the charged and discharged ESMs. Fig. 20 shows that the adequate power supply can be guaranteed all the time when fourteen PV cells with forty-five ESMs need be used. At the moment, the least number of the ESMs is needed. Fig. 21 shows that the adequate power supply can be guaranteed all the time when eleven PV cells with fifty ESMs need be used. At the moment, the least number of PV cells is needed.

According to Figs. 18-21, it is obvious that the adequate power supply can be guaranteed by increasing the number of PV cells or capacity of the ESMs. For the efficiency to use the generated power, their values corresponding to [18:30, 21:45], the power supply does still fail because of the inadequate capacity of the ESMs. In this time the power to compensate load is still supplied by electricity grid, just as Fig. 19(b) has been showing. In addition, the ESMs are charged in time intervals \([8:39, 10:09]\) and \([13:15, 14:11]\) while they will be discharged in time intervals \([6:58, 7:27]\), \([13:15, 13:56]\) and \([17:15, 18:30]\). It is clear that the efficiency to use the generated power will be improved by the charged and discharged ESMs. Fig. 20 shows that the adequate power supply can be guaranteed all the time when fourteen PV cells with forty-five ESMs need be used. At the moment, the least number of the ESMs is needed. Fig. 21 shows that the adequate power supply can be guaranteed all the time when eleven PV cells with fifty ESMs need be used. At the moment, the least number of PV cells is needed.

According to Figs. 18-21, it is obvious that the adequate power supply can be guaranteed by increasing the number of PV cells or capacity of the ESMs. For the efficiency to use the generated power, their values corresponding to [18:30, 21:45], the power supply does still fail because of the inadequate capacity of the ESMs. In this time the power to compensate load is still supplied by electricity grid, just as Fig. 19(b) has been showing. In addition, the ESMs are charged in time intervals \([8:39, 10:09]\) and \([13:15, 14:11]\) while they will be discharged in time intervals \([6:58, 7:27]\), \([13:15, 13:56]\) and \([17:15, 18:30]\). It is clear that the efficiency to use the generated power will be improved by the charged and discharged ESMs. Fig. 20 shows that the adequate power supply can be guaranteed all the time when fourteen PV cells with forty-five ESMs need be used. At the moment, the least number of the ESMs is needed. Fig. 21 shows that the adequate power supply can be guaranteed all the time when eleven PV cells with fifty ESMs need be used. At the moment, the least number of PV cells is needed.
Figs. 18-21 are 52.42%, 68.38%, 80.33% and 99.25%, respectively. For the renewable energy coverage, their values corresponding to Figs. 6-9 are 62.7%, 58.06%, 64.44% and 62.7%, respectively. For the supply and demand ratio of the renewable energy, their values corresponding to Figs. 18-21 are 1.089, 0.9904, 1.387 and 1.089, respectively. For the demanded power from electricity grid, their values corresponding to Figs. 18-21 are 5.908kW, 4.652kW, 0kW and 0kW, respectively. It is obvious from these four targets that, on the one hand, the energy coverage and the supply and demand ratio are not influenced by the use of the batteries while the efficiency to use the generated power is greatly improved. On the other hand, the demanded power from electricity grid can be greatly decreased by increasing the number of PV cells or the capacity of the ESMs.

In these results, Fig.18 and Fig. 19 show the power coupling characteristics of the “III type” load (or “II type” load) and “I type” load in “B area”, respectively. Fig. 20 and Fig. 21 show that, if the grid is not used, the loads in “B area” can be still supplied well on the premise of the surplus PV cells and ESMs, but it is not available because of the high cost. Therefore, a conclusion can be drawn that, for loads in “B area”, the power coupling characteristics shown in Table 4 are accurate and reasonable and the real-time analysis using them is feasible and available.

C. POWER COUPLING ANALYSIS OF A REMOTE TOURIST ATTRACTION

In order to analyze the power coupling characteristics of a tourist attraction, the Enshi Grand Canyon Scenic Area in Hubei Province of China, is selected as the research object. The canyon with a total area of more than 300 square kilometers is 108 km long. There are a lot of cliffs, waterfalls, mountain peaks, primeval forests, ancient villages and so on.

In this simulation experiment, the simulation model built by MATLAB/Simulink tool can be shown by Fig. 22 and the main parameters are shown by Table 7. Where M-WS represents the miniature water supply system, S-WS represents the small water supply system, M-ST represents the miniature sewage treatment system, S-ST represents the small sewage treatment system, L-SF represents the large-size shopping facilities, S-SF represents the small shopping facilities, M-SF represents the miniature shopping facilities. $TP_{PC}$, $TP_{R}$, $TP_{B}$ and $TP_{g}$ represent the total real-time output power of all PV cells, the total real-time consumed power of all tourism facilities, the total real-time charged or discharged power of all ESMs and the total real-time output power of electricity grid, respectively. $C_{PC}$ and $C_{B}$ represent the total cost of all PV cells and ESMs, respectively. The simulation results can be shown by Table 8, Table 9 and Fig. 23.

In simulation model shown in Fig. 22, the number of every tourism facility can be set in submodel “RES”. Meanwhile, by the submodel “RES”, the power coupling analysis of the stand-alone tourism facilities can be completed and the simulation results are shown in Table 8.

In the design, planning and layout of tourist area, the number of PV cells, the number of ESMs, the capacity of storage batteries or super capacitors and so on can be selected again and again until the simulation results are satisfied. The power coupling characteristic between PV system and whole tourist area can be analyzed by the submodel “Output analysis” and the simulation results can be shown in Table 9.
TABLE 7. Main parameters of simulation experiment.

| Parameters                                  | M-WS | S-WS | M-ST | S-ST | CS | CF | AF | MC | LF | L-SF | S-SF or M-SF |
|---------------------------------------------|------|------|------|------|----|----|----|----|----|-----|--------------|
| Number of tourism facilities               | 5    | 1    | 5    | 1    | 10 | 2  | 2  | 1  | 10 | 2   | 10           |
| Number of PV cells in every facility        | 4    | 10   | 2    | 6    | 1  | 11 | 50 | 30 | 1  | 25  | 3            |
| Number of ESMs in every facility            | 0    | 0    | 5    | 0    | 5  | 10 | 0  | 0  | 0  | 0   | 0            |
| Whether or not the renewable system is used | yes  | no   | yes  | no   | yes| no | no | no | yes| no  | yes          |

TABLE 8. Simulation results of every facility 24 hours a day.

| Parameters | M-WS | S-WS | M-ST | S-ST | MS | CF | AF | MC | LF | L-SF | S-SF or M-SF |
|------------|------|------|------|------|----|----|----|----|----|-----|--------------|
| \( W_s \) (kWh) | 5.463 | 13.66 | 2.731 | 8.194 | 1.366 | 15.02 | 68.28 | 40.97 | 1.366 | 34.14 | 4.097       |
| \( W_e \) (kWh) | 2.976 | 9.919 | 1.913 | 5.739 | 0.9501 | 13.74 | 86.68 | 37.61 | 0.9079 | 41.27 | 2.524       |
| \( W_g \) (kWh) | 0 | 0.5733 | 0 | 0.3034 | 0 | 4.354 | 48.29 | 2.92 | 0 | 14.57 | 0           |
| \( r_{pd} \)   | 1.836 | 1.377 | 1.428 | 1.427 | 1.438 | 1.093 | 0.788 | 1.089 | 1.505 | 0.827 | 1.623       |
| \( r_c \) (%)  | 98.12 | 71.87 | 73.39 | 76.05 | 44.43 | 62.7 | 51.94 | 60.89 | 80.26 | 53.09 | 100         |
| \( r_p \) (%)  | 98.12 | 100  | 100  | 100  | 100  | 100  | 100  | 100  | 100  | 100  | 100         |
| \( r_u \) (%)  | 54.74 | 69.5 | 74.55 | 67.37 | 87.31 | 64.3 | 56.23 | 85.11 | 62.57 | 78.35 | 61.93       |

TABLE 9. Simulation results of tourist area 24 hours a day.

| Parameters | \( W_s \) (kWh) | \( W_e \) (kWh) | \( W_m \) (kWh) | \( r_{pd} \) | \( r_c \) (%) | \( r_p \) (%) | \( r_u \) (%) | \( C_{PC} \) (RMB) | \( C_{P} \) (RMB) |
|------------|-----------------|-----------------|-----------------|--------------|-------------|------------|------------|----------------|----------------|
| Total values | 423334.750     | 407407.203     | 141259.979     | /            | /           | /          | /          | 61600          | 9500           |
| Mean values | /               | /               | /               | 1.312        | 70.250      | 98.035     | 69.270     | /               | /              |

According to Table 8 and Fig. 23, firstly, by these built simulation models, the power coupling characteristics between PV system and every tourism facility can be analyzed easily. The simulation results are very useful to assess the design, planning and layout of tourism facilities. Secondly, for the small or miniature tourism facilities, their renewable energy coverage can be more than 90% (even reach 100%) as long as there are the adequate number of PV cells and adequate capacity of ESMs. Thirdly, in some remote areas, the renewable system can be selected as the only power supply to reduce the construction cost and ESM cost, but the power supply maybe fail in certain period of time. Fourthly, the utilization coefficient of renewable energy can be improved by increasing the capacity of ESMs with the higher cost.

According to Table 9 and Fig. 23, firstly, it is obvious that the real-time power coupling characteristics between PV system and tourist area can be analyzed easily, which is useful to the overall design, planning and layout of tourist area. Secondly, the results obtained by simulation experiments again and again can be used to estimate the operation data in practical application, which can decrease the design period of tourist area. Thirdly, the total cost of PV cells and ESMs can be easily calculated to draw up the investment budget of tourist area.

In a word, all simulation results show that the power coupling characteristics shown in Table 4 are accurate and reasonable and the real-time analysis using them is feasible and available regardless of a single tourism facility or a whole tourist area.

VI. DISCUSSIONS

In a remote area, the wind generators, natural gas turbines, fuel cells and so on may be included except PV cells and ESMs. All of them are usually used to guarantee the reliability of electricity supply in a standalone microgrid and some control strategies have been presented to optimize (or improve) their cost, uncertainty and so on [19]–[23]. In this paper, only PV cells and ESMs are taken into account. The reasons can be illustrated as follows: on the one hand, PV system is one of the most widely used renewable systems. Selecting it as research subject is very representative. On the other hand, in the remote tourist area, PV system has some advantages including low construction cost, flexible installation and...
expansion, no environmental pollution and so on. Finally, for other power generation units, the analysis procedure and results can be analogized on the basis of this work. In addition, it is well known that ESM is currently expensive and its installed capacity may not be sufficient to support a remote tourist area, so the method to estimate its construction cost is discussed and an attempt to plan the number of ESM is made in this paper.

In this paper, there are two characteristics: power demand characteristics of tourism facilities and power supply characteristics of PV system. To make the theoretical analysis more convenient, these two characteristic curves are idealized to a certain extent. By contrast, in simulation experiments, their actual characteristic curves are used. Therefore, these data and simulation results are trustworthy and persuasive.

VII. CONCLUSION

In this paper, the power demand characteristics of tourism facilities and power supply characteristics of PV system are analyzed. Based on them, some mathematical expressions are indicated to establish a direct relationship between PV system and tourist facilities are first proposed. These expressions illustrate the power coupling characteristics between PV system and remote tourist area. Finally, simulation experiments show that the presented power coupling characteristics is feasible and available to obtain the real-time analysis results regardless of a single tourism facility or a whole tourist area. By this work, not only the real-time power characteristics of every tourism facility or overall tourist area can be estimated easily, but also the design period, planning time and construction cost can be greatly reduced by conducting the virtual simulation again and again when PV system is involved in a newly developing tourist area.

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