# Income distribution of the bundled transmission of photovoltaic power plant based on DEA game model

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*Received 6 April 2014, www.tsi.lv*

**Abstract**

The insufficient utilization capacity of photovoltaic (PV) power has been considered as the bottleneck for the future development of PV power in China. Nowadays, the bundled transmission mode of PV power is regarded as the most advocated solution by many scholars. Under the current unsound fiscal taxation policies in China, however, participators cannot receive the corresponding policy incentives and financial compensation for the additional contributions in constraining the implementation of the bundled transmission mode of PV power. Based on the basic theory of the DEA (Data Envelopment Analysis) Game, the allocation model of excessive profit was established. The feasibility of the developed model was verified by means of an actual case study. Arguably, the paper provided a certain theoretical basis for the quantity and practical form of excessive income distribution concerning the bundled transmission mode of PV power, and offered a solution to the income distribution for the bundled transmission mode of PV power.

*Keywords:* DEA Game Model, Photovoltaic Power Utilization, Photovoltaic Power Transmission, Income Distribution

## 1 Introduction

Currently, the insufficient utilization capacity of wind power has become a bottleneck for its development. The average utilization rate of many wind turbine generator systems (WTGS) is less than 30%. Therefore, in order to accelerate the development of PV power in China, appropriate countermeasures must be executed to improve the PV power utilization of power grid [1]. In the opening meeting of Research on Connecting PV Power to Power Grid and Market Utilization, organized by the National Energy Administration (NEA) and held in Beijing on March 30, 2010, this issue has been further augmented. Mr. Liu Qi, the Deputy Director of NEA, presented that [2], "the development of PV power and other new energy industries is an important strategic task in China. Strengthening the coordinative development of power grid and PV power is an important foundation for the rapid development of PV power, wherein, the study on grid connection of PV power and market utilization is a top priority."

In order to enhance the utilization capacity of PV power, previous researchers proposed to adopt the bundled transmission mode of PV power for expanding its utilization regions and improving the stability of power grid [3-4]. Furthermore, some researches verified its scientificity and feasibility in various aspects. Bai et al. stated that, "the adjustability of other power supplies (such as thermal power and hydropower) is the decisive factor to determine whether the electrical power system can accommodate the scale of PV power or not. As the domestic wind power resources are concentrated, it is determined that the rapid development and utilization of China's PV power can be realized only when a firm trans-regional interconnected grid is established [5]. Therefore, effective coordination with other types of power supplies and power grid groups are required to provide the support services for the bundled transmission mode of PV power. The bundled proportion of PV power is related to the peak load regulation capacity of thermal power, hydropower, and so forth. Additionally, it is also related to the output characteristics of PV power and the depth of long-distance power transmission in participating in peak load regulation of receiver grid, etc.

Nowadays, the implementation of the bundled transmission mode of PV power has been restricted by the associated fiscal taxation policies in China. Zhang Yunzhou et al. in their paper "A Study of the Major Issues Related to the Development and Utilization of China's PV Power" put forward the major problems including: the subsidy standard stipulated for grid connection is too low; No policy is available regarding the investment returns concerning long-distance transmission and transformation project of large-scale PV power bases; no pricing and compensation mechanism for various support services provided by large grid-connected PV power of other power plants and grids is made, etc [6]. Therefore, to ensure the smooth progress of PV power as well as other types of the bundled transmission, the aforementioned problems must be solved and related fiscal taxation policies must be revised.

Therefore, the distribution of income must be well allocated to guarantee the smooth implementation of the

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bundled transmission modes of PV power. In other word, all parties involved – hydroelectric power, thermal power, pumped-storage power, nuclear power, biomass power and power grid enterprises should get the corresponding incentive compensation for better coordination with the countermeasure and achieving the objective of enhanced PV power utilization capacity. In this paper, DEA Game model is proposed to solve the distribution of income among all parties involved in the bundled transmission of PV power. This in return provides a basis for establishing corresponding subsidy and incentive mechanism.

## 2 DEA Game theory

Nakabayashi and Tone extended the efficiency analysis of multiplayer game proposed by Golany and Rousseau [7]. This set up the idea of qualitative classification on DMU by means of their coalitions, to consider the cooperative game of DMUs, and construct the DEA Game model. This initiated the application foundation of DEA game though the application of DEA Game was still restricted. This is because that the number of participators and standards considered by Nakabayashi and Tone [8] is relative small and the challenge of getting game solutions is augmented with the increase of the number. Therefore, it is worthy of studying how to design the reasonable game solutions for such a problem. Li et al. [9, 10] took fixed cost proportions among DMUs into account based on DEA and coalition game. They analyzed the allocation of coalition game by the Shapley value and nucleus, respectively. Finally, the linear programming algorithms and the genetic inheritance algorithms were developed to solve the problem.

DEA Game model mainly considers the progress of reaching an agreement by multiplayers under various standards. Assume there are n parties and each person has m standards to distribute the given interests. For private interest, everyone wishes to maximize the standard that is beneficial to himself and to minimize the unfavourable standard. In this way, the given benefits are insufficient for distribution. Therefore, the allocation gets stuck into a dilemma. It will inevitably lead to inconsistency when participators determine the weight values of various indexes. However, DEA can solve such kind of problems. DEA Game is based on the assumption that every party in the game is willing to take part in the game and all participators agree to negotiate together so as to reach a reasonable and fair allocation plan. The coalition and distribution of members are also taken into account.

### 2.1 COALITION OF DEA GAME AND THE CHARACTERISTIC FUNCTION

All players are recorded as N, $N = \{1,2,3,\cdots n\}$. Any subset S of N is a coalition, then $S \subset N$. When players are conducting profit (cost) distribution, the index that is agreed to be important is denoted as $i,\ i = 1,2,3\cdots m$.

The $i$ th index score of coalition S is defined as $x_i(S)$:

$$x_i(S) = \sum_{j \in S} x_{ij}\,(i = 1,2,3\cdots,m).$$

*2.1.1 DEA maximum game*

The characteristic function of coalition S is defined as $C(S),(C(\phi)=0)$. C(S) is the maximum profit value obtained by coalition S, and C(S) is expressed by the following linear programming:

$$C(S) = \max \sum_{i=1}^{m} w_i x_i(S), \quad s.t.\begin{cases} \sum_{i=1}^{m} w_i = 1 \\ w_i \ge 0 (i = 1,2,3\cdots,m) \end{cases}. \tag{1}$$

In the equation, $w_i$ is the weight of index $i$ under a certain coalition.

$(N, c)$ is used to represent DEA max game with the participator set of N and the characteristic function of c, which has the transferable utility. The characteristic function of DEA max game has the following properties:

I. For coalitions of S and T, if $S \subset N$, $T \subset N$ and $S \cap T = \phi$, then $C(S \cup T) \le C(S) + C(T)$;

II. $C(N) = 1$.

*2.1.2 DEA Minimum game*

In DEA Minimum game, the characteristic function of coalition S is defined as $d(S),(d(\varphi)=0)$. $d(S)$ is the minimum cost value paid by coalition S, and $d(S)$ can be expressed by the following linear equation:

$$d(S) = mix \sum_{i=1}^{m} w_i x_i(S), \quad s.t.\begin{cases} \sum_{i=1}^{m} w_i = 1 \\ w_i \ge 0 (i = 1,2,3\cdots,m) \end{cases}, \tag{2}$$

where $w_i$ is the weight of index $i$ under a certain coalition. *(N,d)* is used to represent DEA min game with the participator set of N and the characteristic function of d with the transferable function. The characteristic function of DEA min game has the following properties:

I. For coalitions of S and T, if $S \subset N$, $T \subset N$ and $S \cap T = \phi$, then $d(S \cup T) \ge d(S) + d(T)$;

II. $d(N) = 1$.

## 2.2 BENEFIT APPORTIONMENT OF DEA GAME AND THE APPORTIONMENT VECTOR

Benefit (cost) apportionment is the nucleus content of DEA game, as a decisive role in the stability of cooperative alliance. Once a party suffers from unfair treatment, the already formed coalition is at the risk of disintegration. Therefore, to maintain the stability of the cooperation, the benefit (cost) apportionment should satisfy definite rationality.

Assuming that the cooperative cost apportionment can be simplified as a transferable apportionment or utility, namely with side payment (transferable payment), the side payment shall meet the following requirements:

- Every player measures his apportionment with the same utility scale;
- The apportionment of each coalition can be distributed to each participator in any manner. In other words, the apportionment of all players is transferable.

$n$ -dimensional vector $z=\{z_1, z_2, \cdots z_n\}$ is used to represent shares distributed from the coalition apportionment to each player of DEA game. The following condition shall be satisfied:

- Rationality of individuals:

$$z_j \geq C(\mathrm{j}) \text{ or } \mathrm{z_j} \leq \mathrm{d(j)}, (\mathrm{j}=1,2,3,\cdots \mathrm{n}). \quad (3)$$

- Rationality of collectives:

$$\sum_{j=1}^{n} z_j = C(N) = 1 \; or \; \sum_{j=1}^{n} z_j = d(N) = 1 \cdot \quad (4)$$

# 3 Construction of income distribution concerning the bundled transmission of PhotoVoltaic (PV) Power Based on DEA Game Model

## 3.1 MODEL PARAMETERS

As an obstacle of recent research, the distribution of income is related to the immediate interests among every participator of the bundled transmission of PV power.

### *3.1.1 Determination of excessive profit*

The distributed interest in the model refers to the excessive profit of the bundled transmission of wind power, considering the practical planning and operation of electric power system. Under the normal operation of the the bundled transmission of wind power, power grid enterprises will settle with each participator according to the existing system. Combined with the actual cost statement delivered from each participator, the power grid enterprises are compared with previous parameters every half a year to estimate the excessive profit of this section. That is to say, the excessive profit of the bundled transmission of wind power (M) = profit of utilized wind power capacity obtained from the bundled transmission (PU) - profit of utilized wind power capacity that is not obtained from the bundled transmission under current grid development condition (PD) + contribution amount of utilized wind power capacity to the social benefit (PE). The contribution amount of the utilized wind power capacity to the social benefit mainly covers environmental benefits including the saved non-renewable energy resources and so on.

### *3.1.2 Participators of profit apportionment*

Wind power plant – provides wind power capacity and bears the cost of wind power generation.

Power grid enterprise – constructs trans-regional power grid and undertakes the assurance of risk and cost of grid stability after the utilized PV power generation.

Grid-connected power station refers to the power plant used for the bundled transmission (including thermal power plant, hydroelectric power station, pumped-storage power station, gas turbine power station and nuclear power station, etc.) – Except for the basic services, they should also be compensated for the provided support services of automatic generator control (AGC), paid peak load regulation, alternative, paid reactive power regulation, black start and so on.

The support services of grid-connected power station can be divided into the basic support services and the compensated support services. The basic support services indicate the support services that must be provided by generator set to ensure safe and stable operation of electric power system and power quality including primary frequency, basic peak load regulation, basic reactive power regulation, etc. For this part of support services, no distribution of excessive profit concerning the bundled transmission of wind power is required. Only the compensable support service, which is provided by other grid-connected power stations and is included in the bundled transmission of wind power, can participate in the distribution.

## 3.2 BASIC MODEL OF INCOME DISTRIBUTION

This paper mainly involves the application of DEA game in the income distribution of the the bundled transmission mode of PV power. A new scheme has been proposed to take advantage of DEA game model for income distribution. Firstly, all the players, namely all the profit sharers of the the bundled transmission mode of PV power, are recorded as $N$, $N=\{1,2,3\cdots n\}$. Any subset S of $N$ is a coalition, then $S \subset N$. When the players are conducting profit (cost) distribution, the index that is agreed to be important is kept down as $i$, $i=1,2,3\cdots m$. And the index score of each player under every index is evaluated together. $x_{ij}$ is the index score of the $j$ th player under the $i$ th index, $j=1,2,3\cdots n$. The higher $x_{ij}$ under an index reveals that the $j^{\text{th}}$ player has higher evaluation under this index. The matrix constituted by all index scores is set as *X*, namely $X = \{x_{ij}\}_{m \times n}$. And matrix *X* is standardized, namely $\sum_{j=1}^{n} x_{ij} = 1 (i = 1, 2, 3 \cdots, m)$.

The $i^{\text{th}}$ index score of coalition S is defined as $x_i(S)$:

$$x_i(S) = \sum_{j \in s} x_{ij} \, (i = 1, 2, 3 \cdots, m) \cdot \tag{5}$$

Characteristic function of coalition *S* is defined as $C(S), (C(\varphi) = 0)$. C(S) is the maximum profit value obtained by coalition S, and C(S) is expressed by the following linear programming:

$$C(S) = \max \sum_{i=1}^{m} w_i x_i(S),$$
$$s.t. \begin{cases} \sum_{i=1}^{m} w_i = 1 \\ w_i \geq 0 (i = 1, 2, 3 \cdots, m) \end{cases} . \tag{6}$$

In the equation, $w_i$ is the weight of index *i* under a certain coalition. Obviously, C(N)=1. Unit profit share obtained by each person is expressed by vector Z: $z = \{z_1, z_2, z_3, \cdots z_m\}$.

3.3 SOLUTIONS

In the cooperative game, many significant methods can be used to analyze and solve the game, including negotiation set, stabilization set, nucleus, nucleolus and Shapley value. Since the solution of nucleus must be unique and feasible, nucleus is adopted in the paper to solve the model so as to enable the players to get a fair and reasonable profit distribution amount.

Let $e(S, z) = C(S) - \sum_{i \in S} z_i$, then *e(S, z)* is the difference value between total excessive profit obtained by profit sharers when forming coalition S and the actual excessive profit obtained by sharers. The greater the difference, take this strategy is not ideal. Since there are $2^n$ subsets of N, there are also $2^n$ subsets of *e(S,z)*. They can be restructured into a vector according to the order from small to large $\theta(z) = (\theta_1(z), \theta_2(z) \cdots \theta_{2^n}(z))$.

The nucleus is defined as:

$$N(V) = \{z \in E(C) / \theta(z) \leq \theta(y), \forall y \in E(C)\} . \tag{7}$$

wherein, *E(C)*is the set of all allocation vectors.

As known from the above equations, the nucleus is a kind of distribution that allows the minimum excessive vector. All coalitions that might be formed in the cooperation have a definition of excessive value at the nucleus. The nucleus solution can be realized by the following linear programming:

$$min\varepsilon = e(S, z) = C(S) - \sum_{i \in S} z_i ,$$
$$s.t. \begin{cases} \sum_{i \in S} z_i + \varepsilon \geq C(S) \\ \sum_{i \in N} z_i = C(N) \end{cases} . \tag{8}$$

In the equation, $\varepsilon$ is an arbitrary small real number; N is the set of excessive profit sharers of the the bundled transmission mode of PV power; and S is the nonvoid subset of N. This is a standard linear programming problem and it can be solved by virtue of Matlab tool.

## 4 Empirical study on income distribution concerning the bundled transmission of PhotoVoltaic (PV) Power Based on DEA Game Model

To enhance the utilization ability of PV power, N persons are involved in the bundled transmission mode of PV power to split its excessive profit. It means 4 participators of DEA Game if N=4 is selected. It is assumed that the estimate of excessive profit in the first half year of 2012 is 80 million Yuan according to the equation M= PU—PD+PE.

4.1 CASE STUDY

Firstly, 4 players are defined as: A – wind power plant participated in the bundled transmission mode of PV power; B – power grid enterprises to maintain the stability of power grid and trans-regional power grid construction after the establishment of the bundled transmission mode of PV power; C – grid-connected thermal power plant that participates in the bundled transmission mode of PV power; and D - grid-connected hydroelectric power station, respectively.

Secondly, indexes that are agreed to be important by 4 players A, B, C and D are listed: power generating capacity, maintenance of power grid stability, superior alternative emergency power supply for peak load regulation, AGC, workload of reactive power regulation and additional investment of basic construction. Experts are employed to score the above 6 indexes according to the Performance Table of Semi-Annual Power Generating Capacity, Power Supply Reserve for Peak Load Regulation and the Use Condition Table, Analysis Table for Workload of Reactive Power Regulation and Table for Additional Investment Condition of Basic Construction delivered by participators. It should be noted that regarding the continuous distribution of excessive profit, the scores of six indexes will vary dependently on different contribution of involved parties. In order to ensure the accuracy of income distribution, the scoring is needed half a year for the changed materials.

According to the materials in the first half year of 2012 provided by four participants, the above six indexes are scored as shown in Table 1.

TABLE 1 Each Index Score of Every Player

| | A | B | C | D |
|---|---|---|---|---|
| **Power Generating Amount** | 0.5 | 0 | 0.3 | 0.2 |
| **Maintenance of Power Grid Stability** | 0.1 | 0.6 | 0.2 | 0.1 |
| **Superior Emergency Power Supply Reserve for Peak Load regulation** | 0.1 | 0 | 0.5 | 0.4 |
| **AGC** | 0.2 | 0 | 0.4 | 0.4 |
| **Workload of Reactive Power Regulation** | 0.1 | 0 | 0.5 | 0.4 |
| **Additional Investment of Basic Construction** | 0.1 | 0.7 | 0.1 | 0.1 |

Finally, the interest allocations of various alliances are obtained. The characteristic values of function, under different coalitions are calculated by equations (5) and (6), as shown in Table 2.

TABLE 2 All Kinds of Combination Alliances

| Method of coalition | | Nominal amount of excessive profit |
|---|---|---|
| **Independent** | A | 0.5 |
| | B | 0.7 |
| | C | 0.5 |
| | D | 0.4 |
| **Allied by two groups** | AB | 0.8 |
| | AC | 0.8 |
| | AD | 0.7 |
| | BC | 0.8 |
| | BD | 0.8 |
| | CD | 0.9 |
| **Allied by three groups** | ABC | 0.9 |
| | ABD | 0.9 |
| | ACD | 1 |
| | BCD | 0.9 |
| **Allied by four** | ABCD | 1 |

## 4.2 SOLUTION OF CASE MODEL

The above characteristic values of functions are substituted in (8) and further results are obtained:

$$\min \varepsilon = e(S,z) = C(S) - \sum_{i\in S} z_i, \tag{9}$$

$$s.t.\begin{cases} z_A + \varepsilon \ge 0.5 \\ z_B + \varepsilon \ge 0.7 \\ z_C + \varepsilon \ge 0.5 \\ z_D + \varepsilon \ge 0.4 \\ z_A + z_B + \varepsilon \ge 0.8 \\ z_A + z_C + \varepsilon \ge 0.8 \\ z_A + z_D + \varepsilon \ge 0.7 \\ z_B + z_C + \varepsilon \ge 0.8 \\ z_B + z_D + \varepsilon \ge 0.8 \\ z_D + z_C + \varepsilon \ge 0.9 \\ z_A + z_B + z_C + \varepsilon \ge 0.9 \\ z_A + z_B + z_D + \varepsilon \ge 0.9 \\ z_A + z_C + z_D + \varepsilon \ge 1 \\ z_B + z_C + z_D + \varepsilon \ge 0.9 \\ z_A + z_B + z_C + z_D = 1 \end{cases} \tag{10}$$

The presented procedure is employed to solve the multi-objective programming problem. Since the wind power plant must exist as a participator of the bundled transmission mode of PV power, the abovementioned alliance set thus has invalid coalition (supposing the weight of invalid coalition is 0). To deal with this part of the invalid alliance, the linear weighted sum method of Matlab multi-objective programming problem is adopted. The objective functions for each scenarios and the given weight factors are shown as Table 3.

TABLE 3 The Objective Function and Its Given Weight

| Serial No. | Objective Function | Weight |
|---|---|---|
| 1 | $\min \varepsilon = 0.5 - z_A$ | 0.05 |
| 2 | $\min \varepsilon = 0.7 - z_B$ | 0 |
| 3 | $\min \varepsilon = 0.5 - z_C$ | 0 |
| 4 | $\min \varepsilon = 0.4 - z_D$ | 0 |
| 5 | $\min \varepsilon = 0.8 - (z_A + z_B)$ | 0.1 |
| 6 | $\min \varepsilon = 0.8 - (z_A + z_C)$ | 0.1 |
| 7 | $\min \varepsilon = 0.7 - (z_A + z_D)$ | 0.1 |
| 8 | $\min \varepsilon = 0.8 - (z_B + z_C)$ | 0 |
| 9 | $\min \varepsilon = 0.8 - (z_B + z_D)$ | 0 |
| 10 | $\min \varepsilon = 0.9 - (z_D + z_C)$ | 0 |
| 11 | $\min \varepsilon = 0.9 - (z_A + z_B + z_C)$ | 0.15 |
| 12 | $\min \varepsilon = 0.9 - (z_A + z_B + z_D)$ | 0.15 |
| 13 | $\min \varepsilon = 1 - (z_A + z_C + z_D)$ | 0.15 |
| 14 | $\min \varepsilon = 0.9 - (z_B + z_C + z_D)$ | 0 |
| 15 | $\min \varepsilon = 1 - (z_A + z_B + z_C + z_D)$ | 0.2 |

The multi-objective linear programming of Matlab linear weighted sum method is expressed as below:

- Evaluation function of a linear weighted sum method is established as follow,

$$\begin{aligned} \min h(F(x)) &= \lambda_1(0.5 - z_A) + \lambda_2[0.8 - (z_A + z_B)] \\ &+ \lambda_3[0.8 - (z_A + z_C)] + \lambda_4[0.7 - (z_A + z_D)] \\ &+ \lambda_5[0.9 - (z_A + z_B + z_C)] + \lambda_6[0.9 - (z_A + z_B + z_D)] \\ &+ \lambda_7[1 - (z_A + z_C + z_D)] + \lambda_8[1 - (z_A + z_B + z_C + z_D)]. \end{aligned} \tag{11}$$

The corresponding weights into the above equation are substituted, and then the objective function min *h (F(x))* can be sorted out as follow,

$$\min h(F(x)) = 0.875 - (z_A + 0.6\times z_B + 0.6\times z_C + 0.6\times z_D). \tag{12}$$

- The equations are solved with the aid of commercial software MATLAB:
  $z_A = 0.4162, z_B = 0.2618,$
  $z_C = 0.1852, z_D = 0.1368.$
- Excessive profits are distributed as: A of 33.296 million Yuan; B of 20.944 million Yuan; C of 14.816 million Yuan; and D of 10.944 million Yuan.

## 5 Model analysis

From the presented model, targeting at the finite non-renewable energy and environmental pollution that may be caused at present, PV power has become the mainstream of future power supply development, and its utilized amount by power grid will be the key factor to determine whether it can be developed into the mainstream or not. Therefore, to make power supply constituents in a sustainable way, various support services provided by participators should receive corresponding compensation incentives to guarantee the implementation of various policies encouraging the utilization of PV power. Income distribution scheme provided previously expressed the distribution principle with three key issues: firstly, the paper provisionally assumes that the materials provided by grid companies combined parties involved are estimated every six months, but the specific estimation method still needs further study. Secondly, in the scoring six key indexes must be determined according to the contribution degree of various participators. Thirdly, due to the existence of subjective judgment in the model, a comprehensive collection of information is required for all parties. The information shall be reasonable and comprehensive. Briefly, the excessive profit distribution of the bundled transmission mode of PV power is a challenging research topic. In the practical applications, the material submitted by participators should be followed strictly to estimate the excessive profit as accurately as possible; and the value of each index should be strictly determined in order to ensure the relative accuracy of the allocation result.

## 6 Conclusions

Based on the state of art of PV power, the enhancement of PV power utility capacity is proposed as a key to the rapid development of PV power in future. The most highly praised expansion method of PV power utility capacity is the bundled transmission mode of PV power. In light of the constrained situation by some policy towards the implementation of the bundled transmission mode of PV power, DEA Game is proposed in the paper to solve the problem of excessive profit distribution. Based on the hypothesis that all players are willing to participate in the game and consult together to reach a fair and equitable distribution program, a DEA Game distribution model of excessive profit has been established. Through systematically case studies, the feasibility of the model is proved to provide a theoretical basis for the excessive profit distribution regarding the bundled transmission mode of PV power. It allows the participators to obtain appropriate compensation as an encouragement for them to participate in the bundled transmission mode of PV power in a better way. Then the utility capacity of PV power can be expanded.

In the design of excessive profit distribution model for the bundled transmission mode of PV power, the estimation of excessive profit and the determination of six key index scores are required to be combined with a lot of the relevant materials. More concise and accurate methods still are needed in the further studies.

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