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Cost Allocation of Residential Distributed PV Project Based on Cooperative Game Theory

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Abstract: The thesis analyzed the cost allocation of distributed photovoltaic power generation system in China by discussing 15 cities' natural conditions and their subsidy policies as to photovoltaic power generation, focusing on the promising prospect of the system in the country's living buildings, using tools including SAM, SOBRA and MATLAB and taking externality theory and cooperative game theory as the theoretical foundation. The analysis results revealed that state subsidies couldn't benefit the residents in a fair way and local subsidies, to a great extent, decided the development level of distributed photovoltaic system in the region, the sum of which basically was between what was calculated by Shapley value method and by the nucleolus method, that the insufficient amount of local subsidies, low residential electricity price and difficulties obtaining subsidies for power grid companies have led to, as far as the players are concerned, less motivation to invest distributed photovoltaic system, which has developed slower than the expectation.

Keywords: *Distributed photovoltaic system, externality, cooperative game theory, cost allocation*

1. Introduction

Distributed photovoltaic power generation is a way of power generation from the perspective of demand side that by using photovoltaic modules converts solar power into electricity, the promotion and utilization of which is of great significance to the energy structure, energy conservation and emission reduction and air pollution prevention in China. Naturally, in August, 2013, the subsidy policy, that is, a 0.42 yuan/kWh subsidy for distributed solar electricity consumed, was officially promulgated by National Development and Reform Commission [1]. The provinces and cities, then, also came up with various local subsidy policies to facilitate the development of power generation industry. In January, 2015, National Energy Administration set the goal, for 2015, of an increase of 7GW in distributed installed photovoltaics capacity and in December of the same year, has specified the overall development plan to reach a 70 GW capacity of distributed installed photovoltaics by the end of 2020.

According to the statistics from National Energy Administration, however, in 2015, the installed photovoltaics capacity only increased 1.39 GW, far less than the development goal set in early 2015 and with an obviously slowing development speed, even significantly less than the installed capacity increase, 2.05 GW, in 2014. As the photovoltaic system price keeps falling down, the distribution of profits and costs has become unclear among stakeholders and the return on investment is uncertain, which has been the obstacles of distributed photovoltaics development. In recent years, there has been more researches concerning cost allocation of new energies both in China and abroad: Hu Junfeng solved the problem of ancillary services charges in the connection of wind power to grids by exploiting static and dynamic cooperative game theory[2]; Lin Boqiang and Li Jianglong estimated the cost of connecting a variety of new energies within a certain time span and broke down the cost for different parties[3]; N.X. Jia and R. Yokoyama, using cooperative game theory, analyzed the profit sharing for independent energy suppliers in electricity retail market[4]. Yet, the researches now mainly focus on the cost of power transmission and distribution, and there are few researches on the overall cost allocation as to distributed photovoltaics. Therefore, the thesis, taking the light availability, economic development and energy structure into full consideration and based on the calculation of leveled cost of energy of distributed photovoltaic system, analyzed the impacts the distributed photovoltaics development has on the benefits of grid power companies, the government and the residents, and applied, separately, Shapley value method, MCRS method and the nucleolus method in cooperative game theory to solve the profit sharing problem for each party investing in distributed photovoltaics and to acquire the mechanism of cost allocation of distributed photovoltaic suitable for each region.

2. Leveled Cost of Energy of Distributed Photovoltaic System

2.1 Calculation of leveled cost of energy before subsidy

Leveled cost of energy(LCOE) is an important indicator for analyzing the costs of various power generation technologies, which, now broadly applied in energy industry, is the ratio of discounted value between the cost of the system through its lifetime and the electricity amount the system generated. For photovoltaic system, its costs are mainly the initial investment and, then, the cost occurring in operation and maintenance. The expression is:

$$LCOE = \frac{I_0 + \sum_{t=0}^{T} M_t/(1+r)^t}{\sum_{t=0}^{T} E_0\,(1-d)^t/(1+r)^t}$$

Where: I_0 is the initial investment in the first year, M_t is the cost for operation and maintenance each year, E_0 is the electricity generated by the system in the first year, d is the attenuation rate of the system's performance.

LCOE of distributed photovoltaic system is closely related to such factors as its design, modules' performance and the climate. For the convenience of the analysis, the author used SAM[5] to conduct a simulation calculation of LCOE of residential distributed photovoltaic power generation system in 15 cities in China. In the simulation model, the attenuation rate of the system's performance was set at 0.8%, the cost for operation and maintenance 10 yuan/kW, system's lifetime 25 years. In the twelfth year, the inverter has to be replaced, the price for which is set at 1 yuan/W with 8% of social rate of discount. Because it was the distributed photovoltaics in residential buildings that this thesis discussed, the installed capacity is from 1~10 kW as limited and within the range, the unit price is 10~12 yuan/kW. The smaller the capacity is, the higher the price is. According to these parameters, the LCOE of distributed photovoltaics in each city in question was: the northwest region of China received the most sunlight, in which, Tibet and Qinghai province got the most sunlight, and Sichuan basin and the most area of Guizhou province received the least sunlight. As can be seen from Table 1, the highs and lows of the LCOE of distributed photovoltaics demonstrate the light availability in the region. Generally, the regions receiving less sunlight have a higher LCOE and those getting abundant sunlight have a lower LCOE.

Table 1.*LCOE of PV systems in different cities*

Cities	LCOE yuan/kW·h
Baoji	0.94
Beijing	0.87
Changsha	1.09
Chengdu	1.16
Chongqing	1.19
Guiyang	1.18
Hangzhou	1.04
Harbin	0.90
Hefei	1.00
Kunming	0.88
Lanzhou	0.85
Mangya	0.72
Nancheng	1.03
Shanghai	1.01
Wuhan	0.99

2.2 Calculation of leveled cost of energy after subsidy

In addition to the subsidy policy China has revealed that the distributed solar electricity consumed would receive a subsidy of 0.42 yuan/kWh, local governments also came up with subsidy policies to boost the development of distributed photovoltaics industry. The policies put forward by the 15 cities are shown in Table 2.

Table 2.*Local subsidies for distributed PV systems in different cities*

Cities	Subsidy Policy	
	Contents	Subsidy Types
Baoji	1yuan/W	One-time Subsidy
Beijing	0.3 yuan/kW·h, 5 years	According to electricity consumption
Changsha	0.2 yuan/kW·h, 10 years	According to electricity consumption
Chengdu	—	
Chongqing	—	
Guiyang	—	
Hangzhou	0.2 yuan/kW·h, 5 years	According to electricity consumption
Harbin	—	
Hefei	2 yuan/W, Limit to 20 thousand yuan	One-time Subsidy
Kunming	—	
Lanzhou	—	
Mangya	—	
Nancheng	4 yuan/W for the first tome, 3 yuan/W for the second time	One-time Subsidy
Shanghai	0.4 yuan/kW·h, 5 years	According to electricity consumption
Wuhan	0.25 yuan/kW·h, 5 years	According to electricity consumption

State and local subsidies can significantly lower LCOE of distributed photovoltaics for each investor and improve the profitability. The effects of state and local subsidies are shown in Figure 1.

3. Analysis on return for stakeholders

Developing distributed photovoltaic can cause a series of impacts on return for power grid companies, the government and residents, and then, on their enthusiasm in investment. Details of the analysis are elaborated as follows:

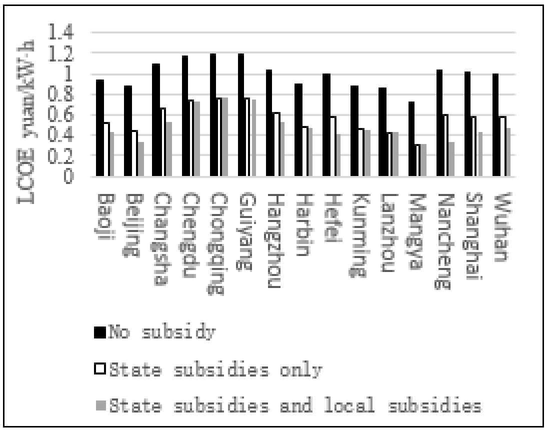


Figure 1.*LCOE of distributed PV systems with subsidies in different cities*

3.1Power Grid Company

3.1.1 Value of slowing down power grid construction: R_p

When power grid companies are planning the construction of power grids, using distributed photovoltaics can reduce the system's demand on the transmission capacity during peak load hour. By doing so, the investment for electricity transmission and distribution can be reduced and the process can slower down. For power grid companies, then, the value of the investment saved is equal to the time value of the capital put in the companies' reform and update.

3.1.2 Improve reliability of electricity supply: R_r

When major power grids broke down, distributed photovoltaics with a moderate capacity can ensure safe and sound operation of important load, so as to improve the reliability of power grids. The value of the resultant economic benefit is equal to the loss caused by power failure of the residents.

3.1.3 Reduce line loss: R_l

Connecting distributed photovoltaics can reduce the long-distance and large-capacity electricity transmission through conventional power grids, and therefore, reduce high-voltage power transmission line loss. The gains (per kWh) from a reduction on line loss for power grid companies are:

$$R_l = \eta \times \frac{P_b}{1-\eta}$$

Where: P_b is local benchmark price for electricity generated from desulfurized coal units going to the grids, η is the average rate of line loss.

3.1.4 Cost for emergency power increases: R_b

Emergency power in a grid system means active power reserves in the electric power system to ensure grid safety and economic operation besides meeting the predicted load demand. Due to strong intermittency and fluctuation in the generation of photovoltaic power generation system, power grid companies have to use emergency power system to regulate peak load and frequency. Thus, the cost for emergency power is the additional cost for power grid companied related to distributed photovoltaics.

3.1.5 Loss of electricity sales: R_e

With distributed photovoltaics, that the electricity generated and consumed on-site leads to a reduction on the amount of electricity residents purchased, and resultantly, power grid companies gain less profits. The profits per kWh are the difference between residential electricity price and local benchmark price for electricity generated from desulfurized coal units going to the grids. If the proportion of the electricity generated by distributed photovoltaics and consumed by the residents on-site was 50%, the loss per kWh as to electricity sales for power grid companies is:

$$R_e = 50\% \times (P_s - P_b)$$

Where: P_s is local residential electricity price

The benefits per kWh power grid companies gain from distributed photovoltaic system are:

$$E_g = R_p + R_r + R_l - R_b - R_e$$

3.2 Government

3.1.1 Benefits from carbon dioxide reduction: R_c

Despite the high energy consumption and the resultant exhaust, waste water and refuse caused in the production of solar panels that have drawn public attention, the emission of various contaminants in a photovoltaic system's lifetime is, still, greatly reduced compared with the old coal power[7]. Data comparison is shown in Table 3:

Table 3.*Pollutants emitted by districted PV systems and coal-fired power plants based on life cycle assessment*

Contaminants	Effect Types	PV Emissions g/kW·h	Coal Power Emissions g/kW·h
carbon dioxide	global warming	28.8	1180
sulfur dioxide	acidification	0.1	0.285
nitric oxide	acidification	0.0775	0.653
volatile organic compound	Photochemical ozone creation Potentials	1.2×10^{-4}	/

The carbon dioxide emission reduced per kWh for using photovoltaic system generating electricity rather than coal power could be transformed into economic benefits. The expression is:

$$R_c = (Q_c - Q_p) \times p_c$$

Where: Q_c is the emission of carbon dioxide per kWh in the lifetime of coal-fired power plant, Q_p is the emission of carbon dioxide per kWh in the lifetime of photovoltaic system, p_c is the unit price for carbon dioxide emission.

For the value of p_c, there has no unified standard for measurement. The differences of calculation results of different models might be enormous within the range of \$10/t to \$150/t[8]. The price was set at \$40/t in this model.

3.2.2 Health benefits: R_h

Compared with conventional coal power, the emission of contaminants in distributed photovoltaics' lifetime are greatly reduced, which will be of help improve local residents' health situation and therefore, lead to less investment by the government in residents' health care. COBRA [9] was adopted to calculate the health benefits and the results showed that the electricity the distributed photovoltaics generated consumed per MWh could bring health benefits of \$53.93.

3.2.3 Employment benefits: R_j

Developing distributed photovoltaics can create more jobs. There are researches showing that with an investment of one million US dollars, photovoltaic industry is able to create jobs for 5.7 years while the industry of electricity generated by coal can only create jobs for 3.9 years [10]. In addition, the government every year gives subsistence allowance to those who live below the poverty line to guarantee social stability and harmony, part of which is saved due to the jobs distributed photovoltaic industry creates. Therefore, the employment benefits per kWh distributed photovoltaic industry bring about are calculated as follows:

$$R_j = \frac{(5.7 - 3.9) \times 12 \times M_l}{10^6} \times LCOE$$

Where:M_l is the minimum monthly subsistence allowance for local urban residents.

In addition to what was discussed above, the government is also gaining positive externality benefits for promoting distributed photovoltaics such as the improvement of cities landscape effect and the development of relevant industries, which are not easy to be quantified and therefore, not being analyzed in the thesis.

Thus, the benefits per kWh the government gets from distributed photovoltaics are:

$$E_g = R_c + R_h + R_j$$

3.3 Residents

Investing distributed photovoltaics can economically impact the residents from two aspects: spending less on electricity and gaining benefits from electricity sales.

3.3.1 Spending less on electricity: R_s

If the proportion of electricity generated by distributed photovoltaics consumed by the residents was 50%, unit electricity distributed photovoltaics generates can save residents:

$$R_s = 50\% \times p_s$$

3.3.2 Benefits from electricity sales: R_b

If the proportion of the remaining electricity sold to the grid was 50%, the benefits unit electricity distributed photovoltaics generates the residents gain are:

$$R_b = 50\% \times p_b$$

According to what discussed, the benefits the residents gain per kWh from distributed photovoltaics are:

$$E_r \square R_s \square R_b$$

4. Cost allocation based on cooperative game

4.1 Cooperative game

The game theory includes cooperative game and non-cooperative game theory. Cooperative theory is mainly about solving the problem of profit sharing by coordinating a number of stakeholders to manage the payoff of the coalition [11], which can be defined with a characteristic function. All players in the game can be demonstrated with a set of, and means the number of the players is the subset, standing for the coalitions formed by the players in the set for their interest. is the corresponding characteristic function for each coalition, that is, the largest benefits the players in the set can get if they work together.

4.1.1 Shapley value

Shapley value was a theory developed in 1950s and 1960s for egalitarianism distribution. According to the theory, the cost the player should pay or the benefits he expects to gain should be equal to the average contribution margin of all players in the coalition. The equation is:

$$X_i(v) = \sum_{S \subseteq N \setminus i} \frac{s!\,(n-s-1)}{n!} (v(S \cup \{i\}) - v(S))$$

4.1.2 MCRS method

The upper and lower bounds in the distribution vector should be determined if MCRS method was adopted, where:

$$X_{max} = (u_1, u_2, \ldots, u_n)$$
$$X_{min} = (l_1, l_2, \ldots, l_n)$$

Then, the solution is the intersection point X^* of point X_{max} and line X_{min} and hyperplane$\sum_{i=1}^{n} x_i = v(N)$, which is acquired by $X = X_{min} + \lambda(X_{max} - X_{min})$ sum $\sum_{i=1}^{n} x_i = v(N)$ [12]. In simplified MCRS method, the marginal cost allocated and the cost the players should pay can be seen, separately, as the lowest and highest cost allocated.

4.1.3 The nucleolus method

B stands for the set of all efficient allocations that satisfy the requirements $\sum_{i \in N} x_i = v(N)$. Then, the only allocation $\gamma = (N, v)$that satisfy requirements $\forall x \in B, x \neq \gamma, e(\gamma) \succ e(x)$ exists in B is called the nucleolus of the game.

The nucleolus evaluates the excess welfare ($e(x; S)$) of the coalition S, or, it can be understood as the excess benefits that bring the coalition a surplus. When calculating the nucleolus, it is of great importance to maximize the smallest excess, and then the second smallest excess and so on. At last, the only allocation is the nucleolus.

4.2 The model for cost allocation of distributed photovoltaics

To find the solution to the problem of cost allocation of distributed photovoltaics, the characteristic function $v(S)$of each coalition S, at first, should be determined.
$N =$
$\{\text{power grid companies, the government, residents}\}$
in the thesis,therefore, there are 2^3 possible coalitions. The characteristic function of a coalition means the overall gains of it can be demonstrated by deducting the cost from the profit [13-14]. The characteristic functions of each coalition are:

For $S_0 = \{\emptyset\}$,$v(S_0)=0$;
For $S_e = \{\text{power grid companies}\}$, $v(S_e) = E_e - LCOE$;
For $S_g = \{\text{the government}\}$,because of the absence of power grid companies, distributed photovoltaic system can only run without the grids and the capacity curve is not able to match user load curve. Some of the electricity, therefore, will be wasted, the proportion of which is assumed to be 50%, and $v(S_g) = E_g/2 - LCOE$;
For $S_r = \{\text{residents}\}$, because of the absence of power grid companies, $v(S_r) = E_r - p_b/2 - LCOE$;
For $S_{eg} = \{\text{power grid companies, the government}\}$, $v(S_{eg}) = E_e + E_g - LCOE$;
For $S_{er} = \{\text{power grid companies, residents}\}$, $v(S_{er}) = E_e + E_r - LCOE$;
For $S_{gr} = \{\text{the government, residents}\}$, because of the absence of power grid companies, $v(S_{gr}) = E_g/2 + E_r - p_b/2 - LCOE$;
For $S_{egr} = \{\text{power grid companies, the government, residents}\}$, $v(S_{egr}) = E_e + E_g + E_r - LCOE$;

Since the profit functions of each coalition is calculated, we now substitute the values of 15 cities in the functions, calculate the profit allocated to each party through three methods, and get the cost allocated by deducting the profit allocated from the gains of each party. The externality profit distribution, notably, needs to be treated differently. If there are only power grid companies and the grid in a coalition, the government actually shares the environmental, social and economic benefits without paying for them, which is unreasonable and needs to be corrected.

4.3 Calculation results of cost allocation for distributed photovoltaics

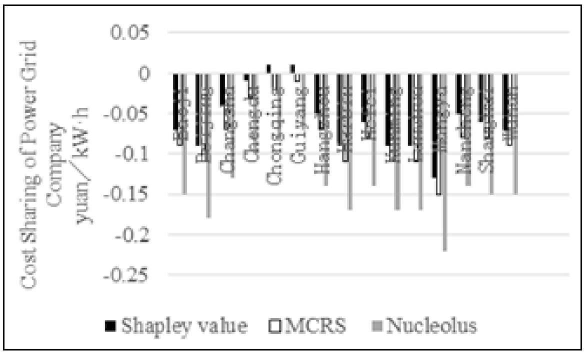
To calculate the profit allocated of each party by the three methods, the average values are shown in Table 4:

Table 4.*The average of profit allocation based on three methods*

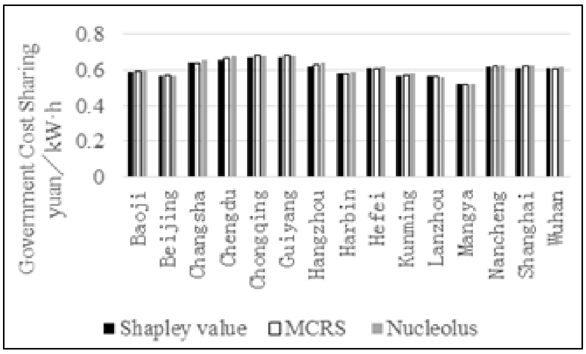
Cities	LCOE	Power Grid Companies	The Government	Residents
Baoji	0.94	0.08	0.06	-0.01
Beijing	0.87	0.12	0.08	0.02
Changsha	1.09	0.08	0.01	0.02
Chengdu	1.16	0.03	-0.02	-0.03
Chongqing	1.19	0.02	-0.03	-0.07
Guiyang	1.18	0.02	-0.02	-0.10
Hangzhou	1.04	0.09	0.02	0.00
Harbin	0.90	0.12	0.07	0.02
Hefei	1.00	0.06	0.04	0.01
Kunming	0.88	0.12	0.08	-0.01
Lanzhou	0.85	0.07	0.09	0.02
Mangya	0.72	0.20	0.13	0.01
Nancheng	1.03	0.05	0.03	0.03
Shanghai	1.01	0.13	0.03	-0.03
Wuhan	0.99	0.08	0.04	0.03

From Table 4, it can be seen that, the profit gained by each party is mostly affected by local LCOE: the higher the LCOE is, the lower the profit is; the lower the LCOE is, the higher the profit is. The sum of profit of power grid companies, the government and the residents in Chengdu, Chongqing and Guiyang is negative, which means, for the grand coalition as a whole, investing in the region's distributed photovoltaics will cause losses, and the main reasons for that are the region's poor sunlight availability and high LCOE. The profit of the residents is not only affected by LCOE but local residential electricity price. For example, Mangya city has the lowest LCOE in the cities in question, but because of low electricity price, the profit gained by the residents does not rank high. Similarly, the residential electricity price in Shanghai, compared with other cities, is rather low, the profit the residents gain from investing distributed photovoltaics, however, is limited and the residents have less motivation to invest.

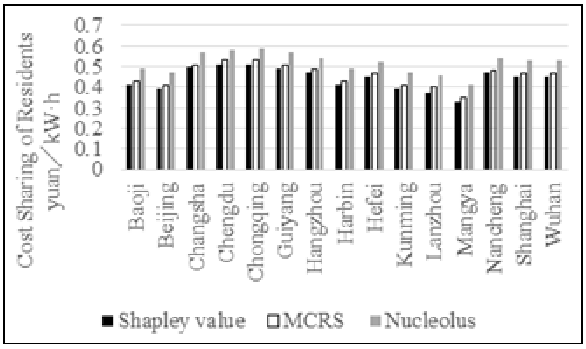
The expenses allocated to the government calculated by the three methods separately are close and the results as to power grid companies and the residents are different. When power grid companies, the government and the residents are in the game, the government and the resident will benefit from the electricity being used that is not able to go to the grid in the first place with power grid companies being in the coalition, and the benefits the government gains are more than those the residents gain. Shapley value method, based on the principle of egalitarian, allocates the expenses, power grid companies, thus, will suffer losses. The principle underlying the nucleolus is trying to equalize the excess profits of each party. In this way, the excess profits the residents gain will be far more less than the calculation results by Shapley value method and power grid companies will gain more of them. Generally, by Shapley value method, expenses allocated to power grid companies are higher and those allocated to the residents are lower; by the nucleolus, power grid companies account for a smaller share than the residents; the number calculated by MCRS are somewhere in between the two results.



a) Cost Sharing of Power Grid Company



b) Government Cost Sharing



c) Cost Sharing of Residents

Figure 2.*Cost allocation of different parties in three methods*

In most regions, the expenses allocated to power grid companies are negative, which means in developing distributed photovoltaic industry, the companies should be subsidized rather than paying for it. It can be assumed that the subsidies for power grid companies should be paid by the government since State Grid Corporation of China, China Southern Power Grid and other power grid companies are state monopolies. Therefore, the power grid companies can be included in the government coalition to simplify the analysis and the expenses allocated to the government can be understood as the theoretical government subsidies. The results after comparing the calculation results with actual government subsidies are shown in Table 5:

Table 5.*The comparison between theoretical government cost allocation and actual subsidies*

Unit:yuan/kW·h

Cities	Shapley value	MCRS	Nucleolus	State Subsidy	State & Local subsidy
Baoji	0.53	0.51	0.45	0.42	0.50
Beijing	0.48	0.46	0.40	0.42	0.54
Changsha	0.59	0.58	0.52	0.43	0.56
Chengdu	0.65	0.63	0.58	0.43	0.43
Chongqing	0.68	0.66	0.60	0.43	0.43
Guiyang	0.69	0.67	0.61	0.43	0.43
Hangzhou	0.57	0.55	0.50	0.43	0.50
Harbin	0.49	0.47	0.41	0.42	0.42
Hefei	0.55	0.54	0.48	0.42	0.59
Kunming	0.49	0.47	0.41	0.42	0.42
Lanzhou	0.48	0.46	0.39	0.42	0.42
Mangya	0.39	0.37	0.31	0.41	0.41
Nancheng	0.56	0.55	0.49	0.43	0.69
Shanghai	0.56	0.54	0.48	0.43	0.58
Wuhan	0.54	0.52	0.46	0.42	0.52

State subsidies are generally less than the theoretical expenses allocated to the government and power grid companies except, after the nucleolus calculation, in the regions with long sunlight hours. The residents are not able to gain benefit if they rely on state subsides alone. The expenses allocated to power grid companies and to the government by Shapley value method are higher than those by the nucleolus. In fact, the sum of state and local subsidies is somewhere in between – when it is higher than the one calculated by Shapley value method, it means the region either has long sunlight hours or receives rather large local subsidies; when it is lower than the one calculated by the nucleolus, it means that the region doesn't have much sunlight and is not suitable to develop distributed photovoltaic industry.

4. Conclusions

The thesis, based on externality theory and cooperative game theory, analyzed leveled cost of energy and expense allocation pattern of residential distributed photovoltaics in 15 cities in China, drew the following conclusions:

1) State subsidies alone cannot meet various regions' needs in investing distributed photovoltaics, and local subsidies can play a supplementary role. The calculation results by Shapley value method show that the expenses allocated to power grid companies are higher and those allocated to the residents are lower, while the results calculated by the nucleolus method show that the expenses allocated to power grid companies are lower and those allocated to the residents are higher. The sum of state and local subsidies in China is, overall, higher than the value calculated by Shapley value method and lower than the one calculated by the nucleolus.
2) China now is implementing a policy that is different from international practices, that is, residential electricity price is lower than industrial electricity price. Despite the fact that the residents have benefited from low electricity price, the low price, however, in promoting distributed energy, will lead to less enthusiasm for the public to participate in it, which will resultantly affect the development of distributed photovoltaics.
3) Power grid companies need the government subsidies in order to gain benefits. In fact, the source of some of the government subsidies is unclear and sometimes power grid companies cannot get the subsidies, or even have to pay by themselves. Therefore, not all power grid companies are excited about participating in developing distributed photovoltaics, which, to some extent, impedes the development of the industry.

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