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RESEARCH ARTICLE

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Benefit-based cost allocation for residentially distributed photovoltaic systems in China: A cooperative game theory approach

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Abstract Distributed photovoltaic (PV) systems have constantly been the key to achieve a low-carbon economy in China. However, the development of Chinese distributed PV systems has failed to meet expectations because of their irrational profit and cost allocations. In this study, the methodology for calculating the levelized cost of energy (LCOE) for PV is thoroughly discussed to address this issue. A mixed-integer linear programming model is built to determine the optimal system operation strategy with a benefit analysis. An externality-corrected mathematical model based on Shapley value is established to allocate the cost of distributed PV systems in 15 Chinese cities between the government, utility grid and residents. Results show that (i) an inverse relationship exists between the LCOEs and solar radiation levels; (ii) the government and residents gain extra benefits from the utility grid through net metering policies, and the utility grid should be the highly subsidized participant; (iii) the percentage of cost assigned to the utility grid and government should increase with the expansion of battery bank to weaken the impact of demand response on increasing theoretical subsidies; and (iv) apart from the LCOE, the local residential electricity prices remarkably impact the subsidy calculation results.

Keywords solar photovoltaic, cost allocation, cooperative game theory, Shapley value, mixed-integer linear programming, levelized cost of energy

1 Introduction

1.1 Background

China has experienced rapid development and urbanization along with increasing and substantial requirements for energy supplies. With the increasing demand for energy diversification, environmental protection, and supply flexibility, the development and utilization of distributed photovoltaic (PV) technology have become a policy priority for the development of renewable energy in China (Zhao et al., 2019). In August 2013, a 0.42 yuan subsidy was implemented by the National Development and Reform Commission (NDRC) for every kWh of electricity produced with distributed PV systems. At the same time, local governments at the provincial and municipal levels actively formulated various policies to provide capital subsidies or extra generation subsidies. Considering the rapid improvements of solar module technology, the NDRC adjusted the original 0.42 yuan/kWh subsidy to 0.37 yuan/kWh in December 2017.

The promotion of distributed PV has been more difficult in practice than expected. Compared with the rapid development of large-scale PV plants in China, the actual adoption of distributed PV is far below expectations (Luo and Liu, 2015). With the intensive decrease in the cost of PV, the unfair allocation of profits and costs among different stakeholders has gradually become the primary impediment to the adoption of PV. This condition, which is context-specific, reflects that various underlying benefits and costs of energy generation are not precisely and

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reasonably recognized, evaluated, and allocated in existing energy markets, while which are addressed in this study.

1.2 Literature review

The application of game theory in energy research has accelerated in recent years because of the development of information technology, enabling the interactions between energy suppliers and consumers (Fernandez et al., 2018) or distributed residential electricity suppliers (Su and Huang, 2014). Game theory can be divided into two categories, namely, non-cooperative and cooperative games, regardless of whether alliances or agreements can be forged (Luo et al., 2019). Non-cooperative game theory is a powerful tool used in strategic analysis to identify the best interactions between multiple players (Tang et al., 2019). Wei et al. (2017) proposed a Stackelberg game model to analyze the multiple energy trading problem in integrated energy systems. Luo et al. (2020) investigated the energy scheduling of a three-level integrated energy system by applying a hierarchical Stackelberg game approach. Li et al. (2019) developed a framework with inter-sectorial interactions among various users by using a non-cooperative game approach. Non-cooperative game theory mainly deals with energy trading and bidding strategies in solving energy issues (Roson and Hubert, 2015), whereas cooperative game theory is widely used in cost and benefit allocation. Luo et al. (2019) utilized the Shapley value to allocate the energy system cost between different stakeholders on an isolated island in the South China Sea. Jing et al. (2018) considered the constraints of game theory-inspired multi-benefit allocation to implement a multi-objective optimization of a neighborhood-level urban energy network. Compared with the traditional cost allocation methods, such as the separable costs-remaining benefits method (Rideout and Wagner, 1986), the cost allocation methods based on cooperative strategies consider the impact of alliance on cost allocation strategies, thereby improving the fairness and accuracy of the allocation results (Luo et al., 2019). Considering the fairness in dealing with cost allocation, cooperative game theory is utilized in this study to investigate the cost allocation schemes of residential distributed PV systems.

This study uses relevant research as the cornerstones because costs and benefits are the determining factors in the cost allocation of PV systems via cooperative game theory. Numerous studies have been conducted on the cost analyses of PV systems. Said et al. (2015) built an improved model using the effective lifetime of various PV technologies to analyze the levelized cost of energy (LCOE) of PV power plants. With the objective of evaluating new options for continuous energy delivery, Parrado et al. (2016) calculated the LCOE of the Atacama Solar Platform for a photovoltaic concentrated solar power plant. Darling et al. (2011) calculated the LCOE of PV systems using an input parameter distribution feeding a Monte Carlo simulation. Branker et al. (2011) reviewed the methodology for calculating the LCOE of solar PV systems, corrected the misconceptions appearing throughout the literature, and provided a template for better reporting of LCOE results for PV technology. Sauhats et al. (2018) analyzed the influence of supporting scheme variants on the profitability of a projected investment in a residential PV system through benefit analyses. Oliva H et al. (2016) conducted an investigation of the annual short-term revenue impacts of PV systems for households, electricity retailers, and network service providers. The impacts of renewable energy grid connection on energy networks were quantitatively analyzed by Costa and Matos (2009) and Lin and Li (2015), and the environmental performance of PV-based electricity generation were examined by Fthenakis and Kim (2011), Peng et al. (2013), Breyer et al. (2015), and Constantino et al. (2018).

Although many studies have been conducted on the cost allocation of energy systems, most of the existing studies have focused on large-scale energy networks, and few studies have completely analyzed residential-scale distributed PV systems. Studies considering the impacts of battery storage and demand response in the allocation are rarely reported. To fill these research gaps, an externality-corrected methodology of cost allocation for distributed PV systems considering battery banks and demand response is proposed in this study using cooperative game theory. The proposed methodology is applied to 15 typical Chinese cities by considering different solar radiation resources and economic development levels across China, and the results are analyzed on the basis of the actual situation in China. The remainder of this paper is organized as follows. Section 2 introduces the mathematical model and optimization approach in detail. Section 3 presents and discusses the allocation results. Section 4 provides the conclusions.

2 Methods

The cost allocation for a distributed PV system mainly consists of cost calculation, benefit calculation, and cost allocation. The details of each step are presented in the following.

2.1 Cost calculation

The cost of a distributed PV system, which is the subject of allocation, should be first determined in the cost allocation. In this study, the LCOE is utilized to calculate the system cost. LCOE is a benchmarking tool used to estimate the price per unit energy generated (Luo and Liu, 2016). This tool is widely used to estimate power generation costs and can be applied to assess the cost effectiveness of different energy generation technologies. The mathematical expression for the LCOE of an energy system is expressed as:

$$LCOE = \frac{\sum_{t=0}^{T} C_t(1+r)^{-t}}{\sum_{t=1}^{T} E_t(1+r)^{-t}}, \tag{1}$$

where C_t is the annual cost of the system, E_t is the annual energy generation, r represents the discount rate, t denotes the tth year life cycle of the PV system, and T is the lifespan.

For a distributed PV system, Eq. (1) can be expressed as follows:

$$LCOE = \frac{I_0 + \sum_{t=1}^{T} M_t(1+r)^{-t}}{\sum_{t=1}^{T} E_1(1-d)^{t-1}(1+r)^{-t}}, \tag{2}$$

where I_0 is the initial investment, M_t is the annual maintenance cost, E_1 is the output of the system in the first year, and d is the degradation rate. The replacement cost should be considered when a battery bank is integrated with the system. In this work, distributed PV systems with different battery capacities are modeled and analyzed to ensure a comprehensive study.

2.2 Benefit analysis

2.2.1 Operation strategy

After obtaining the allocation subject, the operation strategy of a distributed PV system should be determined as the basis for the calculation of benefits. Many factors, such as weather, load curves, and electricity prices, impact the system operation. The addition of a battery bank at the supply side and demand response at the demand side complicates the process. In this study, a mixed-integer linear programming (MILP) model is built to determine the optimal operation strategy for a distributed PV system.

- Constraints

The state of charge (*SOC*) measures the current state of the battery bank in the form of percentage (0% = empty, 100% = full). The *SOC*s for the battery bank can be expressed as follows (Lorestani and Ardehali, 2018):

$$SOC^t = SOC^{t-1} + \frac{P_{\mathrm{BBC}}^t \Delta t \eta_{\mathrm{BBC}}}{E_{\mathrm{BB}}} - \frac{P_{\mathrm{BBD}}^t \Delta t}{\eta_{\mathrm{BBD}} E_{\mathrm{BB}}}, \tag{3}$$

where E_{BB} is the nominal capacity of the battery bank, Δt is the simulation time step, P_{BBC}^t and P_{BBD}^t are the charge and discharge power of the battery bank at time t, respectively, and η_{BBC} and η_{BBD} are the charge and discharge efficiencies of the battery bank, respectively.

At any time, the following constraints must be satisfied for the battery bank:

$$SOC_{\min} \leqslant SOC^t \leqslant SOC_{\max}, \tag{4}$$

$$x_{\mathrm{BBC}}^t P_{\mathrm{BBC,\,min}} \leqslant P_{\mathrm{BBC}}^t \leqslant x_{\mathrm{BBC}}^t P_{\mathrm{BBC,\,max}}, \tag{5}$$

$$x_{\mathrm{BBD}}^t P_{\mathrm{BBD,\,min}} \leqslant P_{\mathrm{BBD}}^t \leqslant x_{\mathrm{BBD}}^t P_{\mathrm{BBD,\,max}}. \tag{6}$$

Binary variables x_{BBC}^t and x_{BBD}^t determine whether the battery bank is working in the charging or discharging mode. The sum of the two variables is constantly less than one to ensure that the battery bank cannot charge and discharge simultaneously. Thus, the following constraint must also be satisfied:

$$x_{\mathrm{BBC}}^t + x_{\mathrm{BBD}}^t \leqslant 1. \tag{7}$$

Transferrable load refers to the load that can be shifted depending on the needs of the consumers, such as the use of washing machines, electric heaters, and disinfection cabinets. At any time, the load transferred in and out should satisfy the following constraints:

$$P_{\mathrm{L}}^t = P_{\mathrm{L,\,o}}^t + P_{\mathrm{Li,\,trans}}^t - P_{\mathrm{Lo,\,trans}}^t, \tag{8}$$

$$f_{\mathrm{i}}^t P_{\mathrm{L,\,o}}^t a_{\mathrm{i,\,min}}^t \leqslant P_{\mathrm{Li,\,trans}}^t \leqslant f_{\mathrm{i}}^t P_{\mathrm{L,\,o}}^t a_{\mathrm{i,\,max}}^t, \tag{9}$$

$$f_{\mathrm{o}}^t P_{\mathrm{L,\,o}}^t a_{\mathrm{o,\,min}}^t \leqslant P_{\mathrm{Lo,\,trans}}^t \leqslant f_{\mathrm{o}}^t P_{\mathrm{L,\,o}}^t a_{\mathrm{o,\,max}}^t, \tag{10}$$

$$f_{\mathrm{i}}^t + f_{\mathrm{o}}^t \leqslant 1, \tag{11}$$

where P_{L}^t and $P_{\mathrm{L,\,o}}^t$ are the actual and original loads at time t, respectively, $P_{\mathrm{Li,\,trans}}^t$ and $P_{\mathrm{Lo,\,trans}}^t$ are the loads transferred in and out at time t, respectively, $a_{\mathrm{i,\,min}}^t$ and $a_{\mathrm{i,\,max}}^t$ are the rates of minimum and maximum possible loads transferred into the original load at time t, respectively, $a_{\mathrm{o,\,min}}^t$ and $a_{\mathrm{o,\,max}}^t$ are the rates of minimum and maximum possible loads transferred out from the original load at time t, respectively, and f_{i}^t and f_{o}^t are the binary values indicating the transfer direction.

Within a given period, the load transferred in must be equal to the load transferred out, and the following equation presents this relationship:

$$\sum_{t=1}^{n} P_{\mathrm{Li,\,trans}}^t \Delta t = \sum_{t=1}^{n} P_{\mathrm{Lo,\,trans}}^t \Delta t. \tag{12}$$

- Optimization objective

This model sets the electricity costs of residents as the optimization objective because residents are the owners and operators of distributed PV systems. The implementation of net metering policies enables owners of PV systems to sell excess solar power to the utility grid, thereby complicating the operation strategy for the PV system. The objective function F is expressed as follows:

$$F = \sum_{t=1}^{n} (P_{\mathrm{B}}^t p_{\mathrm{B}} - P_{\mathrm{S}}^t p_{\mathrm{S}}) \Delta t, \tag{13}$$

$$P_{\mathrm{B}}^t = \max(P_{\mathrm{L}}^t - P_{\mathrm{PV}}^t - P_{\mathrm{BBD}}^t + P_{\mathrm{BBC}}^t, 0), \tag{14}$$

$$P_{\mathrm{S}}^t = \max\left(P_{\mathrm{PV}}^t + P_{\mathrm{BBD}}^t - P_{\mathrm{BBC}}^t - P_{\mathrm{L}}^t, 0\right), \tag{15}$$

where P_{B}^t is the power drawn from the utility grid at time t because the PV system cannot satisfy the electricity demand, P_{S}^t is the power supplied to the utility grid at time t because the PV system generation exceeds the electricity demand, P_{PV}^t is the PV generation at time t, and p_{B} and p_{S} are the electricity price and feed-in tariff, respectively. In China, p_{S} is equal to the benchmark price of coal-fired power sold from power plants to the grid.

The electricity consumed (E_{U}) and sold (E_{S}) to utility grids can be calculated using the following equations:

$$E_{\mathrm{U}} = \sum_{t=1}^{n} \left(P_{\mathrm{L}}^t - P_{\mathrm{B}}^t\right)\Delta t, \tag{16}$$

$$E_{\mathrm{S}} = \sum_{t=0}^{n} P_{\mathrm{S}}^t \Delta t. \tag{17}$$

The rates of electricity consumed (k_{U}) and sold (k_{S}) during PV generation can be expressed as follows:

$$k_{\mathrm{U}} = \frac{E_{\mathrm{U}}}{\sum_{t=0}^{n} P_{\mathrm{PV}}^t \Delta t}, \tag{18}$$

$$k_{\mathrm{S}} = \frac{E_{\mathrm{S}}}{\sum_{t=0}^{n} P_{\mathrm{PV}}^t \Delta t}. \tag{19}$$

2.2.2 Benefit calculation

The development of distributed PV could result in a series of economic and noneconomic impacts on the utility grid, government, residents, and other subjects. Although these impacts are difficult to comprehensively and quantitatively analyzed, some of them are significant and can be quantified using well-tested methods. To assess the benefits among participants significantly affected by distributed PV systems, detailed analyses are given below:

- Utility grid

The delivery of electricity results in some losses because of the resistance of wires, transformers, and other equipment. The generated energy of PV will constantly be consumed locally because it is a form of distributed energy located at the site of use and seamlessly integrated with the utility grid. Therefore, most energy losses can be avoided during the delivery of electricity to the end-users. The simplified calculation for the losses avoided during transmission and distribution (T&D) caused by each kWh of PV power generated (R_{l}) is expressed as follows (Luo and Liu, 2016):

$$R_{\mathrm{l}} = \eta \times \frac{p_{\mathrm{S}}}{1-\eta}, \tag{20}$$

where η denotes the line loss rate.

Distributed PV has the potential to displace the electricity generated from fossil fuels. For residents, savings typically appear as a reduced cost of purchased power. For the utility grid, losses can be understood as a decline in electricity sales. The electricity sale loss caused by every unit of power produced with PV (R_{z}) can be expressed as follows:

$$R_{\mathrm{z}} = k_{\mathrm{U}}\left(p_{\mathrm{B}} - p_{\mathrm{S}}\right). \tag{21}$$

Distributed PV results in many other benefits and losses to the utility grid, such as avoided T&D capacity costs, increased reliability and power quality, determent of network augmentation, and increased reserved capacity fee. Only the primary benefits, such as the avoided electricity loss during T&D and loss of electricity sales, are estimated in this study because of the limited scale of distributed PV in China. The benefits of distributed PV to the utility grid (E_{e}) can be expressed as follows:

$$E_{\mathrm{e}} = R_{\mathrm{l}} - R_{\mathrm{z}}. \tag{22}$$

- Government

All anthropogenic means of energy generation produce pollutants throughout their entire life cycle. However, PV systems do not emit atmospheric pollutants during operation, and they serve to reduce emissions to a large extent in terms of life cycle environmental performance (Luo and Liu, 2016). In China, coal plays a dominant role as the primary energy and electricity supply. The substantial increase in coal consumption has resulted in huge CO_2 emissions, contributing to global warming. In this study, the environmental benefit of each kWh of power generated with a PV system is considered to be equivalent to the avoided emissions of the electricity type being displaced. Given that renewable generated power has priority in integration, coal-fired generation is reduced to accommodate additional renewable energy when the portion of PV-generated energy increases. Therefore, coal-fired power is assumed to be displaced, and the benefit of CO_2 reduction to the government (R_{c}) can be assessed by multiplying the avoided CO_2 emissions by its estimated societal cost (*SCC*) as follows:

$$R_{\mathrm{c}} = \left(F_{\mathrm{coal}} - F_{\mathrm{PV}}\right) p_{\mathrm{CO_2}}, \tag{23}$$

where F_{coal} is the life-cycle CO_2 emission for every unit of coal power, F_{PV} is the life-cycle CO_2 emission for every unit of solar power, and $p_{\mathrm{CO_2}}$ is the *SCC* of CO_2. *SCC* is the monetary value of the damage caused by the emission of one extra ton of CO_2 to the environment or the damage avoided by reducing 1 ton of CO_2 emissions. Many studies have estimated *SCC* because of the notorious adverse effects of CO_2 emissions and achieved varying results. *SCC* ranges from \$10/t to \$150/t depending on the estimation method (Holland et al., 1998; Tol, 2005; Watkiss et al., 2005; Garnaut, 2011; Hope, 2011). The proposed model derives an *SCC* of \$70/t. The values of F_{coal} and F_{PV} are set to 1180 and 28.8 g/kWh, respectively (Ren et al., 2010).

From the government perspective, clean energy initiatives create jobs directly from clean energy activities and indirectly via economic multiplier effects, thereby reducing the annual cost to the government for social welfare. A rule of thumb applied in this model is that every million of dollars invested in PV produces 5.7 job-years versus 3.9 job-years created with coal power. Thus, the benefit of increased employment caused by distributed PV (R_{j}) can be calculated using the following equation:

$$R_{\text{j}} = LCOE(n_{\text{PV}} - n_{\text{coal}})L, \tag{24}$$

where n_{PV} is the job-years derived from a unit investment in PV, n_{coal} is the job-years derived from a unit investment in coal power, and L is the minimum living standard released by the government. The minimum living standards of 15 Chinese cities are listed in Table 1.

Table 1 Minimum living standards of 15 Chinese cities

City	Minimum living standard (yuan/month)
Baoji	495
Beijing	710
Changsha	450
Chengdu	450
Chongqing	375
Guiyang	477.5
Hangzhou	660
Harbin	510
Hefei	510
Kunming	502.5
Lanzhou	451
Mang'ai	373
Nancheng	465
Shanghai	790
Wuhan	580

Hence, the benefit to the government from every unit of PV power (E_{g}) can be written as follows:

$$E_{\text{g}} = R_{\text{c}} + R_{\text{j}}. \tag{25}$$

The utilization of distributed PV reduces the emissions of SO_2, NO_x, fine particulate matter, and volatile organic compounds, resulting in tremendous SCCs. Other benefits to the government from distributed PV include the reduction of health damage costs and stimulation of the development of related industries. However, these benefits are not considered in this study because of the difficulties in their quantitative evaluation.

- Residents

The financial benefits of PV for residents include the reduced expense of electricity bills and income from selling surplus power. The mathematical expressions of the two benefits are expressed as follows:

$$R_{\text{s}} = k_{\text{U}} p_{\text{B}}, \tag{26}$$

$$R_{\text{i}} = k_{\text{S}} p_{\text{S}}, \tag{27}$$

where R_{s} is the saved electricity cost, and R_{i} is the income produced by selling surplus solar power to the utility grid.

The overall benefit to residents per kWh of distributed PV (E_{r}) is obtained by combining R_{s} and R_{i} as follows:

$$E_{\text{r}} = R_{\text{s}} + R_{\text{i}}. \tag{28}$$

2.3 Cost allocation

In this study, cooperative game theory is introduced to solve the cost allocation problem. Many solution concepts are used for cooperative games. The Shapley value is utilized in this study and will be discussed in the following.

2.3.1 Shapley value

The Shapley value, which was developed by Shapley (1953), is a solution concept in cooperative game theory. The Shapley value ensures that the benefit to each player is equal to the average marginal contribution of the player in the coalition. For each cooperative game, this value assigns a unique distribution of the total surplus generated by the coalition of all players (Luo and Liu, 2016). The Shapley value X_i of player i is computed as follows:

$$X_i = \sum\nolimits_{S \subseteq N \backslash i} \frac{s!(n-s-1)!}{n!}(v(S \cup \{i\}) - v(S)), \tag{29}$$

where N is a set of all players in the game, and n is the number of all the players. Any subset S is called a coalition and refers to the coalitions formed by players in the set based on their interests, and s is the number of players in subset S. For each coalition, $v(S)$ is the corresponding characteristic function, which is the profit of each coalition in this study (Luo et al., 2019).

2.3.2 Cost allocation model

The characteristic function of each coalition should be specified first to find the rational cost allocation of a distributed PV system. In this study, the participants in the game comprise the utility grid, government, and residents. Therefore, a total of $2^3 = 8$ possible coalitions are found. All the possible coalitions except for $S = \varnothing$ are illustrated in Fig. 1.

The characteristic function for each coalition expresses

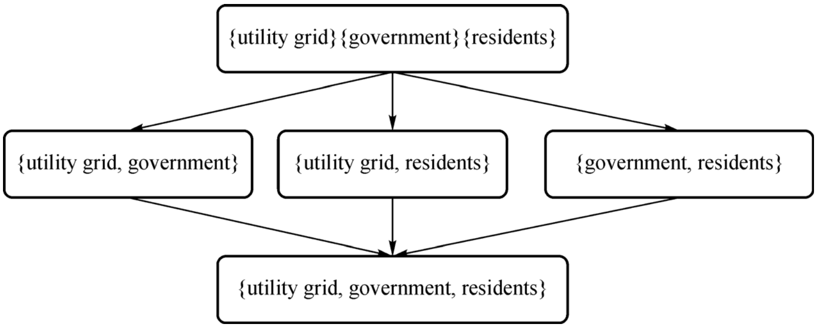

Fig. 1 Possible coalitions.

the profit that the coalition can receive from distributed PV. The detailed expressions are listed in Table 2.

Table 2 Characteristic functions for each coalition

S	$v(S)$
{∅}	0
{utility grid}	$E_e - LCOE$
{governments}	$k_U E_g - LCOE$
{residents}	$k_U p_B - LCOE$
{utility grid, governments}	$E_e + E_g - LCOE$
{utility grid, residents}	$E_e + E_r - LCOE$
{governments, residents}	$k_U(E_g + p_B) - LCOE$
{utility grid, governments, residents}	$E_e + E_g + E_r - LCOE$

Thus, the characteristic function for each coalition is calculated. The desired profit of each participant can be obtained by applying Eq. (29) to the characteristic functions. The cost assigned to participant i (C_i) can be calculated using the following equation:

$$C_i = E_i - X_i, \tag{30}$$

where E_i is the benefit of player i. An externality distribution must be conducted in the final step to correct the results. The government actually reaps the environmental, social, and economic benefits from distributed PV without bearing any cost when only the utility grid and residents are in a coalition, which is obviously unreasonable. To implement this correction, a model based on the Shapley value is used to calculate the externalities assigned to each participant. The detailed characteristic functions are listed in Table 3.

The externality allocated to participant i ($X_{e,i}$) can be determined, and the corrected cost allocated to each participant ($C_{e,i}$) can be calculated as follows:

$$X_{e,i} = \sum\nolimits_{S \subseteq N \backslash i} \frac{s!(n-s-1)!}{n!} (v_e(S \cup \{i\}) - v_e(S)), \tag{31}$$

$$C_{e,i} = C_i - X_{e,i}. \tag{32}$$

Table 3 Characteristic functions for each coalition in the externality distribution

S	$v_e(S)$
{∅}	0
{utility grid}	$E_g + E_r$
{governments}	$k_U(E_e + p_B)$
{residents}	$k_U(E_e + E_g)$
{utility grid, governments}	E_r
{utility grid, residents}	E_g
{governments, residents}	$k_U E_e$
{utility grid, governments, residents}	0

3 Results and discussion

In this study, Canadian Solar CS6X-320P and SMA SB6000US-12 240 V panels are used as solar modules and inverters, respectively, to simulate a 6 kW distributed PV system on System Advisor Model (SAM) software. The technical specifications of the selected module, inverter, and battery are obtained from SAM and listed in Table 4. The system is built with a 180° azimuth, and the tilt angle is equal to the local latitude. The unit investment cost is fixed at 7 yuan/kWh for the system without a battery bank, and the annual maintenance cost is 10 yuan/kWh. The cost and life span of the battery are 850 yuan/kWh and 8 years, respectively. The project operation period is fixed at 25 years, with a system performance degradation rate of 0.8%. Inflation, income tax value, and value added tax are ignored.

3.1 LCOE

The LCOE of solar PV systems intensively varies depending on the system configuration and solar intensity. In this study, the *LCOE*s for distributed PV systems in 15 Chinese cities with different levels of solar resources are calculated and presented in Table 5.

Chinese solar resources exhibit huge diversity because

Table 4 Technical specifications of critical components

Component	Characteristics	Value
Solar module (CS6X-320P)	Nominal efficiency	16.82%
	Maximum power	319.72 W
	Maximum power voltage	36.8 V
	Maximum power current	8.7 A
	Open circuit voltage	45.3 V
	Short circuit current	9.3 A
	Module area	1.90 m^2
	Material	Multi-C-Si
Inverter (SB6000US-12 240 V)	CEC weighted efficiency	95.64%
	Maximum AC power	6000 W
	Maximum DC power	6282 W
	Nominal AC voltage	240 V
	Nominal DC voltage	310 V
	Maximum DC voltage	480 V
	Maximum MPPT DC voltage	480 V
	Minimum MPPT DC voltage	100 V
Battery (single unit)	Nominal capacity	2 kWh
	Charge efficiency	75%
	Discharge efficiency	75%
	Minimum SOC	5%
	Maximum SOC	95%
	Minimum charge power	0.5 kW
	Maximum charge power	2 kW
	Minimum discharge power	0.5 kW
	Maximum discharge power	2 kW

of its enormous territory. Although the western regions have abundant reserves of solar energy resources (e.g., Mang'ai), the development of PV is not cost effective in the eastern or some south-western regions because of their insufficient solar radiance. As shown in Table 5, an inverse relationship is found between LCOE and solar radiation, that is, the LCOEs for PV in regions with worse solar resources are significantly higher than those in regions receiving more sunlight. The integration of a battery bank significantly increases the LCOEs of distributed PV systems.

3.2 Operation strategies

In this model, the load profiles of 15 Chinese cities are obtained from SAM software. The MILP optimization model is formulated in MATLAB and solved using CPLEX. The load consists of two parts, namely, important and transferrable loads. $a^t_{\mathrm{i,min}}$ and $a^t_{\mathrm{o,min}}$ are set to 0.1, whereas $a^t_{\mathrm{i,max}}$ and $a^t_{\mathrm{o,max}}$ are set to 0.5. The electricity prices and feed-in tariffs of the 15 cities are listed in Table 6. The data are obtained from the NDRC.

3.2.1 Demand response

Figure 2 illustrates the impact of demand response on the load profiles of the PV system in Beijing. The demand response centralizes the loads to midday for better utilization of solar radiation at noon. Consequently, additional solar power can be directly consumed, the required battery capacity is decreased, and the economic benefit of the distributed PV system is increased.

3.2.2 Battery bank

The demand response makes the load profiles consistent with the solar radiation, whereas the battery bank makes the entire system output consistent with the load profiles. Figure 3 shows the change in the system output with the addition of batteries. The battery bank shifts the highest system output toward the peak hours of demand, and the system outputs increase during the low-irradiance period (morning and night). The higher the batter capacity the greater the degree of matching between the system output and load profiles will be.

3.3 Allocation results

The externalities assigned to the utility grid, government, and residents of 15 Chinese cities are listed in Table 7.

Only the externality assigned to the utility grid is positive, indicating that the government and residents benefit from the externalities caused by the utility grid. Thus, the government and residents should return a corresponding portion of these benefits to the utility grid.

3.3.1 Without a battery bank or demand response

The corrected cost allocation results based on Shapley value are listed in Table 8.

The costs allocated to the utility grid in all cities are negative, indicating that the utility grid should receive some subsidies rather than pay for the entire cost. The utility grid and government are considered as a whole to simplify the analysis. The subsidies that should be received by the utility grid can be treated as those obtained from the government because the utility grid in China is state-owned. Therefore, the sum of the costs assigned to the government and utility grid can be understood as the theoretical amount of subsidies in the form of power-based incentive (PBI).

As shown in Table 8, the theoretical PBIs in Chengdu, Chongqing, and Guiyang are the highest, whereas those in

Table 5 *LCOE*s of distributed PV systems in 15 Chinese cities

City	Level of solar resources	*LCOE* without battery bank (yuan/kWh)	*LCOE* with battery bank (yuan/kWh)				
			2 kWh	4 kWh	6 kWh	8 kWh	10 kWh
Baoji	III	0.5874	0.6285	0.6697	0.7108	0.7520	0.7931
Beijing	II	0.5241	0.5609	0.5976	0.6343	0.6710	0.7077
Changsha	III	0.6858	0.7349	0.7830	0.8311	0.8792	0.9273
Chengdu	II	0.7311	0.7823	0.8335	0.8847	0.9359	0.9871
Chongqing	III	0.7578	0.8108	0.8639	0.9170	0.9701	1.0231
Guiyang	III	0.7415	0.7934	0.8453	0.8972	0.9492	1.0011
Hangzhou	III	0.6548	0.7007	0.7465	0.7924	0.8383	0.8841
Harbin	II	0.5249	0.5617	0.5984	0.6352	0.6719	0.7087
Hefei	III	0.6324	0.6767	0.7209	0.7652	0.8095	0.8538
Kunming	II	0.5485	0.5870	0.6254	0.6638	0.7022	0.7406
Lanzhou	II	0.5186	0.5550	0.5913	0.6276	0.6639	0.7003
Mang'ai	I	0.4327	0.4631	0.4934	0.5237	0.5540	0.5843
Nancheng	III	0.6448	0.6900	0.7352	0.7803	0.8255	0.8707
Shanghai	III	0.6341	0.6785	0.7229	0.7673	0.8117	0.8561
Wuhan	III	0.6239	0.6676	0.7113	0.7550	0.7987	0.8424

Table 6 Electricity prices and feed-in tariffs of 15 Chinese cities

City	Electricity price* (yuan/kWh)	Feed-in tariff (yuan/kWh)
Baoji	0.7983	0.3545
Beijing	0.7883	0.3598
Changsha	0.8880	0.4500
Chengdu	0.6224	0.4012
Chongqing	0.8200	0.3964
Guiyang	0.7556	0.3515
Hangzhou	0.8380	0.4153
Harbin	0.8100	0.3740
Hefei	0.8653	0.3844
Kunming	0.8000	0.3358
Lanzhou	0.8100	0.3078
Mang'ai	0.6771	0.3247
Nancheng	0.9000	0.4143
Shanghai	0.9170	0.4155
Wuhan	0.8580	0.4161

Note: *Annual household electricity consumption is assumed to exceed 5400 kWh.

Harbin and Mang'ai are the lowest. This result demonstrates that the theoretical PBI is influenced by the local LCOE and an inverse relationship is found between them. Apart from the LCOE, the local residential electricity prices influence the PBI calculation results. For example, the LCOE of Mang'ai is the lowest among the 15 cities, but its corresponding PBI is not the lowest because of its relatively low local residential electricity prices, thereby affecting the enthusiasm of local people for investment in distributed PV. China implements a policy that differs from international practices, that is, residential electricity prices are lower than industrial electricity prices. Although residents save on electricity bills, these low prices result in minimal enthusiasm for the public to participate in distributed solar PV.

In theory, the utility grid requires government subsidies to achieve breakeven, which is different from the existing situation in China. The utility grid has to bear the expenses when subsidies are unavailable because of the lack of clarity on which government department should provide such subsidies. This condition hampers the deployment of distributed PV in China to some extent.

3.3.2 With a battery bank

The addition of a battery bank has a significant impact on the cost allocation results. The proportion of costs assigned to the utility grid, government, and residents with different battery bank capacities are illustrated in Fig. 4.

The utility grid and government should bear considerable costs when the battery bank capacity is large. Correspondingly, the percentage of costs assigned to the residents decreases with the expansion of battery capacity. As previously analyzed, the utility grid plays a special role in the cooperative game because it provides many benefits to other participants through the solar power feed-in tariffs. Thus, the interest of the utility grid should be high, and the cost assigned to the utility grid is relatively small for the

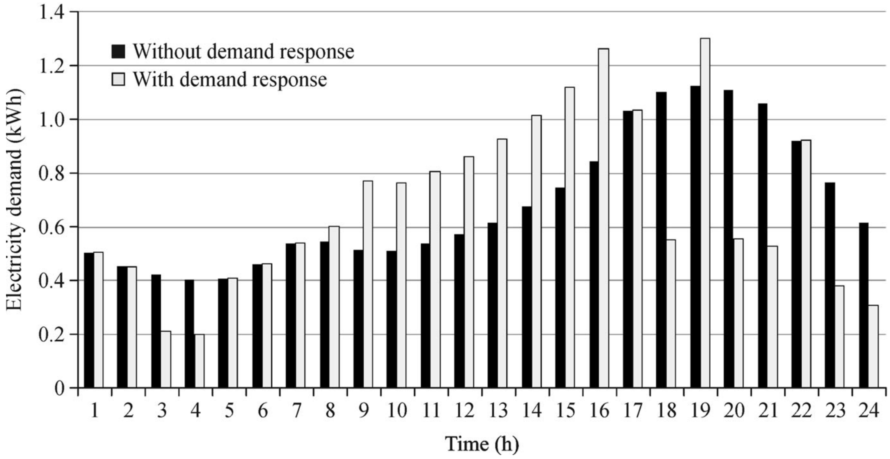

Fig. 2 Impact of the demand response on load profiles.

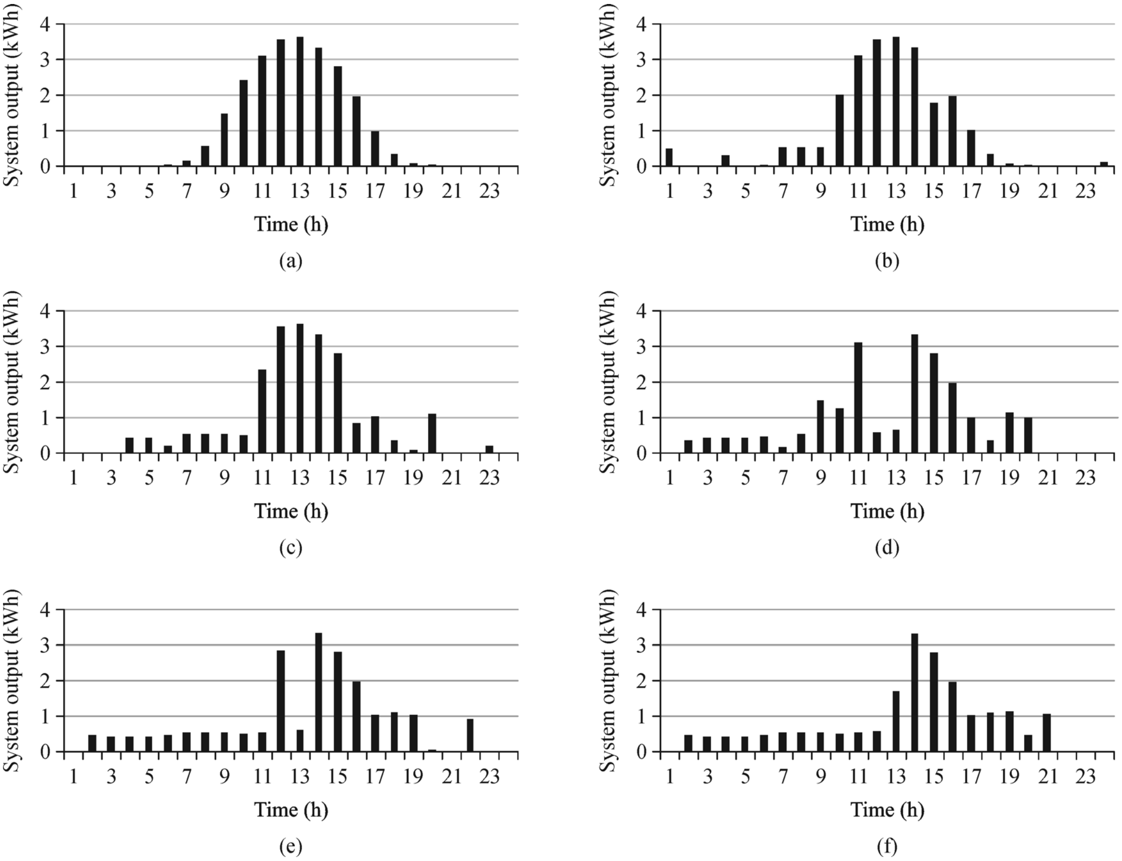

Fig. 3 Impact of the addition of a battery bank on load profiles: System output (a) without a battery bank; (b) with a 2 kWh battery bank; (c) with a 4 kWh battery bank; (d) with a 6 kWh battery bank; (e) with an 8 kWh battery bank; (f) with a 10 kWh battery bank.

system without a battery bank. The expansion of battery capacity enables the storage of excess solar power. In other words, the battery bank provides another method for utilizing the surplus solar power rather than simply selling it back to the utility grid. Consequently, the battery bank gradually replaces the utility grid as a decisive factor for system efficiency and interests of all participants. Thus, the percentage of costs assigned to the owners of the system

Table 7 Externalities assigned to each participant

City	Externality to utility grid (yuan/kWh)	Externality to government (yuan/kWh)	Externality to residents (yuan/kWh)
Baoji	0.4802	–0.2329	–0.2473
Beijing	0.4744	–0.2380	–0.2363
Changsha	0.5272	–0.2175	–0.3097
Chengdu	0.5099	–0.2227	–0.2873
Chongqing	0.5098	–0.2220	–0.2878
Guiyang	0.4856	–0.2316	–0.2540
Hangzhou	0.5054	–0.2279	–0.2775
Harbin	0.4786	–0.2364	–0.2422
Hefei	0.5020	–0.2261	–0.2759
Kunming	0.4745	–0.2340	–0.2405
Lanzhou	0.4642	–0.2357	–0.2285
Mang'ai	0.4440	–0.2455	–0.1985
Nancheng	0.5166	–0.2213	–0.2954
Shanghai	0.5189	–0.2240	–0.2948
Wuhan	0.5093	–0.2252	–0.2841

Table 8 Cost allocation results

City	*LCOE* (yuan/kWh)	Utility grid (yuan/kWh)	Government (yuan/kWh)	Theoretical *PBI* (yuan/kWh)	Residents (yuan/kWh)
Baoji	0.5874	–0.5879	0.6138	0.0259	0.5615
Beijing	0.5241	–0.6239	0.6096	–0.0143	0.5384
Changsha	0.6858	–0.6128	0.6196	0.0068	0.6790
Chengdu	0.7311	–0.5478	0.6298	0.0820	0.6491
Chongqing	0.7578	–0.5330	0.6354	0.1024	0.6554
Guiyang	0.7415	–0.5051	0.6421	0.1370	0.6045
Hangzhou	0.6548	–0.6067	0.6293	0.0226	0.6322
Harbin	0.5249	–0.6393	0.6117	–0.0276	0.5525
Hefei	0.6324	–0.6006	0.6197	0.0191	0.6133
Kunming	0.5485	–0.5918	0.6037	0.0119	0.5366
Lanzhou	0.5186	–0.5908	0.6009	0.0101	0.5085
Mang'ai	0.4327	–0.6162	0.5889	–0.0273	0.4600
Nancheng	0.6448	–0.6180	0.6173	–0.0007	0.6456
Shanghai	0.6341	–0.6332	0.6222	–0.0110	0.6451
Wuhan	0.6239	–0.6191	0.6149	–0.0042	0.6281

with a battery bank, that is, the residents, should be decreased accordingly.

3.3.3 With demand response

The demand response focuses on the interests of residents while imposing obvious impacts on the costs assigned to the government and utility grid. The impacts of demand response on theoretical subsidies with different battery bank capacities are listed in Table 9.

As shown in Table 9, the expansion of battery bank weakens the impact of demand response with increasing theoretical PBI. This finding can be attributed to the similar effects of demand response and battery bank on matching the demand and supply curves. As analyzed in Section 3.2, the demand response and battery bank adjust the power demand and supply relationship from the demand and supply sides, respectively. The demand response smoothens the demand curves, and all participants gain benefits accordingly when the capacity of the battery bank

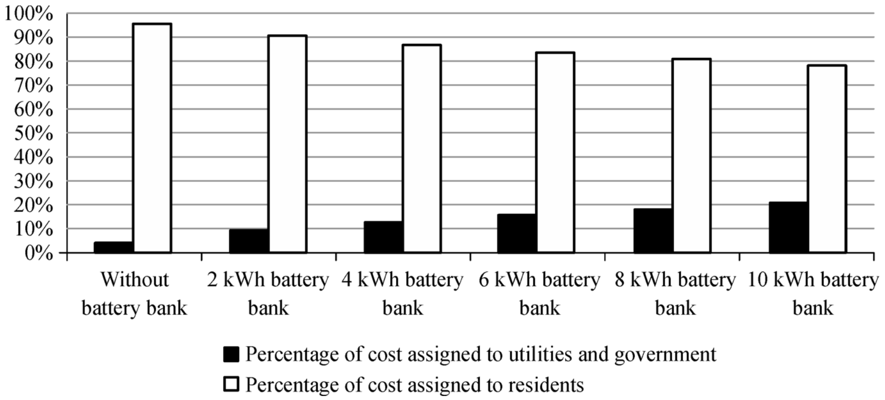

Fig. 4 Percentage of costs assigned to participants in Beijing with different battery capacities.

Table 9 Impact of demand response on theoretical subsidies with different battery bank capacities

City	Without battery bank (yuan/kWh)	With battery bank (yuan/kWh)				
		2 kWh	4 kWh	6 kWh	8 kWh	10 kWh
Baoji	+0.0053	+0.0030	+0.0006	−0.0019	−0.0044	−0.0056
Beijing	+0.0075	+0.0059	+0.0044	+0.0028	+0.0036	+0.0099
Changsha	+0.0090	+0.0063	+0.0034	+0.0006	−0.0056	−0.0183
Chengdu	+0.0079	+0.0048	+0.0017	−0.0015	−0.0201	−0.0278
Chongqing	+0.0071	+0.0037	+0.0002	−0.0031	−0.0263	−0.0291
Guiyang	+0.0081	+0.0048	+0.0016	−0.0017	−0.0205	−0.0258
Hangzhou	+0.0107	+0.0083	+0.0055	+0.0028	+0.0049	−0.0012
Harbin	+0.0081	+0.0065	+0.0047	+0.0029	+0.0088	+0.0152
Hefei	+0.0018	−0.0009	−0.0034	−0.0062	−0.0517	−0.0762
Kunming	+0.0022	−0.0001	−0.0024	−0.0045	−0.0068	−0.0128
Lanzhou	+0.0025	−0.0047	−0.0069	−0.0092	−0.0114	−0.0149
Mang'ai	+0.0145	+0.0132	+0.0121	+0.0107	+0.0046	−0.0111
Nancheng	+0.0023	−0.0004	−0.0031	−0.0059	−0.0894	−0.0096
Shanghai	+0.0013	−0.0016	−0.0048	−0.0076	−0.0068	−0.0084
Wuhan	+0.0075	+0.0053	+0.0029	+0.0005	−0.0004	−0.0002

is small. As the executor, the residents should bear less cost, whereas the two other parties bear more. Thus, the theoretical PBI increases when demand response is applied. The combination of demand response and battery bank jointly act to improve the system efficiency with the increase in battery bank capacity. Therefore, the benefit increase attributed only to demand response is reduced with the increase in theoretical PBI.

4 Conclusions

In this study, LCOEs, operation strategies, and cost allocation patterns for residential distributed PV systems in 15 Chinese cities were analyzed using externality and cooperative game theories. The conclusions are summarized as follows:

- An inverse relationship is found between the LCOEs and solar radiation. Considering that the LCOE has a direct impact on determining the subsidy standard and Chinese solar resource distribution has great diversity, a multilevel (national–provincial–municipal) distributed PV subsidy policy based on local conditions is required.
- The inclusion of battery bank and demand response increases the degree of matching between the generation curves and load profiles for distributed PV systems from the supply and demand sides, respectively. Thus, the percentage of costs assigned to the utility grid and government should increase with the expansion of battery bank to weaken the impact of demand response on the increasing theoretical PBI.
- The utility grid provides extra benefits to the

government and residents through excess solar power feed-in tariffs. Hence, the utility grid should be subsidized the most among the participants. The absence of relevant policy and regulations makes the utility grid to bear most of the relevant expenses, thereby dissipates the enthusiasm of utility grids for distributed PV, and hampers the deployment of distributed PV in China.

- The electricity price is positively associated with the PBI calculation results. Given that the residential electricity prices are lower than industrial electricity prices in China, residents can be encouraged to participate in distributed solar PV.

As previously stated, some benefits and losses to the participants from distributed PV are not considered in this study, such as the benefits to the government from the reduction of health damage costs and stimulation of the development of related industries. Future studies will conduct a comprehensive analysis of the benefits and losses to participants caused by distributed PV and will consider hybrid multi-generation energy systems.

References

Branker K, Pathak M J M, Pearce J M (2011). A review of solar photovoltaic levelized cost of electricity. Renewable & Sustainable Energy Reviews, 15(9): 4470–4482

Breyer C, Koskinen O, Blechinger P (2015). Profitable climate change mitigation: The case of greenhouse gas emission reduction benefits enabled by solar photovoltaic systems. Renewable & Sustainable Energy Reviews, 49: 610–628

Constantino G, Freitas M, Fidelis N, Pereira M (2018). Adoption of photovoltaic systems along a sure path: A Life-Cycle Assessment (LCA) study applied to the analysis of GHG emission impacts. Energies, 11(10): 2806

Costa P M, Matos M A (2009). Avoided losses on LV networks as a result of microgeneration. Electric Power Systems Research, 79(4): 629–634

Darling S B, You F, Veselka T, Velosa A (2011). Assumptions and the levelized cost of energy for photovoltaics. Energy & Environmental Science, 4(9): 3133–3139

Fernandez E, Hossain M J, Nizami M S H (2018). Game-theoretic approach to demand-side energy management for a smart neighbourhood in Sydney incorporating renewable resources. Applied Energy, 232: 245–257

Fthenakis V M, Kim H C (2011). Photovoltaics: Life-cycle analyses. Solar Energy, 85(8): 1609–1628

Garnaut R (2011). The Garnaut Review 2011: Australia in the Global Response to Climate Change. Cambridge: Cambridge University Press

Holland M, Berry J, Forster D, Watkiss P, Boyd R, Lee D, Schneider T, Scheiber C, Tort V, Dreicer M (1998). ExternE: Externalities of Energy—Vol. 7, Methodology 1998 update (EUR19083); Vol. 8, Global warming (EUR 18836); Vol. 9, Fuel cycles for emerging and end-use technologies, transport and waste (EUR 18887); Vol. 10, National implementation (EUR 18528). Luxembourg: Commission of the European Communities

Hope C (2011). The social cost of CO_2 from the PAGE09 model. Economics Discussion Paper, 39

Jing R, Wang M, Liang H, Wang X, Li N, Shah N, Zhao Y (2018). Multi-objective optimization of a neighborhood-level urban energy network: Considering game-theory inspired multi-benefit allocation constraints. Applied Energy, 231: 534–548

Li Y, Yang W, He P, Chen C, Wang X (2019). Design and management of a distributed hybrid energy system through smart contract and blockchain. Applied Energy, 248: 390–405

Lin B, Li J (2015). Analyzing cost of grid-connection of renewable energy development in China. Renewable & Sustainable Energy Reviews, 50: 1373–1382

Lorestani A, Ardehali M M (2018). Optimization of autonomous combined heat and power system including PVT, WT, storages, and electric heat utilizing novel evolutionary particle swarm optimization algorithm. Renewable Energy, 119: 490–503

Luo X, Liu J (2015). Economic analysis of residential distributed solar photovoltaic. Frontiers of Engineering Management, 2(2): 125–130

Luo X, Liu J (2016). Cost allocation of residential distributed PV project based on cooperative game theory. International Journal of Earth Sciences and Engineering, 9: 2106–2112

Luo X, Liu Y, Liu J, Liu X (2019). Optimal design and cost allocation of a distributed energy resource (DER) system with district energy networks: A case study of an isolated island in the South China Sea. Sustainable Cities and Society, 51: 101726

Luo X, Liu Y, Liu J, Liu X (2020). Energy scheduling for a three-level integrated energy system based on energy hub models: A hierarchical Stackelberg game approach. Sustainable Cities and Society, 52: 101814

Oliva H S, MacGill I, Passey R (2016). Assessing the short-term revenue impacts of residential PV systems on electricity customers, retailers and network service providers. Renewable & Sustainable Energy Reviews, 54: 1494–1505

Parrado C, Girard A, Simon F, Fuentealba E (2016). 2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile. Energy, 94: 422–430

Peng J, Lu L, Yang H (2013). Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renewable & Sustainable Energy Reviews, 19: 255–274

Ren H B, Zhou W S, Nakagami K, Gao W J, Wu Q (2010). Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Applied Energy, 87(12): 3642–3651

Rideout D, Wagner J E (1986). An analysis of the separable costs–remaining benefits method of joint cost allocation. Canadian Journal of Forest Research, 16(5): 880–884

Roson R, Hubert F (2015). Bargaining power and value sharing in distribution networks: A cooperative game theory approach. Networks and Spatial Economics, 15(1): 71–87

Said M, El-Shimy M, Abdelraheem M A (2015). Photovoltaics energy: Improved modeling and analysis of the levelized cost of energy and grid parity–Egypt case study. Sustainable Energy Technologies and

Assessments, 9: 37–48

Sauhats A, Zemite L, Petrichenko L, Moshkin I, Jasevics A (2018). Estimating the economic impacts of net metering schemes for residential PV systems with profiling of power demand, generation, and market prices. Energies, 11(11): 3222

Shapley L S (1953). A value for *n*-person games. Contributions to the Theory of Games, 2(28): 307–317

Su W, Huang A Q (2014). A game theoretic framework for a next-generation retail electricity market with high penetration of distributed residential electricity suppliers. Applied Energy, 119: 341–350

Tang R, Wang S, Li H (2019). Game theory based interactive demand side management responding to dynamic pricing in price-based demand response of smart grids. Applied Energy, 250: 118–130

Tol R S J (2005). The marginal damage costs of carbon dioxide emissions: An assessment of the uncertainties. Energy Policy, 33(16): 2064–2074

Watkiss P, Downing T, Handley C, Butterfield R (2005). The impacts and costs of climate change. Final Report. European Commission DG Environment

Wei F, Jing Z X, Wu P Z, Wu Q H (2017). A Stackelberg game approach for multiple energies trading in integrated energy systems. Applied Energy, 200: 315–329

Zhao H Y, Yang R, Wang C H, Pabasara W M, Wijeratne U, Liu C Y, Xue X L, Abdeen N (2019). Effects of design parameters on rooftop photovoltaic economics in the urban environment: A case study in Melbourne, Australia. Frontiers of Engineering Management, 6(3): 352–367