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Cost–Benefit Analysis of Distributed Energy Systems Considering the Monetization of Indirect Benefits

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Abstract: Driven by market value, a co-benefits assessment framework to encompass various benefits arising from distributed energy systems is developed. Using a monetization approach, a quantitative analysis model is established to evaluate both direct and indirect benefits. According to the simulation results of typical distributed energy systems, the distributed photovoltaic (PV) system demonstrates superior economic performance compared with the gas-fired distributed energy system, highlighting its potential for widespread commercialization. Moreover, the inclusion of indirect benefits significantly enhances the economic viability of the distributed energy system. While the PV system exhibits a more favorable promotional impact, it also renders the gas-fired distributed energy system commercially feasible.

Keywords: distributed energy system; co-benefits; index system; monetization approach; cost–benefit evaluation

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1. Introduction

A distributed energy system is an innovative approach to energy generation and distribution that promotes the decentralization and diversification of energy sources. It encompasses a variety of technologies that generate electricity at or near where it will be used, such as photovoltaic (PV) units and combined heat and power (CHP) systems [1]. Acknowledged as an efficient, reliable, and environmentally friendly alternative to the traditional energy system, it is globally recognized as a promising solution for energy sustainability [2,3].

In the late 1970s, two oil crises promoted developed countries like those in Europe, America, and Japan to focus extensively on energy efficiency. In this context, the cogeneration system gained widespread attention and emerged as the primary form of distributed energy in its early stages, driven by the concept of energy cascade utilization [4,5]. After entering this century, global environmental concerns, particularly related to greenhouse gas emissions, have escalated. Distributed energy has assumed a new role in addressing these challenges. It has evolved from conventional fossil fuel-based systems to encompass distributed renewable energy solutions like PV and decentralized wind power. This evolution has led to the creation of a multi-energy complementary distributed energy system [6,7]. In recent years, propelled by advancements in modern information technology and the advent of digital and sharing economies, distributed energy has undergone a transformative upgrade. This upgrade is evident in the emergence of concepts such as integrated energy systems and the energy internet, facilitated by cross-border integration [8,9].

Despite its widespread popularity and the global push for energy transformation, the actual installation of distributed energy systems has not met expectations. Shanghai, a pioneer in China's distributed energy development, has introduced five rounds of subsidy policies for gas-fired distributed energy systems over a decade. Surprisingly, the total number of projects amounts to only about 70, making a negligible contribution to Shanghai's overall energy supply. Beyond the well-discussed issues like gas prices, heat prices, and initial investment, the undervaluing of distributed energy systems might pose significant constraints on their promotion [10]. As a component of urban energy infrastructure, the distributed energy system holds a distinct social and public dimension. Its successful implementation not only yields direct economic benefits, primarily through reduced energy costs, but also generates broader indirect advantages, including socio-economic development, improved residential living standards, and a secure and sustainable energy supply. These indirect benefits are substantial, and understanding them comprehensively can significantly enhance the societal welfare stemming from distributed energy systems, further driving project implementation. Conversely, a lack of recognition regarding these benefits may result in a limited understanding of the value of deploying distributed energy systems, leading to an incomplete assessment of overall benefits and impeding their commercialization and widespread application.

Since the inception of the distributed energy concept, studies have predominantly concentrated on evaluating its technical [11], economic [12], energy-saving [13], and environmental [14] merits, which were easily quantifiable and analyzable. In recent years, scholars have started to recognize the inherent public attributes of energy projects and analyze their indirect benefits, such as environmental improvement and risk mitigation [15]. For instance, Nehler et al. [16] conducted a qualitative analysis of the indirect benefits generated by industrial energy conservation, underscoring the importance of assessing these indirect gains to drive investments in energy efficiency. Skumatz [17] analyzed the relevance of indirect benefits in the planning, evaluation, and decision-making of energy efficiency programs. Fleiter et al. [18] confirmed the importance of indirect benefits with the creation of a classification table for energy efficiency programs. Trianni et al. [19] proposed a comprehensive framework for designing energy efficiency programs while considering indirect benefits. Tonn et al. [20] conducted a quantitative analysis of the indirect benefits associated with energy efficiency programs, such as residential upgrades, the impact of disaster prevention and evacuation, and regional economic effects. Schweitzer et al. [21] examined the indirect benefits of energy efficiency retrofit programs for low-income buildings in the United States and discovered that the overall value of the indirect benefits exceeded the direct economic advantages of the retrofits. Outcault et al. [22] discussed the occupant non-energy impacts of an energy retrofit.

According to the above discussion, the evaluations of indirect benefits have concentrated on energy-saving endeavors within individual units, such as industries and buildings, thus overlooking the potential indirect benefits of distributed energy systems. To foster the healthy and sustainable development of distributed energy systems, it is of vital importance to establish a comprehensive co-benefits assessment framework that encompasses both direct and indirect advantages. This study aims to reconstruct the valuation framework for distributed energy systems. Using a unified monetary assessment encompassing both direct and indirect benefits, this study aims to augment the perceived value of distributed energy systems. The main contributions of this study are as follows:

(1) A comprehensive assessment index system that considers both direct and indirect benefits of the introduction of distributed energy systems is proposed.
(2) The monetization measures of various indirect benefits are proposed using diverse non-market value assessment methods.

Therefore, this study is organized as follows: Section 2 introduces the assessment index and corresponding monetization measures. Section 3 presents the assumptions of the numerical study. A detailed discussion is given in Section 4. The conclusions are given in Section 5.

2. Materials and Methods

2.1. Index System and Evaluation Method for Co-Benefits

The direct benefits of distributed energy systems primarily entail the economic advantages directly derived from their operation. These stem from the systems' high efficiency, leading to reduced operational costs. Moreover, the demand-side proximity allocation principle results in savings in initial investment costs for pipelines and associated equipment. On the other hand, distributed energy systems bring about indirect benefits, particularly in terms of environmental advantages. With energy cascade utilization and the substitution of clean energy, these systems contribute significantly to reducing carbon emissions and other pollutants such as SO_2 and NO_x.

Moreover, the introduction of distributed energy systems on the demand side holds the potential to generate a ripple effect within the regional economy. The establishment of energy infrastructure and investments in associated equipment are poised to stimulate nearby industries, fostering regional economic growth. Simultaneously, the implementation of these systems will elevate the quality of nearby commercial and residential buildings, augmenting the value of real estate assets. In addition, deploying distributed energy systems will ensure a diversified and reliable supply for various energy needs like cooling, heating, and electricity. This diversification fosters energy complementarity, reducing risks and creating a mutual insurance effect against potential energy-related challenges.

On the other hand, for end-users, the utilization of distributed energy systems results in improvements to both indoor and outdoor micro-environments. This enhancement leads to increased comfort levels and higher work efficiency within indoor spaces. Furthermore, as an emerging energy technology, distributed energy systems contribute to an improved perception of energy conservation and environmental preservation among users. This creates a demonstration effect and yields promotional advantages for the technology.

Following the analysis of direct and indirect benefits discussed earlier, a structured co-benefits evaluation index system for distributed energy systems was developed, which is presented across three hierarchical levels, as outlined in Table 1. The index system includes primary indexes encompassing direct and indirect benefits, secondary indexes featuring direct economic benefits, environmental benefits, regional economic impact benefits, risk aversion benefits, popularization and inspiration benefits, and comfort enhancement benefits. Additionally, these secondary indexes feed into a tertiary index, composed of ten distinct benefits, offering a comprehensive assessment of the impact of distributed energy systems across various facets of the regional economy, environment, and society with greater granularity.

Table 1. Evaluation index system for the co-benefits of distributed energy systems.

Primary Index	Secondary Index	Tertiary Index
Direct benefits	Direct economic benefits	Energy cost reduction benefits
Indirect benefits	Environmental benefits	Carbon emissions reduction benefits Green energy penetration benefits
	Regional economic impact benefits	Equipment investment ripple benefits Real estate value-added benefits
	Risk aversion benefits	Energy supply interruption avoidance benefits
	Popularization and inspiration benefits	Low-carbon concept popularization benefits Advanced technology advertising benefits
	Comfort enhancement benefits	Indoor comfort enhancement benefits Health level enhancement benefits

The estimation of direct economic benefits is typically straightforward, relying on the direct market method. However, for some indirect social benefits (such as comfort enhancement and risk aversion) lacking clear market-oriented values, the non-market value assessment method is necessary. After analyzing the core principles, applicability, scope, strengths, and limitations of prevalent non-market value assessment methods (e.g., cost-of-illness method, alternative market method, etc.), specific evaluation methods compatible with each benefit were identified and refined.

(1) Energy cost reduction benefits.

As mentioned earlier, distributed energy systems can effectively reduce energy consumption and energy costs. These benefits can be quantified and converted into monetary values using the direct market approach, as shown in Equation (1).

$$B_c = \sum_{m=1} C_m \cdot P_m \tag{1}$$

where B_c is the monetary value of energy cost reduction (USD/Year), C_m is the amount of energy reduction of the mth energy source (MJ/Year), and P_m is the market price of the mth energy source (USD/MJ).

(2) Carbon emissions reduction benefits.

The application of either gas-fired distributed energy or distributed renewable energy can result in significant reductions in carbon emissions. These benefits can be monetized by considering the current carbon market price, as shown in Equation (2).

$$B_o = C_o \cdot P_o \tag{2}$$

where B_o is the monetary value of carbon emission reduction benefits (USD/Year), C_o is the volume of CO_2 emissions reduction (t-CO_2/Year), and P_o is the market price of CO_2 (USD/t-CO_2).

(3) Green energy penetration benefits.

Distributed energy systems can acquire green power certificates (referred to as green certificates) through the production and utilization of renewable energy. Each green certificate typically represents 1000 kWh of green power and can be traded on the market. The trading price of green certificates is generally determined by market supply and demand. Therefore, the benefits of green energy penetration can be realized with the trading of green certificates, as shown in Equation (3).

$$B_g = P_g \cdot n \tag{3}$$

where B_g is the green energy penetration benefit generated by green certificate trading (USD), n is the number of green certificates (Sheet), and P_g is the price of green certificate trading (USD/Sheet).

(4) Equipment investment ripple benefits.

As energy infrastructure, distributed energy systems usually involve a relatively high initial investment. The investment and operation of equipment will continuously impact the regional economy, which can be estimated using Equation (4).

$$B_i = I_0 \cdot \alpha / T_i \tag{4}$$

where B_i is the ripple effect of the equipment investment (USD/Year), I_0 is the initial investment of the project (USD), α is the crude value-added productivity (%), and T_i is the duration of the ripple effect (Years).

(5) Real estate value-added benefits.

Distributed energy systems can enhance the quality of the local micro-environment, such as reducing the heat island effect, leading to optimized nearby residential and commercial settings. This enhancement is often reflected in increased property values and the willingness of individuals to invest in real estate. By utilizing the alternative market approach, the added value of distributed energy systems on real estate can be estimated, as shown in Equation (5).

$$B_r = A \cdot P_r \cdot \eta / T_r \tag{5}$$

where B_r is the monetary value of real estate appreciation (USD/Year), A is the land area of the study object (m^2), P_r is the unit price of the original real estate (USD/m^2), η is the growth rate of house price (%), and T_r is the duration of the value-added effect (Years).

(6) Energy supply interruption avoidance benefits.

The implementation of distributed energy systems can enhance the reliability of energy supply. This improvement can be estimated using the value of energy services offered by distributed energy sources during interruptions in conventional energy supply, as demonstrated in Equation (6).

$$B_s = P_s \cdot C \cdot t_s \cdot \beta \tag{6}$$

where B_s is the energy supply interruption avoidance benefit (USD/Year), P_s is the unit energy supply interruption loss amount (USD/kWh), C is the capacity of the distributed energy system (kW), t_s is energy supply interruption time (Hours/Time), and β is the energy supply interruption incidence (Times/Year).

(7) Low-carbon concept popularization benefits.

The introduction of distributed energy as a pioneering energy technology can inspire and educate communities about energy conservation and environmental protection, yielding intangible social benefits. To quantify this benefit, it can be estimated by considering the costs incurred by non-profit institutions in promoting these concepts, as illustrated in Equation (7).

$$B_e = N_e \cdot P_e \cdot \lambda_e \tag{7}$$

where B_e is the enlightenment benefit for popularizing low-carbon and environmental protection concepts (USD/Year), N_e is the number of target population (person/Year), P_e is the unit cost of enlightenment and education (USD/Person), and λ_e is the impact coefficient (Year/Year).

(8) Advanced technology advertising benefits.

As demonstrated earlier, the integration of advanced energy technologies like distributed energies can enhance the reputation of a company or region, yielding intangible advertising benefits. This benefit can be estimated using Equation (8).

$$B_a = P_a \cdot \mu \cdot \lambda_a \tag{8}$$

where B_a is the benefit of advertising and publicizing advanced technologies and ideas (USD/Year), P_a is the equivalent advertising and publicizing cost (USD/Year), μ is the coefficient of advertising and publicizing effect, and λ_a is the impact coefficient (Year/Year).

(9) Indoor comfort enhancement benefits.

Using the Conditional Value Assessment Method (CVM), the benefits associated with improved life satisfaction and comfort resulting from the implementation of a distributed energy system, such as increased willingness to pay for indoor comfort, can be indirectly quantified, as depicted in Equation (9).

$$B_{ic} = F \cdot N_{ic} \tag{9}$$

where B_{ic} is the monetary value of comfort enhancement benefits (USD/Year), F is the average willingness-to-pay measure (USD/Person-Year), and N_{ic} is the number of subjects (Persons).

(10) Health level enhancement benefits.

The value of enhancing residents' health with distributed energy systems can be estimated using the cost-of-illness method. This method takes into account all costs associated with illness, including medical expenses and income loss due to absenteeism. By assigning an economic value to the time and resources consumed by illness, Equation (10) illustrates how this estimation can be performed.

$$B_{ih} = \sum_{k} (W_k + M_k) \cdot N_k \cdot \delta \quad (10)$$

where B_{ih} is the monetary value of the health enhancement benefit (USD), W_k is the average level of wages lost due to illness and the inability to go to work (USD/Person), M_k is the average cost of medical care (USD/Person), N_k is the number of people impacted (Persons), and δ is the probability that the impact will occur (%).

2.2. Framework of the Cost–Benefit Analysis

Using the co-benefits evaluation index developed for distributed energy systems, specific quantitative indexes of co-benefits can be obtained for a particular distributed energy system with monetized evaluation methods like the market value method and alternative market method. Combining these indexes with the calculation of project-related investment and operation costs establishes the framework for conducting a cost–benefit analysis of the distributed energy system, as shown in Figure 1.

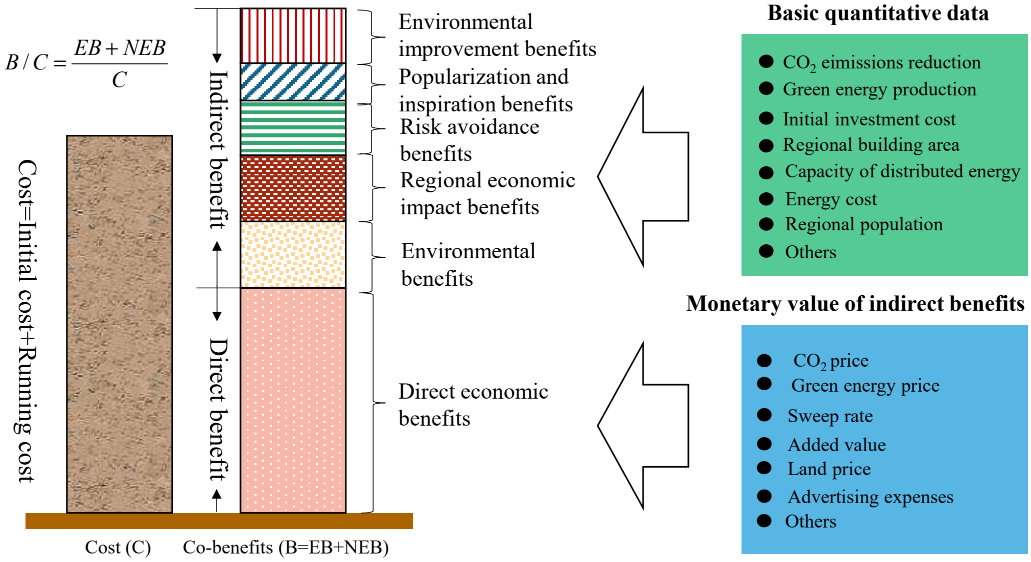


Figure 1. Image of the cost–benefit analysis.

The total monetized benefits of the distributed energy system are calculated by considering both direct and indirect benefits, as illustrated in Equation (11).

$$B = EB + NEB \quad (11)$$

where B, EB, and NEB are the co-benefits, direct benefits, and indirect benefits of the distributed energy system, respectively.

The direct benefits can be calculated directly using Equation (1), while the indirect benefits are the sum of all the indirect benefits mentioned earlier, as indicated in Equation (12).

$$NEB = B_o + B_g + B_i + B_r + B_s + B_e + B_a + B_{ic} + B_{ih} \quad (12)$$

The monetized co-benefits and total monetized costs of the distributed energy system are combined to establish the cost–benefit assessment method, as shown in Equation (13).

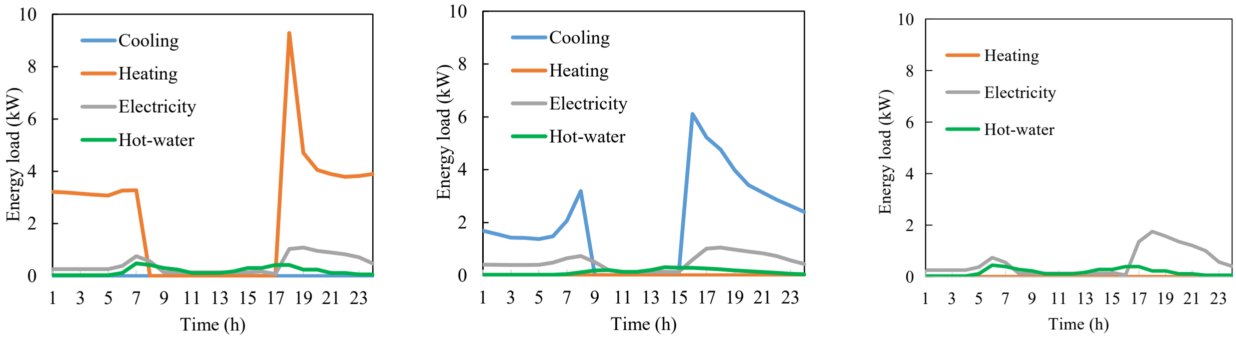
$$B/C = \frac{EB + NEB}{C} \quad (13)$$

where C is the total cost of the distributed energy system, and the calculation details can be found in Ref. [23].

3. Numerical Analysis

3.1. Study Object and Load Characteristics

In this study, a residential neighborhood in Shanghai is selected as the research subject, encompassing a total floor area of approximately 100,000 m^2 with an average building height of four floors. Figure 2 illustrates the hourly energy loads on typical days during the winter, summer, and transitional seasons. Normally, residential demand is concentrated during non-working hours, peaking between 17:00 and 19:00. The cooling and heating loads display notable seasonal fluctuations and are the predominant load patterns in the summer and winter, while electrical and hot-water loads remain relatively stable.

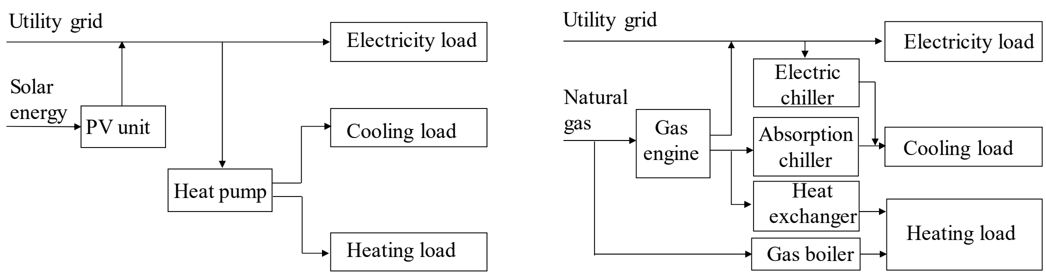


(**a**) Winter (**b**) Summer (**c**) Transitional season

Figure 2. Hourly energy loads on typical days.

3.2. Design of the Distributed Energy System

In accordance with green and low-carbon design principles, two typical distributed energy systems, namely, the PV system and the CCHP system, are examined, as illustrated in Figure 3. The PV system's structure is relatively straightforward, utilizing the community's roof resources to install PV cells, following the conventional separated energy supply mode. The power generated by the PV system is primarily consumed within the community, with any excess sold back to the grid.



(**a**) PV system (**b**) CCHP system

Figure 3. Flow chart of the distributed energy system.

The deployment of the CCHP system involves a comprehensive transformation of the entire regional energy supply structure. It necessitates the establishment of a centralized energy center at the community level, equipped with on-site power generation units like gas engines, to fulfill the region's electricity demand. Any deficit in power supply will be supplemented by the utility grid, while surplus electricity can be returned to the grid. Moreover, the waste heat generated during power generation is utilized to provide heating and cooling for the area. If the waste heat output is insufficient, gas boilers and electric chillers are used as additional sources for heating and cooling, respectively.

The installed capacity of the distributed energy system is confined to 2.5 MW for the PV system, constrained by the available roof space within the community. As for the primary power source, a gas engine with an installed capacity of 650 kW was selected, aligning with pertinent design expertise [24].

3.3. Parameter Setting

The technical parameters for both the PV system and the CCHP system were established using data from reputable manufacturers and references, detailed in Table 2 [25–29]. The capacity subsidy, an essential policy promoting the adoption of the CCHP system, was taken into account.

Table 2. Technical parameters of energy equipment.

Equipment	Parameter	Unit	Value	Reference
Gas engine	Electricity efficiency	%	40	[25]
	Heat recovery efficiency	%	45	[25]
	Initial investment	USD/kW	1118	[25]
	Subsidies for installation	USD/kW	350	[26]
	Operation and maintenance cost	USD/kWh	0.01	[25]
PV unit	Efficiency	%	20	[27]
	Initial investment	USD/kW	560	[27]
	Operation and maintenance cost	USD/kWh	0.001	[27]
Absorption chiller	COP	-	1.2	[28]
Electric chiller	COP	-	5	[28]
Air conditioner	COP (cooling)	-	4.4	[28]
	COP (heating)	-	3.7	[28]
Heat exchanger	Efficiency	%	95	[29]
Gas boiler	Efficiency	%	90	[29]

Given the economic focus of this study, the establishment of energy-related parameters is pivotal and primarily relies on the present conditions in Shanghai, outlined in Table 3 [30,31]. In addition to the time-of-use tariff for electricity purchase, the feed-in tariff for surplus electricity sold back to the grid was also considered. Moreover, a discounted price was available for the gas consumption of the CCHP system.

Table 3. Information on energy prices [30,31].

Energy Form	Price Pattern	Unit	Value
Electricity	Time-of-use tariff (peak hour)	USD/kWh	0.095
	Time-of-use tariff (valley hours)	USD/kWh	0.047
	Feed-in tariff	USD/kWh	0.058
	PV subsidies	USD/kWh	0.021
Natural gas	Gas for CCHP systems	USD/m^3	0.369
	Gas for non-residential users	USD/m^3	0.510
	Gas for residential users	USD/m^3	0.461

Furthermore, for the monetized conversion of indirect benefits, related parameters are assumed as presented in Table 4 [32–37].

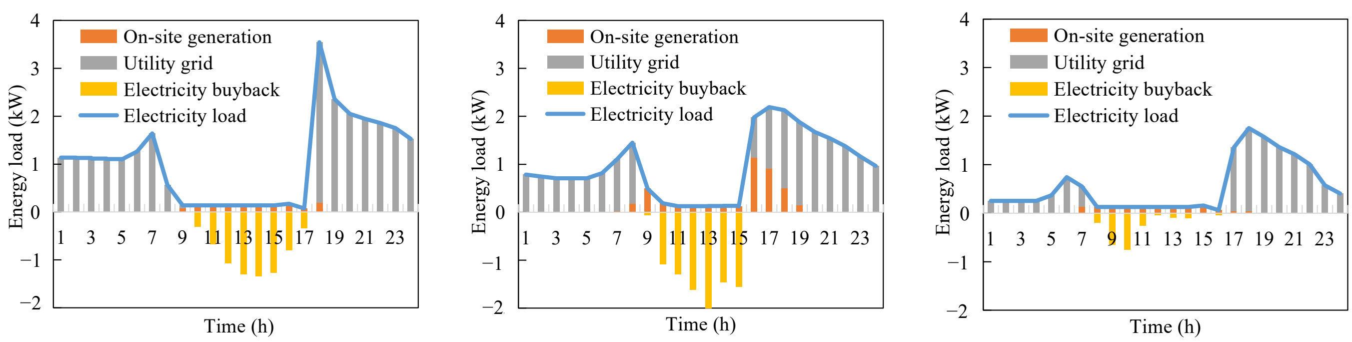
Table 4. Parameters for monetization conversion of indirect benefits.

Parameter	Unit	Value	Reference
CO_2 price	USD/t-CO_2	16.77	[32]
Green certificates trading price	USD/Sheet	0.978	[33]
Crude value-added rate	%	50	[34]
Duration of the ripple effect	Year	20	[35]
House price growth rate	%	0.5	[36]
Duration of value-added effect	Year	20	[35]
Amount of loss per unit of interrupted energy supply	USD/kWh	25.72	[35]
Duration of interruptions in energy supply	Hours/Time	72	[35]
Incidence of energy supply disruptions	Times/Year	0.022	[35]
Unit cost of inspired education	USD/Person	27.67	Field investigation
Impact factor	-	0.3	Field investigation
Advertising and promotion costs	USD/Year	70,000 (PV)/84,000 (CCHP)	Field investigation
Coefficient of advertising	%	2	Field investigation
Average value of willingness to pay	USD/Person	14 (PV)/70(CCHP)	Field investigation
Average medical costs	USD/Year	674	[37]
Probability of occurrence	%	1	[35]
Number of people affected	-	2000	Field investigation
Average absence pay	USD/Day	36	Field investigation

4. Results and Discussion

4.1. Operation Strategy of the Distributed Energy System

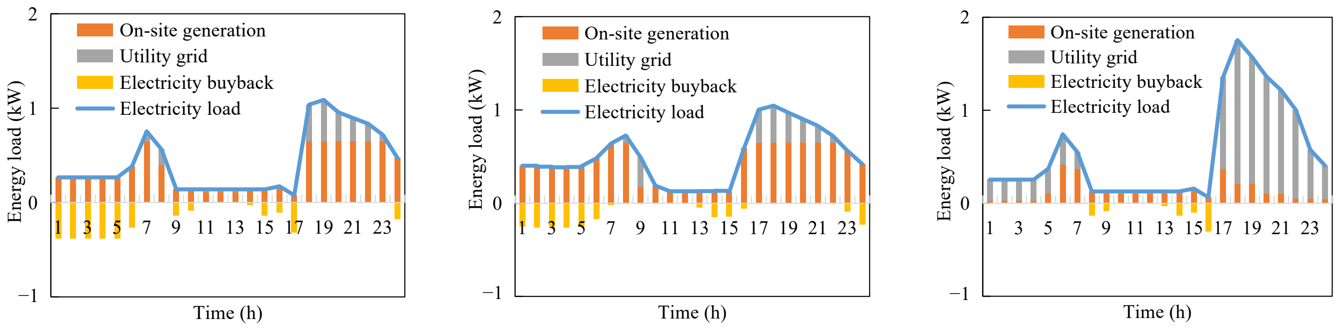
After the installation of the PV system in the designated area, the hourly electrical balance on typical days is depicted in Figure 4. Given that the cooling and heating needs in the community are met with domestic air conditioners, they are converted into electrical loads, causing a rise in overall electrical demand during the winter and summer. As shown in Figure 4, due to the mismatch between the PV output period and the electricity consumption period of residential users, the amount of PV output used for self-consumption is relatively limited. Subsequently, a considerable portion of the on-site generation is fed back into the grid. Consequently, the introduction of PV systems in residential areas does not substantially promote the local utilization of renewable energy, and a majority of the electrical demand continues to rely on the utility grid.



(**a**) Winter (**b**) Summer (**c**) Transitional season

Figure 4. Electrical balance of the PV system on typical days.

After the installation of the CCHP system, the hourly electrical balance on typical days is illustrated in Figure 5. Operating in heat-tracking mode, the CCHP system generates substantial electricity throughout both the winter and summer. During peak periods, the system operates at its rated load, mainly producing electricity for self-consumption, with any surplus electricity sold back to the grid. Conversely, during transitional seasons with reduced hot water demand, the prime mover generates less electricity, and the grid meets the majority of the electrical demand.



(**a**) Winter (**b**) Summer (**c**) Transitional season

Figure 5. Electrical balance of the CCHP system on typical days.

4.2. Results of the Co-Benefits Evaluation

For the two system forms (PV and CCHP systems) implemented in this study, the system configuration and operation strategy are determined based on the hourly load characteristics of the selected neighborhood. Utilizing these data, the overall energy supply cost in the district, encompassing annualized investment costs and operating costs, can be calculated. Furthermore, by taking into account the pertinent assumptions provided in Table 4 for monetizing indirect benefits, the co-benefits arising from the implementation of the distributed energy system, covering both direct and indirect benefits, can be estimated. The findings from these estimations are presented in Table 5.

Table 5. Results of cost-benefit analysis for two systems.

Type of Cost or Benefit			Cost-Effectiveness Value (Million USD/Year)	
			PV	**CCHP**
Cost (C)	Annualized investment costs		8.41	4.01
	Annual running costs		0.40	42.31
Direct benefits (EB)	a. Direct economic benefits	a1. Energy cost reduction benefits	24.98	40.15
Indirect benefits (NEB)	b. Environmental benefits	b1. Carbon emission reduction benefits	2.26	13.15
		b2. Green energy penetration benefits	0.28	-
	c. Regional economic impact benefits	c1. Equipment investment ripple benefits	2.62	1.25
		c2. Real estate value-added benefits	0.87	0.87
	d. Risk aversion benefits	d1. Energy supply interruption avoidance benefits	10.18	2.65
	e. Popularization and inspirational benefits	e1. Low-carbon concept popularization benefits	8.30	8.30
		e2. Advanced technology advertising benefits	0.04	0.05
	f. Comfort enhancement benefits	f1. Indoor comfort enhancement benefits	1.40	6.99
		f2. Health level enhancement benefits	1.06	1.06

Generally, within the spectrum of co-benefits, direct economic benefits account for 47% and 57% for PV and CCHP systems, respectively. Concerning indirect benefits, the PV system demonstrates a relatively significant share of benefits in terms of energy supply interruption avoidance and popularization of the low-carbon concept. In contrast, the

CCHP system exhibits substantial benefits in carbon emission reduction, popularization of the low-carbon concept, and improvement in indoor comfort.

4.3. Overall Cost–Benefit Analysis

The results of the overall cost–benefit analysis for the two distributed energy systems are presented in Figure 6. Without considering indirect benefits, the B/C values for the PV and CCHP systems stand at 2.2 and 0.8, respectively. Despite the PV system's inability to utilize its power generation for self-consumption in residential areas, it still generates considerable economic benefits due to the notable decrease in PV investment in recent years. Conversely, the CCHP system's direct economic benefits are less promising, posing challenges to its support and application. Similarly, the direct economic benefits of gas-fired distributed energy systems are discouraging, hampering their widespread adoption. However, when considering indirect benefits, the B/C values for the PV and CCHP systems increase to 4.7 and 1.4, respectively, marking a substantial increase of approximately 114% and 75%.

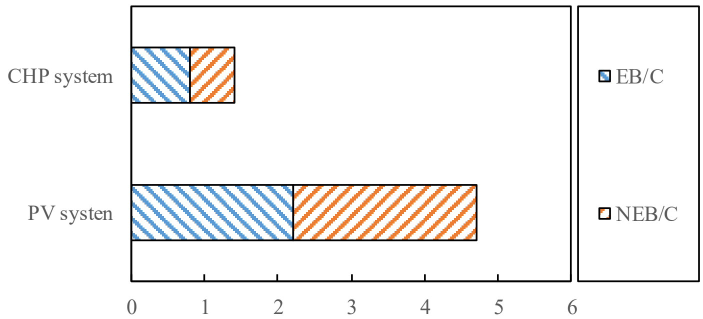


Figure 6. B/C analysis of distributed energy systems.

Therefore, considering indirect benefits may positively influence the deployment of distributed energy systems, particularly in promoting distributed renewable energy systems like solar power. Owing to their inherent social advantages, the indirect benefits of distributed renewable energy systems might even outweigh their direct benefits.

5. Conclusions

As a holistic energy-saving solution, distributed energy systems exhibit distinctive traits, including substantial investment, extended construction timelines, and slower efficiency gains. These factors considerably impede their commercialization process in comparison with conventional single-unit energy-saving approaches. In this study, a co-benefits evaluation index system is introduced, shaped by market value considerations, to encompass the diverse advantages derived from deploying distributed energy systems. Using monetization methods, both direct and indirect benefits are quantitatively assessed. Using a numerical analysis of an illustrative example, the following conclusions can be drawn.

(1) Distributed PV systems demonstrate superior economic performance compared with gas-fired CCHP systems, positioning them favorably for commercial promotion.
(2) The incorporation of indirect benefits notably bolstered the economic feasibility of distributed energy systems. While it notably benefits the promotion of distributed PV systems, it also fosters favorable commercial conditions for CCHP systems.

It is important to highlight that the effective collection and rational setting of parameters play a crucial role in evaluating indirect benefits. In this study, some parameters were determined based on individual case investigations. For more scientific and reasonable evaluation outcomes, conducting a large-scale investigation in future studies could be advantageous. Additionally, the diverse benefits outlined in this study may pertain to different stakeholders. To enhance the enthusiasm of all parties in promoting distributed energy systems, rational allocation of benefits among stakeholders becomes vital. Thus, developing a reasonable benefit allocation mechanism is expected in future studies.

Furthermore, this study exclusively focused on PV and CCHP systems for the numerical analysis. However, the proposed assessment framework is adaptable for conducting cost–benefit analyses of diverse distributed energy systems, incorporating both direct and indirect benefits. Future research endeavors are anticipated to delve into an in-depth cost–benefit analysis of an integrated energy system covering diversified distributed generators.

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