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"Photovoltaic+Energy Storage": Analysis of the Impact on Household Users and Economic and Environmental Benefits after Large-scale Integration to Distribution Network

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Abstract: Driven by the carbon peaking and carbon neutrality goals, distributed photovoltaic (PV) systems with energy storage are transitioning from demonstration projects to large-scale deployment. However, the mechanisms underlying their impact on household users and system-level economic-environmental benefits remain unclear. This study breaks through the conventional unidirectional “generation-grid-load” analysis paradigm by constructing a “generation-grid-load-storage” coordinated optimization model. It pioneers the application of Contingent Valuation Methodology (CVM) to household energy storage investment decisions, quantifying the endogenous impact of behavioral variations on economic viability. Using 1,000 households in high-irradiance City A and medium-to-low-irradiance City B as samples, four scenarios were designed for comparative analysis. Results indicate: 1) All “PV+storage” solutions yielded positive net present values (NPV). However, demand response is key to unlocking storage value, nearly doubling NPV in low-irradiance areas and reducing payback periods by 4 years; 2) The cost-benefit analysis of system-level expansion shows that the external benefits brought by demand response and delaying power grid expansion account for 33% of the total benefits, which is significantly higher than the traditional assessment of saving electricity;3) The payback period for the household system can be shortened by about 0.7–1 years if a carbon inclusive mechanism is incorporated, given its average annual CO_2 emission reduction of 3–5 tons; 4) Households with high incomes and strong environmental awareness demonstrate an average 30% higher willingness to pay (WTP) for energy storage solutions. Targeted subsidies prove over 20% more effective than blanket subsidies. This research provides quantitative evidence for designing differentiated policies, market mechanisms, and carbon credit programs in regions with high distributed energy grid integration.

Keywords: Photovoltaic; Energy Storage; Household Users; Economic and Environmental Benefits; Large-scale Access; Distribution Network.

1. Introduction

The global energy system is undergoing a profound transformation from centralized fossil energy to distributed renewable energy. As the largest photovoltaic (PV) market in the world, China has maintained a growth rate of more than 50% for three consecutive years, and the evolution of distribution network from "one-way power reception" to "two-way interaction" has become an inevitable trend [1]. The high proportion of renewable energy access brings three challenges to the distribution network, such as large power fluctuation, mismatch between electricity consumption and power generation during peak hours and poor value transmission mechanism, which leads to rising risk of voltage exceeding limit, difficult matching between supply and demand and long return period of energy storage investment [2]; However, the existing research is mostly limited to improving the efficiency of equipment, ignoring the differences of users' behaviors, and the demand response income is not included in the economic evaluation, and there is also a lack of quantitative analysis on the synergistic effect of electricity and carbon market at the policy level, which restricts system optimization and investment incentives [3-4].

This study breaks through the traditional unidirectional “source-grid-load” analysis paradigm of energy systems by establishing a “source-grid-load-storage” collaborative model that incorporates the dynamic characteristics of energy storage. It proposes a household energy storage investment decision-making method based on Contingent Valuation Methodology (CVM), filling a gap in the application of behavioral economics within the energy sector. Provide a basis for grid enterprises to formulate differentiated grid-connected standards, reveal the economic differences in different climate zones, and guide the accurate formulation of regional policies; the reduction effect of "PV+ energy storage" on household carbon footprint is calculated to provide data support for the design of a carbon-inclusive mechanism.

2. Analysis of Influence Mechanism and Model Construction

2.1. The Path of Influence on Home Users

As a "prosumer", the influence path of household users mainly includes the change of electricity consumption behavior, the optimization of electricity expenditure and the investment decision-making mechanism. These paths are significantly affected by user heterogeneity. In this study, CVM and investment decision-making models are combined to quantify the impact of user behavior differences on system access [5].

The influence path of users' participation in the distributed energy system is as follows: PV power generation can save electricity fees for their own use and gain online income, and peak-valley arbitrage combined with energy storage can directly reduce the cost of electricity consumption [6]; On this basis, users make energy storage investment decisions based on economic and psychological factors such as policy subsidies, electricity price mechanism and personal risk preference. With the deepening of participation, users actively adjust their electricity consumption behavior in response to signals such as time-of-use prices, providing behavioral feedback on the demand side and dynamically influencing the load characteristics of distribution network, thereby realizing two-way interaction and co-evolution between source and load.

CVM surveys users to measure their willingness to pay (WTP) for energy storage, revealing their behavioral preferences. A two-boundary dichotomous choice method is employed to reduce bias [7]. WTP is estimated using a Logit model:

$$\Pr\left(Yes_i\right)=\Lambda\left(\alpha\beta_1\ Income_i+\beta_2 Load_i+\beta_3 GreenAttitude_i+\beta_4\ Policy_i\right) \tag{1}$$

Where $\Pr\left(Yes_i\right)$ represents the probability that the user i accepts the given bid value; Λ is Logistic cumulative distribution function; α is the intercept term, β_1 is the income coefficient ($Income_i$ stands for annual household income), β_2 is the electricity consumption coefficient ($Load_i$ stands for daily average electricity consumption), β_3 is the environmental protection attitude coefficient ($GreenAttitude_i$ is based on Likert scale), and β_4 is the policy perception coefficient ($Policy_i$ stands for subsidy policy awareness). The model outputs the WTP distribution of users, which is used to segment user groups.

The investment decision model is based on net present value (NPV) calculations, integrating CVM results to account for behavioral differences:

$$NPV_i=\sum_{t=1}^{T}\frac{B_{i,t}-C_{i,t}}{\left(1+r\right)^t}-I_0+WTP_i DR_i \tag{2}$$

Where NPV_i is the NPV; of the user i; $B_{i,t}$ is the income in the t year (including electricity saving, surplus electricity online income and demand response income); $C_{i,t}$ is the operation and maintenance cost; r is the discount rate (taking the social discount rate of 5%); I_0 is the initial investment cost; WTP_i is the WTP obtained by CVM, which is used to adjust psychological benefits; DR_i is demand response participation (0-1 variable, determined by user type). When $NPV_i>0$, users choose to invest. This model internalizes behavioral factors and makes up for the deficiency of traditional economic evaluation.

2.2. Dimensions of Influence on Economic and Environmental Benefits

Economic and environmental benefits include system cost savings, market gains and carbon emission reduction externalities [8]. This study quantifies the positive and negative spillover effects of "PV+ energy storage" from the whole distribution network, and introduces the collaborative analysis of power market and carbon market.

Economic benefits include household users' income, power grid delayed investment savings (reducing the demand for expansion due to peak load shedding), system consumption cost reduction (reducing light waste), and demand response income (participating in the auxiliary service market). Environmental benefits include carbon emission reduction accounting and linking the carbon market to realize value; Consider life-cycle emissions to avoid carbon leakage.

Economic benefits are assessed using a system-level scaled cost-benefit analysis (CBA), calculated as follows:

$$NetEconomicBenefit=\sum_{i=1}^{N}\left(NPV_i\right)+GridBenefit+MarketBenefit \tag{3}$$

Where N is the total number of home users; $GridBenefit$ is the power grid benefit, and the calculation formula is:

$$GridBenefit=\lambda\Delta P_{peak}C_{inv} \tag{4}$$

Where λ is the peak load reduction ratio (from load simulation), ΔP_{peak} is the peak load reduction (kW), and C_{inv} is the power grid investment cost per unit capacity (Yuan/kW); $MarketBenefit$ is the market income, including the demand response income $\sum_t\left[P_{DR}\left(t\right)Q_{DR}\left(t\right)\right]$, where $P_{DR}\left(t\right)$ is the response price of the period t and $Q_{DR}\left(t\right)$ is the response power.

Environmental benefits are based on carbon emission reduction accounting and linked to carbon inclusive mechanism:

$$CarbonReduction=\sum_{t=1}^{T}\left(E_{PV}\left(t\right)EF_{grid}\right)-E_{storage}EF_{battery} \tag{5}$$

Where $E_{PV}\left(t\right)$ represents PV generation during the t period (kWh), EF_{grid} denotes the grid emission factor (kgCO₂/kWh, derived from regional averages), $E_{storage}$ indicates the lifetime electricity consumption of energy storage (accounting for manufacturing and losses), and

$EF_{battery}$ signifies the carbon emission intensity of energy storage batteries (kgCO₂/kWh). Net carbon reduction can be converted into carbon revenue: $CarbonRevenue = CarbonReduction \cdot P_{carbon}$, where P_{carbon} is the carbon price (CNY/kgCO₂). This model supports regional differentiation analysis by adjusting EF_{gris}, P_{carbon} to reflect climate zone variations.

2.3. Analysis Model

The model integrates the cooperative operation of "source-network-load-storage" and uses the dynamic optimization framework to simulate the distribution network behavior under a high proportion of access [9-10]. The model aims at minimizing the total cost of the system (including economic and environmental costs), and the constraints cover the physical network and user interaction.

The model framework is based on linear programming, with a time resolution of 1 hour and a period of 1 year. Decision variables include PV output, energy storage charge and discharge, and power grid purchase and sale. Minimize the total social cost:

$$\min \sum_{t=1}^{T} \left[C_{grid}(t)P_{grid}(t) + C_{curtail}(t)P_{curtail}(t) + C_{emis}(t)E_{emis}(t)\right] \quad (6)$$

Where: $C_{grid}(t)$ represents the grid electricity price during the t period (RMB/kWh), $P_{grid}(t)$ denotes the power flow direction (positive for electricity purchase, negative for electricity sale); $C_{curtail}(t)$ indicates the curtailment penalty cost (RMB/kWh), $P_{curtail}(t)$ signifies the curtailed power generation volume; $C_{emis}(t)$ reflects the carbon cost (RMB/kgCO₂), $E_{emis}(t)$ represents the carbon emissions volume.

Dynamic constraint of energy storage:

$$E(t) = E(t-1) + \eta_{ch}P_{ch}(t)\Delta t - \frac{1}{\eta_{dis}}P_{dis}(t)\Delta t \quad (7)$$

Where $E(t)$ is the energy storage capacity (kWh) at t moment; η_{ch}, η_{dis} is the charging and discharging efficiency (take 0.95); $P_{ch}(t), P_{dis}(t)$ is the charging and discharging power (kW); Δt is the time step (1 hour). At the same time, it constrains $E_{\min} \le E(t) \le E_{\max}$ (capacity limit).

The security constraints of distribution network include voltage deviation constraint $V_{\min} \le V(t) \le V_{\max}$ and line capacity constraint $P_{line}(t) \le P_{line,\max}$. The simplified DistFlow model is adopted for voltage calculation, which is suitable for radial distribution network.

3. Empirical Research

3.1. Data Source and Scene Design

Two typical climate zones in China (A city in northwest China representing high radiation and B city in east China representing low and medium radiation) are selected for case analysis. Using the data of typical meteorological years, the hourly solar irradiance and ambient temperature in A and B cities were obtained. The annual electricity consumption data of 1000 households were obtained from the local power grid company and clustered into three typical electricity consumption modes: high, medium and low. The unit investment cost of PV is 3.5 yuan /W, the energy storage system is 1.5 yuan /Wh, and the cycle efficiency is 90%. The typical service life of PV is on the order of 25 years, whereas that of the energy storage is approximately 10 years. Residential time-of-use electricity rates are applied: peak rate of 0.8 yuan/kWh (6:00 PM–10:00 PM), off-peak rate of 0.3 yuan/kWh (11:00 PM–7:00 AM), and standard rate of 0.5 yuan/kWh. Excess electricity fed into the grid is priced at 0.4 yuan/kWh. Assume an initial investment subsidy of 20%. Carbon pricing is set at ¥50/ton of CO₂. A total of 500 questionnaires were distributed across both cities, achieving an 85% valid response rate. The average willingness-to-pay (WTP) was estimated using a Logit model.

For comparative analysis, the following four scenarios are set:

A. Scenario 1 (benchmark scenario): No PV, no energy storage, all electricity is purchased from the power grid.

B. Scenario 2 (PV only): 5kW household PV is installed without energy storage.

C. Scenario 3 (PV+ energy storage, no response): 5kWPV+10kWh energy storage is installed, but the user does not participate in the demand response.

D. Scenario 4 (PV+ energy storage, with response): 5kWPV+10kWh energy storage is installed, and users participate in demand response (electricity consumption behavior is adjusted based on time-of-use price).

3.2. Results and Analysis

Based on the investment decision model, the key economic indicators of typical families in different scenarios are calculated, as shown in Table 1.

The NPV of all "PV+" scenarios is positive, indicating that it is economically feasible. The NPV of scenario 4 (PV+ energy storage+demand response) is the highest, which shows that demand response can significantly improve the project economy, especially in city B, where the NPV is nearly doubled compared with scenario 3. Because of the superior lighting resources, the economy of all scenes in City A is obviously superior to that in City B. The payback period of investment in Scenario III in City B is as long as 14.5 years, which is close to the energy storage life. Without policy support or demand response, users' willingness to invest will be greatly reduced. Simply comparing scenarios 2 and 3, the addition of energy storage prolongs the payback period of investment, but its core value lies in improving the self-use rate and participating in system services. Combined with the demand response (scenario 4), the value of energy storage is fully activated.

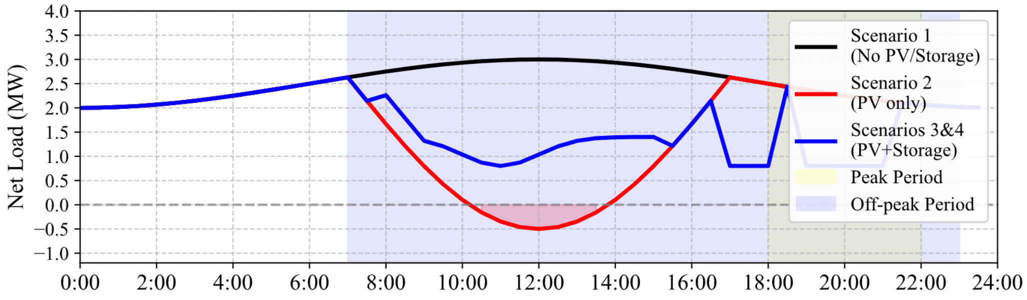
Table 1. Economic comparison of typical family (annual electricity consumption of 5000kWh) in the whole life cycle (25 years) (unit: yuan)

Index	A city (high radiation)			B city (Medium and low irradiation)		
	Scene 2	Scene 3	Scene 4	Scene 2	Scene 3	Scene 4
Initial outlay	14,000	29,000	29,000	14,000	29,000	29,000
Total electricity saving	48,500	58,200	65,100	32,800	41,500	48,000
Demand response income	-	-	8,500	-	-	7,200
Carbon gain	2,250	2,150	2,150	1,520	1,450	1,450
Calculate NPV	**36,750**	**31,350**	**46,750**	**20,320**	**13,950**	**27,650**
Payback period of investment (year)	6.5	10.2	7.8	9.8	14.5	10.5

Note: The total electricity expenditure in the benchmark scenario (scenario 1) is about 75,000 yuan (city A) and 68,000 yuan (city B).

The voltage and load curves of distribution network nodes on typical days (high load and high radiation) in summer are simulated, and the results are shown in Figure 1. In the traditional mode, the net load presents a single peak curve at night; However, with the large number of PV connections, a "duck curve" appears. The peak of PV output at noon leads to a sharp drop in net load or even a reverse transmission of power, while the sharp drop of PV in the evening leads to a steep load rise, which has a significant impact on the power grid. The introduction of energy storage systems demonstrates their peak shaving and valley filling capabilities in Scenarios 3 and 4. By charging during midday and discharging in the evening, peak loads are effectively reduced by 25%-30%, while smoothing the net load curve. Additionally, regarding voltage control, during periods of high PV generation, voltage exceeded the safety threshold (1.07 p.u.), posing a risk of voltage overshoot. However, after implementing energy storage, voltage was stably maintained within the safe range of 1.02–1.05 p.u., demonstrating the critical role of energy storage in enhancing the stability and safety of distribution grids.

(a) System Net Load Profile



(b) End-line Voltage Profile

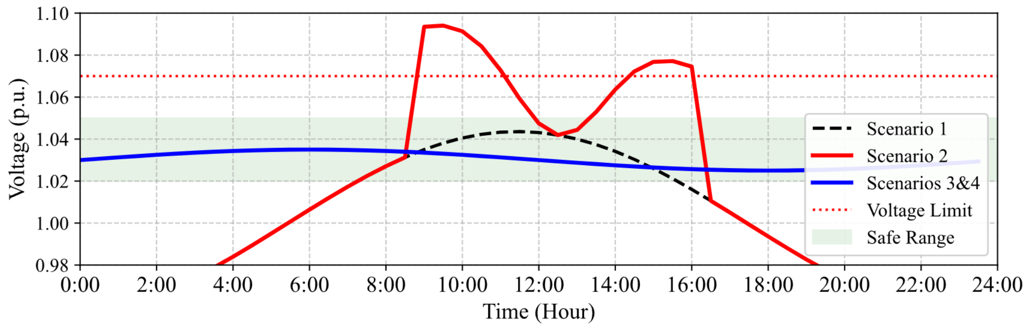


Figure 1. Load and voltage changes in a station area of A city on typical days in summer

Based on the extended CBA model, the system-level benefits of two typical scenarios (high radiation A market+ demand response) are quantified, as shown in Figure 2.

The traditional evaluation only pays attention to the savings of users' electricity bill (450,000 yuan), but through systematic analysis, this study finds that demand response income and grid delayed investment savings constitute significant external benefits (230,000 yuan in total), accounting for 33% of the total benefits. This proves that the value of "PV+ energy storage" far exceeds the category of individual families and has positive public benefits. At present, carbon benefits account for a relatively small proportion, but with the increase in carbon price, their importance will increase.

The results of CVM show that the WTP of high-income and high-awareness families is 30% higher on average. This means that the "one-size-fits-all" subsidy policy is inefficient and should turn to precise subsidies or green financial products for specific groups. In high-irradiance regions (e.g., City A), policy priorities should focus on incentivizing the “PV + energy storage + demand response” model while refining market mechanisms. Low-irradiance regions (e.g., City B) require more substantial initial investment subsidies or higher feed-in tariffs to guarantee basic returns, thereby stimulating market vitality. Empirical evidence indicates that residential PV systems can reduce annual CO_2 emissions by 3-5 tons. Integrating this data into carbon credit platforms can assign tangible value to these emission reductions—for example, generating an additional annual income of 150-250 yuan per household—effectively shortening the investment payback period.

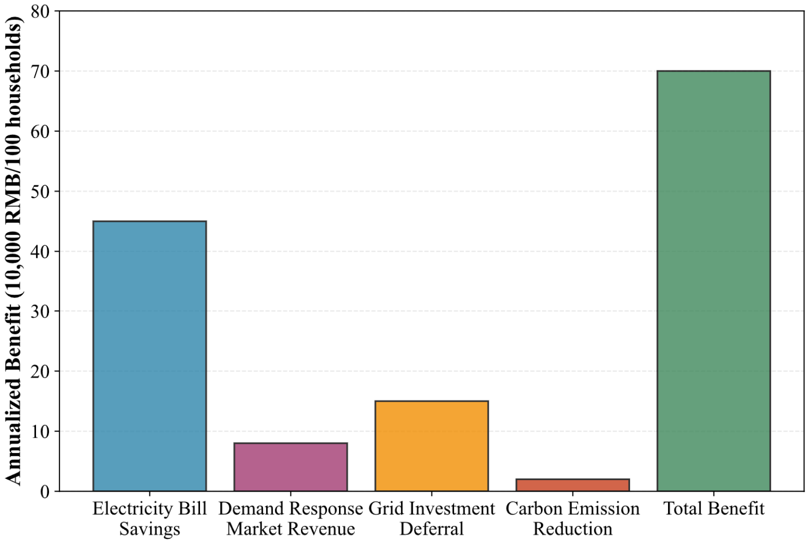


Figure 2. The annualized benefit composition of PV+ energy storage (Scenario 4) in City A (unit: 10,000 yuan/100 households)

4. Conclusion

By constructing a "source-network-load-storage" collaborative model, this study deeply analyzes the influence of the "PV+ energy storage" system on household users and economic and environmental benefits after it is connected to the distribution network on a large scale. The research shows that the "PV+ energy storage" system can effectively reduce the electricity expenditure of household users, improve the self-use rate, and increase the extra income through the demand response mechanism. Economic analysis shows that although the initial investment is high, in the long run, the system has a high NPV, especially in high irradiation areas such as A city, and its economic benefits are more significant. In addition, the system has a positive impact on the stability and security of the distribution network, which can effectively smooth the load curve and reduce the risk of voltage exceeding the limit. In terms of environmental benefits, the system significantly reduces the carbon footprint of families, and its environmental value will be further highlighted with the increase in carbon price. At the policy level, it is suggested to implement differentiated subsidies and incentives for different regions and user groups to promote the wide application of "PV+ energy storage" technology and enhance market vitality. Generally speaking, the "PV+ energy storage" system not only brings economic and environmental benefits to home users, but also provides important support for the sustainable development of distribution network.

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