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ECONOMIC EFFICIENCY EVALUATION OF DISTRIBUTED PHOTOVOLTAIC-ENERGY STORAGE HYBRID SYSTEM BASED ON THE DYNAMIC LOAD

Changhui Yang[1*], Tianyi Sun [2]
1 Key Laboratory of Process Optimization and Intelligent Decision-Marking (Ministry of Education), Hefei University of Technology, Baohe District, Hefei 230002,China
2 School of Management, Hefei University of Technology, Baohe District, Hefei 230002, China

ABSTRACT

Based on the dynamic load of the client and the dynamic output power of the generator, this paper establishes the economic efficiency evaluation model of the distributed photovoltaic-energy storage hybrid system (DPV-ES), quantitatively analyzes the system by the carbon trading income, and considers the depreciation tax-deduction benefit and residual net income in the model. In the empirical case, this paper studies the cost, benefit, net present value (NPV), and payback period (PBP), and conducts sensitivity analysis for six types of policy variables. At the same time, the Multi-factors influence on the economic benefits of the system is studied. According to the empirical results, the corresponding policy recommendations are given for users and governments.

Keywords: DPV-ES, Carbon emissions trading, PBP, Policy variables, subsidy

1. INTRODUCTION

Photovoltaic energy has the advantages of clean, renewable and pollution-free. In recent years, it has entered a period of rapid development [1] [3]. In 2018, the cumulative installed capacity of photovoltaic power generation in China exceeded 170GW, an increase of 34% over the previous year, accounting for more than 9% of the total installed capacity [2] . PV generation is intermittent and unstable. Installing energy storage system in distributed photovoltaic system is an effective means to overcome the above shortcomings [3] .

At present, there are few studies related to the energy saving and emission reduction benefits of DPV-ES [4] . Even if there is, it is only a qualitative statement. In this paper, environmental benefits are incorporated into the economic efficiency analysis model of DPV-ES through carbon emissions trading.

2. MODEL OF DPV-ES ECONOMIC EFFIENCY

2.1 Cash outflow

It is assumed that the hybrid system is built on the basis of self-generation, self-use, and surplus power connected to grids.

1.The initial cash outflow C_0 is shown in Eq.1.

$$C_0 = C_{equ,DPV} \times (1 + K_{ins,DPV}) \times （1\text{-}K_{loan}) + C_{equ,ES} \times (1 + K_{ins,ES}) \quad (1)$$

Where $C_{equ,DPV}$ denotes the equipment cost of DPV,$K_{ins,DPV}$is the ratio of ES Installation cost, $C_{equ,\mathrm{ES}}$ denotes the equipment cost of ES, $K_{ins,\mathrm{ES}}$is the ratio of DPV Installation cost, K_{loan}indicates the loan ratio.

2.The Operation and maintenance costs of $C_{o\&m}$ can be expressed in Eq.2 and Eq.3.

$$C_{o\&m,DPV}(i) = C_{equ,DPV} \times (1 + K_{ins,DPV}) \times K_{o\&m,DPV} \quad (2)$$

$$C_{o\&m,ES}(i) = C_{equ,ES} \times (1 + K_{ins,ES}) \times K_{o\&m,ES} \quad (3)$$

Where $K_{o\&m,DPV}$is the ratio of DPV operation and maintenance cost, $K_{o\&m,ES}$ is the ratio of ES operation and maintenance cost.

3.The financial cost of $C_{o\&m}$ is shown in Eq.4.

$$C_{fin,DPV}(i) = C_{equ,DPV} \times (1 + K_{ins,DPV}) \times K_{loan} \times i_{loan} \quad (4)$$

Where $C_{fin,DPV}(i)$ indicates the DPV financial cost, i_{loan}denotes the lending rate.

4.The Principal repayment $\mathrm{C_{fin,DPV}(i)}$ can be expressed as Eq5 .

Consider N as the Loan term of initial investment. Loans are repaid with equal principal per year.

$$C_{loan,DPV}(i) = \frac{C_{inv,DPV} \times K_{loan}}{N} \quad (5)$$

Let $P_{load}(t)$ be the user's power load in time t (t=1,2,3⋯⋯8760), $P_s(t)$=$\mathrm{E}_{pv}\eta(t)$ be the DPV output power, WhereE_{pv}denotes the DPV installed capacity, and $\eta(t)$ denotes DPV generation efficiency.

Whereas ΔP=$P_{load}(t)$-$P_s(t)$ represents the difference between power load and output power. Then $E_{bat}(t)$ is the electric quantity stored in ES, and ES capacity has the upper limit χb_{max} and the lower limit χb_{min} .The charging and discharging efficiency of ES denote δ_{cha} and δ_{dis}respectively.

$E_{bat}(t)$ can be expressed in Eq.6.

$$\mathrm{E}_{bat}(t)=\begin{cases}\max\left[E_{bat}(t-1)-\dfrac{\vartriangle P(t-1)}{\sigma_{dis}},\lambda_{\min}E_b\right],\vartriangle P(t-1)>0\\ \min\left[E_{bat}(t-1)-\sigma_{cha}\vartriangle P(t-1),\lambda_{\max}E_b\right],\vartriangle P(t-1)\le 0\end{cases}\tag{6}$$

Therefore, purchasing quantity $q_{dis}(t)$ from power grid is given by Eq.7.

$$q_{dis}(t)=\max\left\{\vartriangle P(t)-[E_{bat}(t)-\lambda_{\min}E_b],0\right\}\tag{7}$$

5.Thus, purchasing fee $C_{ele}(i)$ can be expressed in Eq.8.

$$\mathrm{C}_{ele}(i)=h_p\sum_{t\in T_p}q_{dis}(t)+h_f\sum_{t\in T_f}q_{dis}(t)+h_v\sum_{t\in T_v}q_{dis}(t)+h_v q_{ch}\tag{8}$$

Where h_p, h_p, h_v, h_frepresent electricity price in peak hours, valley hours, normal hours respectively. q_{ch} indicates the charging quantity of ES in valley hours.

6.Let $C_{loss}(i)$ and $C_{outage}(i)$ be the Line loss fee and outage cost , which can be can be expressed in Eq.9 and Eq.10.

$$C_{loss}(i)=\left\{\left[q_{\mathrm{self}}(i)+q_{sale}(i)\right]\times\left(h_{sn}+h_{sl}\right)+q_{\mathrm{self}}(i)\times h_g\right\}\times K_{loss}\tag{9}$$

$$C_{outage}(i)=\left\{\left[q_{\mathrm{self}}(i)+q_{sale}(i)\right]\times\left(h_{sn}+h_{sl}\right)+q_{\mathrm{self}}(i)\times h_g\right\}(1-K_{outage})\tag{10}$$

Where $q_{\mathrm{self}}(i)$,$q_{sale}(i)$,$\boldsymbol{h_{sn}}$,h_{sl},$h_g$are the self-use quantity, sale quantity, national subsidy, local subsidy and local benchmark price of coal-fired units. $K_{loss}$and K_{outage}denote the line loss rate and reliability rate of power supply.

2.2 Cash inflow

2.2.1 Economic benefits

The subsidy income $I_{sub-per}(i)$ can be expressed in Eq.11.

$$I_{sub-per}(i)=(h_{sn}+h_{sl})\sum_{t\in T}P_s(t)\tag{11}$$

The self-use quantity $q_{self}(t)$ and income $I_{self}(i)$ are shown in Eq.12 and Eq.13.

$$q_{self}(t)=\begin{cases}P_{load}(t),\vartriangle P(t)\le E_{bat}(t)-\lambda_{\min}E_b\\ P_s(t)+E_{bat}(t)-\lambda_{\min}E_{b,}\vartriangle P(t)>E_{bat}(t)-\lambda_{\min}E_b\end{cases}\tag{12}$$

$$I_{self}(i)=h_p\sum_{t\in T_p}q_{self}(t)+h_f\sum_{t\in T_f}q_{self}(t)+h_v\sum_{t\in T_v}q_{self}(t)\tag{13}$$

Considering the ratio of grid-connected surplus electricity $K_{sur-sale}$, the sale quantity $q_{sale}(t)$ and the cash inflow of the surplus electricity sales $I_{sale}(i)$ can be listed as follows.

$$q_{sale}(t)=\max\left\{P_s(t)-P_{load}(t)-\left[\lambda_{\max}E_b-E_{bat}(t)\right],0\right\}\times\mathrm{K}_{sur-sale}\tag{14}$$

$$I_{sale}(i)=h_g\sum_{t\in T}q_{sale}(t)\tag{15}$$

Assuming that the tax law period is equal to its operating period n, the tax law period is equal to its operating period n, depreciation is carried out according to the sum of years, the depreciation tax-deduction benefit of DPV-ES $I_{Dep}i)$ can be expressed in Eq.16.

$$I_{Dep}(i)=\frac{\left(\mathrm{C}_{inv,DPV}+\mathrm{C}_{inv,\mathrm{ES}}-\mathrm{RV}_{\mathrm{DPV}}-\mathrm{RV}_{\mathrm{ES}}\right)\times(n-t+1)}{\left[(n+1)\times n\div 2\right]}\times t_{inc}\tag{16}$$

Where RV represents the legal residual value of DPV -ES.

The residual net income I_{RV} can be shown in Eq.17.

$$I_{\mathrm{RV}}=CR-(CRV-RV)\times t_{inc}\tag{17}$$

Where CRV denotes the realizable value of DPV-ES.

2.2.2 Environmental benefits

The income of Carbon Emission Trading $I_{coal}(i)$ is given by Eq.18.

$$I_{coal}(i)=Q_{gen}(i)\times\left(\frac{EF_{grid,OM,y}}{1-K_{loss}}\times 50\%+\frac{EF_{grid,BM,y}}{1-K_{loss}}\times 50\%\right)\times P_{coal}(i)\tag{18}$$

Where $EF'_{grid,OM,y}$ and $EF'_{grid,BM,y}$ represent the adjusted marginal emission reduction Factor of electricity and capacity. $Q_{gen}(i)$ is the power generation quantity, and $P_{coal}(i)$ is carbon trading price per carbon emission.

3. EMPIRICAL CASE

3.1 Data sources

In this paper, a new DPV-ES hybrid system installed by an enterprise user in Shanghai in 2019 which is taken as an example. The specific data as follows:

Table 1 Basic data in case

Symbol	Value
E_{pv}	100KW
n_1	25 years
$C_{equ,DPV}/\mathrm{E}_{pv}$	9000 yuan/KW
$\boldsymbol{K_{ins,DPV}}$	20%
$K_{o\&m,DPV}$	2%
$\mathrm{RV}_{\mathrm{DPV}}$	1026,000 yuan
$\mathrm{CRV}_{\mathrm{DPV}}$	0 yuan
K_{loan}	70%
i_{loan}	5.145%
E_b	50KW
$C_{equ,ES}\times(1+K_{ins,ES})$	100,000 yuan
$K_{o\&m,ES}$	2%
$\mathrm{RV}_{\mathrm{ES\text{-}1}}$	95,000 yuan
$\mathrm{CRV}_{\mathrm{ES\text{-}1}}$	0 yuan
$\mathrm{RV}_{\mathrm{ES\text{-}2}}$	36666.67 yuan

$\mathrm{CRV}_{ES\text{-}2}$	3333.33 yuan
χ_{max}	100%
χ_{min}	0%
δ_{cha}	93%
δ_{dis}	93%
h_{s_n}	0.32 yuan/KWh
h_{s_l}	0.25 yuan/KWh
h_g	0.4155 yuan/KWh
P_{coal}	35.96 yuan /t
n_1	25 years
n_2	15 years
n_3	5 years
$EF'_{grid,BM,y}$	0.4923 tCO2/MWh
$EF'_{grid,OM,y}$	0.8046 tCO2/MWh

Data sources: Refs. [3].

In summer, h_p, h_v are 0.925 yuan/KWh and 0.448 yuan/KWh. In non-summer, h_p, h_v are 0.894 yuan/KWh and 0.417 yuan/KWh.

On a certain day in 2019, according to the dynamic load of a enterpriser user and the installed DPV generation efficiency, the PV output and the user's power load curves are drawn in Fig1.

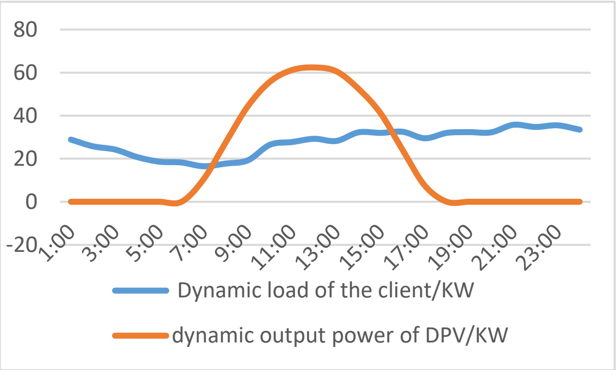

Fig 1 The PV output and the user's power load curves

3.2 Empirical results

3.2.1 Environmental benefit analysis

Details can be seen in the Table 2.

3.2.2 The sensitivity analysis of policy variables

The sensitivity analysis shows that the current carbon trading price is less sensitive to DPV-BES, which is not enough to have a significant impact on reducing PBP. If higher carbon credits can be obtained in the future, the payback period for DPV-ES operation can be further reduced. Details can be seen in Figure 2.

3.2.3 The influence of different ES capacity on benefits

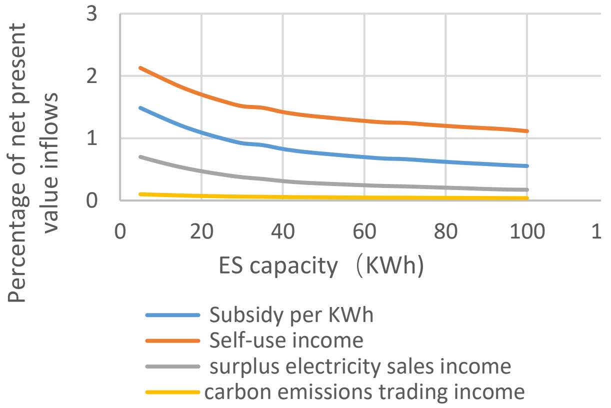

Fig 3 The ratio of different income to the net cash flow

It can be seen that the economic efficiency of DPV-BES is less dependent on governmental subsidies for DPV electricity price and the Feed-in-tariff of DPV. Figs. 3 shows the results of the sensitivity analysis.

Figs. 4 shows that the capacity of ES needs to be reasonably allocated, not the bigger the better, excessive ES capacity will limit the economic efficiency of the system.

3.2.4 The sensitivity analysis of policy variables

Under the premise of maintaining the current investment PBP of DPV-BES unchanged, electricity subsidy per KWh can be reduced appropriately.

	With the benefits of carbon emission trading	Without the benefits of carbon emission trading	Increase Or Decrease	Change ratio
NPV（RMB）	150370.93	106923.70	↑	40.63%
Static PBP（Year）	10.53	11	↓	-4.32%
Dynamic PBP（Year）	18.23	20.21	↓	-10.86%
IRR	10.39%	9.70%	↑	7.15%

Table 2 Economic benefit assessment of DPV-ES Hybrid System

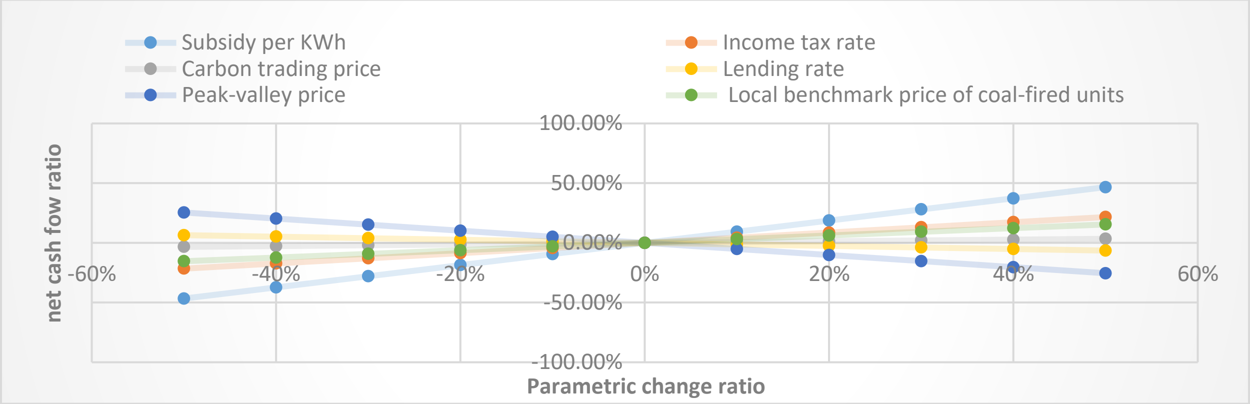

Fig2 The sensitivity analysis of policy variables

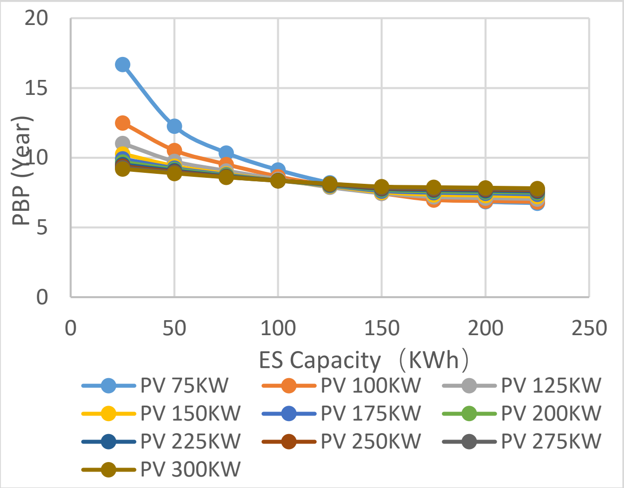

Fig 4 The influence of ES capacity on PBP

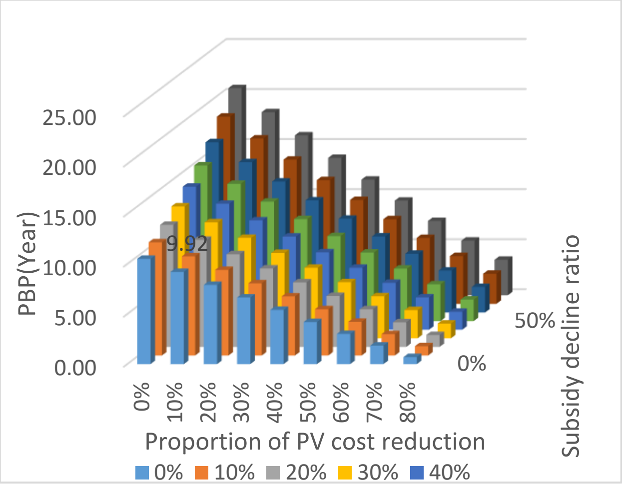

Fig5 Integrated Impact of PV Cost and Electricity Subsidy

The above Figs. 5 shows that with the development of PV module technology, the installed cost of PV system is decreasing. When the cost of PV drops by 60%, even if the government cancels the subsidies for DPV generation, the PBP for hybrid systems will still be reduced to 9.56 years.

4. CONCLUSION

Carbon trading helps to improve the overall economic benefits of system operation. The economic Efficiency of DPV-ES is less dependent on government photovoltaic price subsidy and distributed photovoltaic grid-connected price currently. Compared with the unit cost of ES, the unit cost of PV has a greater impact on the economy of hybrid system. Under the same cost of PV equipment, installing distributed photovoltaic equipment with larger installed capacity can effectively reduce the payback period of hybrid system investment.

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